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DYNAMIC COST RISK ASSESSMENT FOR CONTROLLING THE COST OF NAVAL VESSELS

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Dynamic Cost Risk Assessment for Controlling the Cost of Naval Vessels

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Abstract

Naval vessels, like most large-capital projects, have a long history of cost growth. To get a handle on this problem, NAVSEA's Cost Engineering & Industrial Division, NAVSEA 05C, has introduced Probabilistic Cost Risk Analysis (PCRA) into the Department of Defense (DoD) Planning, Programmatic, Budgeting, and Execution System (PPBES). The quantification of cost in terms of cumulative probability distribution functions (CDF) or "S-curves" provides a macroscopic view of project risk. Risk curves alone do not provide adequate visibility into the individual project risk drivers; therefore, they are insufficient for planning and managing risk reduction activities (RRA). Complex projects typically involve a set of high-consequence, project-specific risks that require detailed analysis and for which risk response actions need to be developed and implemented. The analysis of specific risks and RRAs requires a microscopic view. We present a practical and mathematically sound approach using scenarios and Monte Carlo simulation within the framework of decision trees and risk curves. The approach is detailed using a realistic but simplified case of a project with three technical risks.

Introduction

Cost growth has been a major problem for the US Navy. Over the past four decades, the growth of US Navy ship costs has exceeded the rate of inflation. In the past 50 years, annual cost escalation rates for amphibious ships, surface combatants, attack submarines, and nuclear aircraft carriers have ranged from 7 to 11% (Arena, Blickstein, Younossi & Grammich, 2006). Along with real cost growth, the DoD has had significant problems with cost estimates. By and large, the DoD and the military departments have underestimated the cost of buying new weapon systems. A recent study by RAND (Arena, Leonard, Murray & Younossi, 2006) indicates that there is a systematic bias toward underestimating weapon system costs and substantial uncertainty in estimating the final cost of a weapons system.

The DoD recognizes that uncertainty is an important part of cost estimating. During a 2007 seminar with a naval aviation program official, the Assistant Secretary of the Navy for Research, Development and Acquisition, Dr. Etter (Burgess, 2007), stated:

> Program managers not only need to know a realistic cost estimate for their program, they need to know the percent probability of achieving that target. For example, a ship with a 40% chance of coming in on budget has a 60% chance of being over budget. Such a situation should prompt the project manager to seek help from the acquisition community. (p. 42)

There is an ongoing major shift in R&D and complex engineering projects from deterministic to probabilistic approaches. Probabilistic Cost Analysis (PCA) provides the proper framework for handling the many different elements of cost uncertainty, including project-specific, high-consequence risks. These risk drivers must be identified, assessed, mitigated, and controlled through formal risk management—which is an essential and critical discipline implemented in today's DoD projects. *The Risk Management Guide for DoD Acquisition* (2006) reads:

> Risk management is a continuous process that is accomplished throughout the life cycle of a system. It is an organized methodology for continuously identifying and measuring the unknowns; developing mitigation options; selecting, planning, and implementing appropriate risk mitigations; and tracking the implementation to ensure successful risk reduction. Effective risk management depends on risk management planning; early identification and analyses of risks; early implementation of corrective actions; continuous monitoring and reassessment; and communication, documentation, and coordination. (p. 3)

The DoD considers the definition, implementation and documentation of risk management essential to acquisition success. The DoD risk management process outlined in the Risk Management Guide consists of the following five activities performed on a continuous basis: Risk Identification, Risk Analysis, Risk Mitigation Planning, Risk Mitigation Implementation, and Risk Tracking.

This process is consistent with the AACE definition, which includes identifying and analyzing risk factors or drivers, mitigating the risk drivers where appropriate, estimating their impact on plans and monitoring and controlling risk during execution (Hollman, 2006). To be effective, PCA must interface with each of the risk management activities.

An emphasis on risk management supports efforts to reduce lifecycle costs of system acquisitions. An often-neglected concept in project risk management is the consideration of the entire project lifecycle. Analysis of risk over the lifecycle of a system can yield substantial benefits. Conversely, ignoring important stages of the lifecycle can lead to substantial problems in terms of risk for product development at the beginning of the lifecycle and for product upgrade or replacement at the end (Pennock & Haimes, 2001).

Many sources of cost uncertainty in naval vessel construction—such as economic/business factors (rates-wages, overhead, G&A, vendor/supplier stability, inflation indices, multi-year assumptions, etc.), learning/rate/curve assumptions, and cost-reduction initiatives—are well understood within the framework of a macroscopic perspective; these are effectively modeled with classical Probability Distribution Functions (PDF) such as the triangular, Beta, lognormal, and Weibull distributions. However, these factors constitute only a fraction of today's typical project risk drivers and, therefore, cost uncertainty.

The construction of naval vessels, like most complex engineering projects, is also susceptible to project-specific risk drivers, such as: low Technology Readiness Level (TRL); high design, manufacturing, and complexity; significant requirement changes; sizeable quantity changes; large funding uncertainty; severe acts of nature; and serious accidents.

It is tempting to assume or claim that the PDFs typically elicited for cost elements also quantify the project-specific, high-consequence risks. Sometimes cost analysts will go through the effort of identifying and discussing risk drivers, but when it comes to quantifying the risks and estimating contingency, they simply apply high/low ranges to WBS elements without thinking about how a particular risk driver affects one or more cost elements. We think it is invalid and counterproductive to do this because it leads to the loss of valuable information and visibility into these risks. Also, this approach tends to focus on cost reduction rather than risk mitigation. Hollmann (2007) notes that in best practice, risk analysis should begin with the identification of risk drivers and events. The cost impacts of the risk drivers and events are then considered specifically for each event.

The analysis of specific risks and Risk Response Actions (RRA) requires a microscopic view and is best carried out with tools such Decision Trees (DT), influence diagrams, or other discrete representations. This microscopic perspective offers many benefits. It is a powerful risk analysis method to explicitly model high-consequence risks and RRAs, and thereby provides a tool for making better decisions. It also assists subject-matter experts (SMEs) to think about credible, high-consequence events and better deal with overconfidence or optimism biases. However, the microscopic view is too cumbersome to individually analyze every risk and source of cost uncertainty. It complements and needs to be integrated within the PCA.

In this paper, we propose to develop a microscopic/macroscopic PCA as an integral entity of the DoD risk management process, as follows:

1. The cost and/or risk analyst (simply referred to as analyst below) and the SMEs jointly identify the individual risks using the standard DoD risk-identification process.

2. The analyst and the SMEs jointly screen the identified risks for further analysis and risk mitigation.

3. The analyst and SMEs jointly identify realistic RRAs for the screened risks.

4. The analyst models each risk and its RRAs using a DT.
5. The analyst works with the SMEs to quantify the value of the decisions and outcomes for each DT using discrete and continuous distributions. We favor the Direct Fractile Assessment (DFA) method for data elicitation and fitting the associated cost elements with a three-parameter Weibull distribution.
6. The analyst quantifies the DTs using Monte Carlo simulation. Risks and RRAs are then modeled in terms of risk curves. We, thereby, avoid relying on the minimum expected risk value, which is a serious shortcoming of standard decision analysis.
7. The analysis is readily performed using commercial Excel add-ins (Crystal Ball, @Risk…) or more specialized tools (DecisionPro, Analytica…).

The goal of this paper is to present a realistic and practical method for explicitly analyzing and controlling the cost impact of project risks and realistic RRAs. Projects can then dynamically determine the optimal temporal set of decision gates for a given probability of success—thereby reducing cost while increasing the probability of project success. We illustrate the method using a realistic but simplified case of a project with three technical risks. We close with some concluding remarks and recommendations for further development.

The Quantification of Multiple Project Risks

Consider a project with n credible, high-consequence risks $\{R_i\}$. Each risk, R_i, is characterized by a probability of occurrence p_i and a spectrum of possible outcomes with a PDF $L_i(x)$, where x is a random variable that represents the magnitude of the associated cost or loss. One may then think of this set of risks as a risk portfolio or repository (Kujawski & Miller, 2007) with a generalized discrete PDF $R_S(x)$ given by:

Equation 1.

$$R_S(x) \equiv \left\{ \langle p_1, L_1(x) \rangle, \langle p_2, L_2(x) \rangle, \ldots, \langle p_n, L_n(x) \rangle, \left\langle 1 - \sum_{i=1}^{n} p_i, 0 \right\rangle \right\}$$

The total project cost is a random variable that consists of the sum of the m base cost elements $\{BC_i\}$ and the explicitly identified risk costs $\{RC_i\}$. Depending on the state of knowledge of the data, the base cost elements BC_i may be modeled as either point estimates or continuous PDFs. The total project cost TC is then the probabilistic sum of the *m* base cost elements and *n* risk-driver costs:

Equation 2.

$$TC(x) = \sum_{i=1}^{m} BC_i(x) + \sum_{i=1}^{n} p_i L_i(x)$$

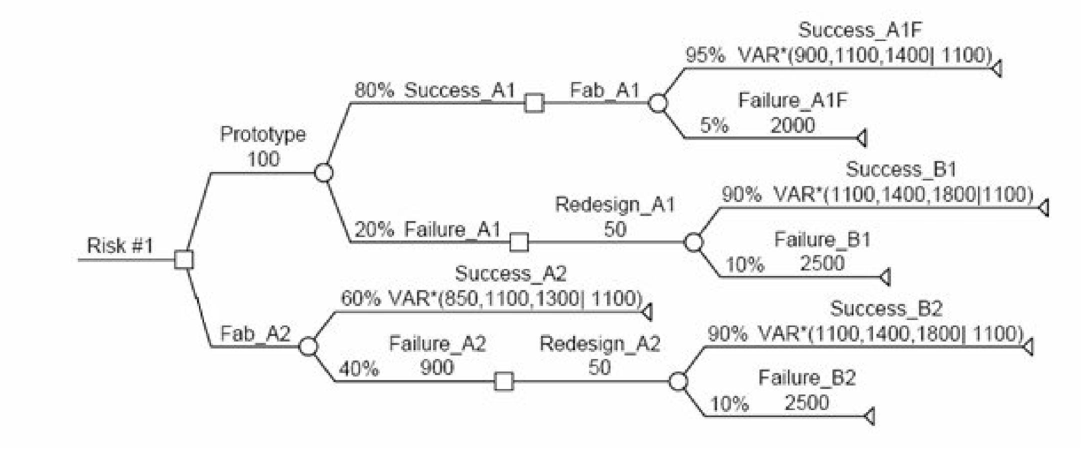
Equations 1 and 2 provide visibility into the link between the credible, high-consequence risks $\{R_i\}$ and the total project cost-risk curve. Monte Carlo simulation tools such as Crystal Ball and @Risk can also provide tornado charts that conveniently quantify the importance of the various risk drivers and their link to the overall cost risk. Projects can use this information to rationally identity risks. This is in sharp contrast with: (1) the use of point estimates that are at best ambiguous because overly confident staff provide low cost estimates, while others may inflate their cost estimates to make it easier to achieve success, (2) decision-making based on qualitative assessments, and (3) the consideration of only S-curves, which only provide a macroscopic and somewhat “black box” view of project risk and cost uncertainty.

Modeling and Analyzing Risk Response Actions

We model and analyze each screened risk and the proposed RRAs using a generalized DT—where PDFs rather than discrete branches are associated with the chance nodes, and the outcomes are analyzed using Monte Carlo simulation (Kujawski, 2002). This provides a powerful technique for dealing with the complex situations typical of today’s DoD projects. It avoids bushy trees and generates risk curves, thereby removing the reliance of decision-making based on expected value.

To illustrate the approach, consider the risk depicted in Figure 1. To be concrete, Risk #1 is associated with fabricating a complex module. The two risk response actions are: (i) Directly fabricate the module, or (ii) Build a prototype and then fabricate the module. The generalized DT follows the standard DT representation. Decision nodes and chance nodes are depicted as squares and circles, respectively. The branches that originate with decision nodes represent the available RRAs. The branches that originate with chance nodes represent the possible probabilistic outcomes. A descriptive label, a probability, and a cost distribution are associated with each branch. These probability and cost values are conditional on the RRA and may also be conditional on the outcome of other risks in case of interdependencies. We model the cost values using a three-parameter Weibull distribution fitted to the 10th, 50th, and 90th percentiles determined in accordance with the Direct Fractile Assessment (DFA) method.

In this example, we assume that the baseline cost is $1,100K. Risk is then given by the Value At Risk (VAR) relative to this value. The VAR corresponds to the events whereby production of the module exceeds $1,100K. The ordering of the decision nodes corresponds to different temporal deterministic events in the development and fabrication cycle of the module.



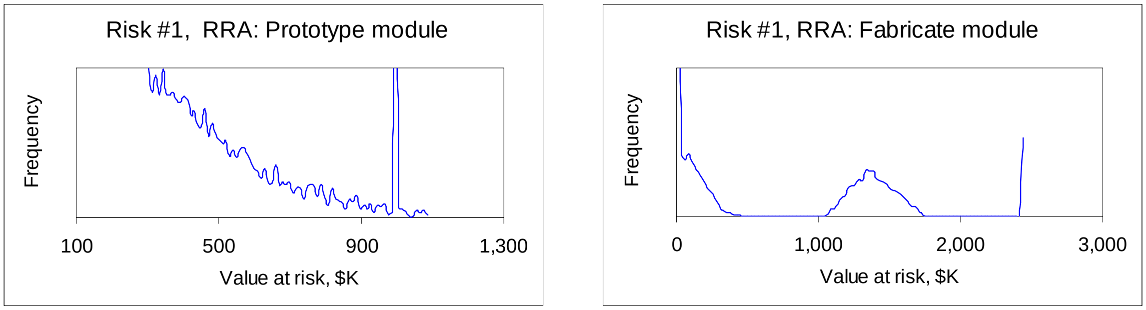
Note: In this hypothetical case, the values may be thought of as $K.

Figure 1. Generalized Decision Tree for Risk #1 and Two Initial Candidate Risk Response Actions

We evaluated each RRA in Figure 1 using the Excel Monte Carlo simulation add-in, Crystal Ball. The selection of a RRA is a deterministic event, and only the associated outcomes can be realized. It would, therefore, be inappropriate to weigh or combine the outcomes of the two RRAs since they are mutually exclusive. The PDFs and risk profiles for each individual RRA at the start of the project are depicted in Figures 2a and 2b, respectively. The PDFs are multimodal and cannot be represented using any of the well-known probability distribution functions. The peak for the “prototype” RRA corresponds to the outcome in which the fabrication of the module fails. The PDF for the “direct fabrication” RRA has two modes corresponding to the sequence of events in which the first fabrication and the subsequent fabrication following redesign both fail.

The Complementary Cumulative Distribution Functions (CCDF) or risk curves are shown in Figure 2b, in which the exceedance probability is the probability of exceeding a given consequence or (1 – the probability of success). For example, looking at the VAR(Fab_A2) curve in Figure 2b, one reads that there is approximately a 30% probability that the cost will exceed $1,500K. Equivalently, one can state that there is a 70% probability that the cost will be less than $1,500K. The risk curve and the cumulative distribution function carry identical information content. Since we are focusing on specific risks and VAR, we favor the risk curve or CCDF because, in our opinion, it provides a better view of the residual risk and management reserve than the S-curve (or CDF) that typical represents the total cost (including the baseline and risk cost elements).

For any given value on the x-axis, the risk curve that corresponds to the lowest exceedance probability represents the lower risk. Figure 2b illustrates that the prototype risk curve is significantly lower than the fabrication risk curve and, thus, has less risk. In this hypothetical but realistic situation, the investment of $100K for building a prototype provides a significant return on the investment as measured by the significant risk reduction. To be more precise, the prototype RRA presents a lower cost of risk mitigation for all values greater than $200K. For the manager trying to decide if it is worthwhile to invest in the prototype option, the answer is to invest as long as the anticipated benefits from the prototype (whether it be cost savings, time savings, information, etc.) exceed $200K.



Note: Given the different scales, the two PDFs are shown separately for greater visibility.

Figure 2a. Probability Distributions Corresponding to the Two RRA Options for Risk #1

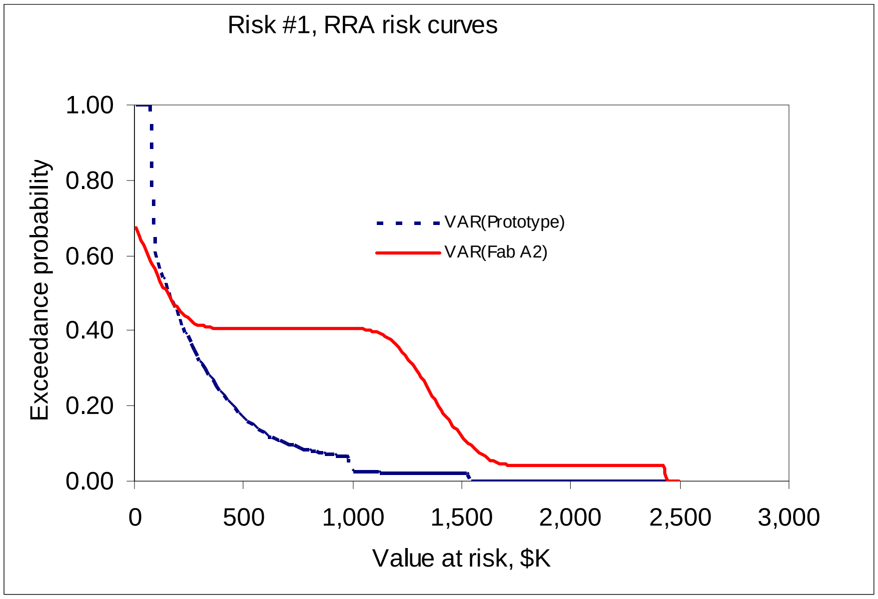


Figure 2b. Risk Curves for the Two RRA Options for Risk #1

The Dynamic Character of Risk Response Actions

As a project progresses, its risk picture is dynamic. The sources and consequences of risks continue to evolve and change over time. As more information is obtained about a particular risk, the RRA options might change; thus, it is necessary to constantly monitor risk. In general, at any point in time there will be a mix of acceptable and unacceptable results. The performance of the RRAs should be monitored and controlled to ensure they are adequately mitigating risk. Concurrently, management reserves should be reviewed on a periodic basis and dynamically allocated where needed to ensure project success. The Lockheed Management Student Guide (1998, p. 33) states, “Risk management efforts that fail do so because the risk control actions did not keep up with a changing program situation.”

As discussed in the previous section, we use risk DTs to model the evolution of the potential RRAs. For example, Figure 3 depicts the Risk #1 risk curves at the start of implementation of the “Prototype” RRA and after the successful demonstration of the prototype. The latter risk curve moves to the left of the original risk curve and is narrower, which reflects a reduced risk. These two risk curves represent the value of the unmitigated risk exposure at two different points in time and, thereby, provide a metric for the risk exposure characteristics. This information is essential if analysts are to track the value of the residual exposure versus the value or cost of the expended RRAs and modify the RRAs as needed to ensure mission success. Note that if the risk curve moves to the right of the original risk curve, it means that risk exposure is increasing, and RRAs need to be re-evaluated.

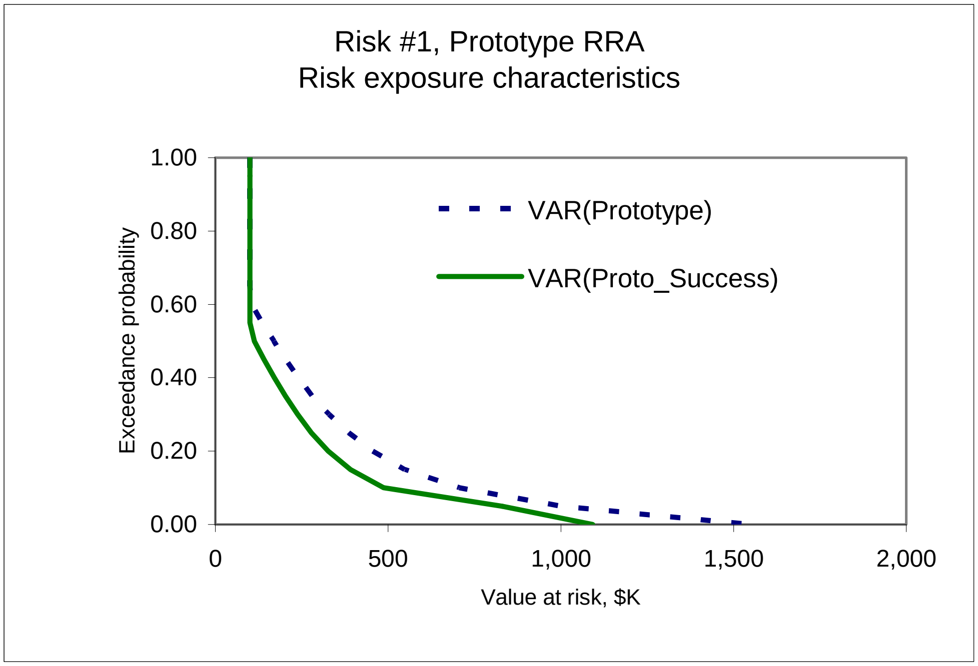


Figure 3. Risk Exposure Characteristics for Risk #1 with Development of a Prototype for Risk Mitigation at the Start and after Successful Demonstration

Application to a Project with Multiple Risks

Now consider the hypothetical project with the following three independent risks: Risk #1 depicted in Figure 1; Risks #2 and #3 depicted in Figure 4a and 4b, respectively. It is both rich and simple enough to illustrate: (1) several diverse RRAs and their analysis, (2) the dynamic nature of the risk picture, and (3) the monitoring of individual risks and allocation of management reserves. The approach readily extends to dependent risks using different probability and outcome values that reflect causality effects among the risks.

Figure 4a may be thought of as the prime contractor subcontracting the engineering and fabrication of a complex module. The prime is considering the following two options: (1) subcontract to a single contractor A, denoted by the branch PDR_A associated with the initial node; (2) carrying two subcontractors and selecting the best one for fabrication at the Preliminary Design Review (PDR). The labeling is somewhat cumbersome because each branch needs to be uniquely identified. The PDR_A sequence represents the decision to proceed with a single contractor. The PDR_AB sequence represents the decision to proceed with two contractors and, at PDR, to select the best one for manufacturing. By selecting two different contractors with different offerings, the prime significantly reduces the probability of PDR failure. RW represents the cost associated with rework; it is modeled with a three-parameter Weibull distribution specified in terms of the 90th, 50th, and 10th percentiles provided by SMEs or historical data.

Figure 4b may be thought of a prime contractor who considers two different Verification and Validation (V&V) strategies as a means for risk reduction. The branch VVS_1_(Start or CDR) represents the use of the standard approach with planned expenditures of $300K. The branch VVS_2_ (Start or CDR) represents the use of a more thorough V&V strategy with greater use of simulation and planned expenditure of $1,000K. The branch RW_1_(PDR or

CDR) represents the rework following the PDR and CDR, respectively. The rework is assumed to be inversely related to the V&V effort, and it is modeled with a three-parameter Weibull distribution specified in terms of the 90th, 50th, and 10th percentiles provided by SMEs or historical data.

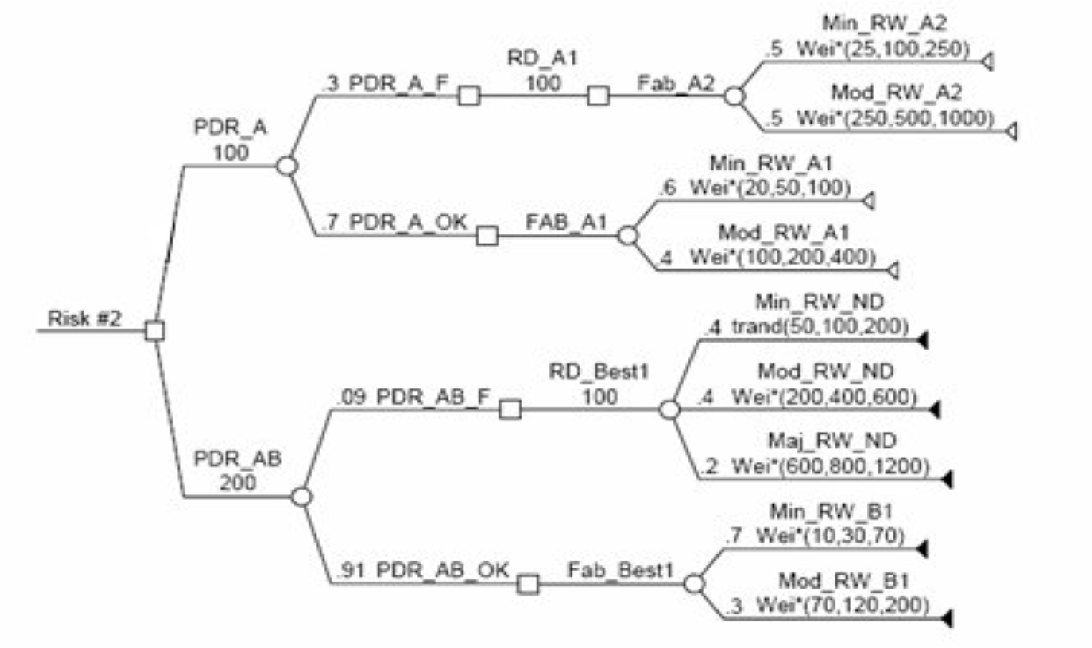
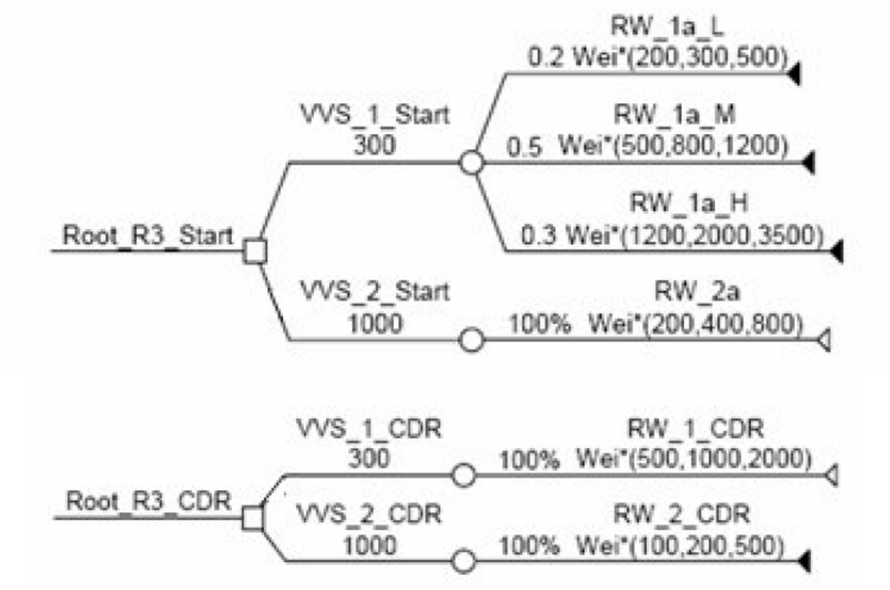


Figure 4a. Generalized Decision Tree for Risk #2 and Two Initial Candidate Risk Response Actions



Note: The start (or PDR) and CDR periods are shown separately to simplify the representation of the sequence of events.

Figure 4b. Generalized Decision Tree for Risk #3 and Two Initial Candidate Risk Response Actions

Given the above illustrative project—with three risks each with two potential RRAs—there are eight possible initial Total Project RRAs (TPRRA). As previously discussed, the risk picture is dynamic and gets quite complex as through time. Consider Risk #1 with development of a prototype as a risk reduction option. The prototype may fail or succeed, and the fabrication of the final module may fail or succeed. The full representation of the set of all possible outcomes for even this project is overwhelming and beyond the scope of a symposium paper. We, therefore, limit ourselves to reporting an interesting subset of the complete analysis as follows:

1. We consider only two of the eight TPRRAS.
   a. Strategy 1. Use of the lowest cost-mitigation option for each risk, which is equivalent to proceeding as normal—i.e., no specific RRA for any of the three risks. This is the approach that a risk-seeker project manager would favor.
   b. Strategy 2. Use the most effective RRA for each risk. This corresponds to: (1) developing a prototype for Risk #1, (2) proceeding with two contractors for Risk #2, and (3) implementing a more thorough V&V effort for Risk #3. This is the approach that a risk-averse project manager would favor.
2. For each strategy, we assume the best possible outcomes for the probabilistic nodes through time T1: the Risk #1 prototype and the Risk #2 review PDR_AB succeed. Risk #3 has no gates; the risk reduction is directly accounted in the magnitude of the rework. Figure 5 compares the initial and residual risks under the two strategies.
3. For each strategy, we assume the worst outcomes for the probabilistic nodes through time T1: the Risk #1 prototype and the Risk #2 review PDR_AB fail. Risk #3 has no gates; the risk reduction is directly accounted in the magnitude of the rework. Figure 6 compares the initial and residual risks under the two strategies.
4. For convenience, we also report the 50th, 80th, and mean values for the aggregated risks and individuals risks for strategies 1 and 2 in Tables 1 and 2, respectively.

Useful Information about Risk

We now make a few brief observations. By plotting the risk curves over time for each strategy, we can see from Figure 5 that if the best outcome is realized, both strategies reduce risk (as seen by the T1 curves moving left and becoming more vertical than the start curves over most of the range of analysis). Likewise, we see that if the worst outcome prevails as shown in Figure 6, then both strategies actually increase the cost risk exposure of the project. Graphing risk curves over time thus provides a metric to measure the success of risk mitigation efforts.

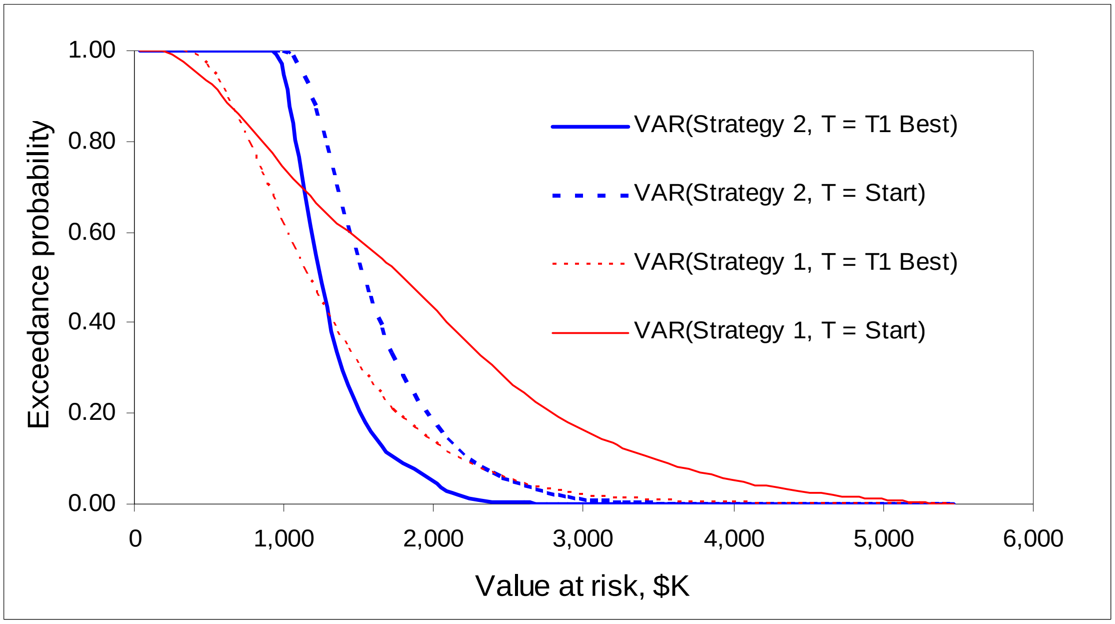


Figure 5. Risk Exposure Characteristics for a Risk-seeking Strategy (Strategy 1) and a Risk-averse Strategy (Strategy 2), Assuming Good Luck Prevails on the Project

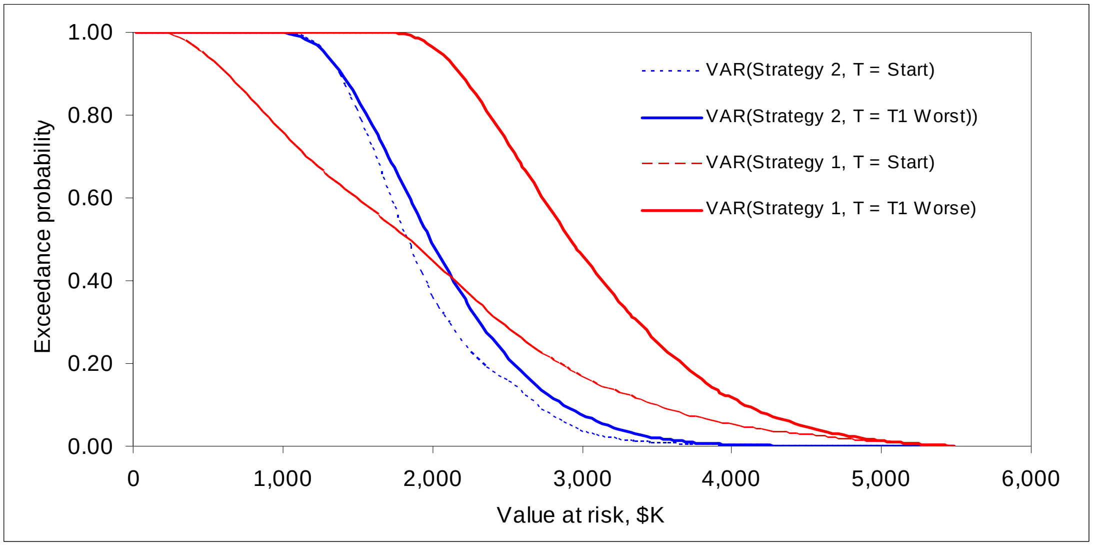


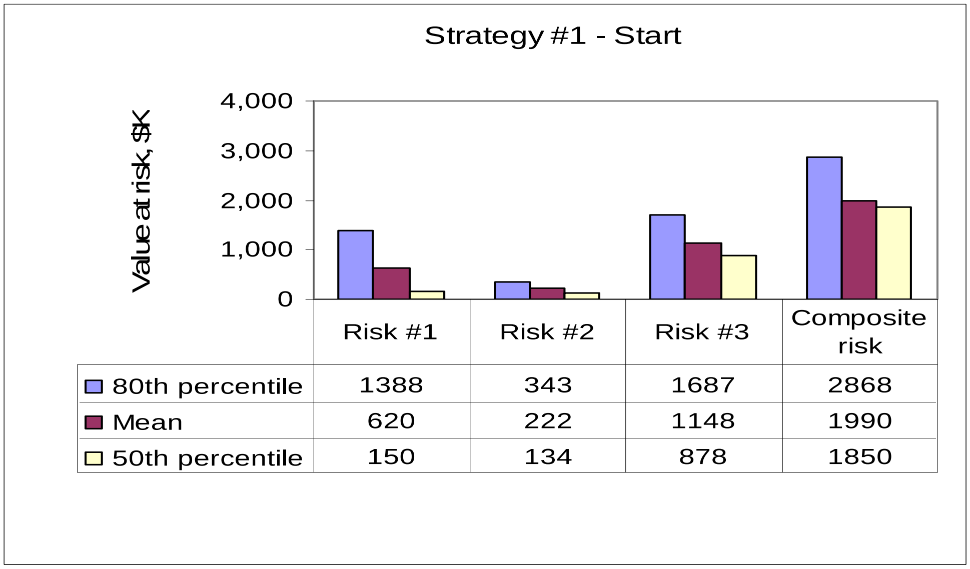
Figure 6. Risk Exposure Characteristics for a Risk-seeking Strategy (Strategy 1) and a Risk-averse Strategy (Strategy 2), Assuming Murphy's Law Prevails on the Project

But the graphs provide even more information. They allow us to consider the risk mitigation qualities of each strategy and to quantify our risk exposure. This information can be used to choose between the two strategies. Note that under the best-case scenario (Figure 5), at the start of the project, Strategy 1 offers a lower risk exposure below $1,500K, while Strategy 2 offers a lower risk exposure above that value. Both strategies are equal in terms of exceedence probability (60 %) at the "breakeven" point of $1,500K. What do we gain by extending the analysis to time T1? We see that the "breakeven" point is lower ($1,200K), and the risk at that point is also lower (40%). So, which one is the best choice? If we were optimists and certain that the best outcome would be realized, we could make a choice based on the expected benefits. As long as the expected benefits of the RRA are greater than $1,200, we would choose Strategy 2. But of course, we have no such assurance, so let's examine the worst-case scenario.

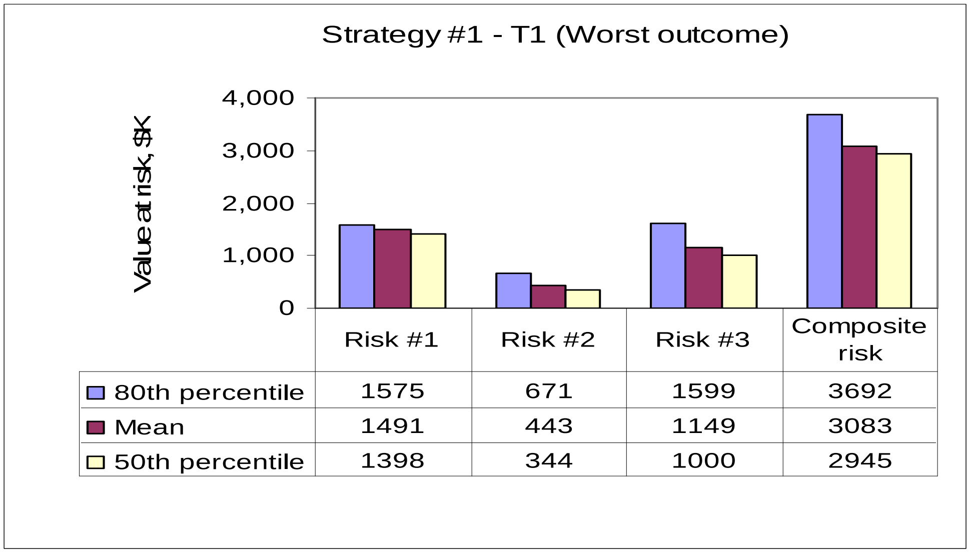
Figure 6 shows the results of implementing each strategy over time assuming the worst outcome (Murphy's Law). As expected, the risk-seeking Strategy 1 significantly increases our cost risk exposure when things go bad, but the more conservative Strategy 2 is much less sensitive to bad outcomes. In fact, at T1, Strategy 2 dominates Strategy 1— meaning it has a lower risk for any value. If we were pessimists, our choice would be simple: Strategy 2 is especially effective in providing insurance against the worst outcomes.

Which strategy is chosen depends on the decision-maker's risk aversion. Is he/she an optimist or a pessimist? In either case, if the expected benefits of risk mitigation exceed $1,200K, Strategy 2 is the best choice. We believe examining risk information in this way provides useful insight and helps project managers make better choices.

Table 1. Strategy 1 Risk Characteristics at Start and at T1, Assuming that Murphy's Law Prevails on the Project

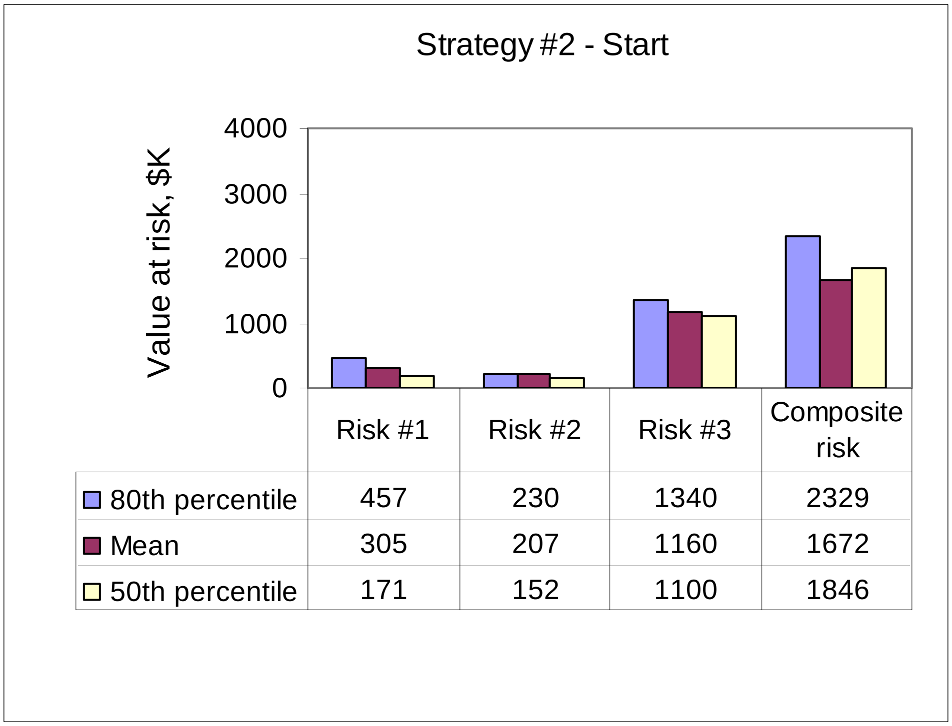

Strategy #1 - Start

	Risk #1	Risk #2	Risk #3	Composite risk
🟦 80th percentile	1388	343	1687	2868
🟥 Mean	620	222	1148	1990
🟨 50th percentile	150	134	878	1850

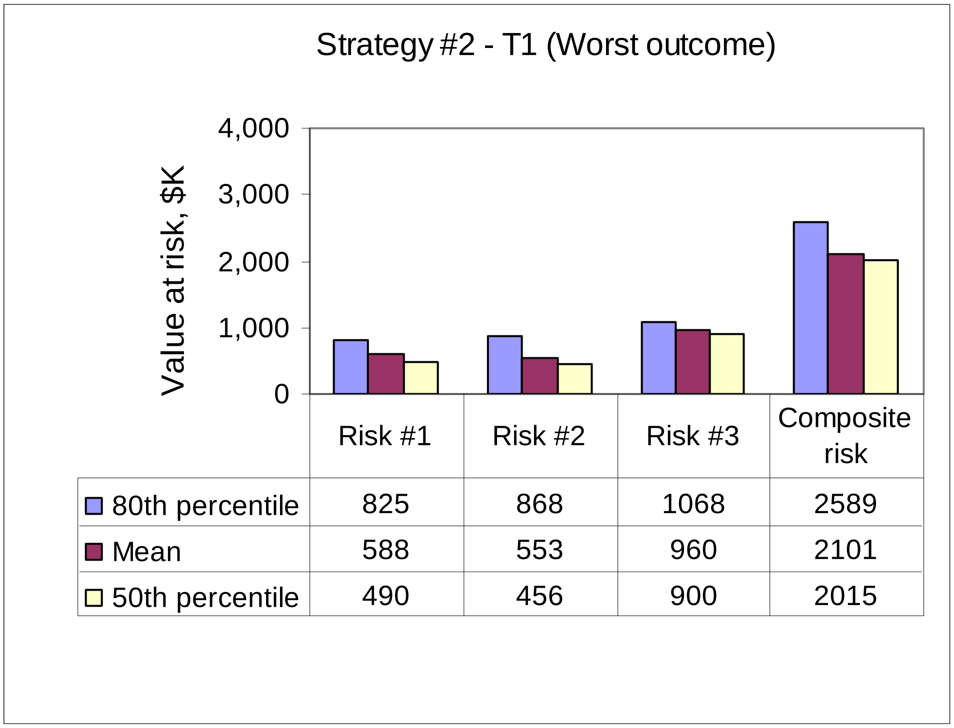

Strategy #1 - T1 (Worst outcome)

	Risk #1	Risk #2	Risk #3	Composite risk
🟦 80th percentile	1575	671	1599	3692
🟥 Mean	1491	443	1149	3083
🟨 50th percentile	1398	344	1000	2945

Table 2. Strategy 2 Risk Characteristics at Start and at T1, Assuming that Murphy's Law Prevails on the Project


Strategy #2 - Start

	Risk #1	Risk #2	Risk #3	Composite risk
🟦 80th percentile	457	230	1340	2329
🟥 Mean	305	207	1160	1672
🟨 50th percentile	171	152	1100	1846


Strategy #2 - T1 (Worst outcome)

	Risk #1	Risk #2	Risk #3	Composite risk
🟦 80th percentile	825	868	1068	2589
🟥 Mean	588	553	960	2101
🟨 50th percentile	490	456	900	2015

Tables 1 and 2 suggest that the use of mean values is not necessarily a cautious approach for planning project contingency.

Conclusions

We have presented a method for evaluating and tracking project-specific risks at the microscopic level. This type of analysis, as opposed to the macroscopic-level risk analysis, is essential for risk management. While the macro level provides some information about total cost risk, the micro level allows the project manager to plan and control risk response actions that influence total cost risk.

We demonstrated the use of risk decision trees to model the evolution of the potential RRAs, and we used risk curves to evaluate the risk. We believe risk curves are better than the expected-value results usually given by traditional DT analysis because they contain all the risk information both in terms of probabilities and value at risk. This thorough approach allows management to consider what they mean by “acceptable” risk and explicitly models the tradeoff between risk and benefits of any given RRA.

We recommend the use of risk curves to evaluate the performance of RRA and to track their performance over time. If the RRA is working (at reducing risk), we should see the corresponding risk curve move to the left and/or become more vertical. This tracking over time is key to understanding the dynamic nature of risk management and can reveal necessary changes in strategy.

Risk curves derived from Monte Carlo simulation on DTs are particularly useful when analysts are comparing different risk-mitigation strategies. The “breakeven” points help the risk manager understand the conditions under which each strategy is most appropriate. Combined with scenario analysis, it offers an opportunity to make cost-benefit tradeoffs among strategies.

We think that these results provide the detailed information that program managers need and want when they face hard decisions on programs. There is a cost for this type of analysis, but it is small considering the potential benefits. The proposed approach is both practical and mathematically valid and can be implemented using commercially available tools such as Crystal Ball and @Risk. The challenge is to start implementing these more refined cost models and risk management practices.

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