Quantifying Cost Risk Early in the Life Cycle

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Abstract. A new method for analyzing life cycle cost risk on large programs is presented that responds to an increased emphasis on improving sustainability for long-term programs. This method provides better long-term risk assessment and risk management techniques. It combines standard Monte Carlo analysis of risk drivers and a new data-driven method developed by the Hoy and Hudak (1994). The approach permits quantification of risks throughout the entire life cycle without resorting to difficult to support subjective methods. The Hoy-Hudak methodology is shown to be relatively straightforward to apply to a specific component or process within a project using standard technical risk assessment methods. The total impact on system is obtained using the program WBS, which allows for the capture of correlated risks shared by multiple WBS items. Once the correlations and individual component risks are captured, a Monte Carlo simulation can be run using a modeling tool such as Analytica to produce the overall life cycle cost risk.

INTRODUCTION

Projects need to quantify risk at various stages of a project starting with the conceptual phase, so that suppliers can make a bid proposal that has a reasonable chance to be profitable and so that managers can prepare a budget that has adequate reserves and a financing method that is prepared to respond to the cost risks that are inherent in the project. Cost analysts often use subjective probability assessment techniques to quantify cost risk based on engineering judgment from designers, who provide the most likely, most optimistic, and most pessimistic outcomes for items being costed. Quantifying cost risk using this "traditional" approach before a reasonably firm design is available during the conceptual design phase of a project is not readily supported by engineering judgment due to the lack of specificity in the design.

Life cycle cost analysis, which is one of the key objectives that is considered in conceptual design and architecture trade studies (Buede, 2004), is particularly vulnerable to this problem as the actual hardware and software design represents only a very small part of the life cycle cost when compared with operating and disposal costs, which have significant uncertainty in early project stages. Some traditional cost risk assessment may be possible for the engineering and development costs that will be incurred in the near term, but generally it is not feasible for costs that will be incurred in later years of the project because specific risk drivers are hard to pin down and the project scope is frequently subject to change. Cost of operations will carry significant risk until the design is advanced and has increasing risk the further out in time the projection goes. The cost of closure and dismantlement will remain quite uncertain until very late in a program due to regulatory uncertainty if nothing else.

The Civilian Radioactive Waste Management System (CRWMS), commonly known as the Yucca Mountain Project, has a life cycle cost time horizon of 120 years. Such a long time frame exacerbates the uncertainty in cost data and has provided the motivation to examine new approaches to assessing risk in early stages of a project life. Research of the available literature identified the potential of the method developed by Hoy and Hudak (1994) for the U.S. Defense Airborne Reconnaissance Office that has been used by the U.S. Department of Defense Ballistic Missile Defense Office (BMDO). The Hoy-Hudak method is a very reasonable basis for estimating risk even where there is little design specificity. The large investment the U.S. Department of Defense in statistical analysis of historical cost data correlated actual cost changes to technical risk assessment levels that are more readily assessed when there is less specificity in a design concept.

COST RISK ASSESSMENT METHODS

Monte Carlo analysis of project costs has become increasingly more common due to several factors:

1. decision makers have a desire for better analytical underpinnings to manage project risks, which includes a stronger rationale for managing contingency funds
2. the introduction of computer hardware and software that permits Monte Carlo analysis in spreadsheets and project planning software
3. requirements by governmental agencies for treatment of uncertainty in regulatory analysis (OMB, 2003)

To implement Monte Carlo analysis requires assessment of the probability distributions of the input variables. The traditional method of assessing cost risk probability distributions is to directly assess expected cost ranges and convert them to a probability distribution for Monte Carlo analysis. An alternative approach is to assess the underlying technical risk parameters that are driving the cost ranges and to use these parameters to define the cost risk probability distribution.

Traditional Cost Risk Assessment Methods. The traditional method for assessing cost is to provide inputs from engineering design staff that capture the range of uncertainty for individual cost accounts within a Work Breakdown Structure (WBS). Figure 1 illustrates the triangular probability distribution for a high uncertainty project where the baseline estimate is the most likely value for project cost, a 50 percent under run is the minimum value, and a 175 percent overrun is the maximum value. The triangular distribution is skewed to the right, because the maximum uncertainty range is a higher percentage of the baseline than the minimum,

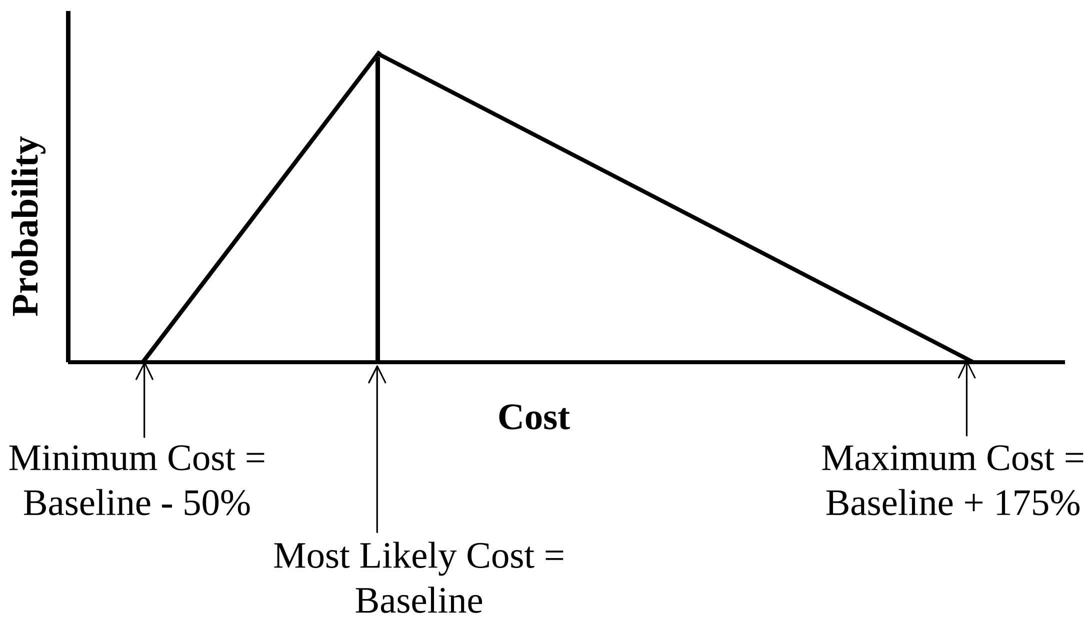

Figure 1. A Typical Probability Distribution Used for Cost Risk Assessment

For reasonably well-defined designs for which the anticipated costs are not incurred over a very long period of time, this assessment approach is reasonable. There are several issues with using this assessment approach for conceptual designs and for operational costs that occur much further in the future.

1. The engineering design staff may provide inaccurate assessments due to inadequate experience on multiple projects to provide the assessment;
2. the design may be so immature and lack enough detail, so that even experienced design staff may not be able to accurately assess the range of possible outcomes; and
3. program management may not tolerate the potential for large overruns, and thus would influence the engineering staff to bias their maximum cost risk assessments downward.

U.S. Defense Historical Data And Cost Risk Assessment Method. An alternate approach to assessing cost risk for large-scale, long-term projects was developed by Hoy and Hudak (1994) and applied by the Ballistic Missile Defense Organization (BMDO, 2001). It uses the correlation of technical risk scores to actual cost overrun experience on multiple programs and therefore has a strong empirical foundation that is missing in more subjective approaches.

A risk score is used as a measure of the technical analyst's confidence regarding the achievability of the requirements given by the program director. This confidence is then used to determine the parameters of the expected cost growth distribution. The greater the analyst's confidence (the lower the risk score), the greater the likelihood that the final program cost will be less than the initial point estimate and the lower the likelihood that the final program cost will exceed the initial point estimate. Conversely, as confidence level decreases (risk score increases), there is a greater probability that the final program cost will exceed the initial point estimate.

Risk scores used on various U.S. defense projects range from 0 to 10 and are determined using a variety of scales that are adapted to the particular item being assessed. Assessing risk scores is well within the capability of design engineers with modest training, as it only requires the ability to assess how well the design information data is known according to a structured scale. For conceptual design, perhaps the most important risk scale is the Requirements Maturity scale shown in Table 1. This scale measures uncertainty of system performance due to lack of requirements definition and requirements verification data.

Table 1. Requirements Maturity (RM) Scale

Level	Risk Assessment Criteria
10	Mission objectives not quantified or baselined *(volatility in mission)*
8	System concept formulated, but functional decomposition (input, output, process, timeline) is incomplete and/or driving component performance parameters are not identified *(volatility in system concept)*
6	The functional requirement decomposition and mapping to this component is complete. Performance parameters are identified, but most parameter values are "TBD" *(volatility in key requirements)*
4	The functional requirement decomposition and mapping to this component is complete. Most performance parameter values driving component are TBR or the supporting analysis is incomplete *(volatility in minor requirements)*
3	All TBR parameter values which drive the component selection have been resolved and the supporting analysis is complete *(little to no change in requirements expected)*
2	Requirements traceability is established. Test requirements are defined. Requirement and parameter values have been validated as necessary by models of appropriate fidelity (mostly for software/avionics?). Specification is under formal configuration control *(changes in requirements cause contract changes, test requirements defined)*
1	Verification tests and acceptance limits have been specified to demonstrate that component hardware/software satisfy requirements *(component test plan complete)*
0	Design verification is complete *(requirements are verified)*

Additional scales can be obtained from BMDO (2001), Kenley and Creque (1999), and GE Aerospace (1992) to be applied to the particular item being costed.

The BMDO report provides the following sets of multiple scales for various categories of items being costed. Hardware items have six risk scales: Technology Advancement, Engineering Development, Reliability, Producibility, Alternatives, and Schedule. Software items have seven risk scales: Technology Approach, Design Engineering, Coding, Integrated Software, Testing, Alternatives, and Schedule. Integration, Assembly & Test items have nine risk scales: Technology, Hardware Engineering Development, Software Engineering Development, Interface Complexity, Subsystem Integration, Major Component Production, Hardware Schedule, Software Schedule, and Reliability.

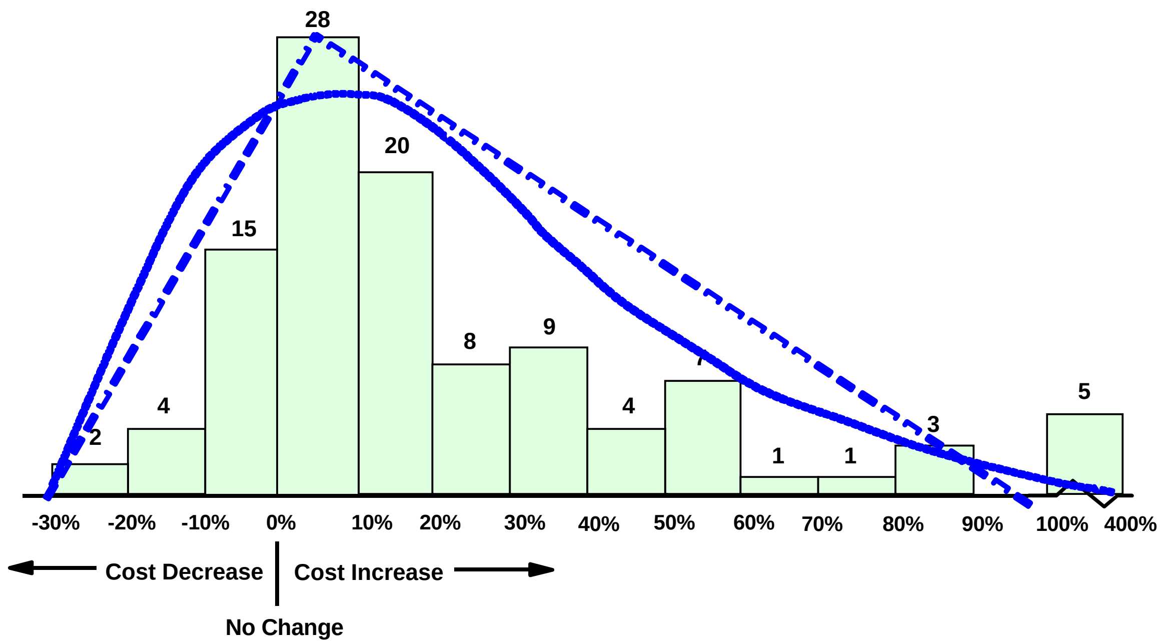

Figure 2. Historical Cost Overruns Used for Hoy-Hudak Analysis

The original Hoy-Hudak analysis collected data from 435 individual Selected Acquisition Reports representing 44 programs dating back to 1982. The cost risk results from the analysis are shown in Figure 2 and are skewed to the right and follow either a Triangular or Lognormal distribution, which does validate the choice to use a Triangular distribution for traditional cost risk analysis.

Hoy and Hudak assessed risk scores for all of these programs and performed a regression of the cost growth against the risk scores for a subset of programs to yield the following equations to be used as the parameters for a Triangular distribution of the cost growth multiplier for Research, Development, Test, and Evaluation (RDT&E):

Eqn. (1) $S_{\max} = 1 + 0.057x + \sqrt{6} * 0.055x$

Eqn. (2) $S_{ave} = 1 + 0.057x$

Eqn. (3) $S_{\min} = 1 + 0.057x - \sqrt{6} * 0.055x$

Eqn. (4) $S_{\sigma} = 0.055x$

The variable x in the above equations is the risk score for an item measured on the applicable 0-10 scale. The first coefficient in Eqn. (1), 0.057 is the average correction factor for risk. The result is that for every one-point increase of risk score, there is a 5.7% increase in cost growth expected. The second coefficient, $\sqrt{6}$, is a correction to set the standard deviation of the triangular distribution equal to the standard error of the estimate of the normal distribution developed in the regression that underlies the results. It can be shown that the standard deviation of a symmetrical triangular distribution is less than the half base length by this factor. The third coefficient, 0.055, is the standard error of the estimate for the underlying regression.

The U.S. defense data could be augmented or verified by corporate experience data if it is available. To do so would require historical estimates and actual costs; and a retrospective assessment of the technical risk levels using appropriate risk scales.

Comparison of Traditional and Hoy-Hudak Cost Risk Assessment for Near-Term Costs. For near-term cost for which design engineers are able to provide accurate direct assessments of cost risk, we compared the cost risk for the CRWMS program calculated via Monte Carlo methods using direct cost risk assessment to the best fit cost risk probability distributions using the U.S. defense risk scoring methodology. The Hoy-Hudak cost risk probability distributions are a good fit to the Monte Carlo output, and the derived risk scores are reasonable based on previous experience in applying technical risk assessment scales.

The CRWMS program uses a Bechtel Corporation proprietary cost risk methodology known as BecRAC. The BecRAC method uses a hierarchical method to assess cost risks. In BecRAC, the program WBS items are called "Terms", and for each term, up to five "Variables" that drive the cost risk of the term are defined. Examples of variables for CRWMS are: Estimate Errors and Omissions, Project Complexity, Design Evolution, Work Scope and Quantity, Assumed Market, Facility Access Restrictions/Delays, Cost Performance (labor/unit rates, etc.), and Materials Science Evolution. The variables in BecRAC are in essence the root causes of cost changes. For each Variable, a cost multiplier impact probability distribution is assessed from design engineers and the BecRAC uses the mapping from Variable to Term to generate the final cost risk probability distribution by Monte Carlo analysis. Note that this hierarchical method is an improvement over directly assessing the cost risk on the WBS items in that it assesses the impacts of the root causes on the costs.

Figure 3 shows the results on one of the Hoy-Hudak cost risk probability distribution fits to BecRAC results. The BecRAC results in the figure are based on assessment performed in December 2002 for costs that will occur between 2007 and 2011. The cost account shown is for stainless steel waste packages, for which there is no major technology development is required. The best-fit Hoy-Hudak Triangular distribution to the BecRAC Monte Carlo results is defined by a risk score parameter of 5.61. Referring to Table 1 a Requirements Maturity score of 6 is characterized as "The functional requirement decomposition and mapping to this component is complete. Performance parameters are identified, but most parameter values are TBD (*volatility in key requirements*)"; and a score of 4, as "The functional requirement decomposition and mapping to this component is complete. Most performance parameter values driving component are TBR or the supporting analysis is incomplete (*volatility in minor requirements*)". This level does match the maturity of the requirements for the waste packages in December 2002. The supporting analysis was incomplete, and the key requirements were in the process of being quantified in order to develop the specifications for a prototype that would provide validation of the concept and provide data to finalize the requirements for the waste packages.

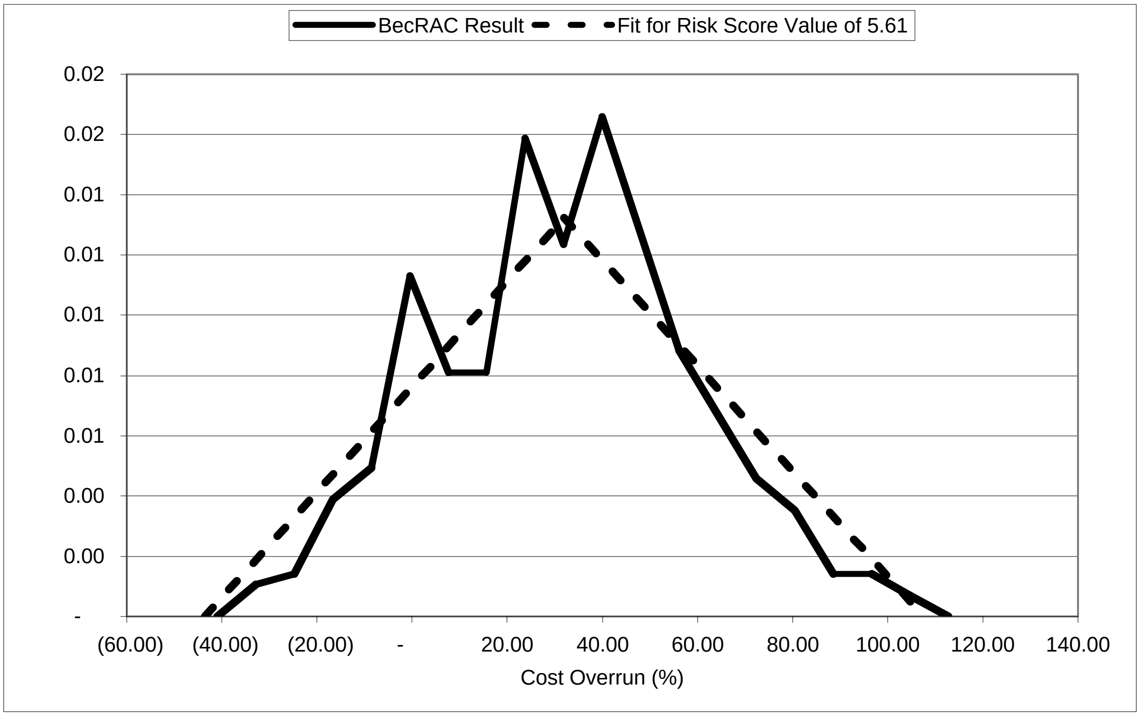

Figure 3. Comparison of BecRAC Results to Risk Score Fit

IMPLEMENTATION OF COST RISK ASSESSMENT

Assessment Process. The first step in assessing risk for life cycle (or any project) cost and for risk mitigation planning is to establish the project WBS and determine the lowest level of the WBS for which risk will be assessed. In this way, the baseline cost and the risk assessment use the same foundation, which leads to consistent, credible, defensible results. Quite often, early in a project it will be the case that the WBS is not adequately defined for the entire system life cycle, and some additional effort must be made to develop or extend WBS elements to incorporate the operational and disposal phases of the project. Also, for assessing and understanding technical risk for WBS elements, it is valuable to have a system hierarchy and specification tree that are consistent with the life cycle WBS, since the risk assessments scales usually are framed in terms of progress in completing activities that increase the technical maturity of the system's design and requirements documentation.

Once the WBS is established and understood, technical risk assessment scales can be selected from various sources to apply to the program. Each WBS item is assigned a responsible person to assess the technical risk. Quite often this is the design engineer who also is responsible for providing inputs for cost estimation. The technical risks are assessed using the relevant scales for each WBS item. The great benefit of this approach is that the raw data used to establish a risk mitigation plans is the same data that is used for determining life cycle cost risk probability distributions.

It is during this step in the process that it may be discovered that the level within the WBS being assessed is too low or too high, so that the assessment must be done at a higher rolled-up level in the WBS or the WBS item must be decomposed further to better assess the risks. Also, there may be several WBS items which have risks driven by the same root cause, but which are scattered throughout the project WBS so that rolling them up to a higher level will confound them with other WBS items which do not share this risk. For risk mitigation planning, it may be possible to identify a single risk mitigation plan that covers all of the correlated WBS items. For life cycle cost Monte Carlo simulation, the cost multiplier for all of the WBS items that are correlated in this way is sampled from just one probability distribution. This method will better model the design engineers' understanding. For those familiar with BecRAC, this equivalent to assigning the same Variable to multiple Terms when assessing cost risk.

Modeling Using A Combination of the Traditional and Hoy-Hudak Techniques. It is also possible to integrate the traditional and Hoy-Hudak assessment methods by using the traditional method for near term cost risk assessment and the Hoy-Hudak method for far term assessments. Converting the Monte Carlo-based results into equivalent risk scores does this.

To test this approach, a prototype model was developed that utilized this data for assessing overall uncertainty in life cycle costs using the Analytica software package. By using a modeling package with embedded Monte Carlo risk capability rather than a spreadsheet, it was possible to fully propagate risk throughout the life cycle analysis and incorporate a very robust cost array structure that supports a myriad of purposes. Furthermore, adaptation of the analysis as the project or program proceeds is very common and is very difficult using a spreadsheet, especially one as large as a life cycle model requires. One particular benefit of the modeling approach is that the cost structure can evolve as the program matures and the basic analysis is not affected. Early in a program the WBS tends to evolve as the design changes and morphs into the desired result placing a premium on flexibility of approach. By using the Analytica modeling software we were able to devise an analysis model that is essentially independent of the WBS. By relating the risk scores to the WBS elements, only the input cost data structure must be changed as the design and project strategy evolves. Adapting the modeling approach to another project would be relatively straightforward because of the ease of developing and adapting models in Analytica.

Application of Results. Once the risks are assessed and placed into a Monte Carlo life cycle cost model, the input risk are converted into outputs that can serve multiple purposes that include contingency recommendations, and forecasting of expected costs and cost ranges, whichever is appropriate to the situation. For risk mitigation planning, it is possible to evaluate the cost-benefit tradeoffs of pursuing various risk mitigation strategies, such as trading off acceptance of the market offerings for a higher risk technology being developed by third parties versus investing internally in technology development to mitigate the risk.

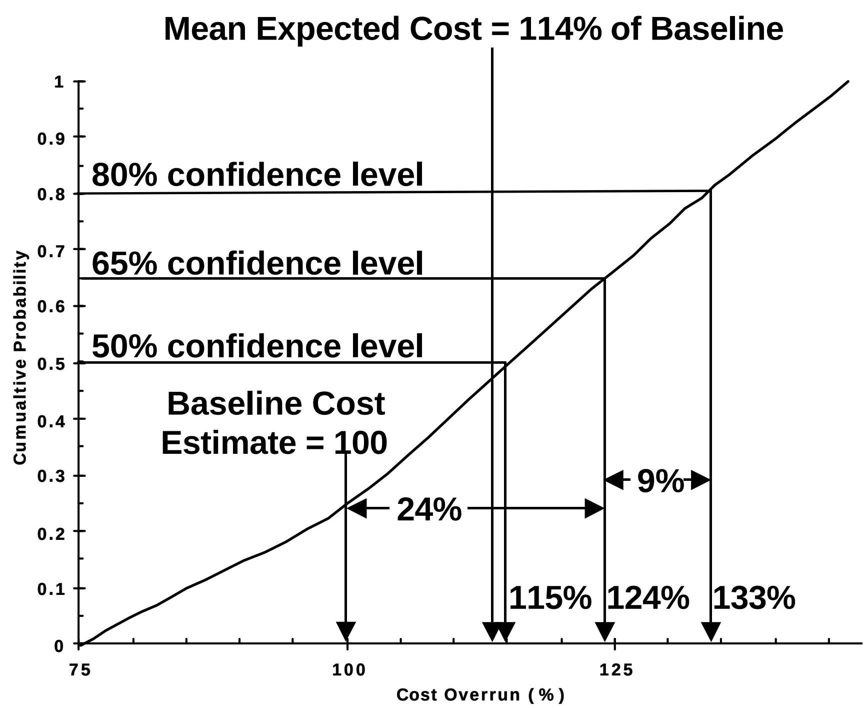

Figure 4. Example Output from Cost Monte Carlo Analysis

Figure 4 shows a typical output from a Monte Carlo cost analysis. This example has shows a maximum possible under run of 25% and a maximum possible overrun of 50%. It shows an expected cost that is 114% of the baseline. The expected cost should be greater than the baseline as the historical data shows that cost over runs are more likely to occur than under runs.

It is a management decision to determine adjustments to cost baseline and budgets based on expected cost results of risk analysis. Typically, a contingency is budgeted to cover costs that exceed the baseline cost estimate. Some methods allocate the contingency to the supplier versus the buyer. In the example, the difference between the baseline and the 65% confidence level is allocated as supplier contingency or supplier management reserve (24% of the baseline cost in this example). The difference between the 65% confidence level and 80% confidence level is allocated as buyer contingency (9% of the baseline in this example).

The ranges, cumulative probability, and expected value representations are most useful in representing the entire uncertainty picture, particularly for life cycle costs. Recent directives form the U.S. Office of Management and Budget should significantly increase the importance of this information on projects that are subject to regulatory oversight. OMB Circular A-4 (2003, p. 18) states:

> "When benefit and cost estimates are uncertain… you should report benefit and cost estimates (including benefits of risk reductions) that reflect the full probability distribution of potential consequences. Where possible, present probability distributions of benefits and costs and include the upper and lower bound estimates as complements to central tendency and other estimates."

The impact of this is far reaching. Even the Social Security Program (2004) has begun analyzing the impact of uncertainty of retirement projections and inflation.

Improving the data. The authors also believe that the U.S. defense data can be extended by individual organizations willing to put the effort into analyzing their own experience base. Private entities may find that extending the U.S. defense data with their own experience provides a competitive edge and governmental agencies may find that by investigating their own experience that they may become more confident of their ability to extrapolate the U.S. defense DO data base to future projects and programs. In the meantime, the Hoy-Hudak U.S. defense data effort remains the best data available to estimate risks over the entire life cycle and appears to be far more defensible than more subjective methods.

SUMMARY AND CONCLUSIONS

Summary. The authors have presented a new method for analyzing life cycle cost risk on large programs. This method combines the traditional technical risk driver Monte Carlo analysis with a new methodology developed by Hoy and Hudak and permits quantification of risks throughout the entire life cycle without resorting to difficult to support subjective methods. We have shown that traditional direct cost risk assessment can be rationally combined with the Hoy-Hudak method for risk quantification to yield an overall projection of cost uncertainty that cannot be reasonably accomplished any other way. The risk assessment methodology required when using the Hoy-Hudak cost risk equations is shown to be relatively straightforward for an engineer to apply to a specific component or process within a project.

We have shown how the risk data must be related to the project WBS and how this can be adapted as the program or project evolves. The end result is applied in a life cycle model, either a spreadsheet with Monte Carlo extensions or, preferably, in a modeling system like Analytica that makes the on-going adaptation to project needs relatively simple and painless compared to modifying a large spreadsheet.

Conclusions. There is clearly an increased governmental emphasis on better assessing and managing risk for federal programs. The authors sought out a methodology to accomplish this and our analysis of the options for analyzing life cycle cost risk suggest there is a better way to do this than the more subjective approaches that are common today, especially in the early stages of a project or program. The more long term the program is, the more useful this methodology becomes. Even in the conceptual phase of a project it becomes possible to quantify risk for all future phases of a project. As the project proceeds and direct cost risk assessment becomes feasible for early phases this can be used in combination with the Hoy-Hudak method to project risk throughout the life of the project or program, including eventual decommissioning and demolition (where appropriate).

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C. Robert Kenley holds a Ph.D. and M.S. in Engineering-Economic Systems from Stanford, a M.S. in Statistics from Purdue, and a S.B. in Management from MIT. He has 24 years experience in aerospace and nuclear systems engineering. His current mission is to provide clients with insight and understanding of systems problems as an independent consultant. He is the chair of the INCOSE Ways and Means Committee. He is a published author of several papers and journal articles in the fields of systems engineering, decision analysis, Bayesian probability networks, and applied meteorology.

James H. Nail holds a M.S. in Nuclear Engineering from Oregon State University and a Bachelor of Engineering Science from the University of Texas at Austin. He has over 40 years of diversified experience in nuclear systems engineering, operations and analysis as well as extensive experience in the development of large integrated computer system models for analyzing a variety of technical problems. He first began analyzing life cycle costs in the 1960’s while examining a substantial number of, then, advanced reactor concepts for the Atomic Energy Commission and has most recently participated in the analysis of life cycle costs for the Civilian Radioactive Waste Management Program at the Department of Energy as a Bechtel contractor employee.