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Monetizing Risk and Risk Mitigation

ABSTRACT

Risk management has traditionally employed qualitative assessments for the probability of a risk event occurring and the consequence of the risk event occurring. Decisions on whether to pursue risk mitigation activities are generally not based on a thorough understanding of the impact of the risk and risk mitigation on program cost. This paper proposes a method to calculate a Return on Investment (ROI) of risk mitigation activities based on Bayes' Theorem. The ROI can be used to actively manage a risk program and help choose which risk mitigation activities to fund. Additionally, this paper advocates that the average value of the risk probability weighted cost for correcting risk events be separately identified as a component of a system cost estimate to facilitate effective risk management.

INTRODUCTION

For many programs, risk management is conducted as an independent activity that only indirectly impacts the estimated program costs. Furthermore, decisions to fund a given risk mitigation activity are often subjective and not evaluated quantitatively. This paper proposes a method for calculating the Return on Investment (ROI) of risk mitigation activities. This method monetizes risk management by estimating the reduction in the expected cost of risk due to a mitigation activity. This paper further proposes that the cost of program risk be separately identified to facilitate its proper management.

While U.S. Department of Defense (DoD) program cost estimates include the impact of risk within the cost estimate, this impact is largely based on the consequences of realized risks on previous programs. The impact of risk within a program is typically not separately identified, hence determining the impact of a given risk mitigation activity on total program cost is difficult. If a cost estimator is aware of significant risks or risk mitigation activities planned for a program, the cost estimator may adjust the cost model to reflect this knowledge, but the impact would typically not be separately identified.

Notation

A	test
A_i	outcome i of test A
$C(\cdot)$	cost of
CDF	cumulative distribution function
$C(M_i)$	cost of mitigation activity i
$C(Z)$	cost of rectifying outcome Z
c_i	cost reduction factor applied by mitigation activity M_i
C_{plan}	(expected) cost of proposed risk mitigation plan
M_i	mitigation activity i

m_i	(probability) mitigation factor applied by mitigation activity M_i
n	number of possible outcomes of a test
$P(\cdot)$	probability of
PDF	probability distribution function
PM	program manager
ROI	Return on Investment
Z	the event of realizing a risk
$\bar{Z}$	the event of not realizing a risk

Usually, the cost of correcting a realized risk is not deterministically known, but can be represented by a random variable. Because all risks are not likely to be realized, the total cost of risk for a program is the sum of the probability of each risk occurring multiplied by the cost of correcting the realized risk (assuming the risks are statistically independent). Since the cost of correcting realized risks is a random variable, the total cost of known risks for a program is also a random number with an average value and standard deviation.

The average value of the total cost for known risks for a program is the sum of the expected values of the cost of all of the known risks, where the expected value is the risk probability adjusted cost of correcting a realized risk (simplified, it's the probability a risk will happen multiplied the cost of correcting the realized risk).

For programs with multiple risks having an expected value for cost of the same magnitude, the total cost for program risk can be estimated as the expected value of all the program risk costs increased by a multiple of standard deviations. A Monte Carlo analysis [1] is beneficial in estimating the probability density function (PDF) and cumulative distribution function (CDF) of the cumulative cost of the risks. The distribution functions assist in the evaluation of the adequacy of the estimate for program risk.

In the past, program managers have attempted to maintain contingency funds within their program. Using this approach, contingency funds were viewed as an asset of the program that could be arbitrarily used to respond to budget cuts, cost overruns, etc. Whether or not there is sufficient budget, the program risk costs are a fiscal liability that exists and has a likelihood of being incurred. The current approach of spreading the impact of risk among all the cost categories may be a consequence of this practice; it is much harder for external organizations to identify the contingency funding for budget cuts. Unfortunately, this practice can result in organizations planning to spend the full amount for a given cost category without accounting for the risks the estimate is intended to include.

The proposed risk monetization calculations allow the program manager to effectively evaluate risk and mitigations quantitatively, and allow decision makers to compare multiple test and mitigation options. Performing the risk monetization calculations encourages users' critical thinking about risk mitigation plans and enhances communication among the program management team, the technical team, and the cost estimators.

Risk Management Process

Risk management is both critical and mandatory for DoD programs, making risk management an active area of research.

The DoD risk management process is defined in the DoD *Risk Management Guide* for Acquisition [2], which is described in more detail below. Lyons [3] studied the *Risk Management Guide* and identified areas of improvement by surveying acquisition professionals on their use and understanding of the risk management guide. While the author found that the *Risk Management Guide* provides the basic structure of the risk management processes, the guide could be improved by providing more information on the evaluation of program risk and providing more information on mitigated risk activities.

Morse and Drake [4] observe that the popular risk management tools are focused primarily on methodology—not data. In practice, acquisition programs use qualitative assessments of risk, and metrics that are used for cost and schedule (such as Earned Value Management) evaluate the consequences, not the root cause. The authors propose new risk metrics that can be tracked on a web-based "portal" for continuous risk management.

Klabon [5] emphasizes the value of quantitative metrics over qualitative adjectives for quantification of the probability of occurrence, with application in the management of software engineering projects. The author applies Bayes' Theorem to conditional probabilities for risks, and then develops Bayesian networks to model the probability of occurrence of a risk.

Irwin [6] describes the development of probability distribution functions with application to schedule risks of the Information Support Plan. The author emphasizes that a quantitative risk assessment creates a common language for communicating about risks between systems engineers and program managers. The choice to use qualitative versus quantitative methods for evaluating risk depends on the availability of data; in the absence of specific data, qualitative analysis can be performed using subject matter experts' input.

Bodner [7] developed a simulation for the schedule and cost risks of a defense acquisition program using a decision/event network. The enterprise simulation models the behavior of the agents involved in the acquisition process and the simulation allows for study of the response of the enterprise to various risks.

Furthermore, the model of series tests and mitigations used in this paper is similar to sequential testing in product development. Thomke and Bell [8] present a model for determining optimal sequential testing during product development, with the objective of reducing uncertainty about technical solutions and customer satisfaction.

DOD RISK MANAGEMENT PROCESS

The objective of risk management is to identify, analyze, and communicate the risks while balancing cost, schedule, and performance goals within program funding. This is especially true for programs with designs that approach or exceed the state-of-the-art or have tightly constrained or optimistic cost, schedule, and performance goals.

The *DoD Risk Management Guide for Acquisition* [2] lists the following key activities in the risk management process:

- Performing Risk Assessments (Identification and Analysis)
- Formulate Mitigation Strategies and Obtain Approvals
- Risk Mitigation Implementation and Tracking
- Risk Monitoring

Risk management begins at the earliest stages of program planning and continues throughout the life cycle of the program.

FIGURE 1. Risk Management Process flow chart [2]. All steps are performed periodically throughout the project's life cycle.

The DoD Risk Management Process is a methodology for continuously identifying and analyzing potential risks; identifying the root cause, selecting/implementing appropriate risk mitigations; and tracking and monitoring the mitigations to ensure successful risk reduction. Figure 1 depicts the risk management cycle as outlined in Reference [2].

A risk assessment identifies critical risk events and analyzes programs to uncover risk events and their potential impacts. Risk assessments consist of risk identification and analysis to determine the probability and consequence of the occurrence.

Prioritizing risks consists of evaluating the assigned likelihood and consequence criteria, determining the risk rating, and reviewing the collective results for all risks identified within a program. Evaluating all program risks establishes prioritization and determines the order in which the risks will be addressed.

The corresponding likelihood and consequence levels of each individual risk can be plotted on the risk reporting matrix. An example is depicted in Figure 2.

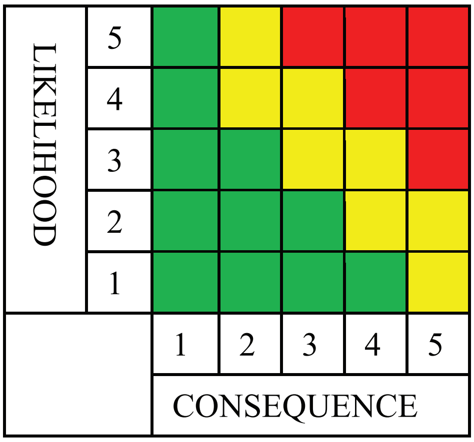
Definitions of the risk ratings low, moderate, and high are as follows:

LOW RISK (GREEN): Has a "very unlikely" to "unlikely" probability of occurring and/or minimal to marginal potential for increase in cost, disruption of schedule, or degradation of performance should the risk be realized. Normal program management attention should result in the adequate handling of the risk.

MODERATE RISK (YELLOW): Has a "possible" likelihood of occurring, and a moderate chance of increase in cost, disruption of schedule, or degradation of performance should the risk be realized. Increased attention and management action should be applied to adequately handle the risk to an acceptable level.

HIGH RISK (RED): Has a "likely" to "near certainty" likelihood of occurrence and would cause critical to catastrophic increases in cost, disruption of schedule, and/or degradation of performance should the risk be realized. Significant attention and high priority management action should be required to appropriately handle the risk to an acceptable level.

After the initial likelihood and consequences have been determined, the next step is to formulate mitigation options. For all moderate (yellow)



LIKELIHOOD						
	5	🟩	🟨	🟥	🟥	🟥
	4	🟩	🟨	🟨	🟥	🟥
	3	🟩	🟩	🟨	🟨	🟥
	2	🟩	🟩	🟩	🟨	🟨
	1	🟩	🟩	🟩	🟩	🟨
		1	2	3	4	5
		CONSEQUENCE				

FIGURE 2. Risk matrix.

A NOTE ON COSTS

Determining the cost of a risk and its mitigation is not trivial. Life cycle cost should be included in the cost of the risk. This approach takes into account the impact on development costs, production costs, and sustainment costs.

and high (red) risks, the risk mitigation strategy is refined by outlining a series of activities and/or decisions which, when executed, are designed to reduce the likelihood and/or consequence of the risk. An example of a risk waterfall chart that is commonly used to communicate how the risk will be mitigated is depicted in Figure 3.

SHORTFALLS OF THE RISK MANAGEMENT PROCESS

The use of the risk matrix combined with the waterfall chart is sufficient for low risks. However, for risks with high risk ratings (red), evaluating multiple mitigation paths and communicating the costs and benefits of the mitigation options often proves to be challenging. In addition, the DoD risk process typically does not include a quantitative evaluation of risk mitigation activities in establishing the value of the mitigation.

Risk Monetization Model

For the Risk Monetization Model, risks are comprised of the following three components:

1. a future root cause,
2. a probability or likelihood of the future root cause occurring, and
3. the consequence (or effect) of that future occurrence.

An example of a risk statement is:

1. If the drag on the ship's hull is too large,
2. which is estimated to occur with 10% probability,
3. then the ship will not meet its speed requirement.

The probability of occurrence $P(Z)$ of the root cause can be estimated, as well as the cost of rectifying the consequence $C(Z)$ once the root cause occurs. The product $P(Z)\ C(Z)$ is the expected value of the risk.

Returning to the example, to rectify the consequence without changing the speed requirement, the ship would require modifications such as increased propulsion power, more efficient propellers, or drag reduction through an improved bow. The cost of incorporating these changes would be reflected in $C(Z)$.

In a risk management program, a risk mitigation activity seeks to reduce either or both $P(Z)$ and $C(Z)$. In general, a risk mitigation activity can be broken down into a *test* and a response to the results of the test (a *mitigation* activity). A test could be physical experiment such as towing a model in a tow tank, or the test could be purely analytical such as a computer model of the design. In either case, the test could be used as evidence either supporting or contradicting the existence of the root cause.

Risks with a very low probability of occurrence and high consequences can have catastrophic impacts on a program, because the expected value of the risk is much lower than the cost of addressing the issue. If the risk is realized, available program funds may not be sufficient and it may be appropriate to cancel or significantly restructure the program. However, Congress has been historically understanding and supportive in funding the corrective action for certain types of events, such as highly disruptive but unusual natural events (for example, severe hurricanes and earthquakes). Early identification of risks enables the program manager to address the problem earlier and minimize the impact on the organization. Considerations should be given to periodically schedule and fund risk mitigation tests to update the probability of occurrence and consequences of the risks.

Risk Management Planning for a Single Risk Mitigation Activity

The risk monetization model defines a risk management plan associated with the risk. The *plan* is a strategy for performing tests and risk

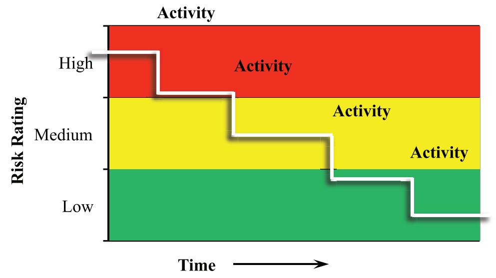


FIGURE 3. Risk waterfall chart.

mitigation actions with two objectives: (1) reduce the likelihood of the risk occurring and (2) reduce the cost of the risk should it be realized. The plan is developed before any tests or risk mitigation activities are performed, and the risk monetization calculations are based on the assumption that the plan is executed as written.

A *test* is defined as a single event that has n possible outcomes that can be listed. The outcome of the test is not known in advance.

In this risk monetization model, the plan defines the test (which has n possible outcomes) and the plan defines one mitigation activity corresponding to each test outcome. The *mitigation* activity is defined as an action that reduces or maintains the cost and/or likelihood of realizing the risk.

A flow chart of the plan, test, and mitigation model used in this example is shown in Figure 4.

A test can provide data for analysis regarding the likelihood of realizing the risk. The test denoted A costs $C(A)$ to perform. Test A has n possible outcomes, each denoted A_i, $i = 1, \ldots, n$.

The accuracy of the test is described by probabilities. The probabilities take two forms: $P(A_i \mid Z)$ and $P(A_i \mid \bar{Z})$, $i = 1, \ldots, n$. $P(A_i \mid Z)$ is the probability that the test outcome is A_i, given that the risk is realized. $P(A_i \mid \bar{Z})$ is the probability that the model test outcome is A_i, given that the risk is not realized. All possible outcomes of the test are assumed to be included in n, or

$$\sum_{i=1}^{n} P(A_i \mid Z) = 1 \qquad (1)$$

$$\sum_{i=1}^{n} P(A_i \mid \bar{Z}) = 1 \qquad (2)$$

Each test outcome has a corresponding mitigation activity M_i based on the outcome of the test: mitigation activity M_i will be performed if the test outcome is A_i.

In addition, each mitigation activity has a cost $C(M_i)$. Performing the mitigation activity M_i reduces the probability of realizing the risk by a factor of m_i. Performing mitigation activity M_i also reduces the cost of correcting the risk, should it occur, by a factor of c_i. For example, reducing the probability of realizing the risk by 10% corresponds to m_i of 0.10.

EVALUATION OF MITIGATED PROBABILITY

The probability of each test outcome is calculated according to

$$P(A_i) = P(A_i \mid Z)P(Z) + P(A_i \mid \bar{Z})\big(1 - P(Z)\big) \qquad (3)$$

$P(Z \mid A_i)$ is calculated using Bayes' Theorem with conditional probabilities that describe the test accuracy.

$$P(Z \mid A_i) = \frac{P(A_i \mid Z)P(Z)}{P(A_i \mid Z)P(Z) + P(A_i \mid \bar{Z})\big(1 - P(Z)\big)} \qquad (4)$$

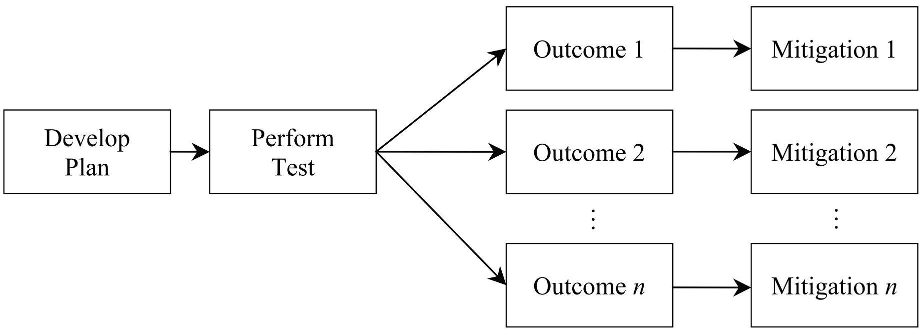


FIGURE 4. Flow chart of risk plan, test, and mitigation.

The probabilities are affected by the mitigation activity, which reduces the probability of realizing the risk. The mitigated probability is denoted with a prime symbol.

$$\mathrm{P}'(Z \mid A_i) = (1 - m_i)\mathrm{P}(Z \mid A_i) \tag{5}$$

The updated probability of realizing the risk, $\mathrm{P}'(Z)$ is

$$\mathrm{P}'(Z) = \sum_{i=1}^{n} \mathrm{P}'(Z \mid A_i)\mathrm{P}(A_i) \tag{6}$$

EVALUATION OF EXPECTED COST

If the test result is A_i and risk *is not* realized, the costs incurred are the cost of the test and the cost of the mitigation.

$$C(A_i \cap \bar{Z}) = C(A) + C(M_i) \tag{7}$$

If the test result is A_i and the risk *is* realized, the costs incurred are the cost of the test, the mitigation, and the (mitigated) cost of correcting the consequence of the risk.

$$C(A_i \cap Z) = C(A) + C(M_i) + (1 - c_i)C(Z) \tag{8}$$

Therefore, the expected cost to implement this risk mitigation plan C_{plan} is

$$C_{plan} = \sum_{i=1}^{n} \left[(1 - \mathrm{P}'(Z \mid A_i))\mathrm{P}(A_i)C(A_i \cap \bar{Z}) + \mathrm{P}'(Z \mid A_i)\mathrm{P}(A_i)C(A_i \cap Z)\right] \tag{9}$$

EVALUATION OF RETURN ON INVESTMENT

A Return on Investment (ROI) can be calculated to evaluate the risk and mitigation. In general, the ROI is expressed as

$$\mathrm{ROI} = \frac{\text{net return}}{\text{investment}} \tag{10}$$

The ROI is defined as the net return divided by the expected cost of investment in the risk mitigation plan. The net return is the reduction in expected cost of the risk. As defined, a 0% ROI indicates a neutral risk mitigation plan and positive ROI indicates a beneficial risk mitigation plan. In calculating the net return, C_{plan} includes the cost of the mitigation test, mitigation activities, and the risk remaining after the mitigation activity:

$$\text{net return} = \mathrm{P}(Z)\,C(Z) - C_{plan} \tag{11}$$

The investment represents the expected amount that must be spent to implement the mitigation plan; it includes the cost of the test and the cost of the mitigation activities.

$$\text{investment} = \sum_{i=1}^{n} \left[\mathrm{P}(A_i)\left(C(A) + C(M_i)\right)\right] \tag{12}$$

The Department of Defense is not a business, so the concept of ROI may not seem appropriate. In a non-profit context, the ROI can be viewed as "Knowledge Value Added," which is a methodology for quantifying organizational output in common units. For further discussion, see Reference [9].

EXAMPLE 1: SINGLE RISK MITIGATION ACTIVITY

Suppose the ship design Program Manager (PM) is concerned about a speed requirement. A risk assessment evaluated the risk that the ship may not make the required speed as high.

Let Z denote the event that the ship does not make the required speed. The design team's hydrodynamics expert estimates that for the current design, the probability $\mathrm{P}(Z)$ that the ship will not meet the speed requirement is 0.1. Furthermore, the PM estimates if the ship does not meet the required speed, the corrective action cost after the ship is built is \$20,000. Therefore, the expected value of the risk is $\mathrm{P}(Z)\ C(Z) = \$2{,}000$.

The PM plans a model test (A), which is a physical test of a representative small-scale model. The model test is expensive; however, it provides very accurate predictions of the full-scale ship's behavior.

The cost of performing the model test is \$500. The PM identifies three possible outcomes of the test:

	ACCURACY OF TEST		MITIGATION ACTIVITY		
Test Outcome	$\mathrm{P}(A_i \mid Z)$	$\mathrm{P}(A_i \mid \bar{Z})$	Cost of Mitigation Activity, $C(M_i)$	Reduction of Probability of Realizing, m_i	Reduction in Cost of Correcting, c_i
A_1	0.80	0.05	\$ 5,000	0.99	0.6
A_2	0.15	0.15	\$ 500	0.75	0
A_3	0.05	0.80	\$ 0	0	0

TABLE 1. Description of tow tank model test A and corresponding mitigation activities.

A_1—the model test predicts that the ship speed is significantly less than required.
A_2—the model test predicts that the ship speed is slightly less than required.
A_3—the model test predicts that the ship meets or exceeds the speed requirement.

For each test outcome, the PM plans the following mitigation activities:

- If the result is A_1, the PM will invest $5,000 in the design of an improved bow. The new bow is very effective and reduces the probability that the ship will fail to meet the speed requirement by 99%. Additionally, the use of the new bow reduces the cost of the corrective action (altering the design) by 60%, should the ship still not meet the speed requirement.
- If the result is A_2, the PM will invest $500 in the design of a stern flap attached to the hull. The stern flap reduces the probability that the ship will fail to meet the speed requirement by 75%, but it does not impact the cost of corrective action if the ship still does not meet speed.
- If the result is A_3, the PM will not make any changes to the design. The probability of realizing the risk is not reduced and the cost of corrective action is not changed.

This risk mitigation plan is summarized in Figure 5.

The PM consults with model test experts who are able to estimate the accuracy of the model test.

The accuracy of the model test is described by probabilities that take the form $\mathrm{P}(A_i \mid Z)$, the probability that the model test outcome is A_i, given that the actual ship speed does not meet the requirement; or $\mathrm{P}(A_i \mid \bar{Z})$, the probability that the model test outcome is A_i, given that the actual ship does meet the required speed.

Test *A* Outcome	$\mathrm{P}(A_i)$	$\mathrm{P}(Z \mid A_i)$	$\mathrm{P}'(Z \mid A_i)$
A_1	0.125	0.6400	0.0064
A_2	0.150	0.1000	0.0250
A_3	0.725	0.0069	0.0069
		$\mathrm{P}'(Z)$ =	0.0096

TABLE 2. Test *A* probability calculations.

The data for Example 1 is summarized in Table 1. For example, $\mathrm{P}(A_1 \mid Z)$ is 0.8, which means that for a design that does not meet the speed requirement, the model test will indicate that the design *does not meet* the speed requirement with 80% likelihood. $\mathrm{P}(A_1 \mid \bar{Z})$ is 0.05 which means that for a design that *meets* the speed requirement, the model test will indicate that the design does not meet the requirement with 5% likelihood.

Table 2 details the calculations for each outcome of test *A*. The probability of each mitigation test outcome $\mathrm{P}(A_i)$ is calculated using Equation (3). $\mathrm{P}(Z \mid A_i)$ is calculated using Bayes' Theorem, Equation (4). The mitigated probability given each test outcome $\mathrm{P}'(Z \mid A_i)$ is evaluated according to Equation (5). The mitigated probability for the risk $\mathrm{P}'(Z)$ is evaluated by Equation (6), which is the sum of the products of columns "$\mathrm{P}(A_i)$" and "$\mathrm{P}'(Z \mid A_i)$" of Table 3. The calculation indicates the probability of realizing the risk has been reduced from 10% to 0.96% by employing the risk management plan by using test *A*.

Table 3 represents the cost calculations for test *A* and the corresponding mitigations. For each test outcome A_i, either the risk will be realized Z,

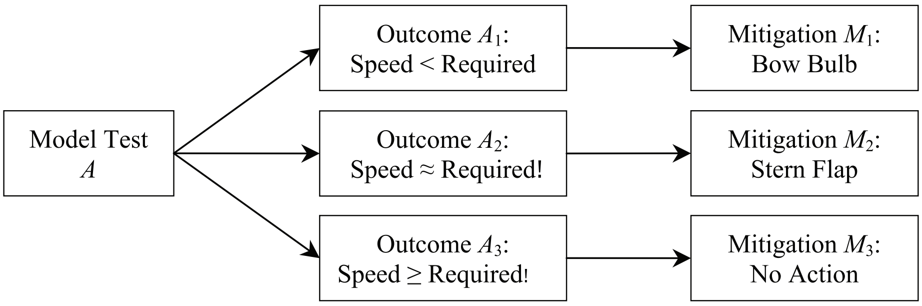


FIGURE 5. Flow chart of risk mitigation strategy for Example 1.

or it will not be realized $\bar{Z}$. The probabilities of the test outcomes $P(A_i)$ and the mitigated risk probabilities $P(Z \mid A_i)$ are repeated from Table 2. The table lists the investment cost of each outcome and the cost of correcting the risk if it is realized in the final column.

The expected investment cost is calculated according to Equation (12), which is the sum of the products of $P(A_i)$ and the investment. The expected investment is \$1,200.

The updated expected cost of the risk is calculated according to Equation (9), which is the sum of the products of the following columns of Table 3: "$P(A_i)$," "$P'(Z \mid A_i)$ or $P'(\bar{Z} \mid A_i)$," and "Total Cost." The updated expected cost of the risk is \$1,381. The initial expected value of this risk is \$2,000, so the net return of the investment in this plan is

$$\$2{,}000 - \$1{,}381 = \$619 \tag{13}$$

Therefore, the ROI is

$$\text{ROI} = \frac{\text{net return}}{\text{investment}} = \frac{\$619}{\$1{,}200} = 0.52 \tag{14}$$

Since the ROI is positive, the proposed mitigation activity has value. An investment of \$1,200 will return \$619 more than the investment. Furthermore, the likelihood of occurrence of the risk has decreased by an order of magnitude: 0.0096 after implementing this plan, vice 0.10 without implementing the plan. After the tests are completed the risk should be reevaluated.

Risk Management Planning for Multiple Risk Mitigation Activities

This method can be applied to a series of risk mitigation tests and activities. To continue to a second test, the analysis is rerun using the updated expected cost and probability as the starting point for the second test and mitigation activity. An application of this approach to a series of two tests and mitigation activities is shown in Example 2.

The series calculations can be updated as information from the test results becomes available. When the results from earlier stages are known, the updated calculations may show a change in the expected cost of the risk, which may indicate a change to the test and mitigation plans is beneficial. Since the PM has a plan in advance, there is an opportunity in advance to evaluate each mitigation plan and choose the plan with the highest ROI. An example of updating the calculations with test results is shown in Example 3.

EXAMPLE 2: SERIES RISK MITIGATION ACTIVITIES

The PM defines the mitigation test and activity presented in Example 1. When implementing the test and mitigation plan of Example 1, the updated probability that the ship does not meet the speed requirement is $P'(Z) = 0.0096$ and the expected cost of the risk is \$1,381.

The PM plans a second risk mitigation test B: high-fidelity computer modeling of the hull form to evaluate the resistance behavior. The modeling efforts cost $C(B) = \$100$. The PM identifies two possible outcomes of the test:

B_1—the speed predicted by the model does not meet the requirement

B_2—the speed predicted by the model meets the requirement.

The PM plans the following risk mitigation activities based on the results of the computer models.

Test *A* Outcome	Risk Outcome	$P(A_i)$	$P'(Z \mid A_i)$ or $P'(\bar{Z} \mid A_i)$	Investment $C(A) + C(M_i)$	Correction $(1 - c_i)\,C(Z)$	Total Cost
A_1	Z	0.125	0.0064	\$ 5,500	\$ 8,000	\$ 13,500
A_1	$\bar{Z}$	0.125	0.9936	\$ 5,500	0	\$ 5,500
A_2	Z	0.150	0.0250	\$ 1,000	\$ 20,000	\$ 21,000
A_2	$\bar{Z}$	0.150	0.9750	\$ 1,000	0	\$ 1,000
A_3	Z	0.725	0.0069	\$ 500	\$ 20,000	\$ 20,500
A_3	$\bar{Z}$	0.725	0.9931	\$ 500	0	\$ 500
Expected Value				\$ 1,200		\$ 1,381

TABLE 3. Test *A* cost calculations.

ACCURACY OF TEST			MITIGATION ACTIVITY		
Test Outcome	$P(B_i \mid Z)$	$P(B_i \mid \overline{Z})$	Cost of Mitigation Activity, $C(B_i)$	Reduction of Probability of Realizing, m_i	Reduction in Cost of Correcting, c_i
B_1	0.80	0.20	$ 100	0.9	0
B_2	0.20	0.80	$ 0	0	0

TABLE 4. Description of CFD test *B* and corresponding mitigation activities.

- If the result is B_1, the PM will invest $100 in a new, low-friction hull coating. The hull coating reduces the probability that the ship will fail to meet the speed requirement by 90%. The hull coating does not affect the cost of corrective action if the ship still does not meet the speed requirement.
- If the result is B_2, the PM will not make any changes to the design. The probability and cost of realizing the risk are unchanged.

The PM consults with hydrodynamics experts who estimate the probabilities for the accuracy of the modeling software's predictions, summarized in Table 4. The series of tests and mitigations for Examples 1 and 2 are illustrated in Figure 6. As depicted in Figure 6, if the values for the second mitigation activity depend on the test results from the first mitigation activity, then the second mitigation activity ROI must be calculated for each possible test result of the first mitigation activity and weighted by the probability of the test results for the first mitigation activity.

Table 5 summarizes the calculations for the series of two tests and mitigations. The column "Outcome" tabulates the possible outcomes shown in the flow chart of Figure 11. The column "$P''(Z \mid A_i \,\&\, B_i)$ or $P''(\overline{Z} \mid A_i \,\&\, B_i)$" lists the updated probability of realizing the risk, after performing both tests *A* and *B* and the corresponding mitigation activities. The "Investment" column lists the investment cost for test *B*, which includes the cost of the test and the mitigation activity. The Total Cost includes the cost of test *A*, mitigation following test *A*, test *B*, mitigation following test *B*, and the cost of correcting the risk if it is realized.

The information in Table 5 is used to evaluate the updated probability of realizing the risk and expected cost for implementing this two-test plan. When implementing test *A* followed by test *B* and the corresponding mitigations, the probability of realizing the risk is 0.27% and the expected value of the cost due to this risk is $1,371.

The expected investment in tests *A* and *B* is $1,321. The initial expected value of this risk is $2,000, so the return of the investment in this plan is

$$\$2{,}000 - \$1{,}371 = \$629 \tag{15}$$

Therefore, the ROI is

$$\text{ROI} = \frac{\text{return}}{\text{investment}} = \frac{\$629}{\$1{,}321} = 0.48 \tag{16}$$

The ROI is positive so this mitigation plan has value. While the ROI is less than with the single mitigation activity, the expected cost decreased (from $1,381 to $1,371), which means it still provides benefit to the program. After the tests are completed the risk should be reevaluated.

When performing a series of tests and mitigation activities, the ROI can be updated after each stage of test and mitigation. The information from the first test can be used to reevaluate the ROI by updating the probability of occurrence given the first test result and mitigation activity. This analysis can be performed for each stage of the analysis before physically completing the tests.

EXAMPLE 3

Suppose the PM initiated the risk mitigation plan using test *A*, and the result was A_1. The first two rows of Table 5 show the possible outcomes given that A_1 occurred. The expected total cost, given that A_1 occurred is

$$P'(Z \mid A_1)\cdot\$13{,}500 + P'(\overline{Z} \mid A_1)\cdot\$5{,}500 = \$5{,}551 \tag{17}$$

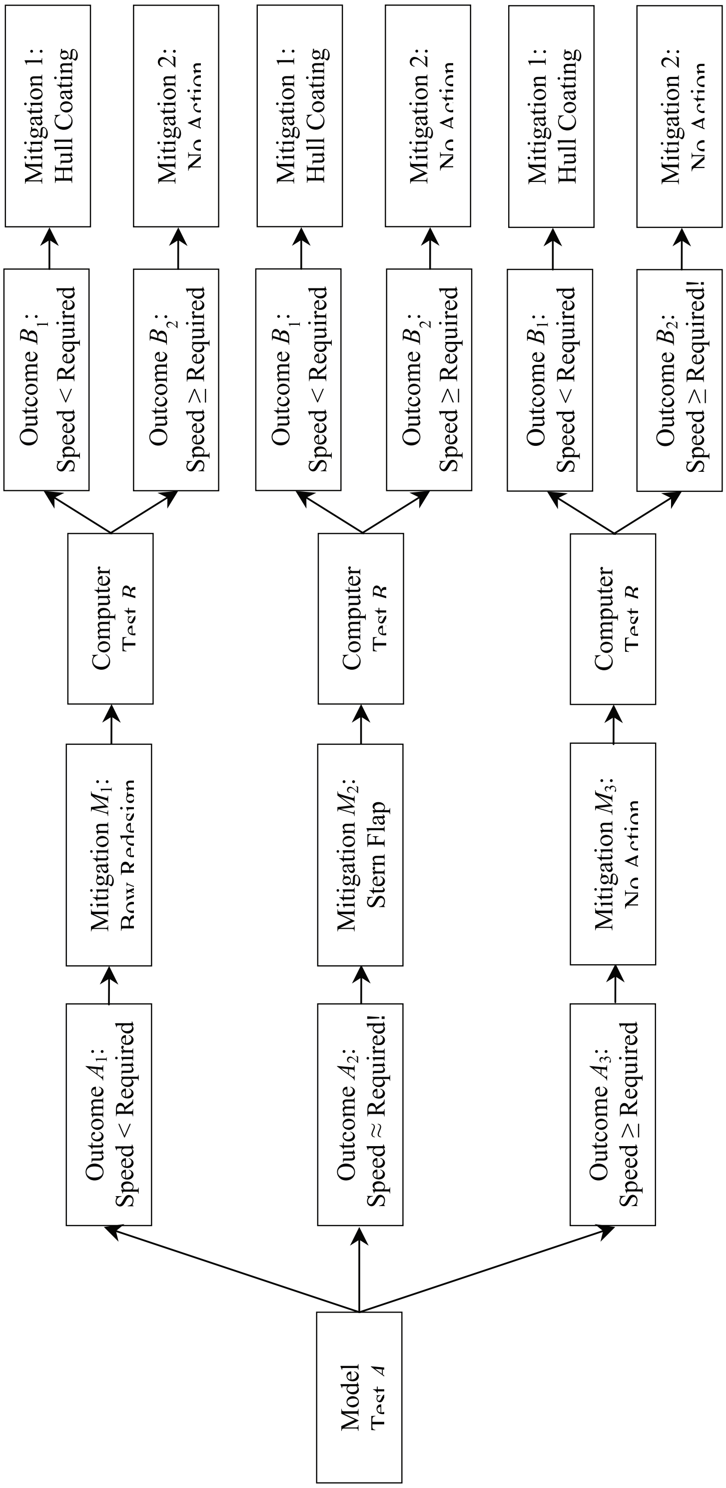


FIGURE 6. Flow chart of series test and activities for Example 2.

Outcome			$P''(Z \mid A_i \& B_i)$ or $P''(\bar{Z} \mid A_i \& B_i)$	$P''(Z \& A_i \& B_i)$ or $P''(\bar{Z} \& A_i \& B_i)$	Investment $C(A) + C(M_i)$	Total Cost
A_1	B_1	Z	0.0025	0.0001	$ 200	$ 13,700
A_1	B_1	$\bar{Z}$	0.9975	0.0254	$ 200	$ 5,700
A_1	B_2	Z	0.0016	0.0002	$ 100	$ 13,600
A_1	B_2	$\bar{Z}$	0.9984	0.0994	$ 100	$ 5,600
A_2	B_1	Z	0.0093	0.0003	$ 200	$ 21,200
A_2	B_1	$\bar{Z}$	0.9907	0.0320	$ 200	$ 1,200
A_2	B_2	Z	0.0064	0.0008	$ 100	$ 21,100
A_2	B_2	$\bar{Z}$	0.9936	0.1170	$ 100	$ 1,100
A_3	B_1	Z	0.0027	0.0004	$ 200	$ 20,700
A_3	B_1	$\bar{Z}$	0.9973	0.1476	$ 200	$ 700
A_3	B_2	Z	0.0017	0.0010	$ 100	$ 20,600
A_3	B_2	$\bar{Z}$	0.9983	0.5760	$ 100	$ 600
					Expected Value	$ 1,371

TABLE 5. Example 2, a series of two tests and mitigation activities.

The PM considers adding the additional test *B*. The first four rows in Table 5 show the possible outcomes given that A_1 occurred. The expected total cost of implementing both tests *A* and *B*, given that A_1 occurred is

$$\frac{P''(Z \& A_1 \& B_1)\cdot \$13{,}700 + P''(\bar{Z} \& A_1 \& B_1)\cdot \$5{,}700 + P''(Z \& A_1 \& B_2)\cdot \$13{,}600 + P''(\bar{Z} \& A_1 \& B_2)\cdot \$5{,}600}{P(A_1)} = \$5{,}635 \tag{18}$$

The expected investment is calculated similar to the expected total cost, where the investment cost for each outcome is $5,500 (the cost of test *A* and the cost of the first mitigation) plus the investment amount listed in Table 5.

$$\frac{P''(Z \& A_1 \& B_1)\cdot \$5{,}700 + P''(\bar{Z} \& A_1 \& B_1)\cdot \$5{,}700 + P''(Z \& A_1 \& B_2)\cdot \$5{,}600 + P''(\bar{Z} \& A_1 \& B_2)\cdot \$5{,}600}{P(A_1)} = \$5{,}624 \tag{19}$$

Therefore, the ROI is

$$\text{ROI} = \frac{\text{return}}{\text{investment}} = \frac{\$5{,}551 - \$5{,}635}{\$5{,}624} = -0.015 \tag{20}$$

When implementing both tests *A* and *B*, given that A_1 occurred, the resulting ROI is -1.5%. The negative ROI indicates that it is no longer worthwhile to conduct the second mitigation test *B* after completing the first test and mitigation activity.

Conclusions

In general, DoD program cost estimates currently do not include an element for aggregated program risk. This paper proposes a method to calculate a Return on Investment (ROI) of risk mitigation activities. The ROI can be used to actively manage a risk program and assist with deciding which risk mitigation activities to fund.

The risk monetization model defines a risk management plan associated with the risk, which allows the program manager to effectively evaluate risk and mitigations quantitatively, and allows decision makers to compare multiple test and mitigation options. Performing the risk monetization calculations encourages users' critical thinking about risk mitigation plans and enhances communication between the risk owner and the risk decision makers.

In closing, performing the risk monetization analysis encourages users to consider tests and possible outcomes, appropriate corresponding mitigation activities, and it provides a communication tool to quantitatively assess risk. This paper also advocates for the inclusion of the price of risk into the cost estimates for a program, independent of whether there is sufficient budget to address the risks.

REFERENCES

[1] W. L. Dunn and K. J. Shultis, Exploring Monte Carlo Methods, 1st ed., Amsterdam: Elsevier, 2011.

[2] Department of Defense, "Risk Management Guide for DoD Acquisition, 6th Edition (Version 1.0)," August 2006. [Online]. Available: http://www.acq.osd.mil/se/docs/2006RMGuide4Aug06finalversion.pdf.

[3] R. C. Lyons, "Acquisition Program Risk Management: Does the Department of Defense Risk Management Practices Guide Provide an Effective Risk Tool for Program Managers in Today's Acquisition Environment?," Aberdeen Proving Ground, MD, 2012. [Online]. Available: http://www.dtic.mil/docs/citations/ADA563263.

[4] K. Morse and D. L. Drake, "Data-Driven Monetization of Acquisition Risk," in *Ninth Annual Acquisition Research Symposium*, Monterey, CA, 2012.

[5] M. L. Klabon, "An Investigation of the Quantification of the Probability of Occurrence of Software Engineering Project Risks with Bayesian Probability," Naval Postgraduate School, Monterey, CA, 2007. [Online]. Available: http://www.dtic.mil/docs/citations/ADA475966.

[6] T. C. Irwin, "Risk Quantification of Systems Engineering Documents Improves Probability of DoD Project Success," Naval Postgraduate School, Monterey, CA, 2009. [Online]. Available: http://www.dtic.mil/docs/citations/ADA510447.

[7] D. Bodner, "Addressing Risk in the Acquisition Lifecycle with Enterprise Simulation," in *Ninth Annual Acquisition Research Symposium*, Monterey, CA, 2012.

[8] S. Thomke and D. E. Bell, "Sequential Testing in Product Development," *Management Science,* vol. 47, no. 2, pp. 308-323, 2001.

[9] J. Mun and T. Housel, "A Primer on Applying Monte Carlo Simulation, Real Options Analysis, Knowledge Value Added, Forecasting, and Portfolio Optimization," Naval Postgraduate School, Monterey, CA, 2010. [Online]. Available: http://www.dtic.mil/docs/citations/ADA518628.

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