UNDERSTANDING THE RESULTS OF AN INTEGRATED COST-SCHEDULE RISK ANALYSIS

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I. ABSTRACT

The recent rise of integrated risk analyses methods has created a new opportunity for complex projects to understand the dynamic inter-relationship of cost, schedule, and risk. NASA has been implementing Joint Confidence Level (JCL) analysis of cost, schedule, and risk for all major projects since 2009 in an attempt to proceduralize and codify the requirements for an integrated risk analysis product. Since the method of integrated risk analysis is itself new, the visualization of analysis results has been challenging. Starting with the simple X-Y scatter plot, this paper will explain how to understand the results of an integrated cost/schedule risk analysis using illustrative examples. The authors will also propose new advanced methods for visualizing results, and provide evidence of the valuable insight that can be gained from conducting an integrated cost/schedule risk analysis.

II. EXECUTIVE SUMMARY

Quantifying the relationship between cost and schedule and understanding the impact of schedule growth on cost growth are extremely important when developing project estimates. Although the mathematical frameworks for conducting an integrated cost-schedule risk analysis have been available since 1999/2000[3], the tabular and graphical outputs created as a result can seem complex since they are still new and contain the probabilistic results of an integrated analysis that includes both technical, cost, schedule, risk, and uncertainty data. Since multiple types of data are used during the integrated analysis, probabilistic results presented by analysts should help illustrate and identify the key contributors. Understanding the relative contributions, key drivers, and probabilistic results can provide valuable insight to management and decision makers.

The scatter plot is the most basic output and shows each individual iteration result from the integrated cost-schedule risk analysis. Since it is a simple X-Y scatter plot, it is easy to determine the percent joint confidence level for a given cost/schedule value. More advanced outputs such as the milestone overlay are extensions of the scatter plot.

Identifying the key contributors and drivers can shed valuable insight on project risk posture and inform risk management activities. The results of an integrated cost-schedule risk analysis can quickly identify both discrete event risks and uncertainty to enable risk driver analysis. Determining risk impacts along the critical path is an advanced analysis of discrete events with likelihood of occurrence and probabilistic impact that influence calculated finish dates.

A significant advantage exists with integrated cost-schedule risk analysis for calculating and viewing time-phased cost risk results aligned with a schedule plan. The calculation results from an integrated cost-schedule risk analysis can display the probabilistic results for cost over-time and quickly enable resource or budget analysis. Presenting the time-phased cost risk results displays the entire statistical output for cost over the identified time period and includes the probabilistic impact of cost and schedule risk.

As NASA has continued its implementation of joint confidence level policy, the development and understanding of integrated cost-schedule risk results has been increasing. As an integrated risk analysis approach, the results can

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[3] In the 1990's both the Aerospace Corporation and MITRE determined that lognormal distributions could be used to represent cost and schedule distributions. By convolving these two distributions, an essential mathematical framework was achieved to perform some of the first join cost-schedule risk analyses. (Book, Winter 2007-2008)

provide decision makers insight into both cost and schedule, including the impacts of both risk and uncertainty. Estimators and analysts continue to refine the visualizations and illustrations of the calculated output in an effort to improve insight and provide increased value to decision makers.

III. INTRODUCTION

The results of the integrated cost-schedule risk analysis can be displayed in a variety of formats. Both tabular and graphical outputs are available. (Darren Elliott, 2011) Estimators and analysts responsible for completing the analysis should utilize multiple statistical outputs to display results. This paper will define and describe the methods for calculating and displaying both standard and advanced results from an integrated cost-schedule risk analysis. This paper describes three types of probabilistic reports: cumulative statistical results, probabilistic sensitivity results, and advanced results.

This paper will assume that the reader has a basic understanding of the methodology behind the integrated cost-schedule risk analysis. This paper will also assume that the reader has ample understanding of traditional cost risk analysis and experience with probability and statistics as applied to simulation modeling. Readers are encouraged to consult the references and citations to learn more about integrated cost-schedule risk analysis and its approach to performing an integrated statistical analysis of cost, schedule, and risk.

A. Cumulative Statistical Results

The cumulative statistical results from an integrated cost-schedule risk analysis are most often used to calculate a desired statistical confidence level. Similar to the traditional cost s-curve, the integrated cost-schedule scatter plot represents a cumulative distribution – of cost and schedule pair values. (Hulett, Integrated Cost-Schedule Risk Analysis, 2011) Cumulative results displayed as scatter plots can be provided at any element level in the integrated cost-schedule risk analysis. The standard display for the cumulative statistical result is the scatter plot in most major software applications such as Oracle Primavera Risk Analysis (OPRA), Joint Analysis of Cost and Schedule (JACS), Polaris, and Deltek Acumen.

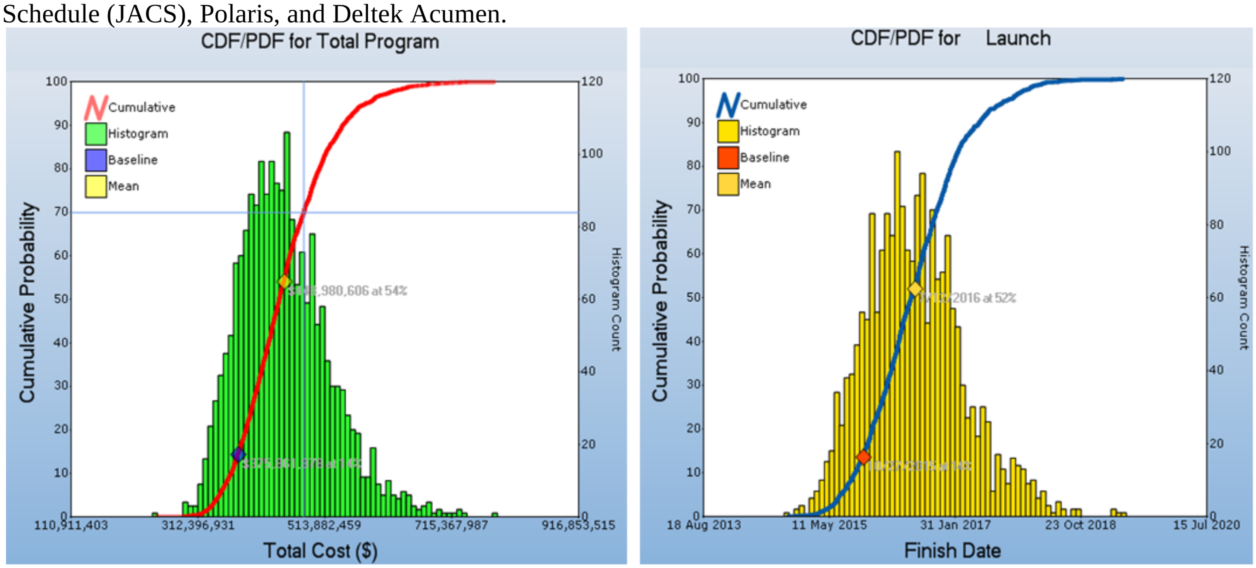

Figure 1 Traditional Cost & Schedule S-Curves (CDF – Cumulative Distribution Function) with Histogram (PDF – Probability Density Function)

1. *Scatter Plot*

The Scatter Plot is the most common output of an integrated cost-schedule risk analysis where each point in the scatter is a result of the statistical simulation and represents a cost/schedule pair value. (Johnson, 2009) The scatter plot is very similar to the "s-curve" in cost risk analysis because both are cumulative statistical results. In Figure 2 an XY scatter plot is shown for total cost and schedule finish date.

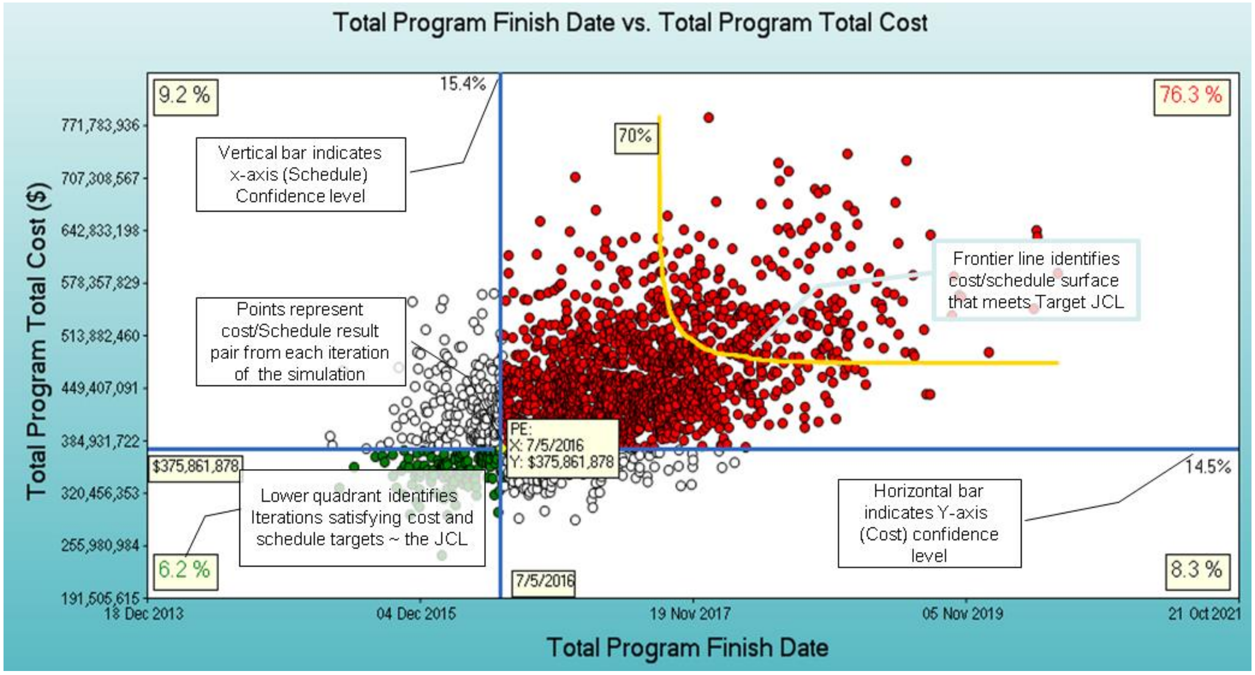

Figure 2 Cumulative statistical result depicted as XY scatter plot with annotations

The schedule finish date is on the x-axis as a date and the y-axis displays total cost. In this example the scatter plot is segmented by two blue lines. The horizontal blue bar displays the statistical cost confidence level and the vertical blue bar of the cross-hair indicates the schedule confidence level. The two blue bars intercept each other and form a 'cross-hairs'. This is annotated as the projects point estimate (PE) (e.g. baseline plan) for this example in the above Figure 2. At bottom left, a quadrant is created by the intersection of the vertical and horizontal blue bars. In this quadrant all points are colored green since they are at, or below, the threshold values set by both blue bars. In other words, each of these results contains a cost and schedule pair value than less than or equal to the projects point estimate. These points represent all the scenarios that are at or below the baseline cost and schedule. The joint confidence level of the project is calculated by determining the total percent of results that fall in this quadrant. (James K Johnson, 2008) The joint confidence level is expressed as the simple equation:

$$JCL\% = \frac{Number\ of\ Iteration\ Results \leq Cost\ \&\ Schedule\ Threshold\ Values}{Total\ Number\ of\ Iteration\ Results} \tag{1}$$

This is essentially the same as a traditional cost s-curve (CDF) when an analyst plots a cost value on the curve and determines its confidence level value in relation to all the statistical results. In Figure 2 the JCL % is shown in green at lower left and corresponds to the number of green points divided by the total number of iteration results, which yields 6.2% Joint Confidence Level (JCL). The blue bars can be set at any cost and schedule value to determine the joint confidence, or they can be locked to a particular targeted joint confidence level.

The yellow line curve shown in Figure 2 is sometimes referred to as a "frontier line", or indifference curve, that specifies all the cost/schedule combinations that will meet a targeted JCL % value. In this example, the frontier curve represent's the 70 percent JCL frontier curve. As a cautionary note to the reader, the asymptotic tails shown are purely academic – it is recommended to be as close to the centrode of the cluster for that given frontier curve.

B. Probabilistic Sensitivity Results

In addition to cumulative statistical results, the results of an integrated cost-schedule risk analysis can be expressed by illustrating the probabilistic sensitivity of elements or inputs present in the model. This is commonly done in cost risk analysis using Tornado or Variance charts that express the relative contribution of the elements by an established metric (correlation, standard deviation, total variance, etc.). (Smith, 2011) These types of rank ordered charts are often referred to as "pareto" charts.[4]

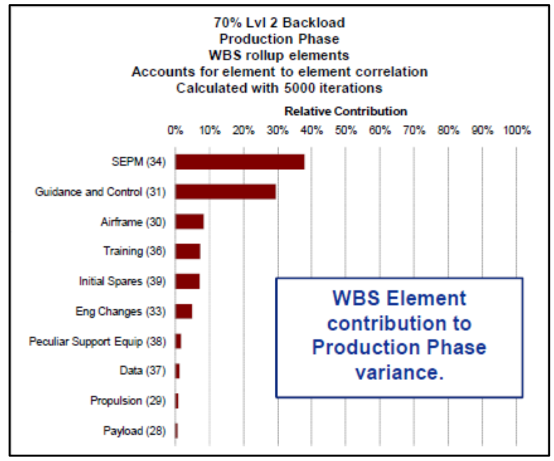

Figure 3 Variance Analysis Charts to Determine Uncertainty Drivers (Smith, 2011)

There are a wide range of probabilistic sensitivity reports available to the analyst and consumer. Many commercial software products that can complete an integrated cost-schedule risk analysis will provide multiple types of probabilistic sensitivity results such as Duration Sensitivity, Cost Sensitivity, Duration to Cost Sensitivity, Criticality Index, and Discrete Risk Criticality. Duration Sensitivity is the correlation between a task's duration and the total program duration. Cost Sensitivity is the correlation between a tasks cost and the total cost of the project. Duration to Cost Sensitivity is the correlation between the tasks duration and the total cost of the program. The Criticality Index provides percentage of time a task spent on the critical path during the probabilistic analysis. The Discrete Risk Criticality is the probability that a risk register event will be on the critical path if it occurs.

In the above sensitivity results, critical path is defined as all tasks or elements with Total Float or Total Start Float that is less than or equal to 0.[5] Checking the Total Start Float as well as the Total Float takes account of tasks with critical starts. Both the Criticality Index and the Discrete Risk Criticality can provide valuable insight into the key drivers of the probabilistic integrated cost-schedule risk analysis.

1. Criticality Index

The criticality index can easily identify tasks or elements in the integrated cost-schedule risk analyses that are impacting the probabilistic schedule results (i.e. finish date or total duration). The criticality index is based on the measuring of the stochastic critical path in the integrated cost-schedule risk analysis. The stochastic critical path can provide the individual tasks or elements frequency expressed as a percent time where total float, or total start float, is less than or equal to 0. This means that elements on the stochastic critical path are directly influencing the finish date or total duration of a project.

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[4] Pareto Charts are named for named after Vilfredo Pareto, and are generally charts that contain both bars and a line graph, where individual values are represented in descending order by bars, and the cumulative total is represented by the line. (Pareto Chart)

[5] Float, as defined in project management and used in schedule analysis is the amount of time that a task in a logically linked network schedule can be delayed without causing a delay to subsequent tasks or project completion date. (Hulett, Practical Schedule Risk Analysis, 2009)

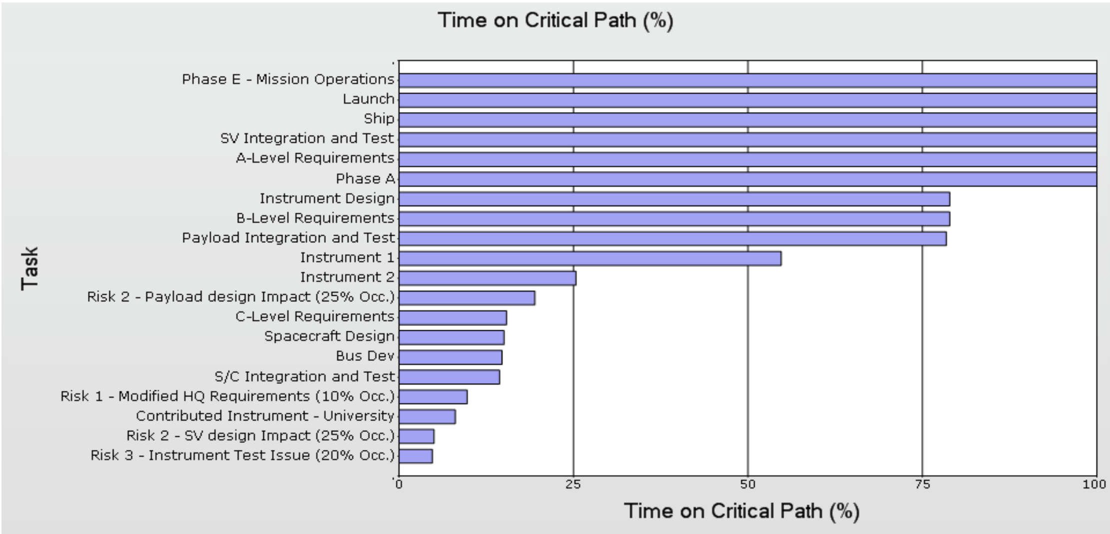

Figure 4 Criticality Index example displays the percentage of time a task spent on the critical path

In the above example Figure 4 the elements are rank ordered by the percentage of time a task spent on the critical path during the analysis. The key contributors to project duration and finish date are those tasks or elements with a 100% criticality index. These tasks or elements, regardless of how the task durations varied during the probabilistic analysis, were always on the critical path. These tasks are therefore likely to be critical to ensuring project completion on time.

2. Discrete Risk Criticality

The Discrete Risk Criticality report is an extension of the Criticality Index and an excellent way to calculate and visualize the key discrete risk events that contribute most to the results of the integrated cost-schedule risk analysis. The discrete risk criticality is calculated as the frequency a discrete risk appears on the critical path when it is active. Since an integrated cost-schedule risk analysis can contain a multitude of discrete risks, each with their own likelihood of occurrence and impact, it is important to analyze those discrete risks that when active, contribute significantly to the probabilistic results. This is most directly accomplished by measuring the risks frequency of occurrence on the critical path.

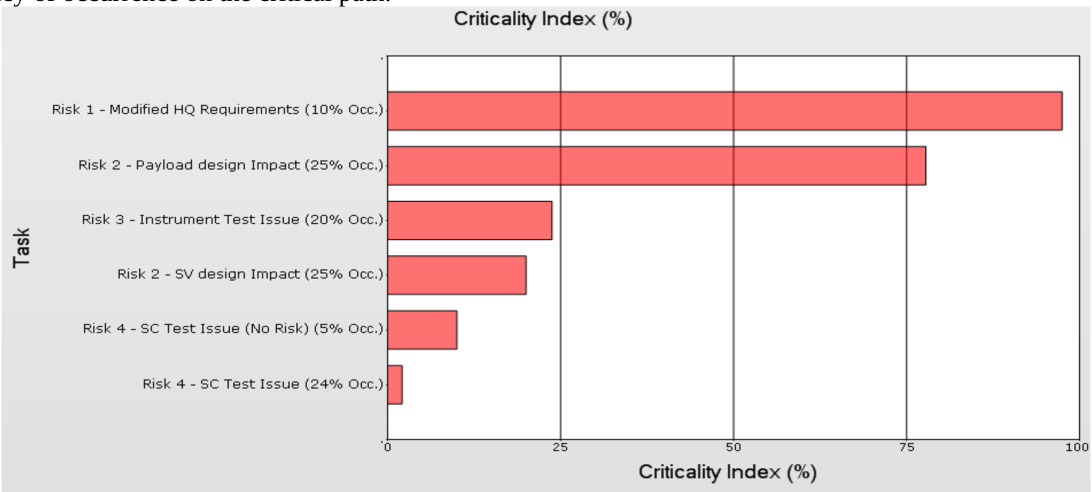

Figure 5 Discrete Risk Criticality Index example shows risk events frequency on the critical path

In the above Figure 5, the elements are rank ordered by a percent (%) Criticality Index. This metric has a range from 0-100 percent, with elements that contribute most having a higher number approaching 100%. The calculation of the criticality index for any discrete risk event in the model is expressed as:

$$Criticality\ Index\ \% = \frac{Number\ of\ Iterations\ where\ Total\ Float \leq 0}{Total\ Number\ of\ Iterations} \tag{2}$$

The integrated cost-schedule risk analysis can provide valuable insight for project managers and others with meaningful probabilistic sensitivity results such as the Critical Index and the Discrete Risk Criticality. All too often projects will focus on a deterministic critical path and not consider the effects of risks or uncertainty not directly linked to the deterministic critical path. By analyzing and illustrating the stochastic critical path, and expressing all key elements with frequency values, additional drivers will be highlighted that have not been previously considered.

C. Advanced Results

Advanced results from the integrated cost-schedule risk analysis can provide enhanced insight into more than just the cumulative results or key drivers. A key advantage of the integrated cost-schedule risk analysis is the ability to generate statistical results over-time. By developing a functional relationship between cost, schedule, and risk, the integrated cost-schedule risk analysis offers the ability to view and analyze results in a time-phased manner. In particular, an integrated cost-schedule risk analysis that utilizes either a cost or resource loaded schedule as its foundation can offer significant advantages for understanding the risk results over time. (Hulett, Integrated Cost-Schedule Risk Analysis, 2011)

The Milestone Overlay and Annual Cost Uncertainty results are both advanced results that display the probabilistic results from an integrated cost-schedule risk analysis in a temporal context. Both the Milestone Overlay and Annual Cost Uncertainty are unique and advanced in that they are not readily available from all commercial software applications that perform integrated cost-schedule risk analysis.[6]

1. Milestone Overlay

The Milestone Overlay is an advanced result that can display multiple XY scatter plot results for any number of pre-determined milestones or key activities. This result is essentially a combination of multiple cumulative scatter plots for selected milestones or key activities in the integrated cost-schedule risk analysis. The flexibility of an integrated cost-schedule risk analysis easily supports this implementation by calculating and displaying the cost/schedule pair values for multiple elements or activities on the same view graph.

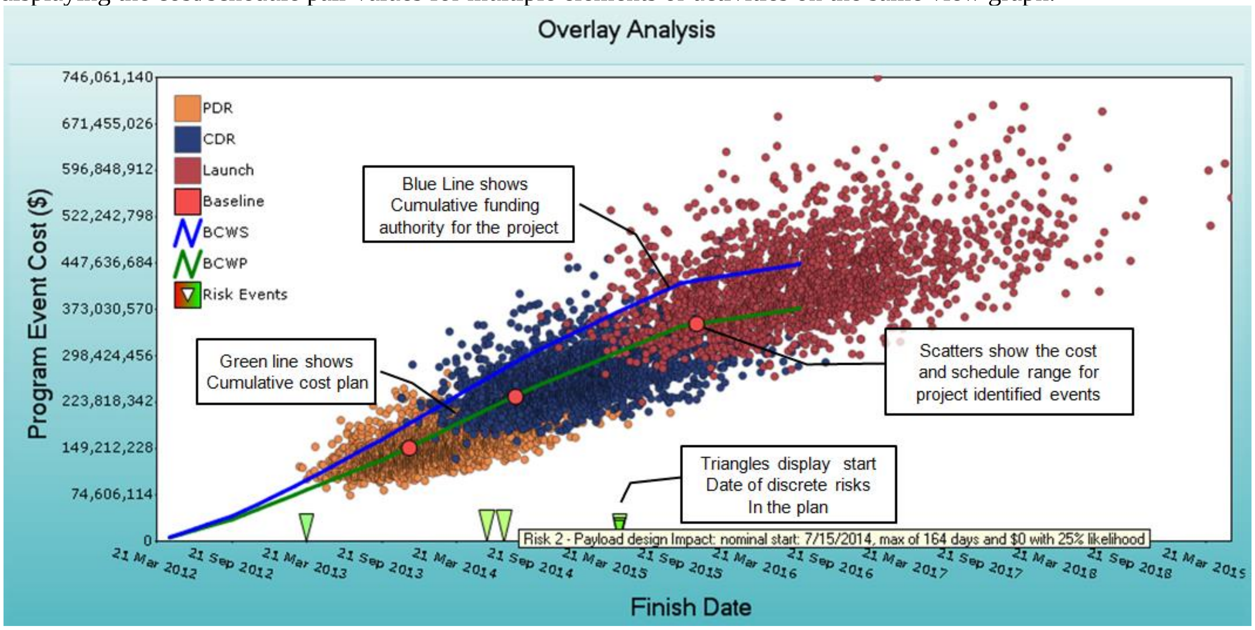

Figure 6 Milestone Overlay advanced result example displays the scatter plots for milestones (PDR, CDR, and Launch) over time

[6] Joint Analysis of Cost and Schedule (JACS), by Tecolote Research, and Polaris, by Booz Allen Hamilton, both offer these outputs standard for analysts.

In the above example Figure 6, a Milestone Overlay result is shown for an example project. In this example, multiple scatter plots are shown and color-coded. Scatter plots for PDR, CDR, and Launch are identified and plotted together against an X-axis of Finish Date and a Y-axis of Total Cost. The integrated cost-schedule risk analysis is able to produce scatter plots of any identified or pre-selected milestone or activity. The Milestone Overlay can combine these together to produce a result that shows the risk to each milestone or activity over time.
The baseline dates and costs for PDR, CDR, and Launch are shown as red circles in Figure 6. These red circles mark projects planned dates and costs for these important milestones. In each case, the red dot can be measured and contrasted against its corresponding scatter plot. Budget lines are also present representing the Budget Cost of Work Scheduled (BCWS) and Budget Cost of Work Complete (BCWP) providing further insight into the initial available resources over time.[7]

Further advancement is offered by the Milestone Overlay with the plotting of the discrete risk events and their occurrences over time. Individual risks are highlighted by triangles and annotated above in Figure 6.
By plotting multiple scatter plots over time in comparison to planned milestones dates and costs, the Milestone Overlay can provide a time-phased view of the cumulative results for multiple events and activities. Including additional data such as the available budget, and discrete risk events further enhances the consumers understanding of the integrated cost-schedule risk analysis results over time.

2. Annual Cost Uncertainty

The cost (or resource) loaded schedule approach to conducting an integrated cost-schedule risk analysis provides additional advancement to analysts that need to compare the annual cost risk to available resources. The Annual Cost Uncertainty results can display the probabilistic results for cost over time and allow for easy comparison to budget data. The key aspect of the Annual Cost Uncertainty result is that it can display the cost risk statistical results by a specified time period (e.g. Fiscal Year). Approaches have existed previously for calculating and displaying the cumulative cost uncertainty for the same budget comparison purpose. (Cyr, 2007) By calculating and viewing the statistical results in an annual time-phased manner, analysts can identify particular time periods that may require reserve utilization and/or contain a significant amount of risk.

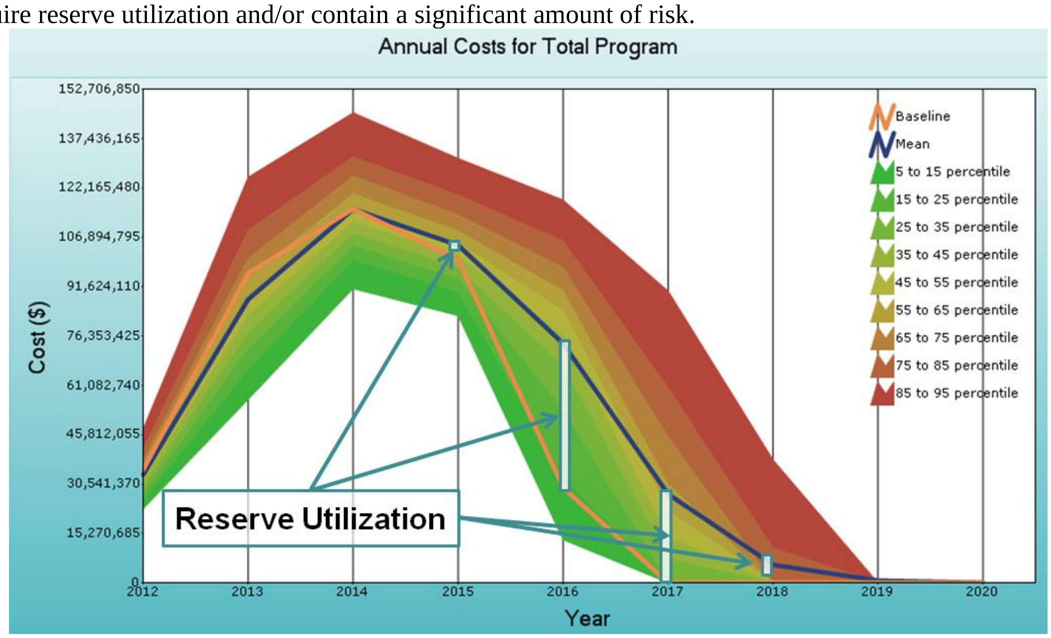

Figure 7 Annual Cost Uncertainty result example displays cost risk statistics over time in comparison to available annual resources

A integrated cost-schedule risk analysis that is developed using a cost (or resource) loaded schedule approach will allow the analyst to produce Annual Cost Uncertainty results since the cost, and probabilistic risk

[7] BCWS and BCWP are common in EVM analysis. Budgeted Cost of Work Scheduled (BCWS) is the sum of the performance budgets for all work scheduled to be accomplished within a given time period. Budgeted Cost for Work Performed (BCWP) is the value of completed work expressed as the value of the performance budget assigned to that work

results, will be phased over the project schedule. Understanding these results can provide insight for analysts and consumers that need to compare the time-phased risk results with available annual budgets. In the above Figure 7, the time phased probabilistic results of the integrated cost-schedule risk analysis are displayed from the 5^{th} to 95^{th} percentile from the years 2012 to 2020. The years 2015, 2016, 2017, and 2018 are annotated above in Figure 7 to highlight the likelihood of reserve utilization. In these years, the available annual resources, denoted by the orange line, are significantly less than the mean statistical result from the analysis, denoted by the blue line.

The creation of advanced results such as the Milestone Overlay and Annual Cost Uncertainty offer unique insight into the statistical results over time. The Milestone Overlay can easily illustrate schedule milestone drift, and allow for analysis of milestone or key event completion. This is an advanced approach to understanding the cumulative results from a scatter plot and offers added insight with the inclusion of an annual budget and the timing of discrete risk events. The Annual Cost Uncertainty result also provides added insight into the results of the integrated cost-schedule risk analysis by displaying the statistical results from 5^{th} to 95^{th} percentile for an identified time period, such as each fiscal year.

IV. CONCLUSION

In early 2000, some of the very first outputs of integrated cost-schedule risk analysis were provided in the book *Probability Methods for Cost Uncertainty Analysis: A Systems Engineering Perspective* (Garvey, 2000). Understanding the results of an integrated cost-schedule risk analysis can seem challenging at first to even a seasoned estimator or analyst. The use of cost, schedule, risk, and uncertainty data in the analysis method can make comprehending the statistical results very difficult. The availability of cumulative statistical, probabilistic sensitivity, and advanced results further compounds the challenge for a consumer or decision maker who is receiving the results of an integrated cost-schedule risk analysis.

By focusing on the underlying calculations of the analysis, and fully comprehending how each of the statistical results is created, the reader has now achieved a better understanding of the results of a integrated cost-schedule risk analysis. In many cases, the results of an integrated cost-schedule risk analysis are similar to the traditional results of a cost risk analysis. The cumulative statistical results, as represented by the scatter plot, are essentially analogous to the cost ‘s-curve’. These results, as with the traditional s-curve, are most often used to calculate a confidence level. The probabilistic sensitivity results, as represented by the pareto bar charts, are used to establish key drivers and contributors to the analysis. Paying careful attention to the metric being measured, such as Criticality, is important to understanding how the drivers are calculated and ranked. Finally, the advanced results such as the Milestone Overlay and Annual Cost Uncertainty can provide valuable insight into the statistical results over-time, displaying risk results in comparison to the available annual resources or budget.

Table of Figures

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Related Works

1. Air Force Cost Analysis Agency, Cost Uncertainty Handbook
2. Naval Center for Cost Analysis, Cost Schedule Risk and Uncertainty Handbook
3. General Accounting Office, Schedule Assessment Guide
4. National Aeronautics and Space Administration, Cost Estimating Handbook
5. National Aeronautics and Space Administration, Joint Confidence Level Handbook