Appendix G: Cost Risk and Uncertainty Methodologies

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:

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).[1] 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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[1] 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[2]; Fuguitt and Wilcox, 1999, pp. 140–141[3]; Garvey, 2000, p. 27[4]; and Hubbard, 2010, pp. 49–50[5]. Most notably, the GAO’s Cost Estimating and Assessment Guide differentiates risk and uncertainty using the following definitions (General Accountability Office, 2009)[6]:

- **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[7] 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,[8] 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-

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[2] Knight, Frank H. (1921) *Risk, Uncertainty, and Profit.*

[3] Fuguitt, Diana; and Wilcox, Shanton J. (1999) *Cost-Benefit Analysis for Public Sector Decision Makers*. Praeger.

[4] Garvey, P. R. (2000). *Probability Methods for Cost Uncertainty Analysis: A Systems Engineering Perspective.* New York: Marcel Dekker.

[5] Hubbard, D. W. (2010). *How to Measure Anything.* John Wiley & Sons, Inc.

[6] 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.

[7] Risks can also be opportunities if the outcome of the event is a positive outcome.

[8] 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[9]:

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, defendable, 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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[9] 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)[10] 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.[11] 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[12]; 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.[13]

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[10] For more information on JCL, refer to Appendix J.

[11] See NPR 7120.5E at http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5E.

[12] 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.

[13] 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.

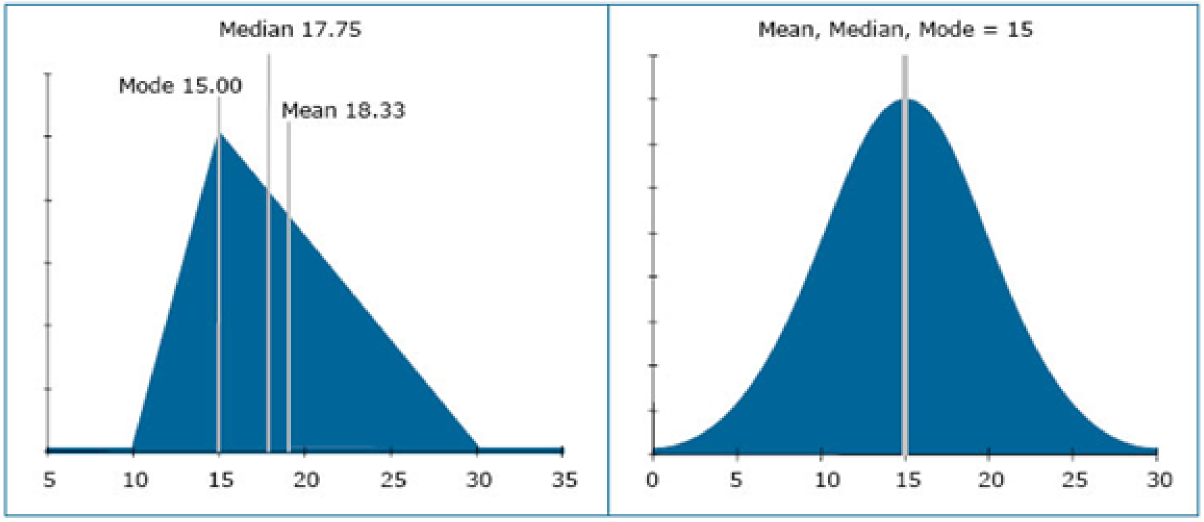

Figure G-2. Statistics of Triangular and Normal Distributions

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.

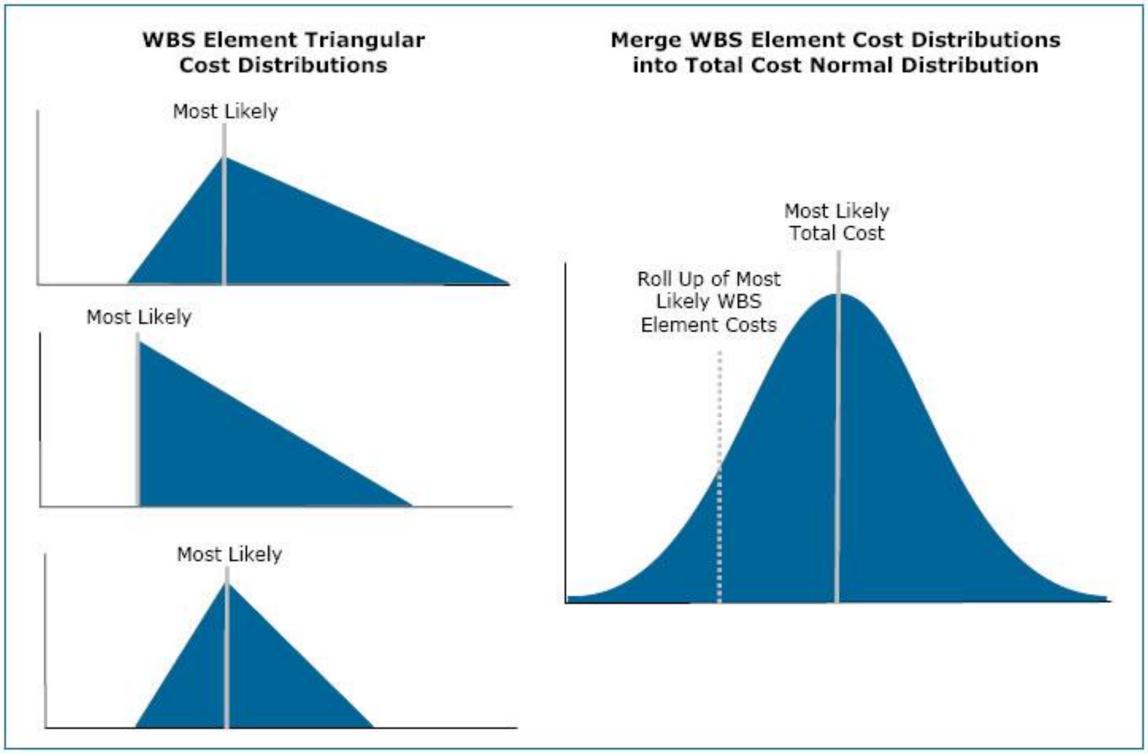

Figure G-3. Central Limit Theorem

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.

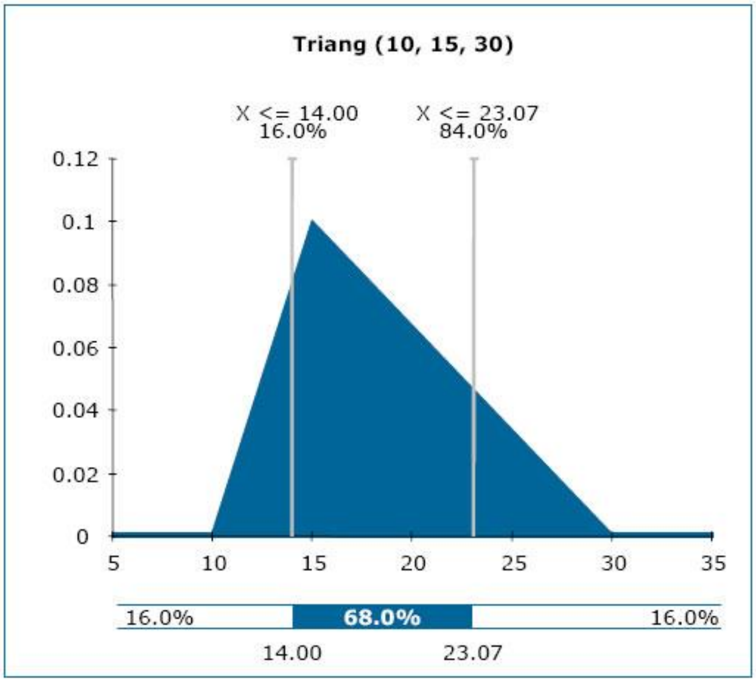

Figure G-4. Triangular Distribution Example

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.

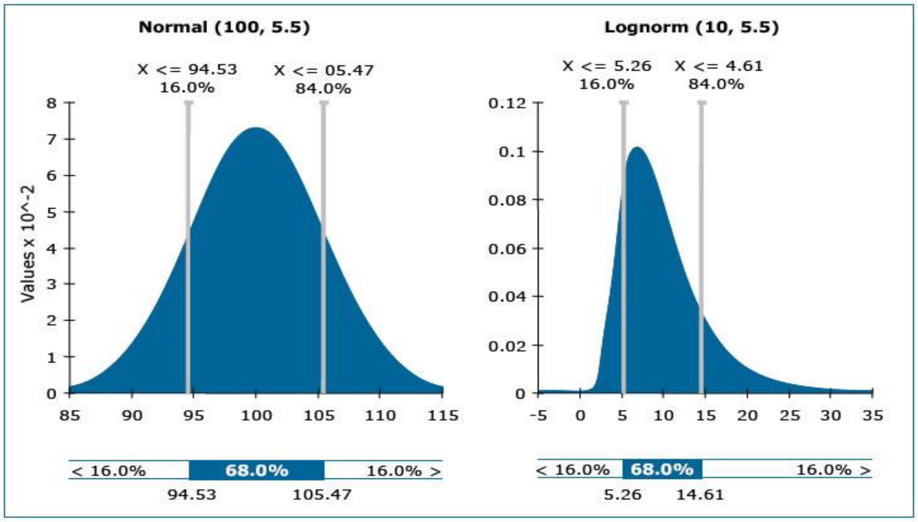

Figure G-5. Normal and Lognormal Distributions

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.
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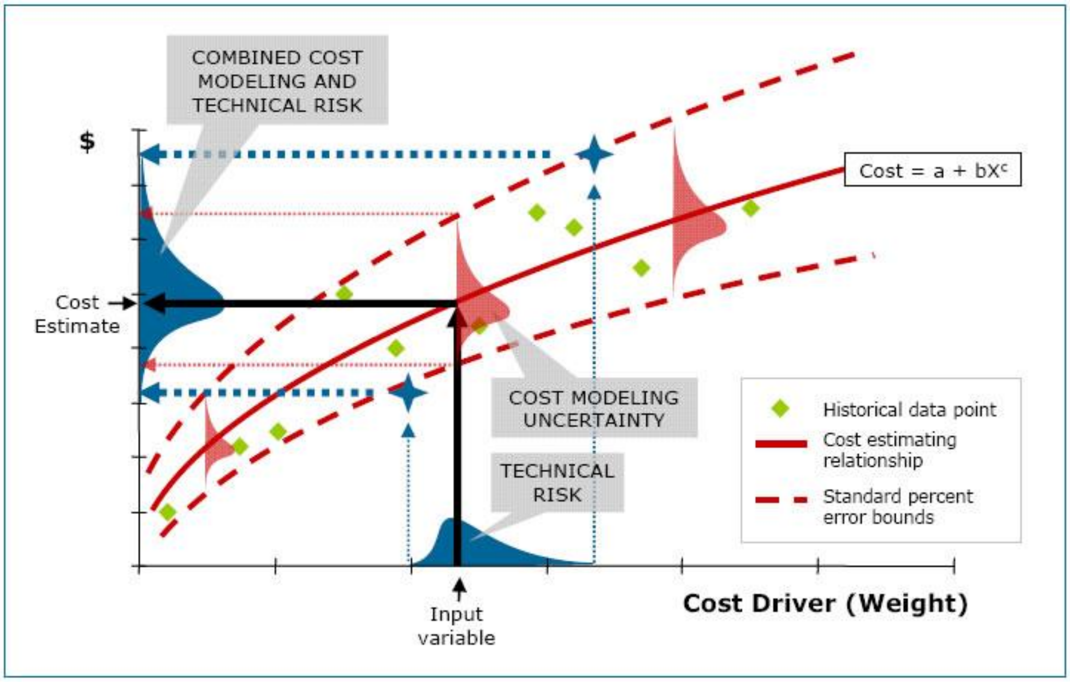

Figure G-6. Cost Modeling and Technical Input Risk

- **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[14] 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.[15] Commercially available products such as Crystal Ball, @RISK, and the Automated Cost Estimator (ACE)

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[14] https://www.ncca.navy.mil/tools/csruh/index.cfm

[15] 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.[16]

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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[16] 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.[17] 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 = ±0.02; mild: r = ±0.2; moderate: r = ±0.6; and high: r = ±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.[18]

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).

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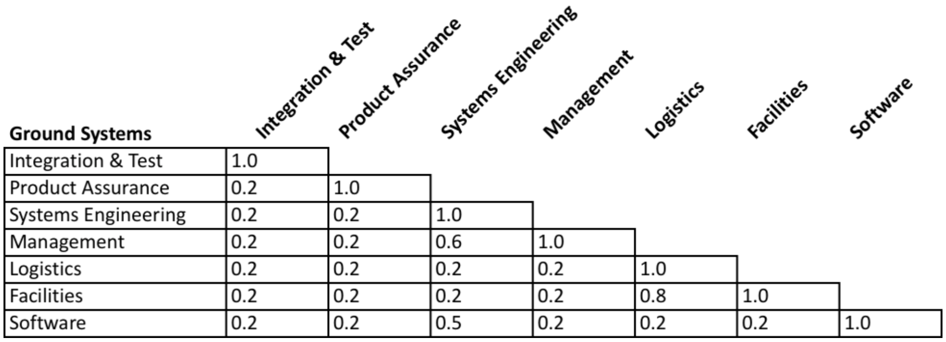
[17] Correlation of Spacecraft Mission and Project Costs, C. Swan, S. Jarrett, JPL, July 2007 (unpublished).

[18] 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[19]



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 ≈ 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.

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[19] SSCRH, p. 28, November 2005.

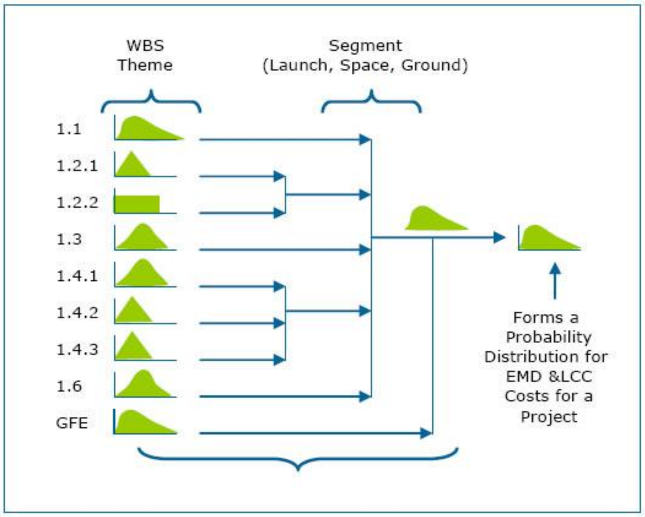

Figure G-7. Statistical Summation Process Results

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:[20]

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.[21] 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.[22]

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.[23]

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*.

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[20] 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.

[21] 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.

[22] AFCRUH, pp. 36–37, April 2007.

[23] 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*

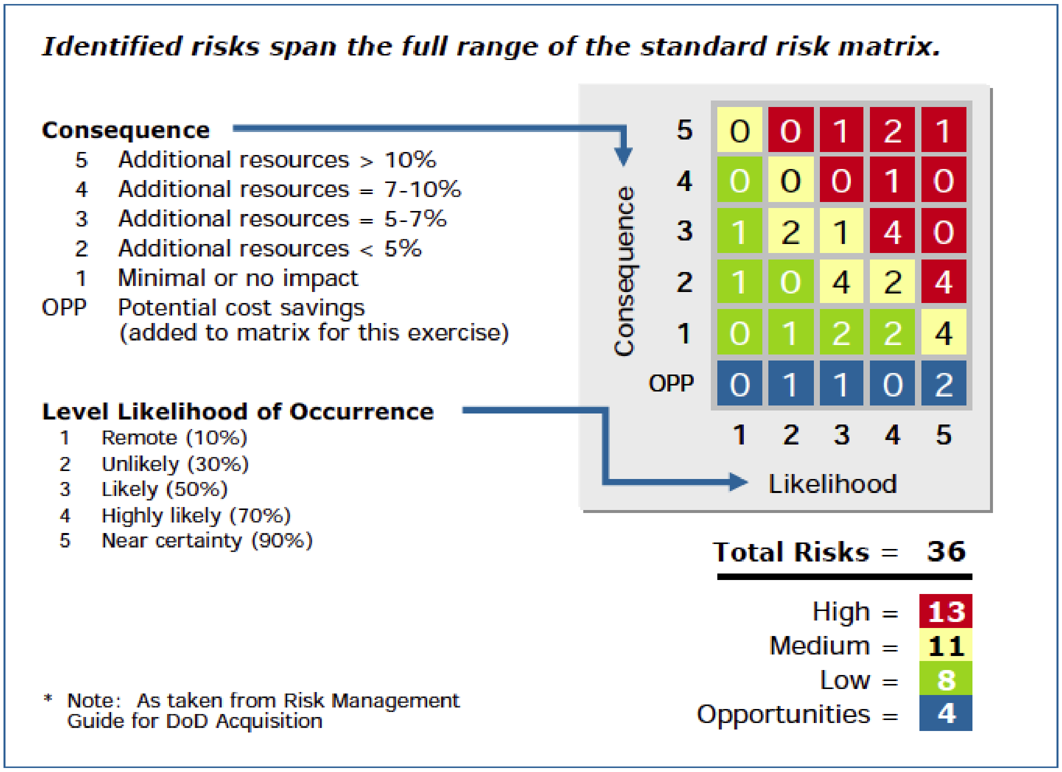
Another cost estimating approach combines scenario-based identification and assessment of the specific risk scenarios with probabilistic analysis of the cost-risk consequences that may occur to create a risk-adjusted cost estimate. This cost-risk assessment and analysis approach (known as the Hybrid 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).



Identified risks span the full range of the standard risk matrix.

Consequence

5 Additional resources > 10%
4 Additional resources = 7-10%
3 Additional resources = 5-7%
2 Additional resources < 5%
1 Minimal or no impact
OPP Potential cost savings (added to matrix for this exercise)

Level Likelihood of Occurrence

1 Remote (10%)
2 Unlikely (30%)
3 Likely (50%)
4 Highly likely (70%)
5 Near certainty (90%)

Consequence	1	2	3	4	5
5	0	0	1	2	1
4	0	0	0	1	0
3	1	2	1	4	0
2	1	0	4	2	4
1	0	1	2	2	4
OPP	0	1	1	0	2

Total Risks = 36

High = 13
Medium = 11
Low = 8
Opportunities = 4

* Note: As taken from Risk Management Guide for DoD Acquisition

Figure G-8. 5 × 5 Risk Matrix (Also Known as a Stoplight Matrix)

Step 3—Run Simulation

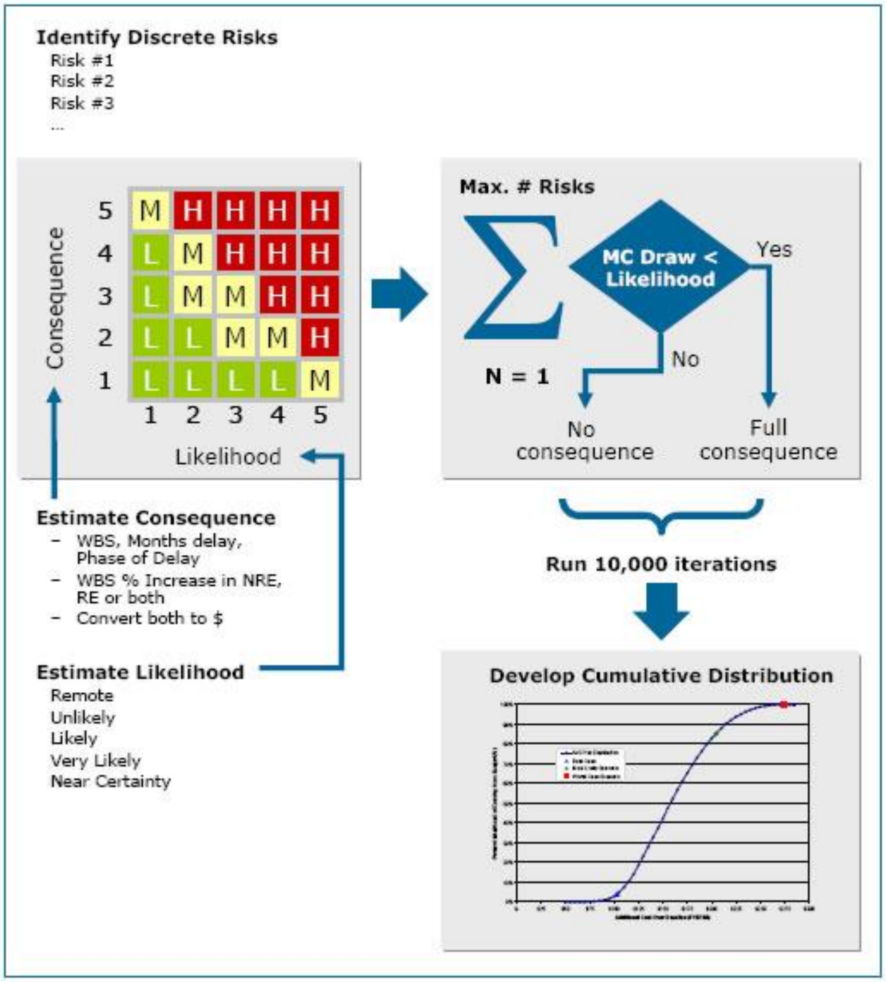
In this step, the cost estimator uses a Monte Carlo simulation to produce a distribution of cost-risk impact that identifies confidence levels associated with each cost value in the range of a cost-risk distribution.

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.



Consequence					
5	M	H	H	H	H
4	L	M	H	H	H
3	L	M	M	H	H
2	L	L	M	M	H
1	L	L	L	L	M
	1	2	3	4	5

Figure G-9. 5 × 5 Matrix Cost-Risk Conversion Process Summary

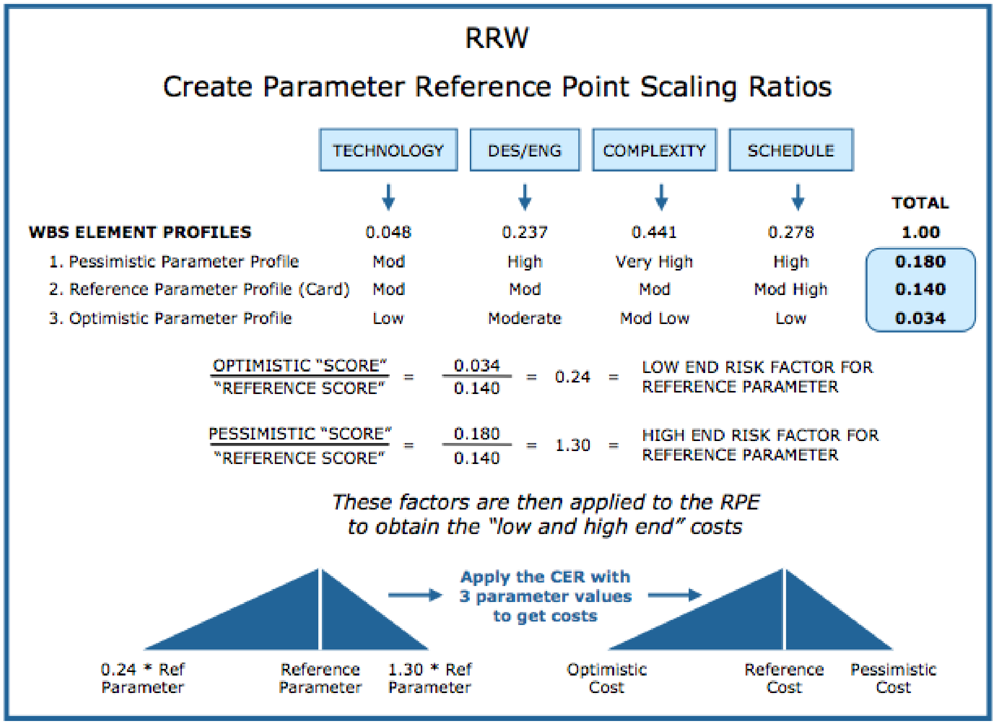
G.3. Discrete Risk Analysis

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.



WBS ELEMENT PROFILES	TECHNOLOGY	DES/ENG	COMPLEXITY	SCHEDULE	TOTAL
	0.048	0.237	0.441	0.278	1.00
1. Pessimistic Parameter Profile	Mod	High	Very High	High	0.180
2. Reference Parameter Profile (Card)	Mod	Mod	Mod	Mod High	0.140
3. Optimistic Parameter Profile	Low	Moderate	Mod Low	Low	0.034

$$\frac{\text{OPTIMISTIC "SCORE"}}{\text{"REFERENCE SCORE"}} = \frac{0.034}{0.140} = 0.24 = \text{LOW END RISK FACTOR FOR REFERENCE PARAMETER}$$

$$\frac{\text{PESSIMISTIC "SCORE"}}{\text{"REFERENCE SCORE"}} = \frac{0.180}{0.140} = 1.30 = \text{HIGH END RISK FACTOR FOR REFERENCE PARAMETER}$$

These factors are then applied to the RPE to obtain the "low and high end" costs

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.[24]

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[24] AFCRUH and SSCRH both provide guidance and examples on performing sensitivity analyses.

G.3.2. *Program Portfolio Effect*[25]

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[26]

		Portfolio Probability	
# Projects	Project 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

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[25] AFCRUH, p. 45, April 2007.

[26] AFCRUH, 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.[27] 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.

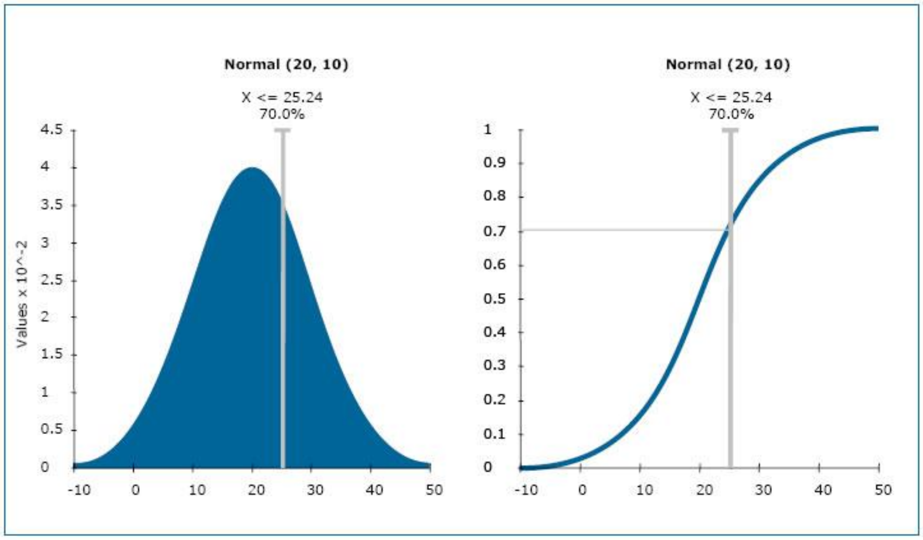

Figure G-11. Probability Density Function (PDF) and Equivalent Cumulative Density Function (CDF or S-Curve)

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.

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[27] 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 [(70th – 50th) / 50th] × 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 Cystal 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[28] 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.

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[28] 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[29] 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)[30] mean of the “least,” “likely,” and “most” values.

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[29] For more information, visit http://www.galorath.com.

[30] 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)[31] 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.

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[31] 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*.

- 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:

$$Y = aX_1^{b1}X_2^{b2} \ldots X_n^{bn}$$

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

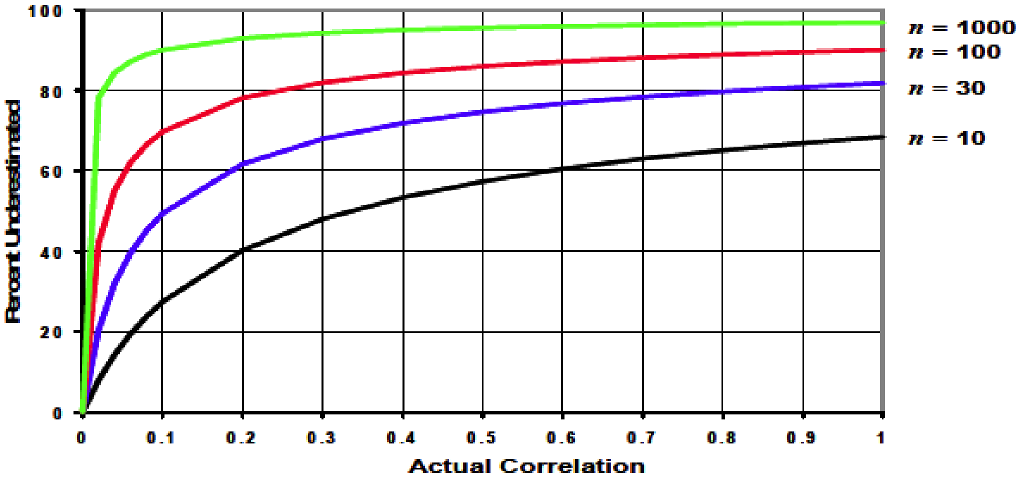

Figure G-12. Effect of Correlation on Estimates

G.4.4. Automated Cost Estimating Integrated Tools (ACEIT) and JACS

ACEIT[32] 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

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[32] For more information, visit http://www.aceit.com or contact 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.

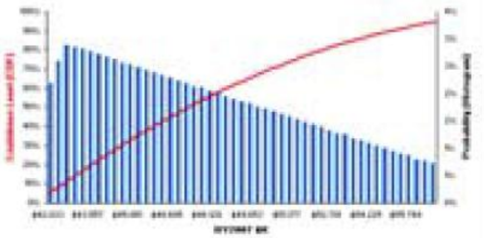
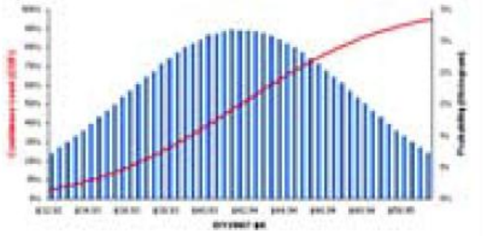
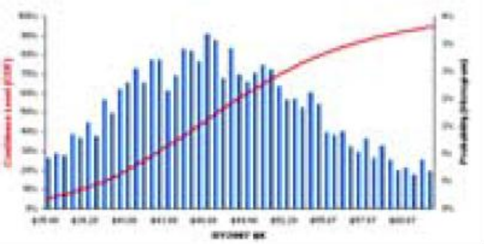
	5% Value	Most Likely Value	95% Value	Distribution Shape
Calculated uncertainty with distribution only on the CER Inputs	**93%**	**$43 K**	**133%**	
Calculated uncertainty with distribution only on the CER	**75%**	**$43 K**	**125%**	
Calculated uncertainty with distribution the CER and the CER Inputs	**81%**	**$43 K**	**144%**	

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.[33] 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.

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[33] 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.

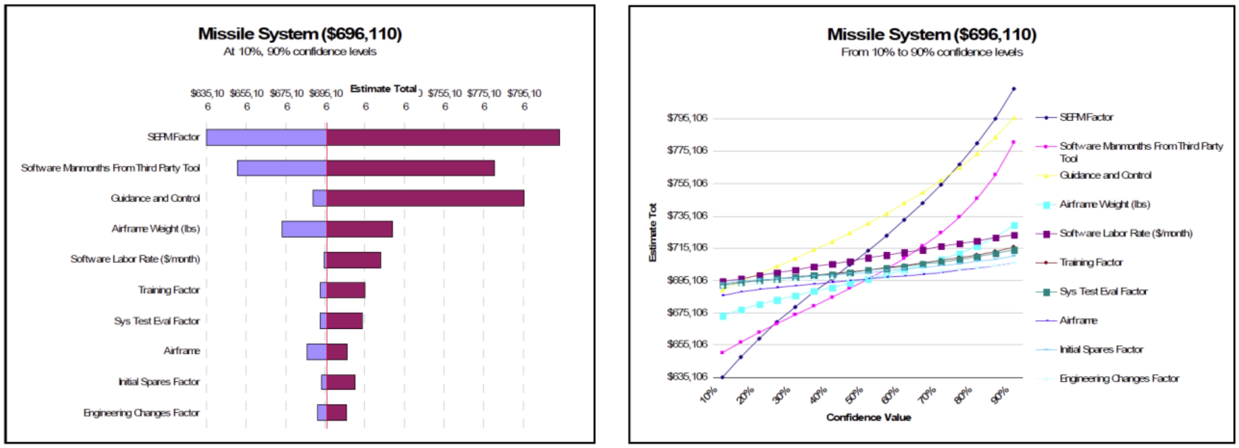

Figure G-14. Future ACEIT Cost-Risk Output Reports

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.[34]

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.[35]

G.4.6. Crystal Ball

Crystal Ball[36] 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).

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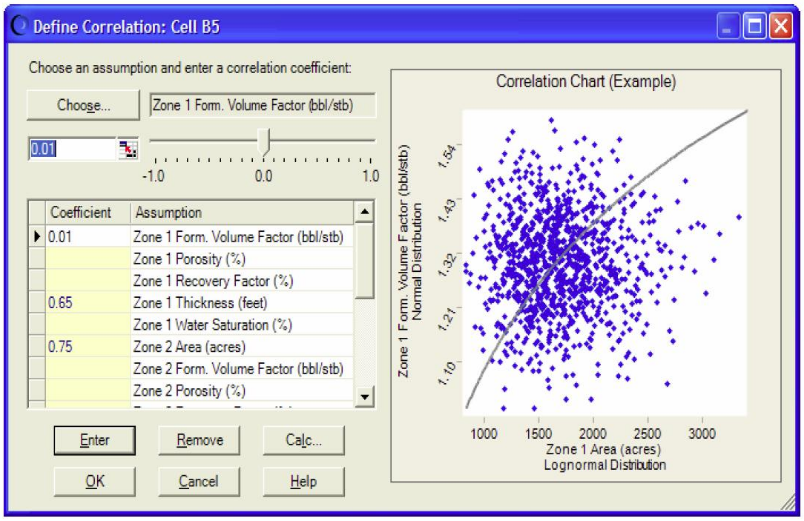
[34] For an explanation of Polaris, visit *http://www.boozallen.com/consulting/products/software/polaris*.

[35] For an explanation of Argo, visit *http://www.boozallen.com/consulting/products/software/argo*.

[36] For more information, visit the Oracle Crystal Ball website at http://www.oracle.com/us/products/applications/crystalball/overview/index.html.



Choose an assumption and enter a correlation coefficient:

Zone 1 Form. Volume Factor (bbl/stb)

0.01

Coefficient	Assumption
0.01	Zone 1 Form. Volume Factor (bbl/stb)
	Zone 1 Porosity (%)
	Zone 1 Recovery Factor (%)
0.65	Zone 1 Thickness (feet)
	Zone 1 Water Saturation (%)
0.75	Zone 2 Area (acres)
	Zone 2 Form. Volume Factor (bbl/stb)
	Zone 2 Porosity (%)

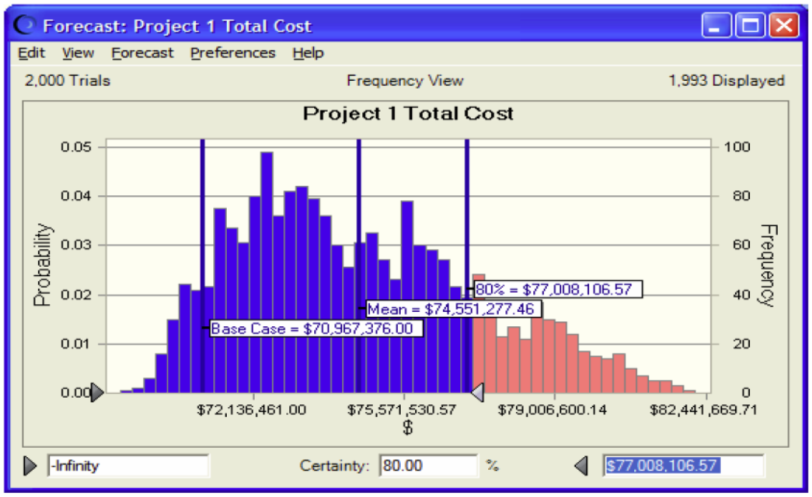
Figure G-15. Crystal Ball Cost-Risk Output Screen

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).



-Infinity

Certainty: 80.00 %

$77,008,106.57

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[37] 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[38] 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.[39]

1. The first step is to identify the project flight system WBS that will be modeled by the Monte Carlo simulation (Figure G-17).

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[37] For more information on @Risk, visit the Palisade website at http://www.palisade.com/risk/.

[38] Sample S-Curve Analysis, David Connor, JPL, August 2011.

[39] Use of @RISK in this example should not be taken as an endorsement. It met the requirements of the analysis and was readily available.

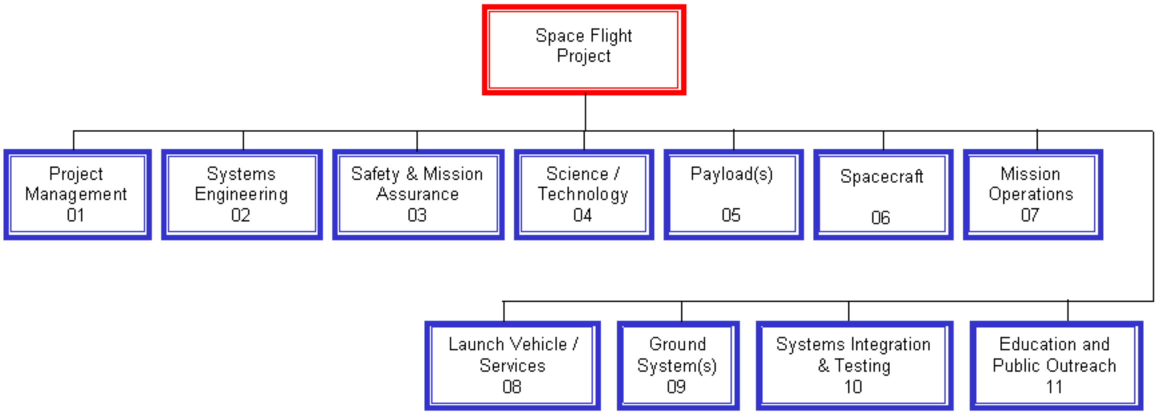

Figure G-17. NASA Standard Level 2 WBS Elements for Space Flight Projects[40]

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

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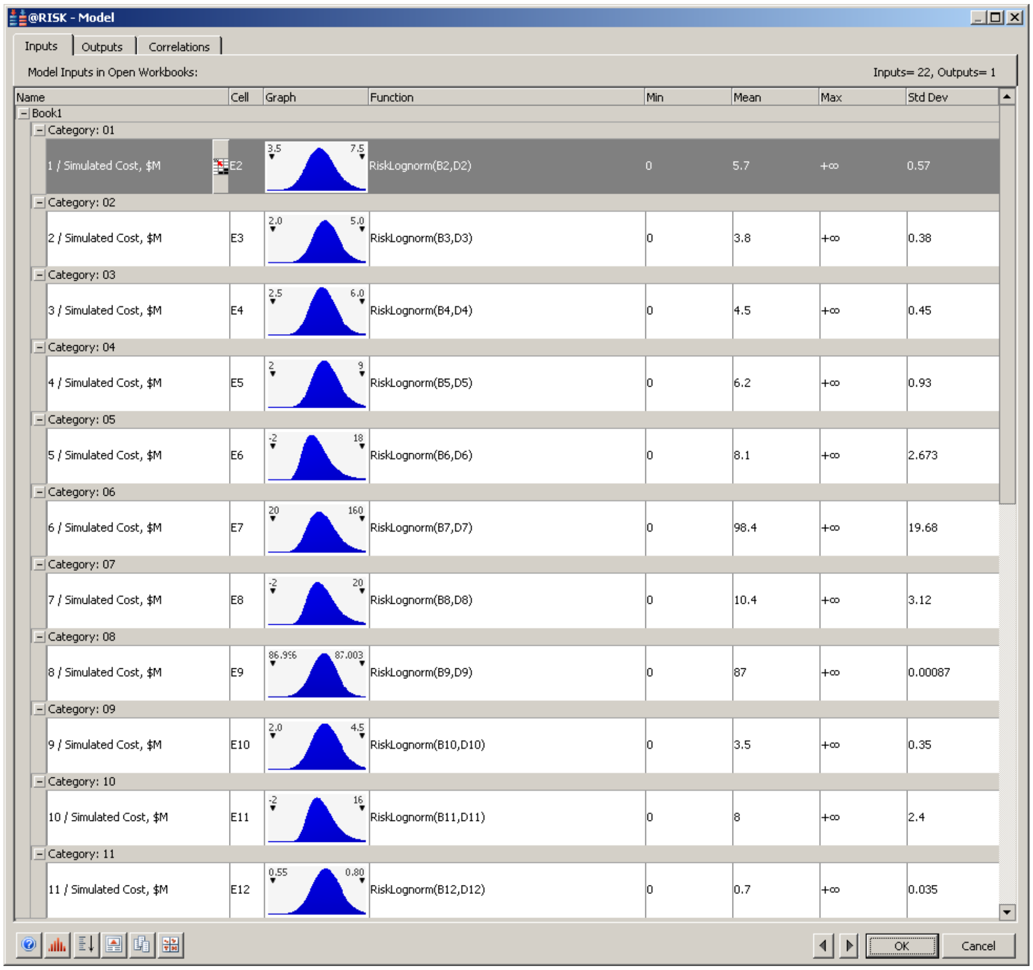
[40] NPR 7120.5E, Appendix H, Space Flight Project Work Breakdown Structure (WBS), August 2012.



Model Inputs in Open Workbooks:

Inputs= 22, Outputs= 1

Name	Cell	Graph	Function	Min	Mean	Max	Std Dev
Book1							
Category: 01							
1 / Simulated Cost, $M	E2	3.5 7.5	RiskLognorm(B2,D2)	0	5.7	+∞	0.57
Category: 02							
2 / Simulated Cost, $M	E3	2.0 5.0	RiskLognorm(B3,D3)	0	3.8	+∞	0.38
Category: 03							
3 / Simulated Cost, $M	E4	2.5 6.0	RiskLognorm(B4,D4)	0	4.5	+∞	0.45
Category: 04							
4 / Simulated Cost, $M	E5	2 9	RiskLognorm(B5,D5)	0	6.2	+∞	0.93
Category: 05							
5 / Simulated Cost, $M	E6	-2 18	RiskLognorm(B6,D6)	0	8.1	+∞	2.673
Category: 06							
6 / Simulated Cost, $M	E7	20 160	RiskLognorm(B7,D7)	0	98.4	+∞	19.68
Category: 07							
7 / Simulated Cost, $M	E8	-2 20	RiskLognorm(B8,D8)	0	10.4	+∞	3.12
Category: 08							
8 / Simulated Cost, $M	E9	86.996 87.003	RiskLognorm(B9,D9)	0	87	+∞	0.00087
Category: 09							
9 / Simulated Cost, $M	E10	2.0 4.5	RiskLognorm(B10,D10)	0	3.5	+∞	0.35
Category: 10							
10 / Simulated Cost, $M	E11	-2 16	RiskLognorm(B11,D11)	0	8	+∞	2.4
Category: 11							
11 / Simulated Cost, $M	E12	0.55 0.80	RiskLognorm(B12,D12)	0	0.7	+∞	0.035

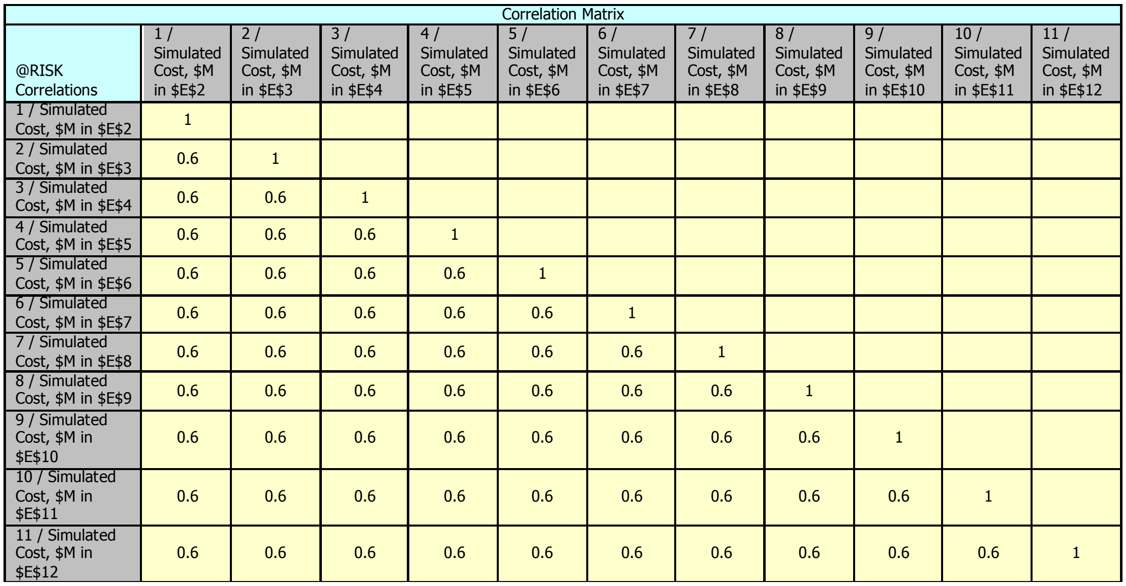
Figure G-18. WBS Distributions (Before Correlation)

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.

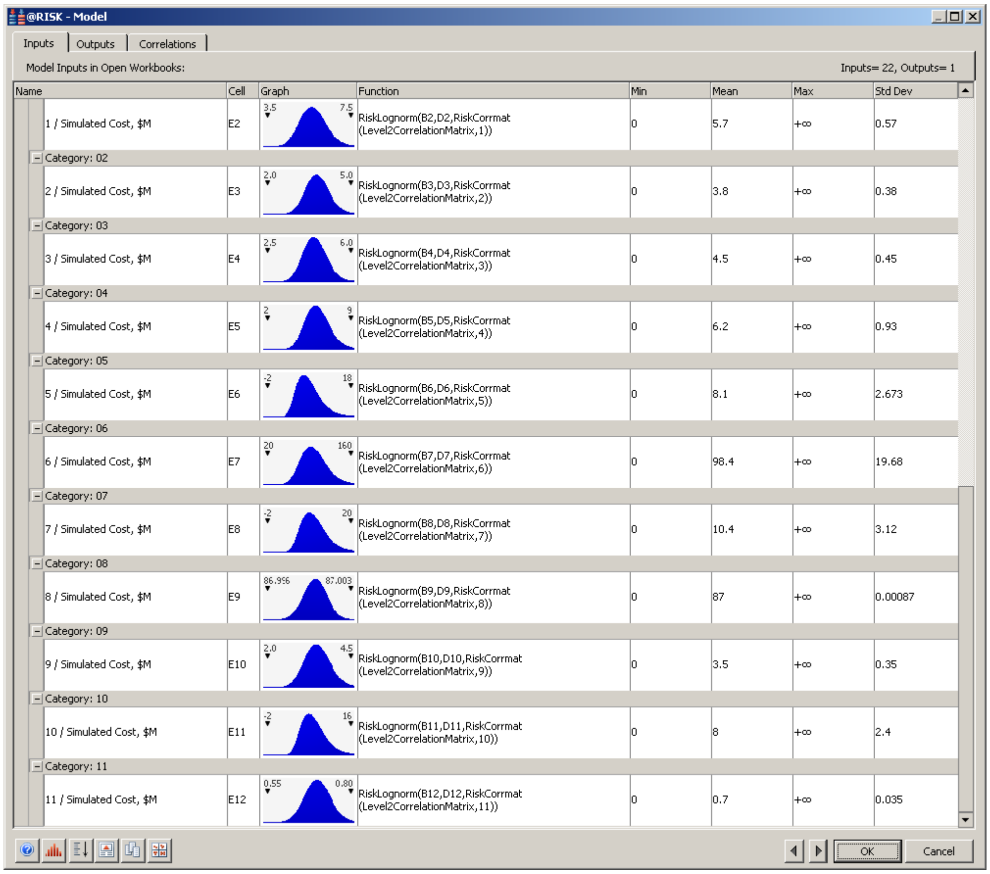
Table G-5. Correlation Matrix

Level 2 WBS Elements Cost and Uncertainty with Correlation				
WBS	**Cost, $M (Mean)**	**Uncertainty, ±1 Standard Deviation (%)**	**Uncertainty, ±1 Standard Deviation ($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
Total				**241.5**

Table G-6. Level 2 WBS Element Cost and Uncertainty with Correlation



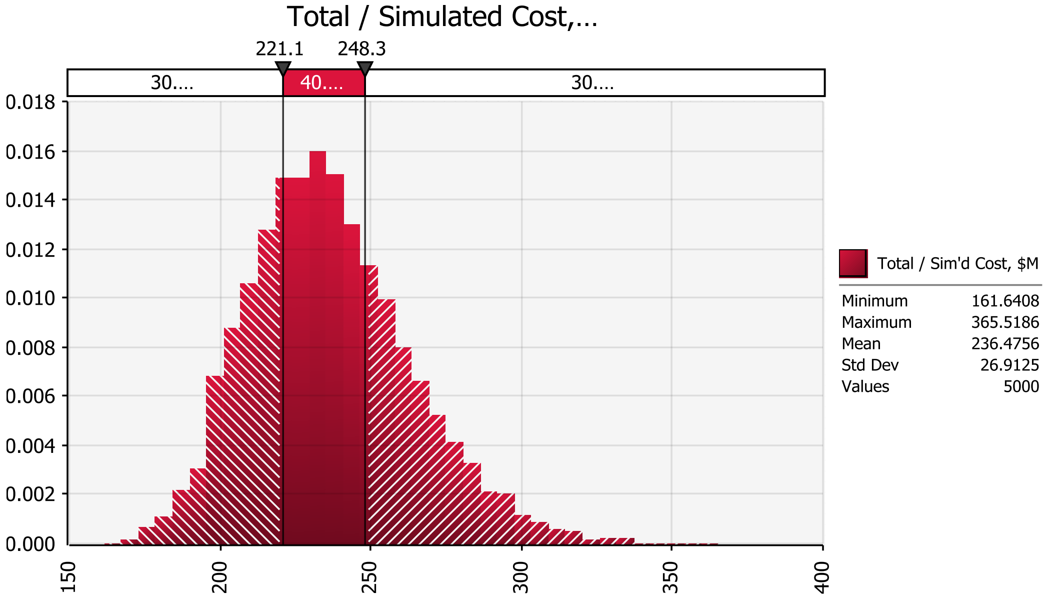
Correlation Matrix											
@RISK Correlations	1 / Simulated Cost, $M in E2	2 / Simulated Cost, $M in E3	3 / Simulated Cost, $M in E4	4 / Simulated Cost, $M in E5	5 / Simulated Cost, $M in E6	6 / Simulated Cost, $M in E7	7 / Simulated Cost, $M in E8	8 / Simulated Cost, $M in E9	9 / Simulated Cost, $M in E10	10 / Simulated Cost, $M in E11	11 / Simulated Cost, $M in E12
1 / Simulated Cost, $M in E2	1										
2 / Simulated Cost, $M in E3	0.6	1									
3 / Simulated Cost, $M in E4	0.6	0.6	1								
4 / Simulated Cost, $M in E5	0.6	0.6	0.6	1							
5 / Simulated Cost, $M in E6	0.6	0.6	0.6	0.6	1						
6 / Simulated Cost, $M in E7	0.6	0.6	0.6	0.6	0.6	1					
7 / Simulated Cost, $M in E8	0.6	0.6	0.6	0.6	0.6	0.6	1				
8 / Simulated Cost, $M in E9	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1			
9 / Simulated Cost, $M in E10	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1		
10 / Simulated Cost, $M in E11	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1	
11 / Simulated Cost, $M in E12	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1



Model Inputs in Open Workbooks: Inputs= 22, Outputs= 1

Name	Cell	Graph	Function	Min	Mean	Max	Std Dev
1 / Simulated Cost, $M	E2	3.5 7.5	RiskLognorm(B2,D2,RiskCorrmat (Level2CorrelationMatrix,1))	0	5.7	+∞	0.57
Category: 02							
2 / Simulated Cost, $M	E3	2.0 5.0	RiskLognorm(B3,D3,RiskCorrmat (Level2CorrelationMatrix,2))	0	3.8	+∞	0.38
Category: 03							
3 / Simulated Cost, $M	E4	2.5 6.0	RiskLognorm(B4,D4,RiskCorrmat (Level2CorrelationMatrix,3))	0	4.5	+∞	0.45
Category: 04							
4 / Simulated Cost, $M	E5	2 9	RiskLognorm(B5,D5,RiskCorrmat (Level2CorrelationMatrix,4))	0	6.2	+∞	0.93
Category: 05							
5 / Simulated Cost, $M	E6	-2 18	RiskLognorm(B6,D6,RiskCorrmat (Level2CorrelationMatrix,5))	0	8.1	+∞	2.673
Category: 06							
6 / Simulated Cost, $M	E7	20 160	RiskLognorm(B7,D7,RiskCorrmat (Level2CorrelationMatrix,6))	0	98.4	+∞	19.68
Category: 07							
7 / Simulated Cost, $M	E8	-2 20	RiskLognorm(B8,D8,RiskCorrmat (Level2CorrelationMatrix,7))	0	10.4	+∞	3.12
Category: 08							
8 / Simulated Cost, $M	E9	86.996 87.003	RiskLognorm(B9,D9,RiskCorrmat (Level2CorrelationMatrix,8))	0	87	+∞	0.00087
Category: 09							
9 / Simulated Cost, $M	E10	2.0 4.5	RiskLognorm(B10,D10,RiskCorrmat (Level2CorrelationMatrix,9))	0	3.5	+∞	0.35
Category: 10							
10 / Simulated Cost, $M	E11	-2 16	RiskLognorm(B11,D11,RiskCorrmat (Level2CorrelationMatrix,10))	0	8	+∞	2.4
Category: 11							
11 / Simulated Cost, $M	E12	0.55 0.80	RiskLognorm(B12,D12,RiskCorrmat (Level2CorrelationMatrix,11))	0	0.7	+∞	0.035

Figure G-19. WBS Distributions (After Correlation)



Total / Sim'd Cost, $M	
Minimum	161.6408
Maximum	365.5186
Mean	236.4756
Std Dev	26.9125
Values	5000

Figure G-20. Probability Density Function

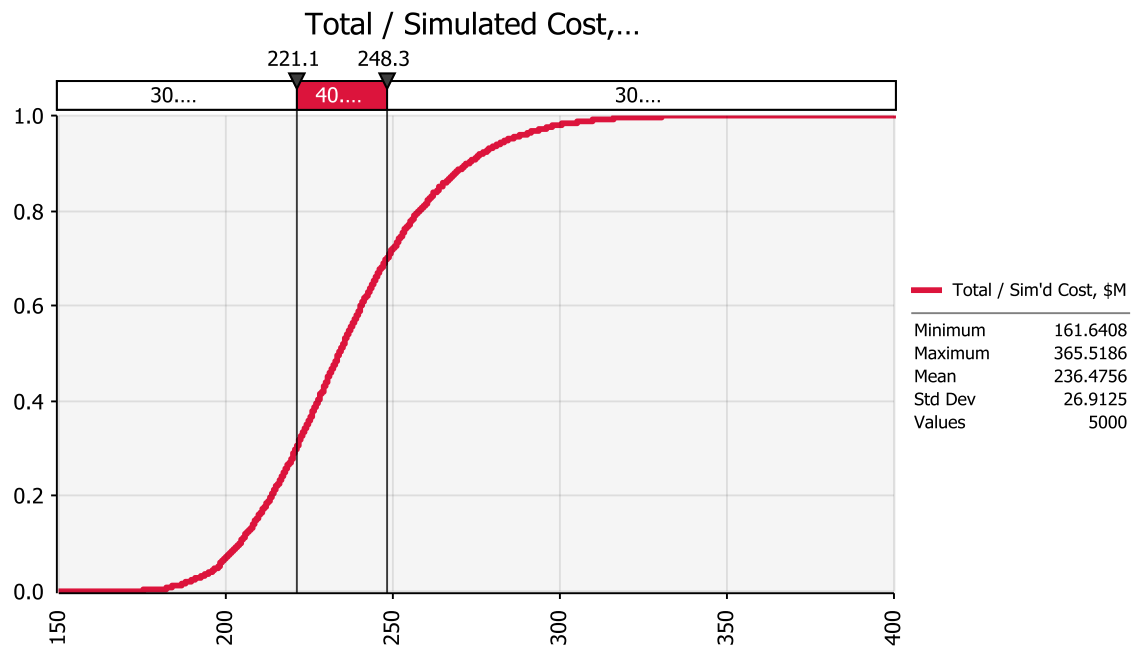


Figure G-21. Cumulative Density Function (CDF) for Total Cost (S-Curve)

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.