ABSTRACT

Title: INTEGRATED SCENARIO-BASED METHODOLOGY FOR PROJECT RISK MANAGEMENT

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Project risk management is currently used in several industries and mandated by government acquisition agencies around the world to manage uncertainty in an effort to improve a project's probability of success. Common practice involves developing a list of risk items scored with probability and consequence ordinal scales by committee usually focusing on cost and schedule issues. A scenario based process modeling construct is introduced using a hybrid Probabilistic Risk Assessment and Decision Analysis framework integrating project development risks with operational system risks. Project management's decisions are explicitly modeled and ranked based on risk importance to the project. Multiple consequence attributes are unified providing a basis for computing total project risk. This study shows that such an approach leads to an analysis system where scenarios tracing risk items to many possible consequences are explicitly understood; the interaction between cost, schedule, and performance models drive the analysis; probabilities for overruns, delays, increased system hazards are determined directly; and state-of-the-art quantification techniques are directly applicable. All these enhance project management's capability to respond with more effective decisions.

INTEGRATED SCENARIO-BASED METHODOLOGY FOR PROJECT RISK MANAGEMENT

By

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In loving memory of my Mother, Clara.

To Karen, Margaret, and Dad
for all your love and support.

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Abbreviations

APM	Association of Project Management
BBN	Bayesian Belief Networks
Bn	Birnbaum
CCDF	Complementary Cumulative Distribution Function
CCF	Common Cause Failure
CDF	Cumulative Distribution Function
CPM	Critical Path Method
CPRM	Composite Project Risk Metric
CPRP	Composite Project Risk Profile
CRM	Continuous Risk Management
DA	Decision Analysis
DAA	Detector / Alarm / Actuator
DoD	Department of Defense
DP	Decision Point
DT	Decision Tree
EPA	Environmental Protection Agency
ES	End State
ET	Event Tree
ESD	Event Sequence Diagram
EVM	Earned Value Management
FAA	Federal Aviation Administration
FMEA	Failure Modes and Effects Analysis
FSD	First Degree SD
FSS	Fire Suppression System
FTA	Fault Tree Analysis
FV	Fussel-Vesely
GAO	Government Accounting Office
I&T	Integration and Test
IE	Initiating Event
IM	Importance Measure
INCOSE	International Council on Systems Engineering
IPRM	Integrated Project Risk Model
ISPAR	Integrated Scenario-Based Project Assessment for Risk
LOM	Loss of Mission
MA	Mitigation Action
NASA	National Aeronautic and Space Administration
PDF	Probability Distribution Function
PE	Pivotal Event
PERT	Program Evaluation and Review Technique
PM	Project Manager
PMBOK	PMI Book of Knowledge
PMI	Project Management Institute
PMF	Probability Mass Function
PRA	Probabilistic Risk Assessment
PRM	Project Risk Management
RAW	Risk Achievement Worth
RC	Root Cause
RI	Risk Item
Rm	Risk Metric
RRW	Risk Reduction Worth
RSD	Risk Sequence Diagram
SD	Stochastic Dominance
SED	Scope Expected Deviations
SEI	Software Engineering Institute
SSD	Second Degree SD
TRL	Technology Readiness Level
WBS	Work Breakdown Structure

Chapter 1 Introduction

The management of a project is a difficult and challenging task due to the many variables determining its final outcome. Although classic project management techniques addressing cost, schedule, and performance requirements have proven effective, projects often run into trouble even when well-planned and sound control methods are employed. A common reason is that threats to projects are not clearly identified and actions to control them not properly implemented or analyzed for secondary impacts. Consequently, project managers and project engineers must be consciously aware of potential threats to success of their projects and take early and effective actions. Risk management is a technique that significantly increases the probability of identifying those threats in time to assure success.

Current project risk management (PRM) techniques view risks as independent entities. Cost and schedule issues are worked separately from performance issues. Furthermore, safety and reliability risks are treated completely separately. An integrated approach is needed.

1.1 Motivation

Most U.S. government projects require a Risk Management presentation as part of the mission operational reviews. A recently attended review was no different. The

Quality Assurance lead proceeded to go through the "Top 5 Risks". Top on the list was a risk titled "Inexperienced Staff on Console" and categorized as "Red" with the risk matrix position of 4x4 (Likelihood=4, Severity=4). This of course meant that the issue would receive significant management "assistance". The briefer described how staff turnover meant that having inexperienced staff sitting on console was highly likely. Further, inexperienced personnel could do many things to end the mission prematurely or not respond correctly, ending the mission. Therefore, risk was "Red". Heated discussions broke out.

As I listened to the arguments, I had a sense that the characterization of the risk was wrong or at best, incomplete. While the statements about the likelihood of inexperienced staff and what could happen with inexperienced staff on console were correct, the conclusion that it was the major risk was not. Sketching out the problem as an event sequence diagram as if performing a Probabilistic Risk Assessment (PRA) it became evident that only one possible endstate had been explored and that a systematic process to describe the scenario emanating from an initiating event would have led the program to a different conclusion. PRA is a systematic, scenarios-based methodology to evaluate risks associated with complex engineered technological systems. Scenarios follow an off-nominal event or condition as it propagates through a system based on designed robustness or procedural responses. More on PRAs is provided in Section 2.5.5. This started my thought process to move Risk Management away from a qualitative brainstorming process to a more systematic quantitative one.

Some of the basic risk assessment characteristics are usually not found in project risk matrices or registers. For instance, within current best practices of project risk assessments, events are assumed to be independent, probabilities are assigned to events with no supporting documentation, no uncertainty about those probabilities are identified, nor are common cause failures addressed. In addition, safety hazards are treated as a separate discipline and not shown on the risk matrices at all.

This approach denies a Project Manager (PM) the ability to adequately answer some basic questions, such as:

- If I spend the money you are asking for how much risk is reduced for my project?
- Can I get more risk reduction, spending that same money elsewhere?
- What is the significance of assumptions made in the likelihood and consequence assignments?

This study shows the Risk Management process can be treated as a technical risk assessment. Several important questions are answered:

- What insights to risk can be uncovered?
- Can it assist leadership in the presence of uncertainty?
- It is likely that this approach will increase cost at the start, so is the value of new insights worth the increased cost?

This study has the following objectives:

- Integrate programmatic cost and schedule metrics, safety, and reliability into one cohesive risk picture.
- Identify “controls” or “decision points” that significantly improve the risk posture of a project.

- Describe and create the transfer function between project models the system models using risk as the common currency.

- Develop risk metrics to provide a basis for decisions in the face of multiple objectives under uncertainty.

- Fit the integrated risk picture within accepted risk management processes.

While much of the pedagogical literature discusses project risk management as a tool to support management of *total risk*, in practice it does not. Reliability, safety, programmatic risk, technology risk, and financial risk are often stove piped and addressed by separate disciplines. Mitigations and controls are measured against reducing a risk of a single item in question, but not against the totality of the project, leading to suboptimum performance. There is also a disconnect between finishing the project on time and within budget and how the system will function and operate. Conrow notes that within military projects performance requirements are paramount, with cost and schedule sacrificed to meet those requirements (Conrow, 2003). Without an integrated framework, the actual risk posture of the project and the decision-makers risk preference are likely to be inconsistent.

PRA is an excellent framework because it is scenario based, multi-disciplined, and systematic; leading to more repeatability of analysis. PRA ensures that dependencies are captured within the scope of the system and that they project through the use of logic models such as Event Sequence Diagrams (ESD) and Fault Tree Analysis (FTA). Uncertainty and variability are explicitly addressed. It also allows for the determination of risk metrics for sensitivity analysis and development of importance measures for relative risk contributions of model constituents.

Decision Analysis (DA) allows for the incorporation of decisions in the modeling framework and provides a systematic mechanism for the incorporation of decision-maker preferences.

1.2 Project Failures

Recent high profile failures and trends show the need for better risk management within projects. This section is devoted to describing how risk management fits into the discipline of project management as well as providing background information on risk assessments and decision analysis.

The press is full of stories detailing the failures (or significant setbacks) of various high profile projects. In March 2009, the CATO Institute published a study titled "Government Cost Overruns." The study compares the original cost estimates at the time that the projects were initiated to the most recent estimates as reported in official estimates from the Government Accounting Office (GAO) or official estimates as reported in the *Washington Post*.

Table 1-1. Government projects overrun in all sectors

	Cost Estimate and Date of Estimate		
	Original Estimate	Recent or Final Estimate	Percent Change
Transportation			
Boston Big Dig highway project	$2.6b (1985)	$14.6b (2005)	462%
Virginia Springfield interchange	$241m (1994)	$676m (2003)	180%
Denver International Airport	$1.7b (1989)	$4.8b (1995)	182%
Hiring of airport security screeners	$104m (2002)	$741m (2006)	613%
Airport security technology upgrade	$1b (2002)	$3b (2005)	200%
Energy			
Hanford nuclear waste clean-up	$4.3b (2000)	$12.2b (2008)	190%
All nuclear waste sites clean-up	$63b (1996)	$105b (2003)	67%
National Ignition Facility	$2.1b (1995)	$4.2b (2000)	100%
Clinch River Breeder Reactor	$400m (1971)	$4b (1983)	900%
Superconducting Supercollider	$4.4b (1987)	$11.8b (1993)	168%
FutureGen clean coal project	$1b (2003)	$1.8b (2008)	80%
Defense Development Costs ($2008)			
Global Hawk surveillance plane	$989m (2001)	$3.7b (2007)	274%
Expeditionary Fighting Vehicle	$1.6b (2000)	$3.6b (2007)	125%
C-130J Hercules	10.9m (1996)	430.3m (2007)	3848%
Extended Range Munitions	86.9m (1997)	500.1m (2007)	475%
DDG 1000 destroyer	2.2b (1998)	9.3b (2006)	323%
V-22 Osprey helicopter	4.0b (1986)	12.5b (2006)	213%
Armed Reconnaissance Helicopter	388.3m (2005)	750.9 (2007)	93%
Space Based Infrared System High	4.2b (1996)	8.5b (2006)	102%
NPOESS Satellite System	5.0b (2002)	7.9b (2007)	58%
Other Defense			
Coastal Patrol Ships	$220m (2004)	$350m (2007)	59%
Joint Strike Fighter	$232b (2001)	$337b (2008)	45%
Marine One (VH-71) helicopters	$6.1b (2005)	$11.2b (2008)	84%
Coast Guard, NSC ships, per unit	$250m (2002)	$536m (2007)	114%
Technology Projects			
Air traffic control modernization	$8.9b (1998)	$14.6b (2005)	64%
FBI Trilogy computer system	$477m (2000)	$600m (2004)	26%
Pentagon airborne laser system	$1b (1996)	$2b (2004)	100%
Border radiation detectors	$2.1b (2008)	$3.1b (2008)	48%
NASA			
International Space Station	$17b (1997)	$30b (2001)	76%
Mars Science Laboratory	$1.6b (2008)	$2.3b (2009)	44%

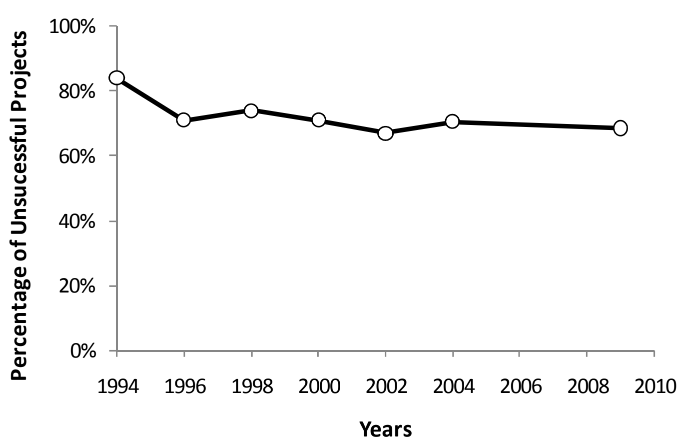
Source: Edwards, C. Government Cost Overruns. CATO Institute. 2009

In addition to the cost and schedule failures, many project suffer from performance shortfalls. For example, the Denver International Airport's much heralded state-of-the-art baggage handling system never met expectations and was eventually scrapped, the FBIs Virtual Case File cost $170 Million and never became operational (Eggen & Witte, 8/18/2006), Mars Science Laboratory is $400M over (due to technical problems with instruments and robotics) and 2 years late and has missed one launch window (Chang, 10/11/2008), the FAAs air traffic control modernization systems spend over $2.6 Billion only to be canceled (R. Charette, 2005), and Boston's Central Artery Project – $2.6 billion to $14.6 billion and years late and plagued with technical problems such as falling panels and leaking tunnels.

Project failure is not just a U.S. phenomena, international construction examples include the Jubilee Line Transit Project in London was 2 years late and £1.4 billion (67%) over budget; the Channel Tunnel was £3.7 billion (80%) over budget; Denmark's Great Belt Link came in 54% over budget.

According to the GAO, in 2000, projected costs of 75 major weapon programs were $42 billion, or 27%, over initial budgets, including average delays before initial deliveries of 16 months. By 2007, 95 major weapons programs, projected cost inflation had risen to $295 billion, or 40% over early estimates, including average delays of 21 months (Savage, 6/4/2008). This is not just a recent trend. For large U.S. government programs, Conrow cites statistics showing cost and schedule variations between 40% to over 200% of project baselines from 1940 thru 1990s (Conrow, 2003). Other authors, like Charette and Verner, cite similar numbers. Kendrick's database also shows similar numbers for smaller projects (Kendrick, 2003). Of particular significance from Conrow's dataset, is that 90% of the programs experienced cost growth and 78% experienced schedule slips. The GAO found similar project performance in DoD, NASA, and FAA projects (GAO, 2009a).

Similar trends are found within the IT sector. Charette lists over thirty high profile software projects that have failed (R. Charette, 2005). He notes the universality of these failures, in that "they happen in every country; to large companies and small; in commercial, nonprofit, and governmental organizations; and without regard to status or reputation." All of which adds an additional $60 billion to $70 billion yearly to software projects in the U.S. alone. The often cited Standish Chaos Report states 84% of software projects either failed or were challenged[1]. While the report has some detractors, its consistency over the past decade shows little project performance improvement (see Figure 1-1).



Source: Standish Chaos Reports as cited by Dan Galorath (www.galorath.com)

Figure 1-1. Trends for IT projects

[1] "Challenged" is defined by the Standish Chaos Report as a project that did not meet cost, schedule, or performance goals.

In 2009, GAO issued a report on NASA's large projects (GAO, 2009b). Excerpts are shown to illustrate breadth of the problem within just one agency. Other agencies (FAA, Census, IRS, DoD, EPA) have similar issues.

> NASA has also had its share of challenges. For example, the X-33 and X-34 programs, which were meant to demonstrate technology for future reusable launch vehicles, were cancelled due to technical difficulties and cost overruns after NASA spent more than $1 billion on them. More recently, the Mars Science Laboratory, which was already over budget, announced a two-year launch delay. Current estimates suggest the price of this delay may be $400 million—which drives the current project lifecycle cost estimate to $2.3 billion, up from its initial confirmation estimate of $1.6 billion. GAO and others have also reported on overruns on many other NASA programs over the past decade. What is common among these and other programs is that whether they succeed or fail, they cost more to build and take longer to launch than planned. As a result, NASA is able to accomplish less than it plans with the money it is allocated, and it is forced to make unplanned trade-offs among its projects—shorting one to pay for the mistakes of another.

More than sensational headlines normally reported in the press or to Congress, consequences can have far more ranging effects as shown in the following excerpt from a *Harvard Business Review* article *(Matta & Ashkenas, 2003)*:

> Big projects fail at an astonishing rate. Whether major technology installations, postmerger integrations, or new growth strategies, these efforts consume tremendous resources over months or even years. Yet as study after study has shown, they frequently deliver disappointing returns—by some estimates, in fact, well over half the time. And the toll they take is not just financial. These failures demoralize employees who have labored diligently to complete their share of the work. One middle manager at a top pharmaceutical company told us, "I've been on dozens of task teams in my career, and I've never actually seen one that produced a result.

As one would expect there are many reasons why projects fail. While the circumstances are as unique as the project, failure modes can be categorized into surprising few reasons. Many authors have complied lists of top reasons (Chapman & Ward, 2003; R. Charette, 2005; Conrow, 2003; Kendrick, 2003; Verner, Sampson, Cerpa, Nicta, & Sydney, 2008). Many focus on governance issues and inadequate risk management as the main culprits (Lawrence & Scanlan, 2007). Their research shows failures of competence by program managers and risk management systems vary in sophistication and effectiveness. Failings typically involve the factors listed below:

- Poor initial planning
- Lack of clear objectives and deliverables
- Lack of understanding of dependencies
- Inadequate resource allocation
- Poor risk analysis
- Poor change management
- Lack of "buy-in" from stakeholders
- Poor understanding of priorities

This list is symptomatic and that the underlying causes of project failure are deep seated, structural and endemic, leading to the weaknesses identified above.

1.3 Document Organization

Current risk management practices may provide more insights for management with the adoption of integrated scenario-based analyses which examines dependencies across risk items and unifies multiple attributes of consequences into a single risk management system. Chapter 2 sets the stage by reviewing current project management and project risk management literature that shows there is still a need to integrate various assessments into a single risk picture for project managers in order to provide insights into the myriad of decisions to be made. Developing an integrated approach requires the combination of several existing assessment methodologies and the creation of techniques to allow seamless communication among them.

The methodology is described in chapters 3 through 8. This methodology examines the project-product system using scenario-based PRA techniques along with DA evaluation methods to focus insights on decisions impacting cost, schedule, and performance of delivered systems. Chapter 4 introduces Risk Sequence Diagrams (RSD), which are hybrid logic diagrams providing a more complete representation of risk items and their array of potential impacts. RSDs are quantifiable and consistent with proven theory, and provide easily understood metrics derived from probability and consequences of risk items. These are combined across an entire project to provide a project-level risk profile metric to aid project endstate analysis and prediction. Several importance metrics are evaluated in Chapter 8 for use in ranking contributors to project risk providing insight to management.

Implementation topics are discussed in chapters 9 through 11. Integration of this new method with current PRM processes, enhances the information available to support project decisions is addressed in Chapter 9. An end-to-end example is presented in Chapter 10 to show its implementation and potential benefits. In addition, this study evaluated two actual development projects with interesting observations and lessons learned.

Finally, Chapter 12 reviews the new methodology developed here and discusses key areas that expands the field of risk assessment. Chapter 13 addresses potential future work needed to expand the theoretical basis of this approach and implement new features.

Chapter 2 Project Risk Management Research

A review of current project management and project risk management literature shows there is still a need to integrate various assessments into a single risk picture in order to provide insights into the myriad of decisions to be made. Developing an integrated approach requires the combination of several existing assessment methodologies and the creation of techniques to allow seamless interactions among them.

This chapter introduces project risk management in the context of project management in order to define the scope of this study. Current PRM practices are discussed as are recent research into various analytical frameworks for modeling and communicating project risk. Gaps between current practice and the potential of using state-of-the-art risk assessment techniques are also provided.

2.1 Project Management

Organizing people and resources have been around since humans were civilized. Modern project management approaches are relatively new as a formal discipline having roots in DoD projects beginning in the 1950s. By the late 1970s, project management was confined to DoD and NASA contractors, and construction companies (Kerzner, 1989). Today, Project Management is ubiquitous. Organizations have formed to promulgate consistent set of tools and techniques such as the Project Management Institute's *Project*

Management Body of Knowledge (PMBOK) (PMI, 2003) and the Association for Project Management's *Body of Knowledge* (APM, 2004).

Changes to the way projects are managed reflect adaptations organizations have made to accommodate ever more complex, sophisticated, customized, dangerous, and costly projects. The complexities and multidisciplinary aspects mean projects now have integrated many moving parts to meet objectives. Along with this came smaller margins of error and the consequences of a failing project are immense, not just in cost, but to careers, reputations, the environment, the economic livelihood of towns and regions. For a full treatment of project management disciplines, see (Kerzner, 1989; Meredeth & Mantel, 1989; PMI, 2003) or any number of other texts.

The PMBOK states that project management is accomplished through the application of processes for initializing, planning, executing, monitoring, controlling, and closing. The basis of performing these processes is the decomposition of the project into more manageable elements by task, by time, and by cost. Each of these breakdowns are associated with different (and independent) tools such as a Work Breakdown Structure (WBS), Critical Path Method / Program Evaluation and Review Technique (CPM/PERT), and Earned Value Management System (EVM). All the activities must be accomplished within the constraints of a budget, a schedule, and performance specification of the product, service, or result. Figure 2-1 shows a project management model commonly used to represent how projects manage resources within these constraints. One side of the triangle cannot be changed without affecting the others. This is often accompanied by the sarcastic slogan "You can have 2 of the 3" belying the fact the constraints compete against each other.

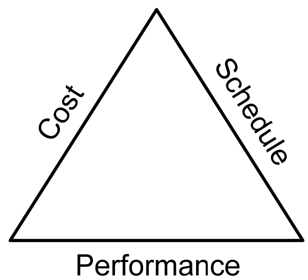


Figure 2-1. Project management triangle

Completing a project within the triangle is usually defined as success. Softer notions of customer relations, reputation (organization's or manager's), and others are interwoven in the success criteria although not explicitly written.

Predicting with certainty at the start of a project, how cost, time, and performance constraints would be achieved would be comforting. There is always considerable uncertainty about the team's ability to meet them, but it is the project manager's responsibility to understand and make good decisions in the presence of this uncertainty. Today's management analysis incorporates uncertainties to provide probability distributions around cost and schedule estimates, often using Monte-Carlo simulation to augment cost and schedule models (Garvey, 2000; Stewart, 1991; Vose, 2008). However, "most project management pedagogical literature does not consider the way that managing uncertainty should be integrated with project management more generally." (Ward & Chapman, 2003) Additionally, project risk management practices do not use methods to quantify uncertainty.

2.2 Risk Assessment

Risk assessments are, at least in principle, designed to inform decision-makers. Straight forward decisions do not require formal risk assessments. However, when decisions are complex, information uncertain, impacts ambiguous, and consequences have multiple attributes, a formal structured systematic risk assessment is useful. Certain characteristics of state-of-the-art risk assessments are now standard (T. Aven, 2003; Bedford & Cooke, 2001; Cox, 2009; Frank, 2008; Henley & Kumamoto, 1996; Modarres, 2006; NASA, 2004; NRC, 1983; Vose, 2008), but are not reflected in current PRM practices. For this study the following risk assessment characteristics are incorporated:

Scenario-based: Assessments that are scenario-based contains model logic tracing events that perturbs nominal functioning of a system and examines how the system responds. Multiple potential outcomes are addressed. These scenarios often include potential mitigation alternatives in order to evaluate their benefit. This tool allows PMs to "think" through situations before they occur in order to prepare for contingencies and provides a platform to quantify consequences and likelihoods.

Integrated: Analyses address a wide scope of concerns for the decision-maker. Integrated frameworks address the entire system/project as a whole, combined effects of multiple risk items, dependencies among and within risk items, and interfaces with other existing risk assessment models. A systematic integrated framework enables trade-off studies and sensitivity analysis across multiple risks and constituent system/project elements.

Quantitative: Model based assessments compute measures representing risk. Emphasis is placed on expressing the likelihood of observable performance measures or events. Probabilities are assigned based on systematic proven processes for data analysis and probability calculus.

Multi-attribute: Decision-makers struggle with multiple aspect of decision consequences that must be unified. They rarely make decisions on risk values alone, but integrate their view of the world. Assessments account for decision-maker's risk aversion levels and preferences to those attributes.

Probabilistic: Any model involves assumptions, simplifications, and data variability. It is essential that decision-makers receive information about all three in the form of uncertainties. Both aleatory and epistemic uncertainties are included as an integral part of the assessments.

Actionable: Framework scope and level of detail must be coincident with decision-makers' ability to take action. This focus on actions that can be implemented is the only way a PM can influence the course of events.

Probative : The ability to rank order important drivers and perform sensitivity analysis enables insights about current situations and future alternatives. Importance measures provide quantitative view of model elements.

As we will see, current project risk management practices do not posses all these characteristics.

2.3 Project Risk Management

One of the project management processes gaining popularity is Project Risk Management. Risk Management is a much discussed topic. A simple Google search on “risk management” returns over 43 million hits of websites discussing or selling various concepts, books, articles, and consulting services. A more limited search in the academic literature (Google Scholar) returns 629,000 hits on various papers addressing risk management. In addition, several books have been published in the past 15 years focused explicitly on project risk management (Chapman & Ward, 2003; Chong & Brown, 2000; Conrow, 2003; Cooper & Chapman, 1987; Cooper, Grey, Raymond, & Walker, 2005; Kendrick, 2003) .

Discussing *risk management* is problematic in the sense that the term is used differently in various sectors and therefore appears differently in the literature depending of what the author’s background is and what issue they are addressing. Even within project management literature one finds the following being addressed.

> Financial risk management articles focus on risks associated with various investment options (Christoffersen, 2003; Duffie & Pan, 1997; McNeil, Frey, & Embrechts, 2005). For example, spending funds on overseas investments could involve assessing political, social, and financial risks as well as the potential market share that could be gained. Assessments such as these inform decisions on where and whether capital should be invested. These assessments deal with controlling variability within portfolios of many assets. The mathematical “products” are designed to hedge against variability.

> Insurance risk management papers addresses how companies evaluate risks when insuring businesses and homeowners against catastrophic situations too costly to recover from (Croson & Kunreuther, 1999; Woo, 2004). They assess the

probability of disasters, such as hurricanes, earthquakes, fires, law suites, and accidents, based on past history and the costs resulting from the damage caused or the lives lost. On the basis of actuarial analysis, companies set policies and costs that apply to businesses and homeowners. These issues often appear in articles about construction project risk (Akintoye & MacLeod, 1997).

Engineering risk management literature discusses assessment of risks related to safety and security when designing and constructing large projects such as chemical plants, nuclear reactors, or bridges (Bier & Azaiez, 2009; Cox, 2009; Vick, 2002). Using risk analysis techniques, engineers examine the possible threats to the safety and security of the structure and evaluate ways to address the threat by considering various design features that could reduce vulnerabilities or consequences.

There is also a sector of sociology and psychology that discusses risk and how it is perceived and how humans respond to risk (Fischhoff, Slovic, & Lichtenstein, 1982; Slovic, 1987; Slovic, Finucane, Peters, & MacGregor, 2004; Tversky & Kahneman, 1974).

Within the government sector, risk management literature shows evaluations of consequences to public health and safety (Cox, 2009; Furberg, Levin, Gross, Shapiro, & Strom, 2006; Henson & Caswell, 1999). For example, the Food and Drug Administration (FDA) assesses risk associated with diseases related to various types of food and the Environmental Protection Agency (EPA) analyzes health risks caused by toxic chemicals, emissions from vehicles, and other sources of pollution. Much is written about models, how risks are perceived, and how to use information to make recommendations and set policies or regulations aimed at improving safety and minimize public risk.

For purposes of this study, the literature review is focused on *project risk management*. PRM is the act or practice of dealing with risk items. It includes planning for risk, assessing (identifying and analyzing) risk issues, developing risk handling options, monitoring risks to determine how risks have changed, and documenting the overall risk management program (DoD, 2006). Although, concepts and ideas pertaining to implementation a PRA framework is also examined. Much of the PRM information focuses on controlling adverse outcomes, primarily cost and schedule. Many non-peer reviewed conference articles advocate building administrative processes and database tools to implement published guidelines and standards. In addition, a lot of energy is spent convincing management that *Risk Management* is worthwhile.

Technology risks is another related topic reviewed that previously was kept separate from the cost and schedule risk discussions. Specifically, DoD and NASA characterize technology risk by using a Technology Readiness Level (TRL) scale. Data is also available to assign percentage of cost overruns and schedule delays based on the project's TRL(Dubos, Saleh, & Braun, 2008).

In many papers reviewed, authors take time to discuss previous work associated with their particular topic within risk management. Two works are noteworthy because they were published as literature reviews.

In 1995, Williams published the first comprehensive PRM bibliography (Williams, 1995). His goal was to take the first step in "integrating this work within a cohesive academic framework." His bibliography contains 241 references that were gathered from research scattered across a wide range of disciplines; management science, operations research, engineering, and psychology. Information was limited to cost and schedule discussions.

Galway, published a report (Galway, 2004) of an internal RAND Corporation study to survey "how quantitative risk management and risk analysis methods were applied to the planning and execution of complex projects, particularly those which planned to use new and untried technologies." Resulting research came from many industries and disciplines. While Galway mentions integrating technical performance with cost and schedule as a desire, he focuses only on cost and schedule risk methods. One self expressed disappointment was the lack of empirical data supporting the value of risk analysis techniques.

> … there is a striking lack of literature on the use of the techniques. This study conducted unstructured interviews with a number of researchers and practitioners. The universal statement about the general utility of quantitative project risk analysis was that it is clearly useful, because it is so widely used and so widely recommended. However, this was always followed by comments that project risk analysis is not well understood by project management. There was also agreement, confirmed by a literature search that virtually all of the evidence for its utility was anecdotal.

Galway asks the community to continue efforts of producing critical literature since 1) methods are not uniformly used, indicating a practical lack of consensus and 2) application of PRM methods is expensive and time consuming, so better guidance about value is needed.

2.3.1 Terms and Definitions

Risk management has many incarnations and therefore terminology is not consistent. This section defines various terms and how they are used herein.

Peter Bernstein chronicles the evolution of risk to modern day sophisticated risk management approaches (Bernstein, 1998). It is quite remarkable that only 350 years separate these approaches from "decisions guided by superstition, blind faith, and instinct." In addition, we are only 50 years removed from the advent of quantitative analysis used to support decisions.

Everyone is familiar with the concept of *risk*. We use it in everyday language to address uncertainties in the world around us and as influences to decisions we make. It is this familiarity that manifests itself in remarkable variety of senses we give to the term. Risk is a calculation. Risk is a commodity. Risk is capital. Risk is a technique of government. Risk is objective and scientifically knowable. Risk is subjective and socially constructed. Risk is a problem, a threat, a source of insecurity. Risk is a pleasure, a thrill, a source of profit and freedom. Risk is the means whereby we control the future. Within technical disciplines, risk is a mathematical combination of probability and consequence. Risk is uncertainty. Risk is an event. Risk is an input function to a project or an output function given project events and conditions. The dictionary defines risk as:

> **1**. exposure to the chance of injury, damage or loss; dangerous chance; hazard. **2**. *Insurance*: **a**. the hazard or chance of loss. **b**. the degree of probability such loss. **c**. the amount that the insurance company may lose. **d**. a person or thing with reference to the hazard involved in insuring him or it. **e**. they type of lass against which an insurance policy is drawn. **3**. To

> expose to the changes of injury or loss; hazard. **4**. To venture upon; take or run the change of. [From the Italian *risicare* to dare]

Even within the smaller subset of PRM, definitions of risk vary. Listed below are three from Project Management Institute (PMI), U.S. Department of Defense (DoD), and International Council on Systems Engineering (INCOSE). There are many others, but these are germane to the discussion.

- An uncertain event or condition that, if it occurs, has a positive or negative effect on a project's objectives (PMI, 2003)
- A measure of future uncertainties in achieving program performance goals within defined cost and schedule constraints (DoD, 2006)
- A measure of the uncertainty of attaining a goal, objective, or requirement pertaining to technical performance, cost, and schedule (INCOSE, 2006)

For purposes here, Kaplan and Garrick's concepts are used (Kaplan & Garrick, 1981). They set the fundamentals of risk analysis to answer three questions 1) What can happen? 2) How likely is it that that will happen? 3) If it does happen, what are the consequences? Answers define a set of triplets containing scenarios of possible outcomes, probability, and consequence (measure of damage) of each scenario. Kaplan notes that "defined in this way, risk is not a number, nor is it a curve, nor a vector, etc. None of these mathematical concepts is 'big' enough in general to capture the idea of risk." (Kaplan, 1997) Components of project risk include: 1) a future root cause, which if eliminated or corrected, would prevent a potential consequence from occurring; 2) a probability assessed at the present time of that future root-cause occurring; 3) the consequence of the future occurrence; and 4) the scenario which connects root cause to consequence.

PRM provides PMs with tools to understand an uncertain future of system development/operations and provide an analytical capability to examine impacts of their decisions. Also we want a definition of project risk that contains quantitative notions of uncertainty described by Kaplan and Garrick; supports decision making processes of management; and acknowledge constraints imposed by contracts or statements-of-work. Therefore,

> *Project Risk* is a measure of future uncertain shortfall, as referenced from the project baseline, in achieving system operational performance goals within defined project's cost, schedule, and technical constraints and is thusly described using a set of quadruplets; scenarios, decision points, consequences, and likelihoods.

A fundamental assumption for use of this definition is that stakeholders have agreed, through negotiations, on requirements and constraints. In other words, they have agreed to a level of residual risk present in cost estimates, projected schedules, and the technical proposal. The embodiment of this agreement takes the form of management reserve funds, schedule slack, and technical margin. So if the project is proceeding within constraints and meets requirements, no risk is incurred. This does not mean that the product is risk free or that the probability of failure is zero. Risk is, in part, a deviation from the agreed residual risk.

Project risk in this context includes only the undesired consequences. Pursuing an "opportunity" as advocated by some (D Hillson, 2006; Sanchez, Robert, & Pellerin, 2008; Ward, 2003) is seen as a variance against the plan (Conrow & Charette, 2008). Most often this leads to requirements creep and therefore increased cost and delay. This is not to say that exploiting opportunities should be ignored, we are saying it is not part of the project risk assessment process. Opportunity belongs to higher organizational levels or enterprise and is embodied in the establishment of a project.

The measure of the *project risk* is measured as a deviation from this baseline curve due to the various risk scenario consequences identified. A thorough treatise of the quantification of the methodology is discussed in Chapters 5 - 7.

A *risk item* is an initiating event or condition which can propagate to an undesired consequence. Also referred to as risk elements, risk events, risk factors, or project risks. Risk items may be associated with more than one consequence category (e.g, cost, schedule). All categories must be carried and propagated through the risk assessment, risk handling, and risk monitoring phases of the management process to evaluate the full impact of a risk item.

Integrated risk is the concept containing a combination of risk items leading to and interacting with consequences of all risk types; cost, schedule, technical, and safety. Within the literature, integration of risk is considered an essential part of the risk management process. However, the literature rarely discusses how to accomplish this. Another issue with “Integrated risks” is that it means different things to different authors. It has been referred to mean cooperation among project elements (Roberts, 2001), consistent process from enterprise to project and task (D. Hillson & Hulett, 2004), incorporation of all project life cycle phases (PMI, 2003), and cost-schedule integration.

Project risks are categorized in many different ways. NASA and the National Research Council broadly define categories as follows (NASA, 2007; NRC, 2005):

Cost Risk –risk associated with the ability of projects to achieve life-cycle cost objectives (*and secure appropriate funding*.)

Schedule Risk –risk associated with adequacy of time estimated and allocated for development, production, implementation, and system operation.

Technical Risk –risk associated with evolution of design and technology implementation affecting level of performance.

Performance Risk – risk associated with how well a given design will operate.

Programmatic Risk – risk associated with action or inaction from outside the project, over which PMs have no control, but which may have significant impact on the project.

Environment, safety, and health risks – risks associated with detrimental effects on the environment or hazards that may be uncovered during project execution. These risks are technical risks but are treated separately here to add focus to the category, and out of tradition. Within government acquisition programs, safety risks are treated separately from project risk management processes.

A risk source is akin to a root cause. The term is used as an overarch set of causes from which risk item spawn. Various industry specific lists exists for software (Dorofee et al., 1993), for construction (Akintoye & MacLeod, 1997) and for large engineering projects (Miller & Lessard, 2001). They can also be project specific. Risk sources are used as a checklist to explore how project elements can go wrong.

2.3.2 Project Risk Management Background

This section provides an overview of common practices for risk management within a project. In a broad sense, assessing risk is a necessary skill for modern day life. Peter Bernstein argues that “the ability to define what may happen in the future and to choose among alternatives lies at the heart of contemporary societies” (Bernstein, 1998). His discussion of probability and risk assessments have fundamentally changed our view of the world from one of predetermined destiny based on pleasing the Gods to one in which the future can be understood and planned.

PMs adopted PRM to help manage uncertainty in achieving project goals and requirements. To this end, PRM seeks to identify all significant risks to understand potential range of consequences and to estimate likelihood of their occurrence. Information is needed to support PM's decision-making process.

While managing large scale projects has been around since humans starting building large structures, the management of risk has not. Most risk management tools were developed by U.S. military programs in the 1950s as part of a wider adoption of quantitative management techniques for defense procurement activities aimed at cost and schedule issues (Galway, 2004). Underlying methodology and philosophy of project risk management tools has not changed a great deal since then.

Common practice for PRM includes a planning activity, assessing risk items, developing and handling alternatives, monitoring to understand changes in risk posture over time, and communicating (internal and external) with documentation throughout the process. They are incorporated as an integral part of the project governance providing decision-makers with risk based view of decisions.

At least within U.S. government procurement, PRM practices are mandated policy as shown in this excerpt from Office of Management and Budget's Capital Programming Guide (OMB Circular A-11):

> Risk management should be central to the planning, budgeting, and acquisition process. Failure to analyze and manage the inherent risk in all capital asset acquisitions may contribute to cost overruns, schedule shortfalls, and acquisitions that fail to perform as expected. For each major capital project a risk analysis that includes how risks will be isolated, minimized, monitored, and controlled may help prevent these problems.

PRM is thought to be vital for the completion of modern large complex engineering projects, within given constraints. At this point in the discussion of PRM, it would be preferable to review evidence supporting (or not) the notion that PRM improves project performance. However, as Galway, Williams, and Lawrence also discovered, no such critical literature exists. These authors speculate two possible reasons. First, interested parties in project management are highly fragmented, being split across a practitioner community and a variety of academic disciplines that publish in very disparate media. Second, failures of projects are highly sensitive and often involve proprietary information, which analysts cannot access.

Another issue in showing PRM importance lies in the fact that adoption of formal project management and project risk management methods coincide with project failure trends. A fact the even Conrow concedes (Conrow & Charette, 2008), stating:

> Alas, our experience suggests that risk management is often poorly performed on many DoD programs. Results from the Tri-Service Assessment Initiative (which looked at 50 major DoD programs), performed a few years ago indicate that while risk management is carried out on most programs, it is often ineffective. Risk management process are often superficial, risk analyses are not communicated, and identified risk frequently do not influence program decision making (e.g., outputs are not utilized to make decision or to improve how the program is being run).

Various industries incorporate PRM methods as part of their management approach. Off-shore oil platform projects used PRM to solve issues relating to safety and supply logistics in the 1980s (Chapman, 1990). Construction projects have long used cost and scheduling models are now using PRM to tie them to project risk (Cooper, et al., 2005; del Caño & de la Cruz, 1998). Utility companies also use PRM in construction projects (Elkington & Smallman, 2002; NRC, 2005). Transportation industry is being forced through government contracts to show project risk evaluations as part of project planning and proposals (CalTrans, 2003). Software projects have taken PRM and incorporated it as part a the development process (Boehm, 1991; R. N. Charette, 1996; Dorofee, et al., 1993).

Ultimately, PRM is about providing PMs with actionable information to steer projects to success. A well-managed risk management program provides a repeatable process for balancing resources within program constraints. PMs can derive benefit from this process when system designs are tightly constrained or have optimistic cost, schedule, and performance goals. Without effective risk management PMs may find themselves in a crisis management mode; a resource-intensive process that is typically constrained by a restricted set of available options (DoD, 2006). PRM allows the PMs an increased confidence in achieving desired outcomes, to effectively constrain threats, and to make risk-informed decisions.

2.3.3 Project Risk Management Standards and Guidelines

This section should have been straightforward. Find risk standards in use, describe best practice methodology, identify some industry examples, and move on. However, the quote from computer scientists Andrew Tanenbaum comes to mind; "*The good thing about standards is that there are so many to choose from*." Due to the same forces that produced a great many perceptions of risk, a multitude of standards exist. National and international standards have been published by several organizations. A comparative study and description of these is outside the scope of this study. See (R. Charette, 2006; Cooper, et al., 2005; Raz & Hillson, 2005) for more detailed information. Here we will focus on just a few to use as a basis for PRM processes:

- *Project Management Book of Knowledge (PMBOK) produced by the Project Management Institute.* PMI's PMBOK addresses all manner of project management issues. Chapter 11 specifically addresses project risk management. It (like the other chapters) is process oriented listing inputs, outputs, and processes needed to complete each of six steps. The focus is on qualitative assessments of risk with minor discussions of quantitative methods as they apply to cost and schedule.

- *Continuous Risk Management (CRM) produced by the Software Engineering Institute (SEI) at Carnegie Mellon University.* SEI's CRM book focuses on risks within software development projects. It is part of the overall software capability maturity model integration process. The book provides a view of what risk management could look like when implemented within a project and shows how an organization might tailor the process to fit in its specific environment.

- *Risk Management Guide for DoD Acquisition produced by the Office of the Secretary of Defense*. This document reflects lessons learned on the application of risk management on past programs. It is structured to provide a basic understanding of risk management concepts and processes. The focus is for DoD to use risk management in the acquisition of systems from contractors and therefore centered on unique DoD environments.

As an indication of how specific PRM guidance has proliferated, the list below shows a sample what is available. Many project specific plans can also be found.

- AS/NZS 4360, Risk Management.
- APM Project Risk Analysis and Management (PRAM).
- NASA NPR 8000.4A, Agency Risk Management Procedural Requirements.
- California Department of Transportation, *Project Risk Management Handbook*.
- Washington State Department of Transportation, *Risk Management Manual*.
- ISO/IEC Guide 73:2002, *Risk management -- Vocabulary -- Guidelines for use in standards.*
- UK Office of Government Commerce, *Management of Risk* (M_o_R) guideline.

One other standard to mention is Mil-Std-882, *System Safety Program Requirements*. While not strictly a risk management guidance document, its processes, techniques, and communication mechanisms mirror those listed above. System safety is risk management focused solely on safety aspects of a system. The majority of the effort is qualitative in nature using the same risk matrix construct to communicate results. Interestingly, the activities performed in this risk matrix are not combined with project risk matrices.

2.4 Risk Management Practice

First thing to note for all the risk management processes is that they are continuous in that they exist in all phases of the project life-cycle and provide a feedback mechanism to track and monitor risk. Figure 2-2 is a typical model depiction of a continuous risk management process. The process balances a number of interwoven elements which interact with each activity. Furthermore, "specific risks cannot be addressed in isolation from each other; the management of one risk may have an impact on another, or management actions which are effective in controlling more than one risk simultaneously may be achievable." (HM-Treasury, 2004)

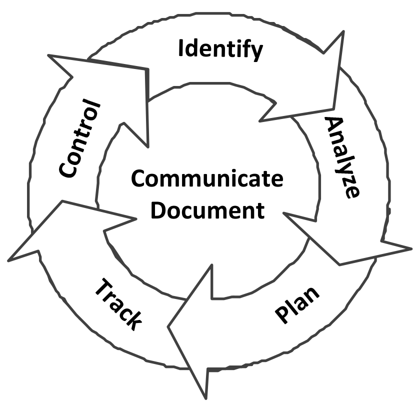


Figure 2-2. Continuous risk management process

Risk management models can become quite intricate with incorporation of multiple organizational layers. The UK's Orange book shows a model that illustrates how core risk management processes are not isolated, but takes place in a context; and, how certain key inputs have to be given to overall processes in order to generate outputs which will be desired from risk management.(HM-Treasury, 2004)

PMBOK's risk management chapter explains how to manage project risk with an approach that is prescriptive dovetailing into all project management processes of book at large. Six steps of this process include:

- Risk Management Planning
- Risk Identification
- Qualitative Risk Analysis
- Quantitative Risk Analysis
- Risk Response Planning
- Risk Monitoring and Control

Other standards and guidelines provide similar steps. Some have more but they describe the same process in differing levels of detail. For example, APM's Project Risk Analysis and Management (PRAM) Guide maps to nine steps, Synergistic Contingency Evaluation and Response Technique (SCERT) uses four, SEI's CRM Guidelines uses five.

The process model used herein is taken from DoD's Risk Management Guide - version 5, (see Figure 2-3). This process includes a planning activity, assessing risk items, developing handling alternatives, monitoring risk posture, and communicating through documentation throughout the process.

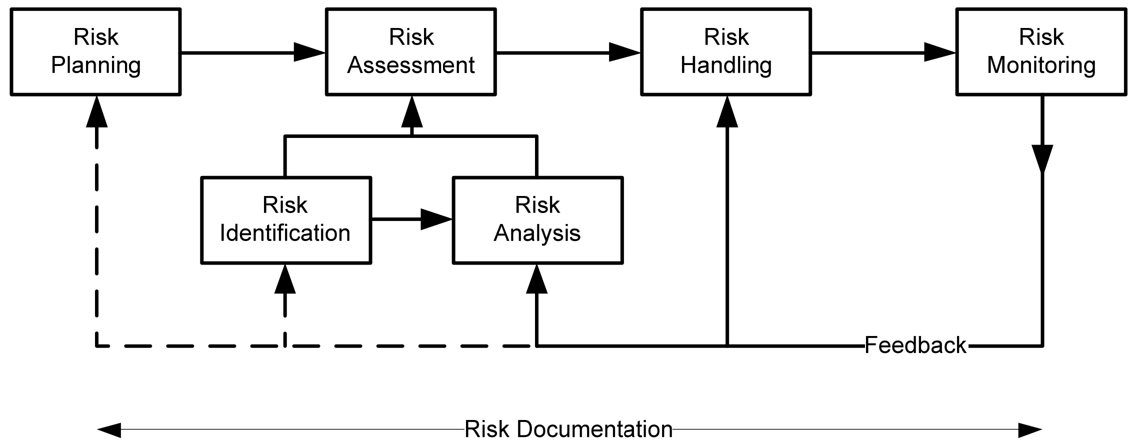


Figure 2-3. Project Risk Management process

These process steps are defined within the DoD risk guide are:

Risk planning is the process of developing and documenting an organized, comprehensive, and interactive strategy, process, and methods for identifying and tracking risk issues, developing risk-handling plans, performing continuous risk assessments to determine how risks have changed, and assigning adequate resources.

Risk assessment is the process of identifying and analyzing project areas and critical technical process risks to increase the likelihood of meeting cost, performance, and schedule objectives. Risk identification is the process of examining the program areas and each critical technical process to identify and document the associated risk. Risk analysis is the process of examining each identified risk issue or process to refine the description of the risk, isolating the cause, and determining the effects (more on this in the next section).

Risk handling is the process that identifies, evaluates, selects, and implements options in order to set risk at acceptable levels given program constraints and objectives. This includes the specifics on what should be done, when it should be accomplished, who is responsible, and associated cost and schedule. Risk handling options include assumption, avoidance, control (also known as mitigation), and transfer. The most desirable handling option is selected, and a specific approach is then developed for this option. The chosen option coupled with the implementation approach is known as the risk handling strategy.

Risk monitoring is the process that systematically tracks and evaluates the performance of risk-handling actions against established metrics throughout the acquisition process and provides inputs to updating risk-handling strategies, risk analysis results, and risk identification information, as appropriate.

Risk documentation is recording, maintaining, and reporting assessments, handling analysis and plans, and monitoring results. It includes all plans, reports for the PM and decision authorities, and reporting forms that may be internal to the program.

Chapter 9 addresses how the new analytical framework fits to this established PRM practices.

As shown above, PRM processes can reside in a much larger process as it is with the PMBOK or by the Orange Book. NASA's process is created to work as an integrated system throughout all levels of the agency. It is also integrated at the project level through explicit coordination with their Risk-Informed Decision Process. The process identifies and rank orders the decision alternatives based on set of performance measures. It employs various boards and panels, Authority to Proceed milestones, Safety Review

Boards, Risk Reviews, Engineering Design and Operations Planning decision forums, Configuration Management process, and commit-to-flight reviews (NASA, 2008).

2.4.1 Risk identification

After the infrastructure is in place, work of analyzing the risk environment begins. First identify the risks. An initial identification occurs early in the project and identification must also occur continuously throughout the project. There is always new information gathered and potential for new risks to appear. During execution of the project, constant examination of current versus baseline staffing levels, cost expenditures, design progress can provide indications for risk items. Monitoring tests for performance shortfalls and failures also provides insights.

The literature provides many tools to perform this activity. Raz and Hillson have compiled a list of risk identification techniques discussed in several PRM guidance documents (See Table 2-1). Two common methods to identify risk items are drawing from experience (personal and corporate) and brainstorming. Another technique advocated by DoD is to analyze each item in the project's WBS and compare against a list of risk sources. The resulting list of risks is captured in a structure called a *Risk Register*. Many authors (Akintoye & MacLeod, 1997; Chapman, 1997; D. Hillson, 2003; Kwak & Stoddard, 2004) suggest organizing the risk items by risk source. A long list without this organization can hide patterns as to which risk sources are contributing to the overall risk.

A common misconception, and project practice, is the identification and tracking problems (not risks) and then manage the consequences. This practice tends to mask true risks, and it serves to track rather than resolve or mitigate risks (DoD, 2006).

Table 2-1. Risk identification tools and techniques

Assumptions analysis	Expert opinion	Prompt lists
Benchmarking	Fault tree analysis	Prototyping
Brainstorming	Flow charts	Questionnaires
Cause and effect diagrams	Hazard and operability studies	Risk assessment workshops
Checklists	Historical data	Root cause analysis
Constraints analysis	Incident investigation	Scenario analysis
Delphi technique	Influence diagrams	Stakeholder analysis
Diagramming techniques	Interviewing	Structured interviews
Documentation reviews	Lessons learned	SWOT analysis
Evaluation of other projects	Nominal group technique	System engineering techniques
Event tree analysis	Peer review	Systems analysis
Experience in organization	Personal observation	Taxonomies
Experience in similar orgs	Previous experience	Technology readiness levels
Examination of vulnerabilities	Project monitoring	Testing and modeling

Source: (Raz & Hillson, 2005)

2.4.2 Risk Register

The Risk Register is a list containing the output of the risk identification process used to assist the project management and project team review project risks. Each risk item is given a separate entry with the following information usually laid out in a tabular format:

- Unique identifier for each risk
- Description of each risk and how it will affect the project
- Assessment of the likelihood and the possible impact
- List of proposed mitigation actions (preventative and contingency)

- Root causes the give rise to the risk item

In many respects it resembles a Failure Modes and Effects Analysis (FMEA) worksheet and suffers from the same limitations in that it is difficult to read as a whole to get the entirety of the project's risk posture. The attraction is its simplicity and convenience.

Risk registers have shortcomings as the project becomes larger and more complex. The issues with this format include: (Chapman & Ward, 2003)

- Individual risk drivers may not be described in sufficient detail to avoid ambiguity and misunderstandings about what risk is being described
- Important inter-dependencies between risks are not readily highlighted
- A table of risk drivers, particularly a long one, provides limited guidance on the relative importance of individual risk drivers

Many large programs subdivide the list so that smaller organizations hold risks relevant to them. This however, tends to compound the issues listed above. In addition, the integration of risk items is not a trivial matter. For instance, a high risk for a small organization may be negligible for the prime organization.

2.4.3 Risk Response

Risk Response addresses how PMs manage risk items. The responses contain approaches and specific actions, as well as, whether each response is to be planned (occurring prior to the risk manifesting), or contingent (occurring once the risk has manifested). There are four different types of risk responses. For every risk, PMs must decide which type of risk response to use. The four types of risk response are:

Mitigation – Mitigation is reducing the probability of occurrence or impact of a risk, before it happens. Mitigation may also include contingency, in the event the risk still happens. Mitigation requires action, resulting in some level of planned response prior to the risk manifesting and/or contingent after the risk manifests.

Acceptance – Acceptance is deciding not to change the project management plan to deal with a risk. Acceptance is a passive response requiring no action.

Avoidance – Avoidance is eliminating the risk, or protecting the project objectives from its impact (i.e. if the risk were to occur, it would not impact the project). Avoidance requires more action, but provides the largest reduction of risk from a particular risk item. Note, eliminating the risk may have unintended consequences elsewhere in the project.

Transference – Transference is shifting the threat of impact and ownership of response to a third party, through a contractual agreement between the two parties. Liability for the costs of a risk is transferred to the other party. In other words, your risk is eliminated and the risk now rests with the third party.

2.4.4 Qualitative Risk Analysis

Once risk items are identified and documented, a probability of occurrence and consequence are assigned to each. This assignment can be a quantitative assessment or a qualitative one. Common practice is to make a qualitative assessment using interviews and meetings with personnel familiar with risk items and assigns an ordinal value from predetermined tables. These tables can be standard within an organization or unique to the project. Table 2-2 illustrates what these tables look like.

Table 2-2. Typical likelihood and consequence scores

Likelihood of Occurrence			Consequence		
5	Very likely	91-100%	5	Critical	The program will fail. Minimum acceptable requirements will not be met.
4	Likely	61-90%	4	Serious	The program will encounter major cost/schedule increases. Minimum acceptable requirements will be met. Secondary requirements may not be met.
3	Possible	41-60%	3	Moderate	The program will encounter moderate cost/schedule increases. Minimum acceptable requirements will be met. Some secondary requirements may not be met.
2	Unlikely	11-40%	2	Minor	The program will encounter small cost/schedule increases. Minimum acceptable requirements will be met. Most secondary requirements will be met.
1	Rare	0-10%	1	Negligible	No effect on the program. All requirements will be met.

The risk matrix (see Figure 2-4) is the preferred communication vehicle for relative risk of risk items. Likelihood of occurrence and consequence are plotted onto a matrix. The matrix itself is coded to identify the level of significant (High, Moderate, Low). This NASA example shows the moderate range to be asymmetrical meaning lower right corner to be more important than the upper left. Other organizations skew the matrix, add levels of granularity to the axes, or increase the number of significance levels. A quick internet search reveals no consistency to how risk matrices are constructed. This variety makes it difficult to compare risks from one organization to another. Even the placement of the high risk region can vary (upper right or upper left).

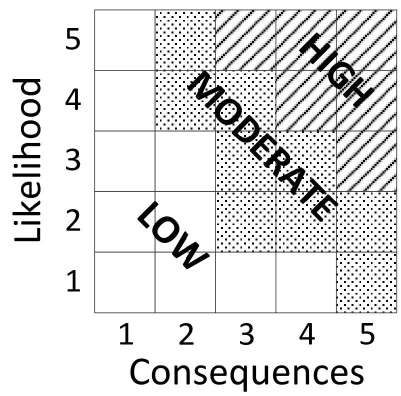


Figure 2-4. Typical risk matrix

The region of the risk matrix then determines the priority of the risk items; "High" (red) gets more attention than "Moderate" (yellow). "Low" (green) risks are usually ignored as insignificant. Think of this as a game of whack-a-mole, where upper management wields the hammer. The idea is to move the risk item to a lower region by developing a response plan. These responses either lower the risk item probability or soften the blow of the consequence. Those that cannot be moved are accepted risks (usually with some supporting rationale).

Despite their extensive use, risk matrices have issues. Even though guidance documents state that risk matrices are not assessment tools (NASA, 2007), tendency has been to consider a subjective placement on a matrix as sufficient. Placement of a risk item provides characteristics of just that item and provides no information about the interactions between risks. In other words, they are treated as independent items. Consequently any attempt to aggregate risks to provide a picture of the total project risk will give significantly incomplete information.

Uncertainty is addressed only in the narrow sense that risk items have a probability of occurrence. A risk item exists in one position assuming that it is within a likelihood range and consequence range, both of which are assumed to be known. This does not represent the realistic uncertainties in analyses. Effects of assumptions, variability in data, and incompleteness of knowledge should be acknowledged and managed with PRM.

The consequence score is typically applied to a single consequence type. A risk item however, may, and usually does, have many consequences of cost, schedule, and performance. This is a multi-dimensional decision problem over-simplified to one ordinal scale. The relative magnitude and relative importance of consequences are not conveyed in the matrix.

In addition, there are some mathematical problems when attempting to perform mathematical operations on ordinal values, and when determining risk ratings unambiguously. Conrow warns against the practice of performing mathematical operations on scale values for probability and consequence (Conrow, 2003). He demonstrates through example the meaningless results from these operations and provides a few examples where project made profoundly incorrect decisions based on these analyses. Unfortunately, this practice is common “having been promoted by DoD in the 1980s to mid-1990s and also widely used by the aerospace and even general commercial industry.” Conrow also profiles how DoD guidance documents contained the calculation errors and the effort to rewrite the offending passages.

Cox examined the mathematical properties of risk matrices and shows limitations with poor resolution, errors, suboptimal resource allocation, and ambiguous inputs and outputs (Cox, 2008). After working through several examples where risk matrices yield incorrect results, he concludes that "risk matrices do not necessarily support good (e.g., better-than-random) risk management decisions and effective allocation of limited management attention and resources." Cox concedes that the creation of risk matrices is too pervasive not to use them, and suggests more research is needed to better characterize the conditions that are helpful and harmful, and thus develop procedures to account for the limitations.

PRM process takes each risk item and assigns a score for probability of occurrences and a score for consequence (usually the worst-case consequence). The assignments of probability and consequences are typically done by committee in brainstorming secessions. The secessions have shown to be very good for identification of risk items when facilitated using checklists, lessons learned data, and examining the WBS. Two problems exist in this approach: first, people are not very good at assigning probabilities to events without detailed supporting analysis or at assessing all possible consequences; and second, people succumb to "groupthink" and other group dynamic forces that distort independent analysis.

Studies have shown people's estimation of probability of uncertain events to be predictably incorrect. People tend to use rules-of-thumb (heuristics) to reduce complexity in their own minds, but they often lead to significant errors. People also suffer from biases (representative, availability, and anchoring) and overconfidence. Consistently, small probabilities are over-estimated and large-probabilities are under-estimated. The estimates made are accompanied by unrealistic overconfidence in the quality of their estimates (Tversky & Kahneman, 1974).

The situation is exacerbated as events are combined into a mix of independent events and dependent events; information combinations from various sources and types; sampling from non-homogenous population sets etc. The tendency is to focus on the worst case consequence and assign its probability to the initiating risk item, or an observable subset of that risk item.

“Groupthink” refers to faulty decision-making in a group (Janis, 1971). Flawed decisions are often the result of the following practices:

- Incomplete survey of alternatives
- Incomplete survey of objectives
- Failure to examine risks of preferred choice
- Failure to reevaluate previously rejected alternatives
- Poor information search
- Selection bias in collecting information
- Failure to work out contingency plans.

Within a project, these committees tend to vote on how risks should be captured and treated, therefore determining resources. These voting schemes based on preferences are not necessarily internally consistent and can result in suboptimal decisions (Arrow, 1963; Franssen, 2005; Hazelrigg, 1996).

I am certainly not claiming that the issues discussed above will go away with the implementation of this approach. However, a systematic process of identifying scenarios, collecting evidence, and documenting assumptions will decrease the occurrences of errors in risk management.

2.4.5 Quantitative Risk Analysis

Quantitative risk analysis is used to numerically determine the probability that projects meet objectives. Techniques such as sensitivity analysis, statistical methods, decision analysis, and simulations provide better insight into project risk. The prevailing guidance is to use quantitative method only under specific circumstances, such as those deemed to have high risk, as determined by qualitative risk analyses. In practice, quantification is done only to uncover details about a particular risk item or, in the case of a large project, to assess cost and schedule objectives.

Whether to quantify risk or not is a much debated subject with some authors expounding the virtues of risk numbers while others point to the amount resources required. For example, a National Research Council report sees quantitative analysis as overkill; "While probabilistic risk assessment methods are certainly useful in determining contingency amounts to cover various process uncertainties, simple computation methods are often as good as, or even better than, complex methods for the applications discussed here" (NRC, 2005). PRM standards echo this bias toward analyzing the risk from a qualitative point of view. PMBOK suggests that quantitative analysis is often unnecessary. In some guidelines no mention is given to the set of quantification tools available (HM-Treasury, 2004).

A common form of quantitative risk analysis uses Monte-Carlo simulations of the schedule. This is now an integrated part of the CPM/PERT computer software. Estimates are often made as triangular probability distributions about task duration times provided as input from interviews or consensus at meetings. Techniques for performing these analyses can found be in texts (Garvey, 2000). The same methodology is applied to cost estimates by treating WBS costs as random variables to get the uncertainty of project costs.

Even though many of the guidance documents say to include technical risk, it is often not considered in the quantification of risk. Only the cost and schedule are combined into a cohesive analysis.

Some PMs and authors question the value of traditional and commonly used expected value concepts. They complement and supplement the concept with conditional expectation, where decisions about extreme and catastrophic events are not averaged out with more commonly occurring events (Haimes, 2004).

2.5 Previous Research

Researchers have focused on the risk analysis aspects of PRM. This section identifies several of them and shows that a true integrated PRM framework is still needed. Separate discussions of PRA and DA are provided since they play a prominent role in the formulation of this framework.

2.5.1 Project Risk Frameworks

Many methods have been introduced and used in industries including construction, chemical processing, and government systems procurement. Lists of risk sources or drivers appear in abundance in the literature, but only a few develop them into methodologies using risk factors. Scenario-based analysis is certainly the foundation for engineering risk assessments which influence some researchers in propagating them into project risk analysis. Failure modes and effects analysis analogies have also been shown as a helpful tool. Project management techniques for cost and schedule estimation have incorporated uncertainty in by using variability of low level cost or tack elements and propagating them through existing models. Bayesian Belief Networks have been shown as an integration tool with Monte-Carlo simulations. Other techniques also show promise.

Los Alamos National Laboratory has developed a systematic qualitative project risk analysis technique called Risk Factor Analysis method as a useful tool for early, pre-conceptual risk analyses (Kindinger & Darby, 2000). The method assigns ordinal values to risk factors for each activity in the project. The risk factors are items such as technical maturity and cost uncertainty. Another approach using risk factors was developed for offshore petroleum installation called risk indicators (Øien, 2001). Risk indicators are established from the performance measures of the system. Embedded in the methodology is a system control view that changes in indicators can alert the project to changes in risk.

LRAM is a methodology created for U.S. Air Force's information system security risk management (Guarro, 1989). The basic structure (Risk Element) includes the combination of a threat initiator, its propagation path (that it ultimately reaches and affects the system assets), the possible resulting consequence, and the applicable controls. A complete list of Risk Elements is then analyzed quantitatively to find risk significant paths and develop mitigation strategies around them. The methodology was later to become the core of a software tool, CARMA (Guarro & Feldman, 2002). Zhang explores vulnerabilities of projects to the operational systems in which they exist (Zhang, 2007).

His methodology examines more than the common view of risks as initiator and consequence as statistical cause and effect relationship. Chapman and Ward (Chapman & Ward, 2003) explored PRM in all phases of a project life cycle and argue for the inclusion of *source-response diagrams* as an integral part of their SHAMPU framework to summarize the links between activities, risk sources, and responses.

Dillon, Pate-Cornell, and Guikema developed a model, Advanced Programmatic Risk Analysis and Management model (APRAM), as a decision-support framework for the management of the risk of failures of dependent engineering projects, based on a series of optimization steps aimed at budget allocation(Dillon, Paté-Cornell, & Guikema, 2003). The framework, originally used for NASAs Mars Exploration Program, has been extended to analyze cost, schedule, and quality in construction projects (Imbeah & Guikema, 2009).

An examination of PRM practice shows a strong resemblance to a Failure Modes and Effects Analysis (FMEA) commonly used in reliability engineering. A gap analysis showed that FMEA processes as defined by Mil-Std-1629A meets the requirements of the PMBOK criteria for risk management (Santos & Cabral, 2008). Risks are prioritized using the FMEA concept of a Risk Priority Number and possibly an addition of a detectability value (Carbone & Tippett, 2004). FMEAs have the ability to examine cost, schedule, and performance simultaneously but does so with ordinal, not cardinal, scales thereby limiting its usefulness.

Hierarchical holographic modeling (HMM) is a holistic philosophy/methodology aimed at capturing and representing the essence of the inherent diverse characteristics and attributes of a system – its multiple aspects, perspectives, facets, views, dimensions and hierarchies (Haimes, 2004). HHM recognizes that most organizational as well as technology-based systems are hierarchical in structure, and thus risk management of such systems must be driven by and responsive to this structure. The risks associated with each subsystem within the hierarchical structure contribute to and ultimately determine the risks of the overall system. This methodology was applied to a large software acquisition project in order to facilitate the risk identification process. As a result the HHM model identified over 250 sources of risk (Lambert, Haimes, Li, Schooff, & Tulsiani, 2001). HHM has also been used to analyze System of Systems projects.(Haimes, 2008) Haimes further suggests that good management must incorporate and address risk management within a holistic and all-encompassing framework that incorporates and addresses all relevant resource allocation and other related management issues. A total risk management approach that harmonizes risk management with the overall system management must address hardware failures, software failures, organizational failures, and human failures.

Dey has built and implemented a PRM model based around analytic hierarchy process and decision tree analysis for petroleum pipeline construction projects (Dey, 2002). Analysis techniques are used to model risk response alternatives for specific work packages. Flyvberg uses decision theory to address inaccurate forecasts of project costs, demand, and other impacts that are identified as project risks (Flyvbjerg, 2006). A decision framework for risk management is proposed by Aven in which they relate several issues of a problem to the decision and various solution alternatives(T Aven, Vinnem, & Wiencke, 2007).

Cost and schedule uncertainty analyses quantify the cost impact of uncertainties associated with estimates. Probability distributions are generated for WBS cost elements or schedule tasks. Monte-Carlo simulations propagate the uncertainty to provide the total project cost and delivery date as distributions (Stewart, 1991). Garvey stresses the importance of this analysis to include: establishing a cost and schedule baseline, determining cost reserve, and conducting risk reduction trade-off analysis (Garvey, 2000).

Earned Value Management (EVM), while not specifically a PRM tool, provides a good frame for integrating cost and schedule metrics. It provides the ability predict future performance based on trends. EVM provides an early warning tool alerting PMs as early as the 15% completion point on a project (Flemming & Kippelman, 2000). This signal allows PMs to forecast final required funds needed to finish the job within a narrow range of values. If final forecasted results are unacceptable, steps can be taken early to alter final requirements.

When projects develop Monte-Carlo simulations for their cost and schedule estimates the impact of probabilistic correlation is often ignored. One alternative to directly solving this difficult problem is the integration of Bayesian Belief Networks (BBN) within the integrated cost-schedule simulation (Arizaga, 2007). BBNs are used to generate dependency among risk factors and to examine non-additive impacts such as reputation of various providers. Fan designed a procedure to incorporate BBNs in a continuous monitoring loop to support the decision- making process of risk management (Fan & Yu, 2004). BBNs were chosen since risk management is performed continuously in a feedback loop so that problems are dynamically detected and adjusted. BBNs' influence diagrams also provide a visual model of cause consequence relations, and thus, help to identify sources of risks. BBNs can also model uncertainties and provides probabilistic estimates. Whenever new evidence is available in the proposed monitoring loop, the new data can be plugged in the related BBNs again to recalculate and update previous estimates.

Uncertainty management requires a "broader perspective" than risk management in order to improve project management (Ward & Chapman, 2003). Their paradigm is an attempt to balance the negative focus on threat with opportunities. Attention shifts from examining only risk items to examining uncertainty in five areas: the variability associated with estimates of project parameters, the basis of estimates of project parameters, design and logistics, objectives and priorities, and relationships between project parties.

Cost and schedule models have difficulty when project tasks are more interdependent than just finishing one before another can start. These models cannot account for the iteration and feedback that often takes place within complex engineering projects. System dynamics models describe and explain how project behavior and performance are driven by the feedback loops, delays, and nonlinear relationships in processes, resources, and management. System dynamics models are based on dynamic feedback taken from control theory. They can be used to evaluate the impacts of various failure modes or root causes, particularly in cases where the root causes can be identified but the ripple effect of their impacts is difficult to estimate with any confidence. System dynamics models have been effectively used for project evaluation, planning, and risk assessment (Lyneis & Ford, 2007; Rodrigues, 1994; Shang, 2002). Although the use of these models is not standard practice for project planning and risk management, they can significantly help to improve understanding of project risks (NRC, 2005).

2.5.2 Probabilistic Risk Assessment

Risk assessment has a long history. Of interest here is the use probabilistic scenario-based analysis to examine engineered systems. Fault Tree Analysis (FTA) were among the first methods developed for this purpose in the early 1960's within the aerospace industry. By the late 1970's the nuclear power industry was using FTA along with Event Trees in what is now called a traditional Probabilistic Risk Assessment. Today it is also being used in petro-chemical, off-shore oil drilling, and defense industries. PRA studies over the past several decade have pioneered the inclusion of new analysis tools like human reliability analysis, common-cause-failure analysis, external event analysis, software reliability, and consequence modeling. All this activity has led Bedford and Cooke to state the “trend in all these areas is for PRA to support tools for management decision making, forming the new area of risk management” (Bedford & Cooke, 2001). This methodology will actively tie PRA to specific decisions to reduce risk.

As mentioned in the discussion of *risk*, Kaplan and Garrick saw PRA as a method to answer three questions: What can go wrong? How likely is it? What are the consequences? The answer to these questions are what project managers needs to know if they are to be successful.

PRA is a top-down examination of a system. Apostolakis summarizes the PRA process as (Apostolakis, 2004):

- A set of undesirable *end states* (adverse consequences) is defined, e.g., in terms of risk to the public, loss of crew, and loss of the system. These answer the third question.

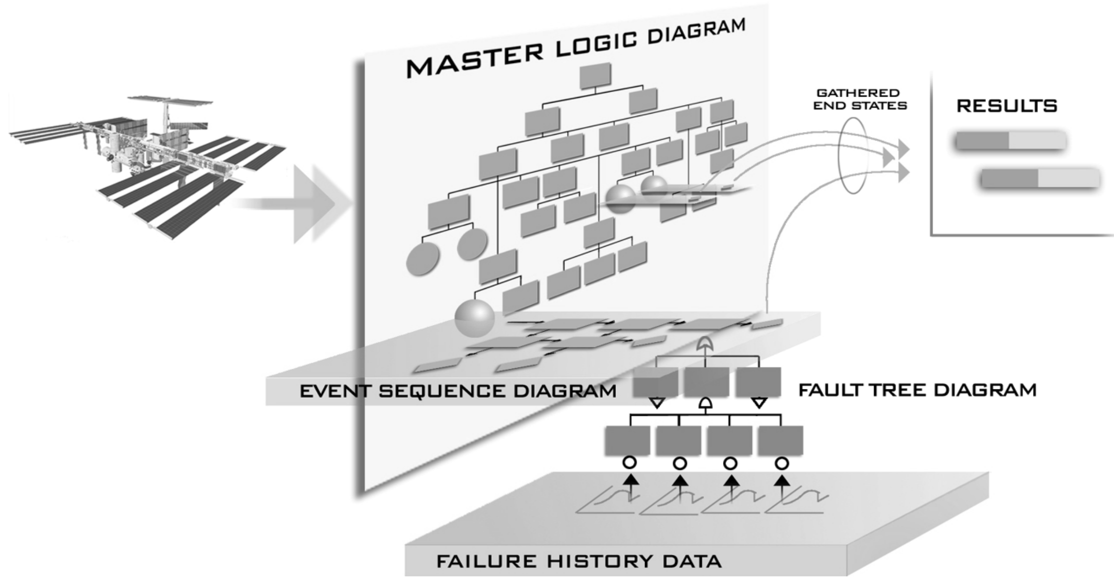
- For each end state, a set of disturbances to normal operation is developed that, if uncontained or unmitigated, can lead to the end state. These are called *initiating events*.

- *Event* and *fault trees* or other logic diagrams are employed to identify sequences of *pivotal events* that start with an IE and end at an end state. Thus, *accident scenarios* are generated. These scenarios include hardware failures, human errors, fires, and natural phenomena. The dependencies among failures of systems and redundant components (common-cause failures) receive particular attention. These scenarios answer the first question.

- The probabilities of these scenarios are evaluated using all available evidence, primarily past experience and expert judgment. These probabilities are the answer to the second question.

- The accident scenarios are ranked according to their expected frequency of occurrence.

These 5 steps are graphically shown in Figure 2-5. All the parts fit together to make one large cohesive risk representation of the system. This is what the new methodology will do for projects.



Source: Smith, C.et.al., *ISS Stage 7A PRA*.
Futron Corporation. 1999.

Figure 2-5. PRA components integrate together to form a cohesive model

The methodology draws from this to form analogies to the PRM process. The *end states* are related to the consequences of cost overrun, schedule delay, and performance short fall. *Initiating events* are the risk items. Accident scenarios are the paths that connect risk items with end states.

A typical representation of risk in PRAs is the use of Farmer Curves or risk profiles. These curves plot magnitude of many different consequences against the complementary cumulative probability distribution of the scenario. Figure 2-6 shows a famous Farmer Curve used to show relative risks of nuclear power plants compared to other risks in the Reactor Safety Study, WASH-1400 (1975). The analyst compares the risk of nuclear power plant fatalities with fatal frequencies by air crashes, fires, dam failures, explosions, chlorine releases, and air crashes. Kumamoto and Henley further explain the figure by stating "Nonnuclear frequencies are normalized by a size of population potentially affected by the 100 nuclear power plants; these are not frequencies observed on a worldwide scale. Each profile in the figure is a Farmer curve; horizontal and vertical axes generally denote the accident severity and complementary cumulative frequency per unit time, respectively."(Henley & Kumamoto, 1996)

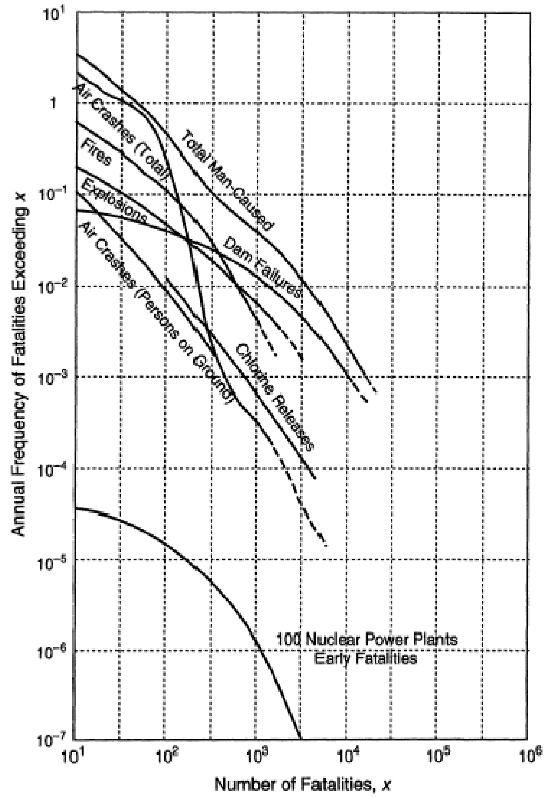


Figure 2-6. Famous PRA Farmer Curves example

This allows an analyst to move away from displaying only a single dimension of risk, but instead the probability for all possible values of consequence. Currently, PRM examines a risk item and assumes a causal link to a consequence. With a PRA view point, risk items take many paths to several consequence values. PRA methods consider thousands of scenarios that involve multiple failures or events, thus providing an in-depth understanding of potential project system failure modes. Such an enormous number of possible scenarios is not investigated by PRM traditional methods.

PRA strengths have been well demonstrated. Each of the benefits realized from PRAs can be provided to project management. Building scenario models increases the probability that complex interactions between events, conditions, systems, and personnel will be identified. The scenario graphics, called Event Sequence Diagrams (ESD) provides an easy to follow flow chart of the analyst's thought process and assumptions while creating a common understanding of the problem, thus facilitating communication among various stakeholder groups.

Quantification of uncertainty creates a better picture of what the community of experts knows or does not know about a particular issue. This gives decision-makers another option to research as particular issue that is driving uncertainty before a decision is made. Good PM do this instinctively, but it is often difficult to quantitatively define the action.

Alignment of PRA's objectives with those of PRM is an ideal fit because it formalizes the process of identifying, and analyzing potential outcomes, and determining uncertainty. Insights gained by conducting a PRA, and its results are currently missing from common PRM practice.

2.5.3 Decision theory

Another branch in the risk assessment story follows along through *decision analysis* (DA), a term coined in 1964 by Howard, but has its roots with the work of Ramsey in the mid 1920s and von Neumann & Morganstern in the late 1940s. "Decision analysis is no more than a procedure for applying logic" (R. A. Howard, 1989). DA systematically examines decisions with tools like decision trees to show alternatives, impacts, and uncertainty of events. Just like PRAs uncertainties are represented through probabilities and probability distributions. The decision maker's preferences about risk are incorporated with utility functions. These methods have been effectively used in many fields, including business planning and marketing, environmental mitigation activities, oil exploration, litigation and dispute resolution (Clemen & Reilly, 1999; Goodwin, Wright, & Phillips, 2004; Keeney & Raiffa, 1993).

In decision theory, risk is defined as variation in the distribution of possible outcomes, a definition that allows risks of alternatives to be quantified, calculated, expressed numerically, and compared (NRC, 2005). Even with uncertainty in possible outcomes, PMs are asked to make decisions. Raiffa describes the problem for decision-makers as “you should scale your subjective feelings about vague but relevant uncertainties in terms of judgmental probabilities and you should use these probabilities to analyze your problem and to decide which action you out to adopt.” (Raiffa, 1968) Decision theory provides many tools and techniques to help sort out the options, and since that is exactly the goal of this study, the decision analysis tools will be an integral part of the study’s methodology.

However, data shows that most project managers do not completely adhere to the decision-theory paradigm. They tend to view risk under the following general characteristics: (March & Shapira, 1987)

- Managers typically define risk as their exposure to loss.
- Managers are more interested in the magnitude of their exposure than reducing project risk to a single number.

- Managers are more likely to take risky actions when their jobs are threatened than when they feel safe.

Therefore the process must be transparent and constituent losses must be identifiable and separable for the project manager to be comfortable.

2.5.4 Discussion

Based on the above summaries, Table 2-3 shows the intersection of frameworks with the characteristics required for a PRM risk assessment method. None provide coverage in all categories. Many of these methods are quite useful and been proven in many projects and assessments. The framework presented herein will use several of the techniques and fundamental structures. Where disparate methods are used, integration methods are developed.

Table 2-3. Characterization of some analytical risk methods

	Scenario -based	Integrated	Unified	Quantitative	Uncertain	Actionable	Probative
Project Risk Management						●	
Cost/Schedule Estimating Methods	●			●	●		●
FMEA Methods			●			○	
Risk Factor Methods						●	
Scenario-based Methods	●			●		●	●
Bayesian Networks	○	●		●	●		
System Dynamic Models		●		●	●		
Probabilistic Risk Assessments	●	○		●	●		●
Decision Analysis		○	●	●		●	●

● - Yes; ○ - Addresses some but not all aspects of the characteristic

Chapter 3 Integrated Assessment Methodology

PRM offers a great many benefits for project management. The ability to anticipate potential problems before they occur is an enormous advantage in achieving project goals within constraints, but only if actions can be taken to mitigate the impacts. Of course, committing resources to eliminate all risk is not feasible and therefore PMs must decide how and where to reduce risk. This starts with a need for an analytical capability to assess risk, but then moves to a need for analyzing decision alternatives.

This methodology is essentially a project risk model. A tool that provides PMs with information regarding the amount of risk deviation from an accepted project plan and alternatives under their control. The methodology evaluates total project risk, risk items decisions, and mitigation strategies. Two separate but similar analysis techniques are melded together; PRA and DA. PRA techniques are used to address risk to a system when it is perturbed by "events" much as a risk item can perturb a baseline project. DA allows the examination of various decisions that must be addressed throughout a project. Both detail concerns with uncertainty in the data, modeling, impacts, and dependencies.

This chapter builds on brief overviews of PRA and DA presented in Chapter 2 to set the foundation for this methodology called *Integrated Scenario-based Project*

Assessment for Risk (ISPAR). Top-level description of the methodology is provided, details of which are covered in subsequent chapters.

3.1 Project As A System

Understanding that development of a project and the product together make up a system is the foundation of ISPAR. A project system in its basic form is the quintessential project management triangle. That construct is insufficient for our modeling purposes, so we expand it to focus on broad risk types and their interactions. Figure 3-1 shows three sides of the triangle recast to three nodes representing cost, schedule, and system performance risk that are linked by resulting “pressure to change”. Dotted lines indicate project requirements seeding risks. At project start, these risks are in equilibrium and residual risk represented is acceptable to all parties (assuming that all risks are known and disclosed). This model is a dynamic system containing pressures to move the system out of equilibrium. As risk increases in one area there is pressure to compensate by changing one or both of the other areas.

This framework extends beyond the development cycle into the operational phase (see Figure 3-2). Pressures due to technical performance risk can translate to operational performance and the operational cost risk. These frequently show up as design risk reduction measures that transfers development problems to operators. One of the enablers for this behavior is often a result of not having an integrated model showing how and where the risk goes. The operational system risk model is different from the performance risk model because of the operational environment, such as maintenance, operating procedures, and the “as built” configuration.

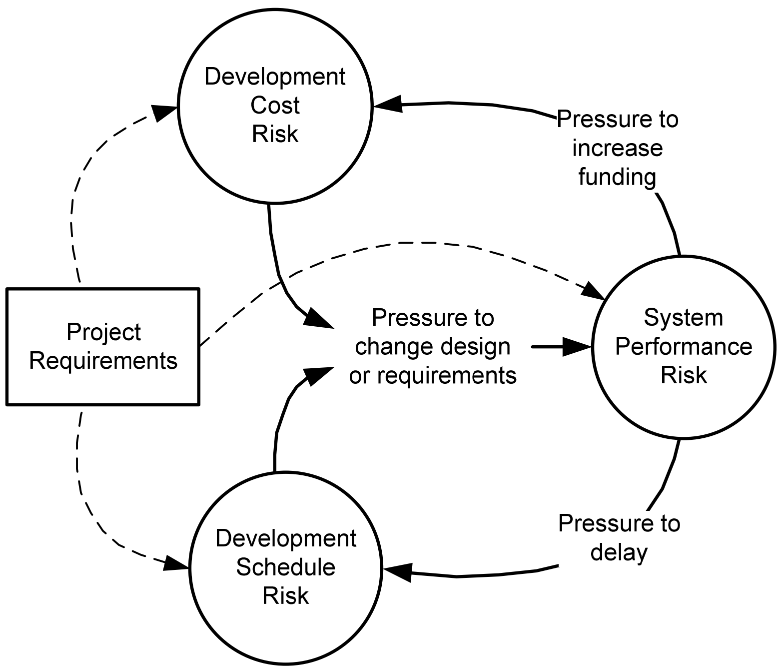


Figure 3-1. Project management system represents risk interactions

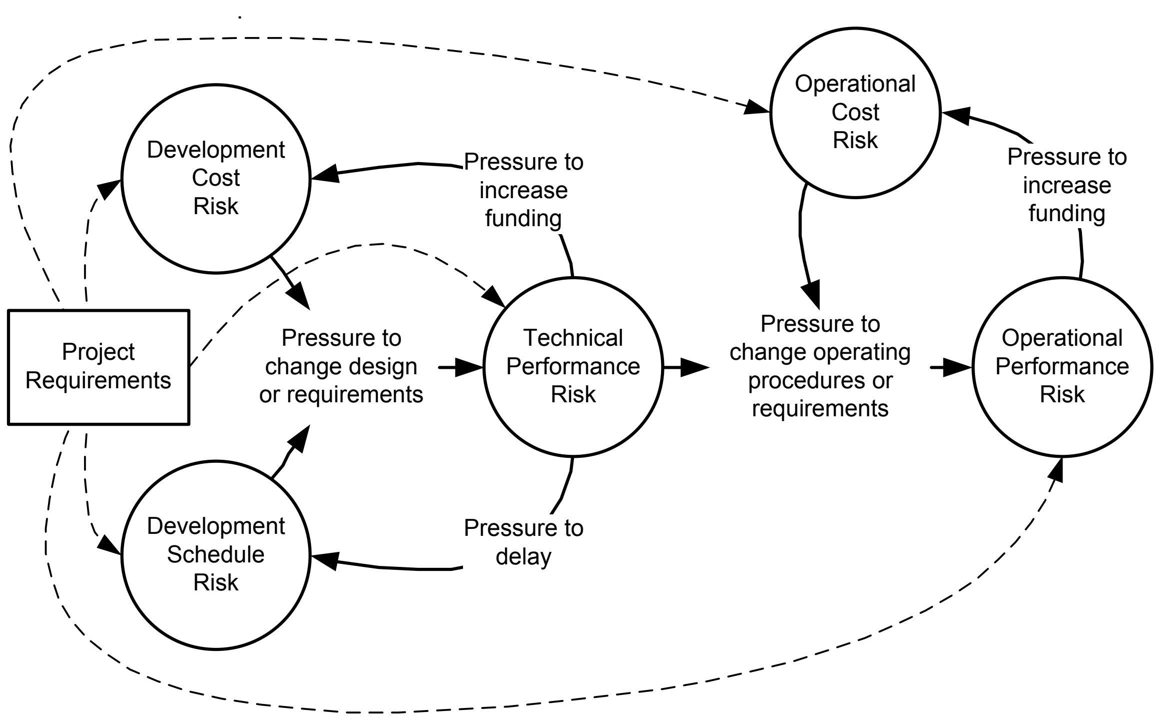


Figure 3-2. Project risks include operational considerations

Risk items are random events or conditions that threaten to decrease the probability of meeting project requirements. Requirements can sometimes include a level of system risk deemed acceptable. Impacts can propagate to other risk areas. Responses or mitigations to risk items may also affect other risk areas. Therefore, risk items may have cumulative effects on the system's equilibrium. For example, Figure 3-3 illustrates a risk item whose performance measure will not meet a requirement and will put pressure on the project to mitigate the concern. The impact means that more cost is needed to devise a technical solution. It would also result in changes to the operational concept of operations. Cost in turn may push for other alternatives with less cost impact, but with significant delays. At some point the project manager will make a decision that sets the system stable, and in the process comes to an optimum choice among competing pressures.

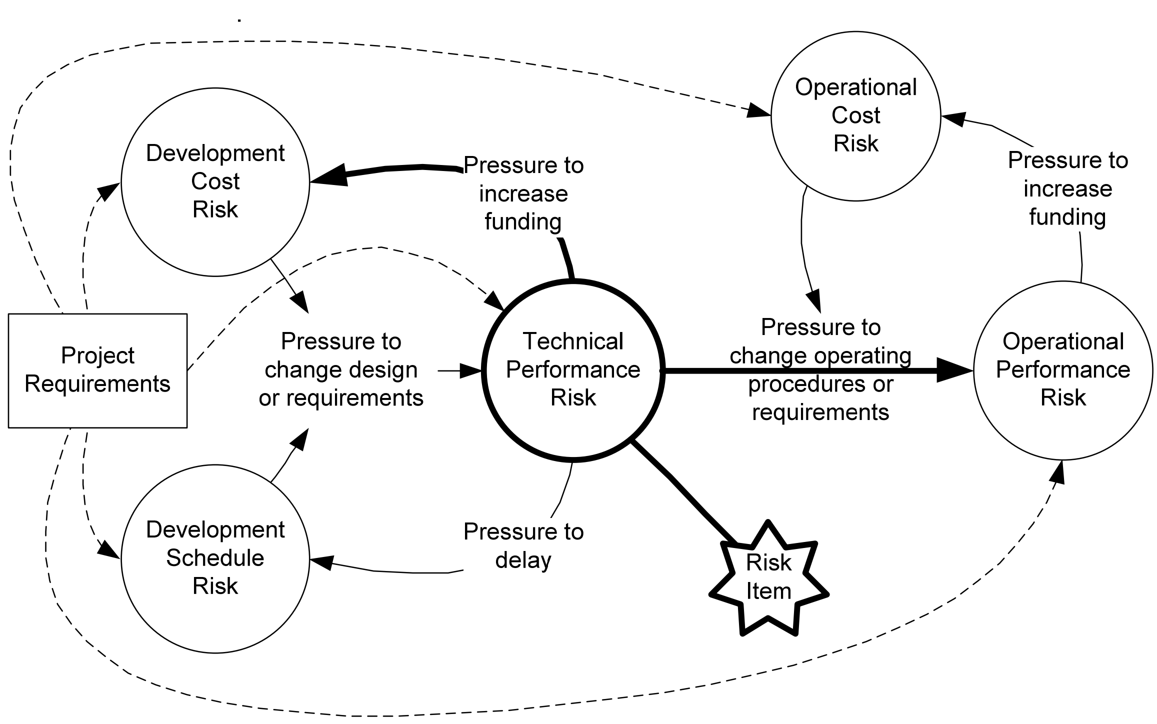


Figure 3-3. Risk items propagate through in various paths

From the perspective of a modeling framework (see Figure 3-4), a risk item elicits a response from the project system. The pressure to response is described by various system models currently in existence in most projects. This framework collects and combines the responses to develop an impact on the system as a whole.

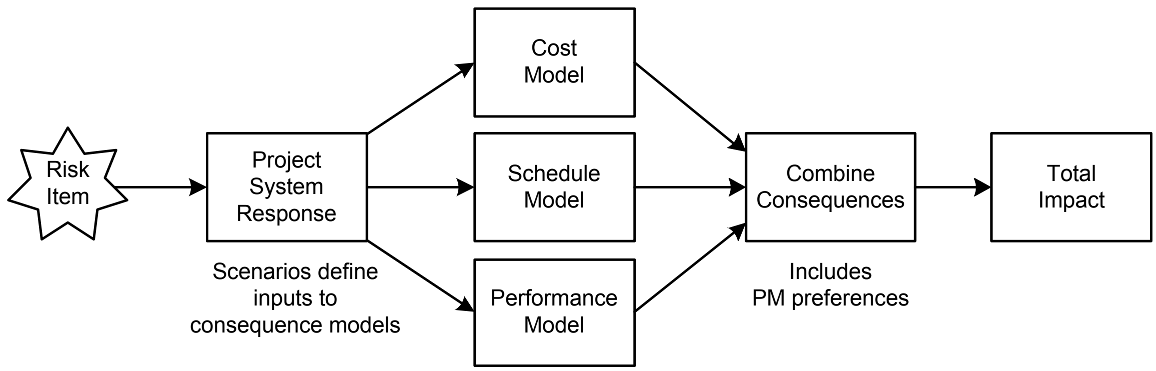


Figure 3-4. Risk item propagates through system models

Currently, PRM examines a risk item and assumes a causal link to a consequence (see Figure 3-5) often using an "if-then" statement to analyze likelihood and consequence shown as a location on a risk matrix. Within ISPAR, risk items may take many paths to several consequence values, thereby considering several scenarios that involve multiple failures, events, or conditions resulting in a risk profile. This provides an in-depth understanding of potential project system failure modes. Such an enormous number of possible scenarios are not investigated by current PRM methods. By extension, these risk profiles can be aggregated across all risk items to produce an understanding of the project's risk profile.

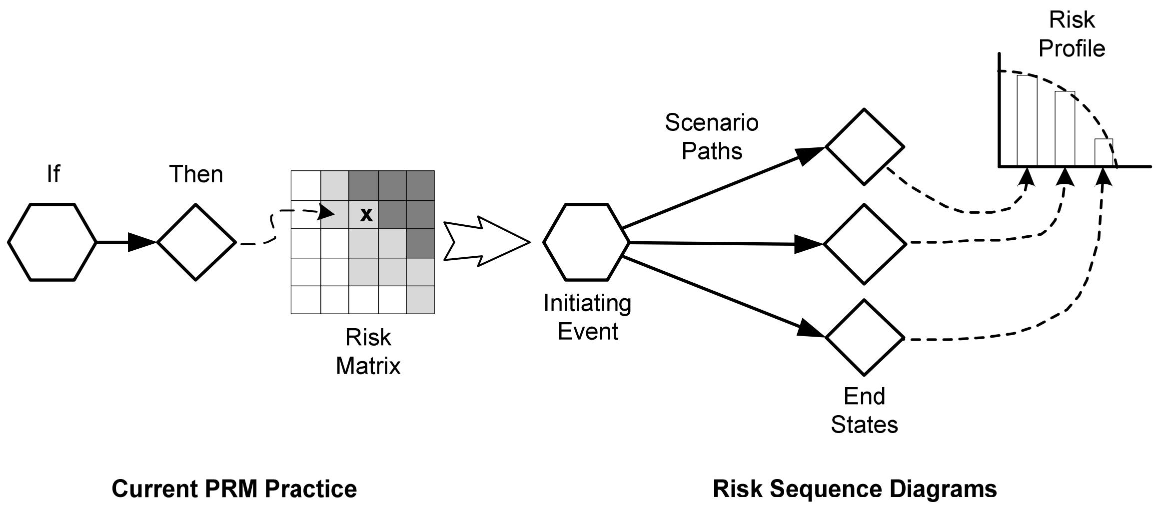


Figure 3-5. PRM translation to scenario-based models

Risk profiles are compared to a project baseline risk profile to determine a risk metric. Risk profiles are also combined into a composite profile and also compared to the baseline for a measure of total project risk. Various importance measure are computed providing insights into the risk criticality of events and model assumptions.

These concepts are generic and do not preclude any risk from any kind of project. The framework scope is only bounded by the project's reach and level of detail required to inform decisions. While it is easier to view this in context of a large project such as a government development or construction project, it is just as capable for use in small projects that currently employ risk management.

3.2 Role of Decision Analysis

A key aspect of ISPAR is the incorporation of PM decisions. It is through decisions that PMs influence outcomes of a project. Decisions are the controls and inputs to the process by which PMs steer projects. Often risk mitigation strategies are enacted without any risk analysis of these decisions. Resources needed to plan mitigations and then implement them are ignored or assumed to be part of the nominal design cost and, more dangerously, independent of other current or future risk activities. Decisions are often difficult. Clemen and Reilly discuss the benefits of decision analysis in addressing four areas: complexity, uncertainty, multiple objectives, and multiple perspectives (Clemen & Reilly, 1999).

Decision analysis is a method to bring structure to decisions. Keeney describes decision analysis as "a formalization of common sense for decision problems which are too complex for informal use of common sense." Since its inception as a discipline in the early 1960s, decision analysis has become a useful tool in commerce, industry, government, military, and medical applications.

Axiomatic foundations were provided by of von Neumann and Morganstern in 1947, Savage in 1954, and Pratt et al in 1964. This work implied that alternatives are chosen based on the likelihood of possible consequences, and the preferences of decision-makers' for those consequences. From this, probability and expected utility are used to include judgments and values in a defensible choice among alternatives. These first steps have been expanded upon greatly by many authors, see (Clemen & Reilly, 1999; PC Fishburn, 1970; Goodwin & Wright, 2004; Keeney & Raiffa, 1993; Raiffa, 1968).

Decision analysis involves decomposing a problem into a set of smaller constituent parts which are then analyzed individually. Decision analysis methods are used to put them back together in a consistent logical framework allowing decision makers to chose a course of action. This has been referred to by Keeney as the "divide and conquer orientation" of decision analysis (Keeney, 1982). This decomposition process is the decision modeling. It takes the form of decision trees to model the structure of the problem, probability to represent the uncertainty, and hierarchical trees to show the relationships among objectives and preferences. As with PRA models these are both graphical and mathematical constructs.

Often, decision analysis is only applied to a part of the process. It is not intended to make the decision but instead inform based on data and stated preferences. Of course, this may conflict with the decision maker's intuitive feelings and should then be investigated. Intuitive judgments may represent only partially formed or inconsistent preferences, or the analysis has overlooked some aspect of the problem. The analysis can help the decision maker to develop a better understanding so that his preference may change towards that recommended by the analysis.

3.3 Components of Integrated Scenario-Based Assessment for Risk

ISPAR is a systematic methodology aimed at investigating how complex projects and systems function, interact, and how they could fail. ISPAR models the interaction between the system being designed and built with the project processes creating the design and building the system. It also examines the interplay among the various aspects that projects are measured against, they are (but not limited to) cost, schedule, and performance.

Through scenario development and system decomposition of potential issues management to gains a deeper understanding of the complexities built into the project system. The model also allows for the prediction of risk (probabilities and consequences) and associated metrics. Just as the value of PRA is discussed by Modarres, the same can be ascribed here:

> The main result of the PRA is not the actual values of the risk computed (the so called bottom-line number); rather it is the determination of the system elements that substantially contribute to the risk of that system, uncertainties associated with such estimates, and effectiveness of various risk reduction strategies available. That is, the primary value of a PRA is to highlight the system design and operation deficiencies and optimize resources that can be invested on improving the design and operation of the system. (Modarres, 2006)

ISPAR has been purposely designed to mimic an engineering style PRA in content for its benefits on many fronts. Components of ISPAR are shown in graphical form (see Figure 3-6). This figure is an adaptation from NASA's PRA Practitioner's Guidelines with several key additions. First, a box for Consequence Analysis is added to emphasize the incorporation of other probabilistic models for endstate attributes. Second, a thread of qualitative only analyses exist within this framework that provides results to the project without quantification (dotted lines). Third, explicit inclusion of performance monitoring after risk mitigations have been implemented feed the data analysis block. Inputs to and output from this illustration support the overall RM process as described in Chapter 9. One omission, when compared to PRA elements, is the planning and familiarization block, because it is assumed that ISPAR exists within a PRM framework that already establishes the planning protocols.

There is one more rather large difference with modeling a system and a project; a project when dealing with risks must make decisions. These decisions are about the implementation of various risk mitigation measures or not. This of course is where the

DA comes into effect and why it is important to have a hybrid modeling approach of scenarios given risk items and the decisions that must / can be made. Decision Analysis structures and procedures are imbedded throughout the methodology.

The following sections briefly describe the components shown in the figure. Again, for RM to be considered a credible assessment tool, it must conform, at a minimum, to the standard elements that define today's PRAs and DAs.

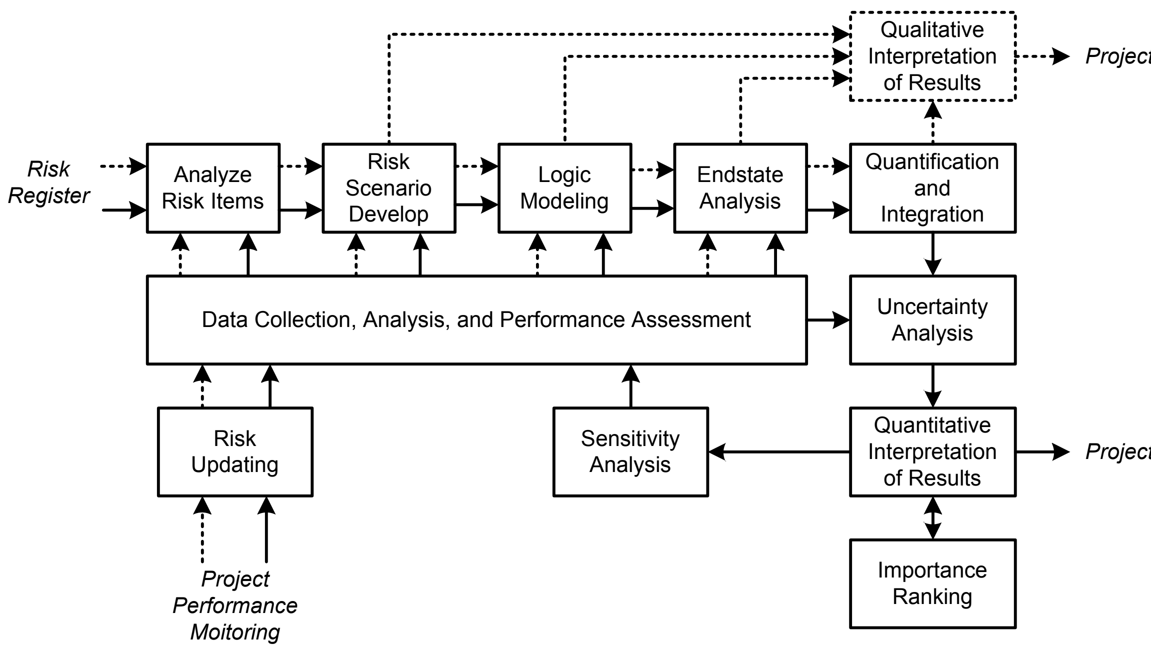


Figure 3-6. Components of ISPAR process

3.3.1 Risk Item Characterization

This element assumes that risk items have been identified. Herein, risk items are analyzed to determine root causes and assign probabilities of occurrence. Risk items having the same effect and response on the project system are grouped together. Relationships among risk items and root causes are captured in a fault tree logic structure.

3.3.2 Scenario and Sequence Development

Scenarios are hypothetical sequence of events, constructed for the purpose of focusing attention on causal processes and decision points. They are coherent descriptions of alternatives images of the future, created from mental maps and models reflecting different perspectives on past, present, and future developments. To be credible as an analytical tool, scenarios must be internally consisted, plausible and recognizable stories (Van Asselt, 2000).

An analyst develops scenarios by analyzing how risk items can propagate through a project and system leading to adverse consequences. Along the way, various pivotal events can occur which either exacerbate that problem or mitigate it. Cause and effect relationships among triggering and mitigating events or circumstances are investigated along with the impacts of risk mitigating actions that may be taken. Risk sequences are determined when decision points are included in the scenarios which can alter the trajectory of the risk item. The path through the scenario is probabilistic, fulfilling the PRA approach to risk as a set of triplets (scenarios, probabilities, consequences).Within PRAs event trees or event sequences diagrams are used. With the addition of decision points a hybrid technique called *Risk Sequence Diagrams* (RSD) are employed. RSDs provide a systematic method to view the potential impacts of the risk items and the overall response of the project. These are covered in greater detail in Chapter 4.

3.3.3 Logic Modeling

Events in an RSD can and should be decomposed further using methods such as fault tree analysis to obtain a credible probability value. In many cases, pivotal events may require equipment to function (hardware and software), people to perform a task, or testing to succeed, all of which can be modeled. Sometimes, failure data of these events is not available which necessitates methods such as fault trees to be developed. Care must be taken to explicitly model dependencies including common cause failures.

3.3.4 Endstate Analysis

Projects currently have models for cost, schedule, and system performance. These might be as simple as costs by task, calendar of task, and performance formula. They may also be sophisticated probabilistic cost rollups, integrated PERT charts, and PRAs of system reliability, availability, and safety. In whatever form, ISPAR integrates existing analyses at each endstate combining the results with a utility function.

3.3.5 Data Collection and Analysis

Collecting and analyzing data is critical to supporting the RSD development. This element determines both the qualitative and quantitative values depending on its use. The best resources for predicting future events are past project experiences and tests. While a large encompassing event may have no past relevant experience for a project, smaller decomposed event will have more accessible data. Hardware, software and human reliability data are inputs to assess performance of triggers and mitigating events. It must be recognized, however, that historical data have predictive value only to the extent that the conditions under which the data were generated remain applicable. Generally within PRAs generic data is collected and statistically analyzed for relevance to the project at hand. Probability distributions are then generated to account for the uncertainty and variability.

Probability distributions may also be generated from expert judgment when interviews and results are conducted properly (Clemen & Winkler, 1999; A. Mosleh, Bier, & Apostolakis, 1988).

3.3.6 Quantification and Integration

Scenarios and event logic are integrated into a larger model and then quantified to determine probabilities of risk items, total risk metrics and associated uncertainties. Boolean expressions are derived from the logic models and then "reduced" to the smallest combination of basic events called minimal cutsets in processes identical to those used in traditional PRAs.

3.3.7 Uncertainty Analysis

Within this context, uncertainties must be communicated to PMs to show impacts of analyst's assumptions, variability in parameters, impact of data incompleteness, and effect of expert opinion. These are captured as probability distributions, which are then propagated through the risk model. Risk metrics can be provided with associated uncertainty.

3.3.8 Importance Ranking

Risk items and events are ranked according to their risk significance. These importance rankings measure elements with respect to a composite risk measure in conjunction with all other elements.

3.3.9 Interpretation of Results

An analyst must verify that risk models are providing results that make sense in a project's context. Interpretation of metrics in combinations with the importance rankings, sensitivity analysis, and uncertainty analysis provides a necessary check. Without this step, it is easy to take results that contain flaws.

3.3.10 Updating and Monitoring

Obtaining feedback allows the model to improve. With probability distribution data in the model, Bayesian updating techniques can be used, making not only predictions for the current project better, but also building a repository of information for future projects.

3.4 ISPAR Model

The process presented in the previous sections results in an integrated scenario-based model of a project, see Figure 3-7. Risk items are transformed into RSDs showing multiple potential paths to several endstates, decision points required by management, and mitigation actions. Pivotal events in the scenarios are supported with probability distributions based on data and judgment. Cutsets of the scenarios are input to consequence models for cost, schedule, and other technical performance measures which in turn are converted into utility values. Endstate probabilities are combined in a composite structure of all RSDs. Both utility values and probabilities combine to produce risk profiles for each RSD individually and the composite project RSD. When compared against the project baseline risk metrics, importance measures, and risk drivers are determined and communicated to project team-members. This comparison is captured in a figure of merit called the Composite Project Risk Metric (CPRM).

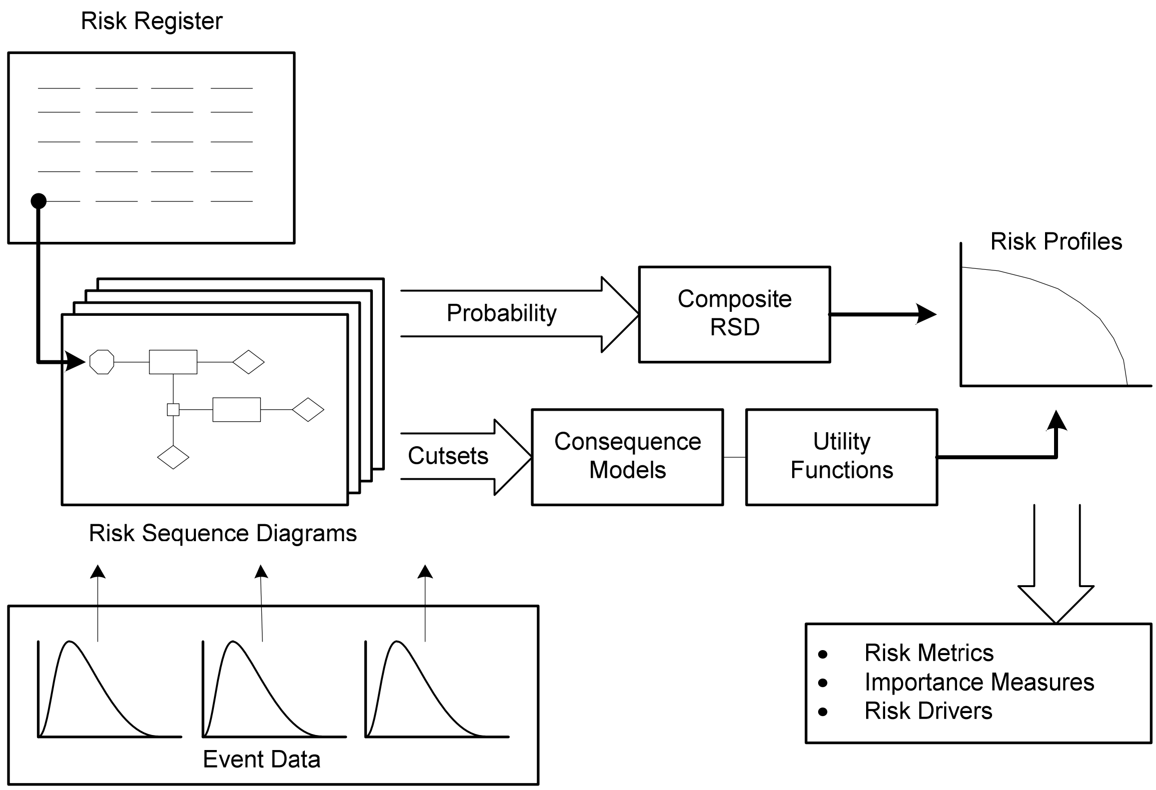


Figure 3-7. ISPAR model depiction

This depiction is intentionally similar to that of a PRA. This structure has proven to be very effective as a modeling tool. Necessary interfaces with other team-members and organizations are well understood and established in organizations using PRAs.

3.5 Assumptions

This new methodology includes few assumptions apart from those inherited as a result of incorporating PRA and DT techniques; they are:

- Consequence models are accurate representations of the project at a level of detail consistent with the risk model

- Consequence models are independent of one another. Dependencies can be handled with the multi-attribute utility function

- Project managers will make decisions that maximize expected utility

- A project baseline is agreed to by the PM and the customer based on shared understanding of all known risk/variability at the time of project initiation

Chapter 4 Risk Scenario Development

Central to ISPAR's modeling methodology is the scenario. Scenarios convey possible courses of action due to probabilistic events that could unfold. Practitioner's of PRA and DA have their own separate diagramming tools. PRA analysts use Event Trees (ET) and Event Sequence Diagrams (ESD) and decision analysts use Decision Trees (DT). A hybrid of both called *Risk Sequence Diagrams* (RSD) is introduced. This chapter discusses RSD diagrams and how to create them within a project setting. Several examples are given.

4.1 Scenario Modeling

Scenarios are stories about hypothetical series of events constructed for the purpose of focusing attention on causal processes and decision points. Scenarios are coherent descriptions of alternative images of the future, created from mental maps of reflecting various perspectives on past, present, and future developments. They are used within risk assessments to broaden views and raise questions about conventional success oriented thinking.

Modeling risk scenarios begins with a description of the success scenario. This scenario can be represented as a trajectory of the system. At each point in this trajectory we can ask "What can go wrong here?" The answer to that question is termed an “initiating event” or in a risk item. Given that a risk item occurs, then, depending on what happens next, a set of paths, emerges from that risk item and terminates at an endstate. In many engineering systems (a project being no exception) there are “safety” or “backup systems” meant to be activated in response to the various events. If backups work as intended, consequences are typically insignificant. However, if the event occurs and corresponding backup systems fail, there could be serious consequences.

Scenarios are useful tools in articulating key considerations, assumptions, and constraints. They provide a platform to blend qualitative and quantitative knowledge of systems and their interactions. Caution still is needed by analysts to avoid common traps of narrowly examining a situation, applying assumptions inconsistently, or not full documenting assumptions thereby reducing transparency.

4.1.1 Event Trees / Event Sequence Diagrams

Technical risk analysts formulate scenarios using ETs and ESDs which are supported with embedded fault trees. Often the terms ET and ESDs are used interchangeably. Here ESD (and therefore RSDs) are flowchart formulations of various scenarios under study, while the reference to ETs is to the branching tree structure used to facilitate computation of probabilities and risk. Both ETs and ESDs are logically equivalent.

ETs are inductive logical constructs showing the progression of an initiating event through a series of uncertain events, system elements, and procedural steps to end-states (consequences). ETs are primary scenario evaluation tools used in PRAs. Analysts have used this technique since the early 1980’s, (Swaminathan & Smidts, 1999) to show qualitative scenario representations and to direct quantitative risk computations. Experience has shown that ETs provide an excellent visualization of scenarios and facilitates communication among analysts, engineers, and managers.

An ET is a diagram showing branch points associated with events resulting in a tree structure. Each path through the tree is a scenario or event sequence. By convention upper branches signify success of the event while lower branches are failures. ET are typically shows with binary branches but do not need to be so. The branching nature allows for easy probability computations using the "split fractions" progressing along a scenario. ESDs are stylized extensions of ETs where the event labels are integral in the path much like a flowchart. They are more readable and convey annotated information facilitating communication of the scenarios.

4.1.2 Decision Trees

Understanding potential scenarios of what can go wrong is only part of the analysis. Exploring the impact of potential mitigation measures (or lack of any) must also be accomplished. This provides management with actions to be taken, i.e., decisions. DTs model sequential decision problems under uncertainty focused on determining the “best” decisions. They graphically describe the decisions to be made, the events that may occur, and the outcomes associated with combinations of decisions and events.

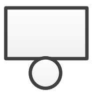
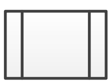
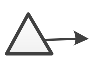
A decision tree is, like an ET, is an abstraction of a problem. "At each tip of the tree there is a consequence that characterizes the full cognitive impact of that position point in time and space. The decision maker is called on not only to rank the consequence at the tips of the tree, but also to evaluation the strengths of his preferences and his attitudes toward risk in terms of a utility function defined on these consequences. This is not an easy task"(Keeney & Raiffa, 1993). Decision theory is often applied to assist decision-makers when faced with decisions under uncertainty. Typical DTs show a series of stochastic events (chance nodes) and decisions (decision nodes). Expected values (or expected utility) is computed and branches with the higher values are chosen as the "best" alternative. This framework carries a number of such future decisions forward in a total project risk picture. For a discussion of their use and implementation see (Clemen & Reilly, 1999; Goodwin & Wright, 2004; Keeney & Raiffa, 1993).

4.1.3 Risk Sequence Diagrams

The goal of RSD development is to create as complete a set of scenarios as possible representing the paths leading to consequences. RSDs are systematic inductive reasoning tool describing potential cause and effect relationships between risk items and subsequent events and decisions. They are ordered chronologically depicting success or failure of events and decision paths available. A path where no decision is made is always shown.

Before describing how to create RSDs, a description of the building blocks, symbols, conventions are presented. RSDs typically flow from left to right indicating chronological progression. Pivotal events typically shows a TRUE response as branching to the right and a FALSE response branching down. Decision points typically show NO DECISION in the down direction. Although if responses are not binary directions may vary. This means that for a simple Risk Item entry, flow is right to left out of Risk Items and down due to a negative pivotal event or no action taken. Table 4-1 shows symbols used RSDs.

Table 4-1. RSD symbols

RSD Symbol	Name	Description
	Risk Item	Top level risk item corresponding to the label or title in a risk register. Logic of root causes will appear below this symbol.
	Basic Event	A basic event requirement no further development. Level at which quantitative data is gathered.
	Pivotal Event	Intermediate event mitigating or exacerbating the path toward a consequence. These may be quantified at this level or it may be further decomposed. (see Embedded Logic)
	Endstate	End of the path through the RSD representing a consequence.
	Decision Point	Decision that must be made to choose among alternative path. This is not a stochastic branch point.
	Mitigation Action	Actions taken to mitigate a potential consequence. These may be quantified at this level or it may be further decomposed. (see Embedded Logic)
	Embedded Logic	A small triangle inside a symbol indicates that the item is further decomposed and that the logic exists elsewhere.
	Transfer	Diagramming is continued elsewhere or logic is replicated.

A RSD is illustrated in Figure 4-1. The link between the risk item and endstate is now a collection of events, conditions, decisions, and mitigations. This RSD will be used throughout the next couple chapters to illustrate methods for quantification.

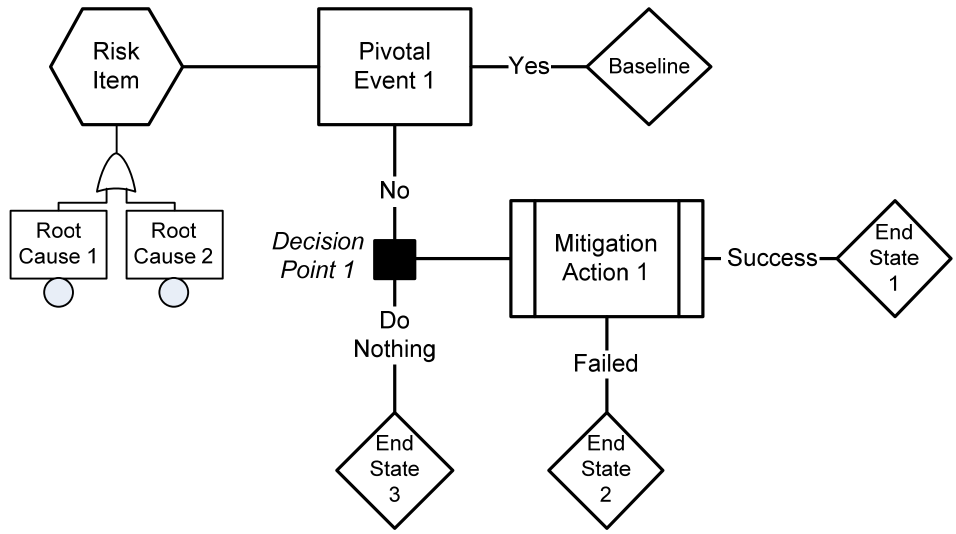


Figure 4-1. Example risk sequence diagram

Risk item descriptions are based on risk register entries. For this example there are two potential root causes (RC); either can cause the *risk item* (RI). *Pivotal Event 1* (PE) is a circumstance that, should it be present, will negate the risk item entirely, sending the path to *Baseline* endstate (ES). If *PE1* were not to occur, a decision is necessary, *Decision Point 1* (DP), either to enact *Mitigation Action 1* (MA) or not. If no decision is made, the path leads to *Endstate 3*. Note, this path is equivalent to the original risk statement. The decision to implement the mitigation could lead to *Endstate 1*, if successful, or *Endstate 2* should the mitigation fail.

Root causes can be derived from a number of places. They may potential failures of hardware, software, or procedures. They may be endstates from other RSDs. They may also be a decision that must be made. Any of the pivotal event or mitigation action boxes can be decomposed using fault trees to show details of the events.

Within PRA, initiating events are organized in a hierarchy called a Master Logic Diagram. Fortunately, Risk Registers can also be similarly organized using a risk breakdown structure (D. Hillson, 2003).

RSDs provide a more robust documentation and communication vehicle than the current "if-then" risk statements. Full scope of potential consequences are analyzed and simplified causal relationships are not implied between initiating event and endstate. They are a departure from ESDs in that decisions are implicitly modeled as part of the scenario. While DTs account for both stochastic events and decisions, they do not typically address causes of stochastic events. RSD formulation, like PRA ET-FTA, allows for the decomposition of events and thereby provides insights into causes that can effect risk items and the mitigations concurrently.

4.2 Dependencies

When moving from a system with a risk register to an integrated scenario based system, dependencies are emphasized. The dependencies can be described in three broad categories: Inter-scenario, Intra-scenario, and Extra-scenario.

- Inter-scenario dependencies are those contained within a scenario across logic segments. Dependencies within a logic structure such as a fault tree are not considered since, by their very construct are explicitly defined. Examples include: root causes of a risk item or pivotal event may also influence subsequent pivotal events and mitigation actions; pivotal events maybe dependent on decision outcomes even though not directly downstream of the decision point; or initiation of one mitigation action may influence the effectiveness of another.

- Intra-scenario dependencies are those that across scenarios, meaning that an element in one scenario is dependent on the outcome of another scenario or element in the other scenario. Examples include: pivotal events in one scenario may be shared or be a root cause in another scenario; mitigation actions or endstates may be a root cause for another risk item; or mitigation actions may be shared among scenarios.

- Extra-scenarios are the dependencies to elements not contained in a scenario. Examples include: PM preferences, time to act, or availability of resources.

Formal recognition of common cause failure (CCF) analysis does not exist in the PRM as it does for the PRA community (A. Mosleh, Rasmuson, & Marshall, 1998). CCFs are those that occur simultaneously or those due to shared causes other than those already in logic models. Typically, they defeat redundancy designs however they could also be circumstances that cut across all RSDs.

By way of illustration, the collapse of American Insurance Group (AIG) in December 2008 shows how a common cause risk could appear in project risk models (O'Harrow & Dennis, 2008). Over several years AIGs Financial Products group had become widely successful based on assessing data daily, recalibrating assumptions constantly, counterbalancing one risk against another and making the hedges. The deals made by Financial Products were always in balance from a risk perspective. However, all the deals written were based on a single foundation, AIG's AAA rating (one of only a handful in the world). It was taken for granted that the AAA rating would always be there as it always has. Due to many circumstances AIG was downgraded to AA. Under the terms of their many contracts, AIG had to keep more capital on hand and pay more in monthly payments, but it could not and the entire system fell apart. The analysts had extremely sophisticated risk models finely tuned and working in real time. The common cause was not accounted for in any of the risk models.

4.3 External Events

Kumamoto and Henley describe external events as, "characteristic of the environment in which the system operates. Such events are considered to be independent of any human influence within the boundaries of the system being analyzed, although risk-management policy is expected to ensure that adequate defenses are available against external events that constitute significant threats to the system" (Kumamoto & Henley, 1996). Although defined in the context of a technical risk assessment, external events can, and do, effect projects.

External events have the potential to affect many parts of the system much like CCFs. However, unlike CCF the affected items do not need to share locations, duty cycle, lot identifiers, or even failure mechanisms. The common assault of an external event may affect several components exciting different responses depending on the type of event, decision, or component. External events may be represented in risk model in several ways shown in Table 4-2.

Table 4-2. Listing of model responses

Affected Model	Change Required
Logic Models	- Add risk items and RSDs - Change RSD logic Dependencies - CCF Logical construct – ESD, FTA
Probability Models	- Failure Models - Add new Failure modes - Add conditional probabilities
Data or Parameters	- Change in stressing conditions - New correlations with existing elements - Shifting parameters Central tendency Uncertainty

4.4 Example RSDs

Two project risk examples are provided. Case I shows the richness of information contained in a RSD when compared to the same risk item originally written in a risk register database. Case II illustrates how worst case assumptions in a risk item can lead to incorrect conclusions. The example also demonstrates potential dependencies among risk items.

4.4.1 Case I: Engineering Risk

A project had started component fabrication prior to entering spacecraft level Integration and Testing (I&T)[2]. A nutation damper experienced a leak in an engineering model during a cold soak cycle test. This leak put the reservoir design in question, which may require some redesign. Dampers are required to be installed on the spacecraft

[2] This example is RI-160 from Project #2 described in Chapter 11 and Appendix B

structure prior to beginning I&T. As a result of the failed test, a risk was entered into the risk register, see Figure 4-2, about consequences of failing the damper re-test. This is a typical technical risk item found in many project risk registers. Risk is classified as 2×2 (Green) based on project specific definitions. The consequence of interest is limited to schedule impact. Mitigation steps are a required element for this program and are listed.

Risk Item: Damper Leak

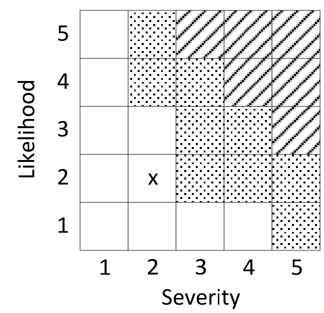
If the damper leak is not resolved in a timely manner, then the beginning of spacecraft I&T will be delayed.

Risk Level: Green

Likelihood: 2

Severity: 2

Class: Schedule



Mitigation Strategies:

Perform room temperature test. Repeat this test at cold
Redesign the piston to increase the amount of compression
Re-inspect piston and cylinder to verify a fabrication error is not causing the leak
Conduct peer review following testing and redesign
Fabricate new piston, assemble damper, repeat testing as described in mitigation step 1.

Figure 4-2. Damper risk register entry

The engineer's thought process for working this risk and potential multiple endstates are hidden. It appears from the mitigation that a set of serial steps need to be added to the process in order to validate the design. In fact, the process can be an iterative one with several potential new tests and redesign efforts. RSD in Figure 4-3 shows these scenarios. The RSD also indicates consequences for cost, technical, and schedule. The technical parameter in this case is the probability of Loss of Mission (LOM) as computed in the mission PRA.

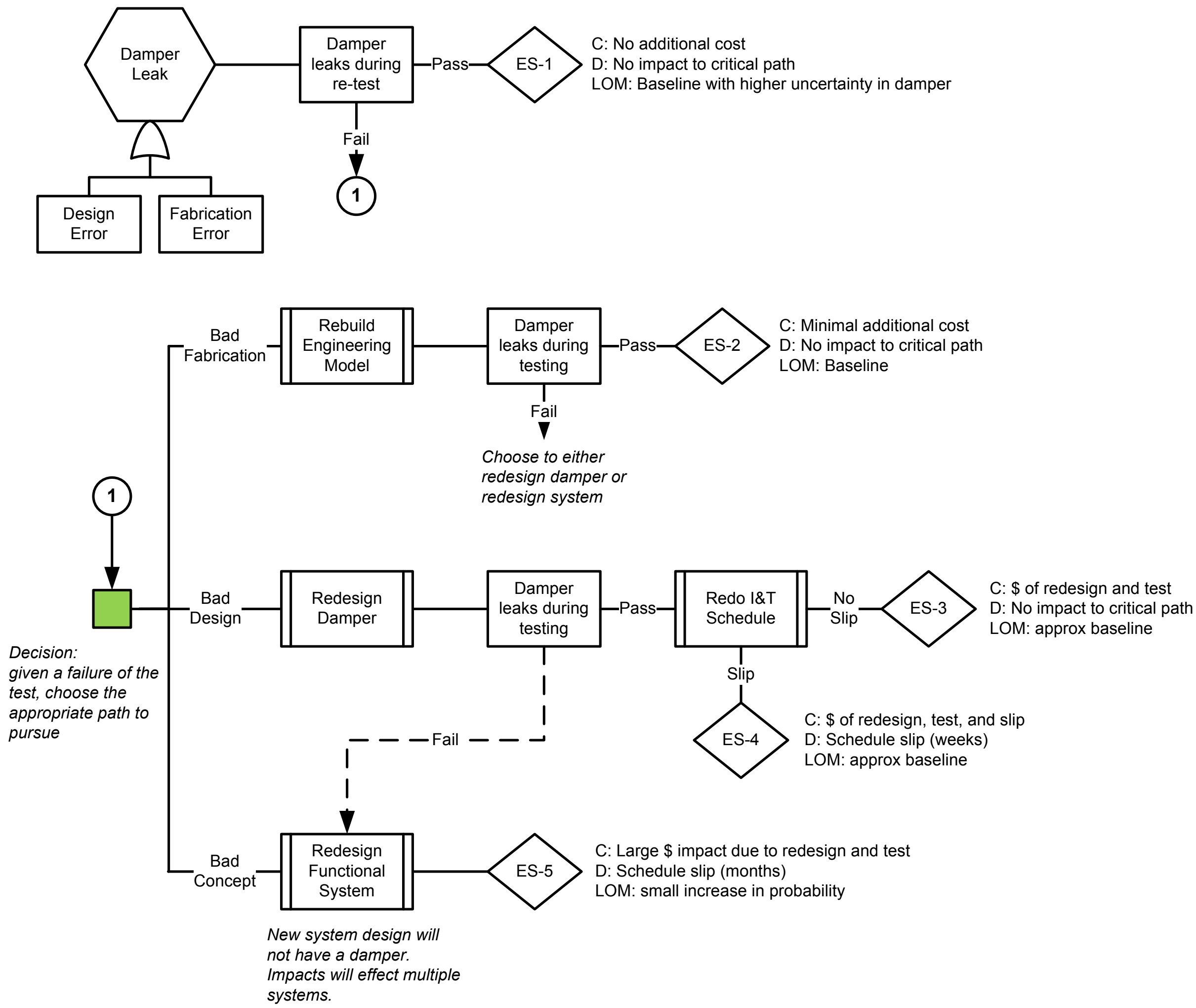


Figure 4-3. Damper risk item RSD

Several endstates appear. At this point only qualitative statements about the cost, delay, and LOM are presented. ES-1 represents the baseline case for damper passing the test. Should the test fail however, results of two failed tests are used to determine the best course of action. The engineer analyzed the very small chance that the damper leaks cannot be overcome necessitating a system redesign without a damper (ES-5). Neither of these possibilities were included in the risk narrative as the scenario was not drawn out fully to examine the failure of the next test of a redesigned damper. In the engineer's judgment, this is a very low probability scenario. The engineer felt that its inclusion in the narrative would have dominated the discussion based solely on its consequences and taken away from the activities needed for retesting and rebuilding the damper.

4.4.2 Case II: Potential Dependencies

In a recent project review the Quality Assurance lead for a spacecraft development project presented the “Top Project Risks”. Number 1 was a risk titled “Inexperienced Staff on Console” (see Figure 4-4) which was categorized as “Red” with the risk matrix position of 4×4. Of course this meant that the issue would receive significant management “assistance”. The briefer described how staff turnover would result in a high likelihood of inexperienced staff sitting on console. Further, inexperienced personnel may respond incorrectly to an anomaly thereby ending the mission.

Risk Item #1: Inexperienced Staff on Console

Staff transition and functions distribution could result in disruption and confusion, reducing the effectiveness and efficiency of the team. This issue is compounded by a complex mission with busy schedule.

Risk Level: Red

Likelihood: 4 (High): Considerable transitions in key positions.

Severity: 4 (High): Significant reduction. May not meet success criteria.

Mitigation Strategies:
Plan for knowledge retention as staff transitions and new staff are integrated into mission efforts.

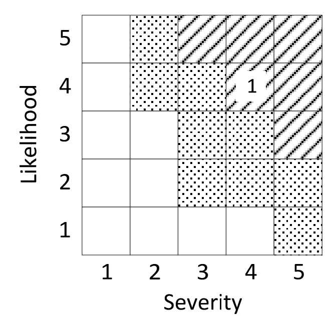


Figure 4-4. Inexperience staff risk item entry

The statements about the likelihood of inexperienced staff and what could happen with inexperienced staff on console were correct, but the conclusion that it was the major risk was not. Using an RSD, it becomes evident that only one of the possible endstate had been explored and that a systematic process to describe the scenarios emanating from an initiating event would have led the program to a different conclusion. The RSD (Figure 4-5 is simplified to show only 2 outcomes and does not include any Decision Points), paths to mission failure do indeed exist. However, many pivotal events are required before a mission failure is realized. When this RSD is analyzed a very different picture emerges. The probability of LOM is only 2% of the risk.

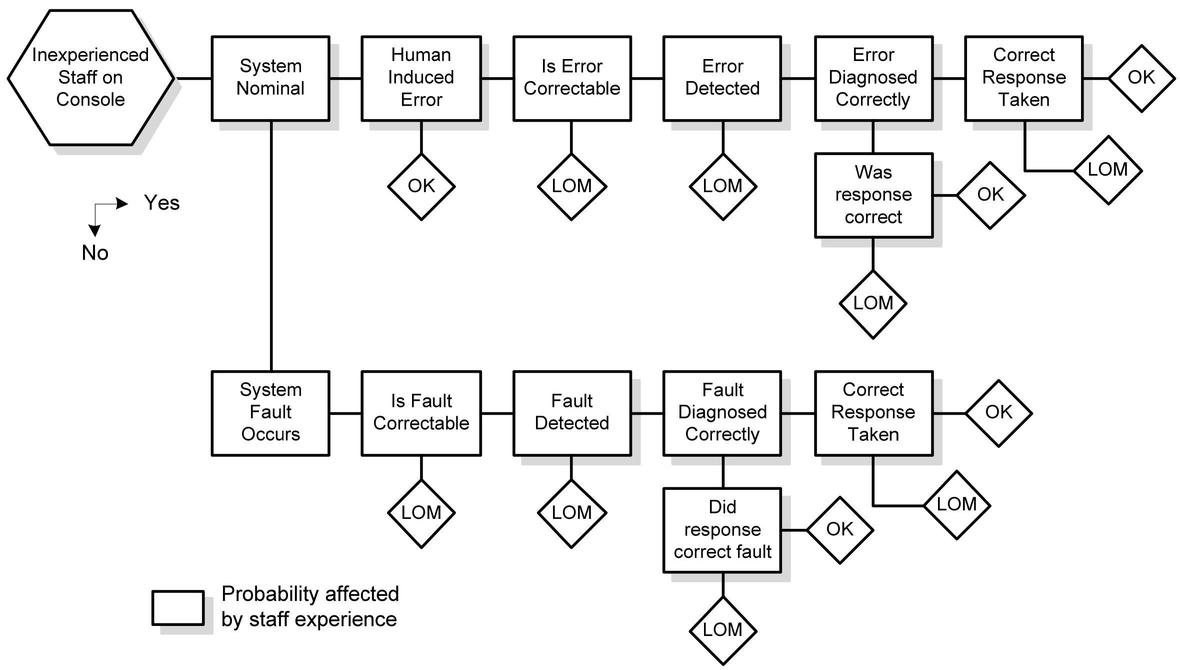


Figure 4-5. RSD shows the complexity of the staffing scenario

The risk matrix should only show 2% of the risk in 4x4 position and 98% of the risk in another box showing high likelihood and low severity as illustrated in Figure 4-6. Discussions about this risk item would have been quite different had the scenario been presented this way. Probabilities would shift more were mitigations addressed.

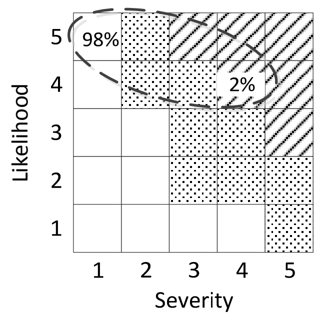


Figure 4-6. Risk allocated to more than one location

Let us now expand the example by considering an additional risk, but not presented during the meeting (see Figure 4-7). Here diagnostic circuits on a board had failed twice intermittently. The circuit is not required to meet mission. Risk Item #2 has been deemed “negligible” by a Risk Board. Indeed a RSD analysis confirms this conclusion. The mitigation was rejected since repairing the circuit card could possibly cause more harm than good. This risk item was closed and accepted as is. However, since diagnostics may not be performed as a consequence, the conditional probabilities of Risk Item #1 change. The net effect is an increase in the likelihood in the High severity category from 2% to 7%.

Risk Item #2: Circuit Board Intermittent Anomaly

Current sensing circuit could fail during flight. The circuit is not used for system control or performance, but only for diagnostic purposes.

Risk Level: Green

Likelihood: 3

Severity: 1

Mitigation Strategies:

Repair board. Pull board, remove potting, unsolder and replace parts.
Re-qualify board for flight and install. Run regression test on system.

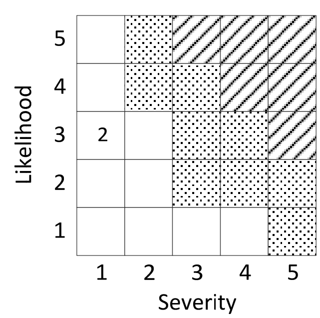


Figure 4-7. Anomaly risk item entry

The net effect of this risk item carries more likelihood in the "Red" risk level than Risk Item #1. In combination, the resulting risk is opposite of the original picture shown. Imagine tens or hundreds of "Green" risk items being accepted. The assumption of independence in this case is shown to be a dangerous one.

4.5 Benefits of RSDs

Risk registers have proved quite useful to many projects. However, they suffer from limitations in analyzing inter-dependant risks and information overload as more and more risk items get added. Narrative risk statements often too narrowly define the potential consequences to a worst-case and only a single attribute. RSDs are design to overcome these shortcomings by combining characteristics of ESDs and DTs providing a robust graphical language depicting risk as off-nominal scenarios.

The process of developing RSDs in and of itself forces analysts to question success oriented conventions and pull out details given potential failures in process, mitigations, equipment, or software. Endstates are addressed as multi-attribute elements of a model which requires all pertinent information to be presented not just a perceived worst-case.

As a communication vehicle, ESDs and by similarity RSDs, enhance discussions among team-members and management and analysts. Focus is drawn away from correct wording of a risk statement for striking a balance between not too much and misleading information and too little resolution of the problem statement.

Appendix B contains risk item RSDs developed during the execution of a Johns Hopkins University Applied Physics Laboratory spacecraft project concurrently with its existing PRM activities.

RSDs are a hybrid of PRA and DA tools incorporating the power as a quantitative platform for analyzing root causes, dependencies, decisions, and effects of management's preferences and risk aversion levels.

Chapter 5 Quantifying Risk Sequence Diagrams

Quantifying an RSD is equivalent to quantifying other scenario-based analyses. This section examines aspects of RSD quantification and emphasizes differences with respect to ESDs, DTs, and current PRM practices. Addressing risk items as one would PRA initiating events is consistent with current proven theory. Any variations are explained and shown to be valid. Later chapters discuss implementation of analyzing several RSDs together. RSDs have been devised to be equivalent to ESDs with one major exception; inclusion of decision points within the modeling logic. Details of PRA quantification techniques can be found in several texts (Bedford & Cooke, 2001; Frank, 2008; Henley & Kumamoto, 1996; Modarres, 2006; NASA, 2004; NRC, 1983).

RSDs are graphical representations of Boolean expressions of risk progression to endstates. Once expressions are generated, they are evaluated by logically reducing the expressions and quantifying them with probability axioms. Next, endstates are evaluated using cutsets to define configuration inputs to various attribute models. Utility functions translate these model results to a risk preference values and then combined to create one number along with its associated uncertainty. Throughout this chapter, we refer to the example RSD used in Chapter 4, Figure 5-1.

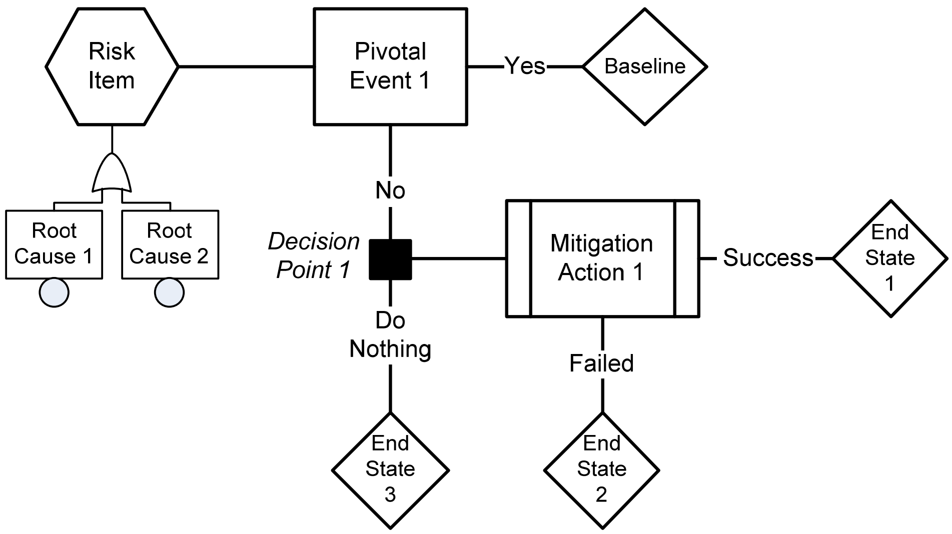


Figure 5-1. Example RSD

5.1 Risk Sequence Probability Quantification

Quantifying RSDs uses the same techniques as those for evaluating integrated event trees - fault tree PRA models; determine the Boolean expressions, logically reduce the expressions, and compute the associated probabilities. Suppose for example RSD probabilities are assigned as follows:

δ = 0.85

E1 = 0.30

M1 = 0.15

RSDs use a split-fraction approach to decompose the total probability of risk items along various branches. First, the non-occurrence of a risk item results the baseline endstate denoted as BL. Endstates are quantified by multiplying probabilities (and complements) along the scenario. Each path is mutually exclusive and independent. An equivalent ET is shown in Figure 5-2. Using ETs simplifies the quantification discussion.

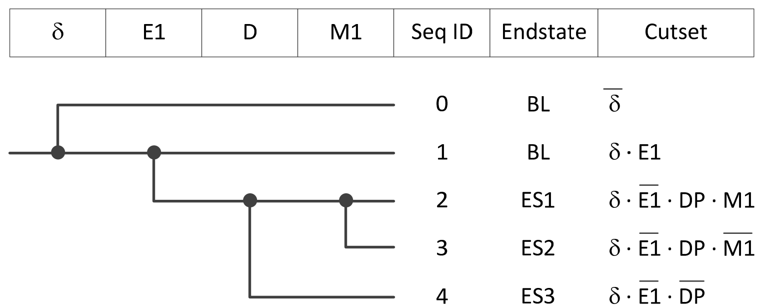


Figure 5-2. RSD translated to pivotal event level event tree

Next we "gather the endstates" by summing the probabilities for identical endstates. This gives the probability of ending the scenario in any identified endstates. Table 5-1shows results for each path using the numerical values given earlier. Notice that the decision point is carried through cutsets like all other events and when quantified lead to two sets of endstate probabilities.

Table 5-1. Pivotal event level results

	Probability	
Endstate	**"Do Nothing"**	**"Implement"**
BL	0.7490	0.7490
ES1	--	0.2132
ES2	--	0.0379
ES3	0.2510	--

So far the quantification has taken place only at the RSD level. Each event can be further decomposed with logic down to lower level events.

5.1.1 Pivotal Event Quantification

At a top-level evaluation, using probabilities for pivotal events provides a sense for which paths and endstates are more likely. However, this masks conditional dependencies which can be uncovered when decomposing the pivotal events into basic events. Pivotal events (often referred to as triggers in PRM texts) are assigned a probability which are obtained by a logic model such as a fault tree. Cutsets from fault trees can be combined with RSD logic to provide a detailed combinatorial evaluation leading to various endstates. Sometimes historical data or expert opinion is used to assign probabilities.

A special form of pivotal events are mitigation actions. These represent a collection of events and/or procedural steps that are planned as a remedy for a particular risk item. In the example, successful implementation of the mitigation action leads to an endstate different from the baseline because mitigation actions brings its own costs, schedule impacts, or technical compromise.

As with all human endeavors, these mitigations are not 100% perfect. Therefore, the question is asked, what happens should a mitigation fail. Failure of a mitigation event may carry additional consequences other than not implementing the action. One can imagine a case where significant additional resources are expended and still incur the unwanted consequence. In such a case the endstate of a failed mitigation action is worse than the original endstate.

By way of expanding the example, the RSD events (δ, *E1*, *M1*) are represented by fault trees and therefore Boolean expressions.

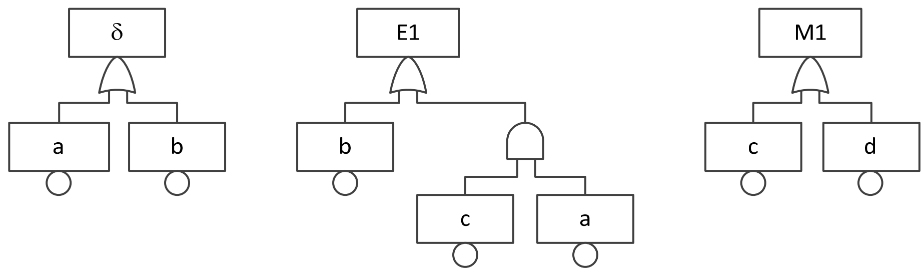


Figure 5-3. Pivotal event fault trees

In addition to the probability assigned to pivotal events, other data elements are also assigned. Pivotal events often have cost, time, mass, system reconfiguration, or part failure rate changes associated with them. As the scenario unfolds these other attributes accumulate or combine based on various consequence models. Cost for example may add directly to the project cost but delay may not if a given task is not on the critical path.

5.1.2 Basic Event Quantification

Basic events represent potential failures of equipment, processes, human error, test results, or adverse conditions. Basic events signify the modeling resulting from a risk narrative decomposition process. They are root causes for risk items or lowest logic levels of pivotal event models. Data supporting basic event quantification is from historical data and/or expert opinion forming probability distributions.

Relevant data sets used to assign probabilities are critical steps in the process. Several authors have written extensively on data collection and quantification for use in technical risk assessments (Bedford & Cooke, 2001; Clemen & Winkler, 1999; Henley & Kumamoto, 1996; A Mosleh & Apostolakis, 1986; Winkler, 1996). Decomposition of events within PRM can be similarly quantified. Data can be collected at this level far more easily than at the level of the risk narrative.

5.1.3 Decision Point Quantification

Decision events are treated differently. It is not the intention to predict how decisions will be made, and therefore they do not have probabilities assigned to them. Instead, they are left as variables without assignments. Decision points act as switches to restructure the system response of a model. In the parlance of fault trees they are "house gates". The effect is multiple mutually exclusive responses exist within a RSD. In terms of cutsets, this translates to some cutsets being ignored while others are not.

There may be non-binary decision points where the choice is among 3 or more options. Within the drawing of the RSD more than 2 lines emerge from the decision event. One way to maintain the functionality of a switching network is to translate this to a combination of binary decisions so that the cutsets show a series of binary events.

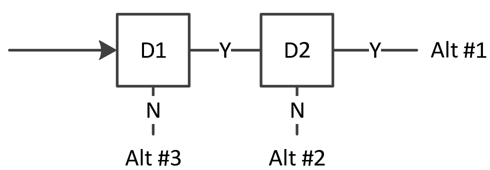


Figure 5-4. Multiple alternative decision modeling logic

5.1.4 Sequence Probability

Once pivotal events have been decomposed, sequence cutsets are more complex and provide more information about the combination of events and conditions that can lead to adverse consequences. Boolean reduction of cutsets incorporate impacts of basic events shared among pivotal events. Using our example, logic now yields the following cutsets.

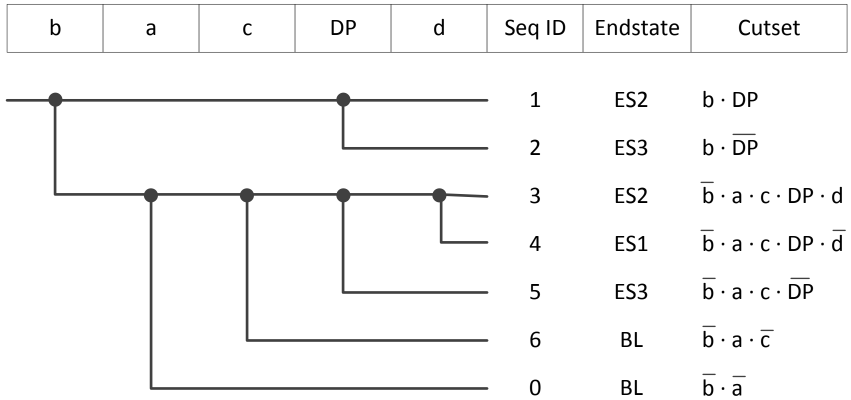


Figure 5-5. Basic event level event tree

Continuing the example, logic for events is used to re-compute sequence probabilities. We set the basic event probabilities equal to:

a = 0.82

b = 0.15

c = 0.21

d = 0.001

Endstate probabilities are recalculated. This time the results are quite different (see Table 5-2) even thought the pivotal event probabilities are the same, reflecting the Boolean reduction of the expressions. This is because of dependencies among the events. Event *b* is common to each fault tree as the cutsets show.

Table 5-2. Basic event level results

	Probability	
Endstate	**"Do Nothing"**	**"Implement"**
BL	0.7036	0.7036
ES1	--	0.1462
ES2	--	0.1501
ES3	0.2964	--

No systematic process exists within current PRM practices to discover dependencies such as these. Instead, they rely on the memory of the risk facilitator. A PRA analyst would be forced to ignore the decision point and run to versions of the analysis for the PM. When examined from a decision tree perspective, notice that the decision is conditioned on whether event *b* occurs as depicted in Figure 5-6 (dotted line indicated that DP is the same decision). Additionally, the nature of the decision impacts changed as well from a decision between two certain choices (ES2 or ES3) to one with uncertainty of event *d* and endstate ES1. Also if neither *a* or *c* occur the decision is moot.

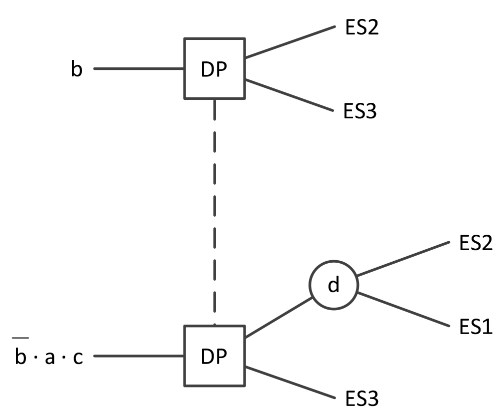


Figure 5-6. Example decision tree

At this point the probabilities are computed for the RSD but the consequences for the sequences are not. The next section examines that step of the process.

5.2 Endstate Quantification

Each endstate represents a potential consequence. More specifically, it is the state of project attributes given a specific path or sequence of events and decisions. Quantification is accomplished by evaluating cost models, schedule models, and system models given the path taken to reach an endstate. Cutsets of paths are used to configure various models as it provides the combination of events and conditions as input. These attributes are then combined using a multi-attribute utility function to provide a single value to represent the endstate.

5.2.1 Consequence Analysis

ISPAR relies on existing tools and models to determine the specific consequences. Tracing paths through the RSD provides a sets of inputs required for consequence models. Figure 5-7 shows the inputs as the set of probabilities, sequences, and decisions as inputs with the consequence value *c* as the output. Risk analysts must work closely with other disciplines to fully populate the risk model. This is an intentional feature in that it forces communication and understanding of potential endstate contexts and therefore risk.

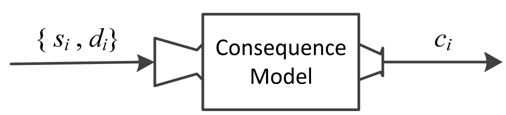


Figure 5-7. Consequence outputs from scenarios and decisions inputs

For example, examine Sequence #3 from the above example with respect to cost only. The sequence identifies that risk item δ occurred, *E1* did not, and *M1* was implemented but failed. Inputs to a cost model would be the costs associated with implementing *M1* and perhaps repair cost for the cause of δ. The project's cost model would return a cost associated with these events and any other dependencies internal to the cost model.

Diamond shapes represent results of this processing (see Figure 5-8). They identify attribute data so that if and when one of the models change attributes or the utility function changes, a new value can be recomputed. Current PRM techniques often force analysts and PMs to choose only the worst-case attribute to focus on. With this implementation all attribute information is kept and analyzed. Should the PM's utility function focus on a particular attribute, so be it, but it is a traceable and defendable aspect of the entire model.

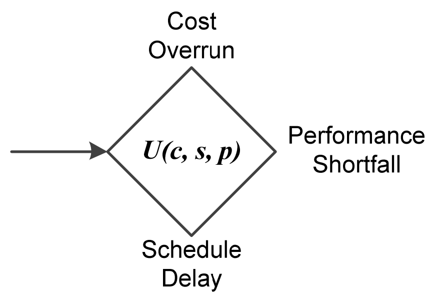


Figure 5-8. RSD endstate depiction

For now, a single attribute endstate is assumed for illustrative purposes. Let us suppose that the risk analyst provides the cost analyst a set of scenarios from our example yielding the following results:

BL = 0
ES1 = 100
ES2 = 125
ES3 = 2000

At this point endstates are "gathered", meaning that probabilities for identical endstates are combined. Since the paths within a RSD are mutually exclusive, the probabilities are summed.

5.2.2 Single Attribute Utility

Using only raw consequence values as the basis for *a risk metric* would be convenient and straight-forward. However, it would be equivalent to computing an average consequence. This can lead to intuitively unpalatable decision recommendations because it does not account for the PM's tolerance for risk or imbedded preferences. Decision analysts solve this problem by using *expected utility theory*. The application of this concept is succinctly characterized in (Keeney & Raiffa, 1993); "If an appropriate utility is assigned to each possible consequence and the expected utility of each alternative is calculated, then the best course of action is the alternative with the highest expected utility." The next step in the endstate evaluation process incorporates utility functions. RSDs, once quantified, simplify to decision trees as found in the decision analysis literature. As such they conform to their assumptions and constraints. Within the field of decision analysis, utility theory is a driving analytic technique for examining decisions with uncertainty (Clemen & Reilly, 1999; P. Fishburn, 1989; R. Howard, 1988; Keeney & Raiffa, 1993; C Kirkwood, 1992; Raiffa, 1968).

Utility functions translate consequences to a unit-less number usually typically scaled so that the least preferred level equates to 0 and the most preferred is 1. It is this value we use to quantify endstates (see Figure 5-9) so that risk profiles and metrics can be computed. How to develop a utility functions for a specific PM is outside the scope of this study.

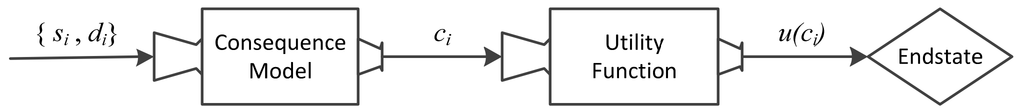


Figure 5-9. Utility value output from scenarios and decisions

One point to note is that utility exists independent of probability and belongs to an individual. Changing the decision-maker or her perspective, i.e. the utility function, can change results significantly. The practical implication here is that we can change the framework based on who is using it (customer, internal Project Manager, Enterprise manager, or vendor) but not the underlying data.

PMs are assumed to be risk averse when making project decisions. Although this is not strictly true, some studies show that PMs are risk neutral toward low consequence decisions and risk averse toward decisions with large consequences (March & Shapira, 1987). But we use this for simplicity only, there is no theoretical limitation to using any valid utility function. Risk aversion assumptions force us to use concave utility functions (Keeney & Raiffa, 1993). A convenient utility function used here is an exponential function provided by (C. Kirkwood, 1991):

$$u(c) = \frac{\exp\left[-\beta\left(c - c_{0)}\right] - 1}{\exp\left[-\beta(c_1 - c_0\right] - 1}$$

where: β is the risk aversion measure and c_0 and c_1 are the minimum and maximum consequence values respectively

Continuing with our example, a cost utility function is generated as shown in Figure 5-10. A minimum cost increase of $0 is the most preferred and a maximum loss of

\$2500 is deemed the least preferable. A β value of 0.0008 was chosen. For comparison the risk neutral function is shown.

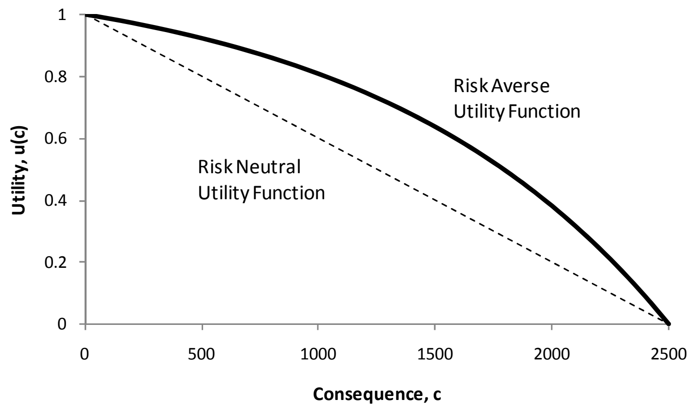


Figure 5-10. Example utility function *u(c)*

Applying this utility function to values from consequence models allows us to expand the results as shown in Table 5-3

Table 5-3. Attribute utility PMF

			Probability	
Endstate	**Consequence**	**Attribute Utility***	**"Do Nothing"**	**"Implement"**
BL	\$0	1.0000	0.7036	0.7036
ES1	\$100	0.9867	--	0.1462
ES2	\$125	0.9832	--	0.1501
ES3	\$2,000	0.3675	0.2964	--

* $u(c) = 1.16 - 0.16 \exp(0.0008\, c)$

5.2.3 Multi-Attribute Utility

We have so far dealt with endstates as a single value (quantity or utility number), however they actually encompass many attributes. Cost, delay, and performance shortfalls (mass, power, speed, reliability, safety, etc.) can all be characteristics of an endstate. Multi-attribute utility theory is commonly used by decision analysts to aggregate many attributes into a single value (Keeney & Raiffa, 1993). Techniques apply the PM's preferences about attributes not particular values of those attributes. So that if a PM is more concerned about cost than schedule, this utility function incorporates that preference.

Cutsets define input parameters for individual attribute models which provide a shortfall quantity. Previously defined utility functions, $u(c)$, are applied to each attribute individually. A multi-attribute utility function, $U[u_1(c), \ldots, u_n(c)]$ is then applied. Figure 5-11 shows an illustration of the entire endstate quantification process resulting in a single utility number to be used in defining the risk profiles.

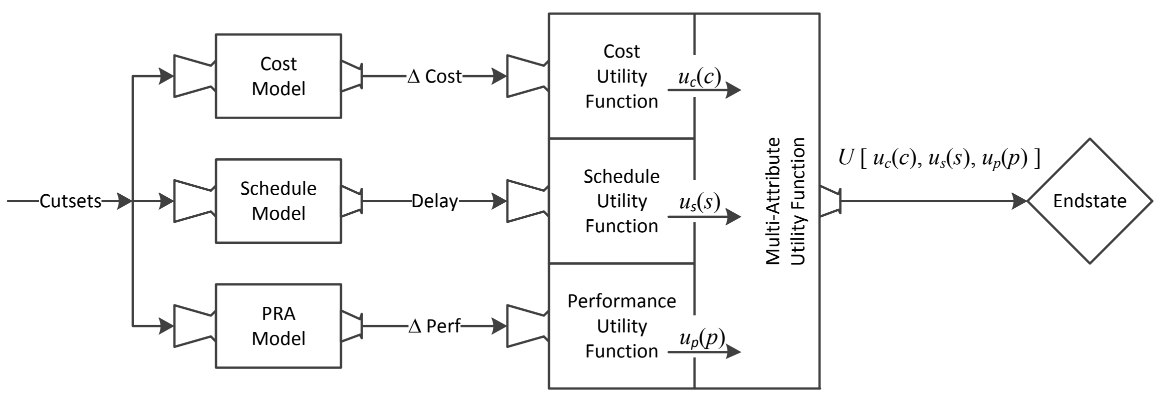


Figure 5-11. Utility output from multiple attributes

Multi-attribute utility functions can take many forms under various assumptions and constraints. For simplicity of showing implementation only, we use the additive form which assumes that consequence utility functions are independent. It is fully recognized that all attributes are not independent, not even in our simple example. One can easily find coupling interactions such as; delays increase cost; mass increases degrade speed; redundancy increases mass, cost and test schedules. How to choose the appropriate multi-attribute utility function, however, is out of scope of this work. See (Clemen & Reilly, 1999; Keeney & Raiffa, 1993) for more information about multi-attribute utility functions. For now the following function is used:

$$U(u_1, u_2, \dots, u_n) = \sum_{i=1}^{n} k_i u_i$$

where: n is the number of attributes

k_i, are weighting factors constrained by $\sum k_i = 1$

This creates a multidimensional surface representing the PM's utility risk aversion for each attribute individually and preferences regard relative importance of each attribute. For our example, a PM's preference weighting factors for cost, schedule, and reliability are:

cost = 0.3
delay = 0.5
reliability = 0.2

Combining the results above and other similar analysis for delay and reliability (not shown) we get results shown in Table 5-4.

Table 5-4. Endstate Utility PMF

		Probability	
Endstate	**Endstate Utility**	**"Do Nothing"**	**"Implement"**
BL	0.9998	0.7036	0.7036
ES1	0.8222	--	0.1462
ES2	0.7477	--	0.1501
ES3	0.6206	0.2964	--

This approach can be further augmented (although not explored here) by implementing principles from *Prospect Theory* (Kahneman & Tversky, 1979) to better account to PMs' decision making behavior. As long as output is a cohesive set of values with respect to endstates, risk profiles can be constructed.

PRM typically investigates risk consequences in one axis at a time, be it cost, schedule or performance. This not to say that projects are unaware of the other aspects, they are. It is typically seen as too hard and complicated. Normal response is to use the worst-case consequence type only as risk ranking criteria. This practice leads programs to 1) get a conservative view of the world since all risk items are treated as their worst-case, 2) relationships such as cost versus schedule, or schedule versus performance are not analyzed for correlations or dependencies, and 3) management's priorities are not considered. A better strategy is to analyze and carry all consequences forward to address in combination. In other words address this as a multi-attribute decision analysis.

Method described here combine consequences at each endstate using a predefined utility function specific to each PM. This means that a different PM may have a different set of utility functions. Imagine a case where a PM reaches a conclusion about a risk item as being not significant. Another manager could look at the very same data and reach a different conclusion. Does this indicate a flaw in the system? Not at all. Consider, a risk impact of $100,000. For the PM of a $100 million program this consequence is in the noise and not significant. However, if this risk is coming from a vendor whose total contract is $500,000, it is extremely significant. ISPAR allows the same data to be used through the lens of utility functions to arrive at different results reflecting appropriate context without having to censor, re-score, or sanitize results.

5.3 Uncertainty

The inclusion of uncertainty is central to PRAs and DAs. As stated earlier, probability distributions are attached to events. The framework structure allows for propagation of these distributions by using Monte-Carlo simulations. Several software codes are available to perform the analysis in its current state. For instance, the above example has been run using Microsoft Excel with Palisades' @Risk add-on.

Table 5-5. Endstate utility PMF with uncertainty

Endstate	Endstate Utility	Probability					
		"Do Nothing"			"Implement"		
		5th	Mean	95th	5th	Mean	95th
BL	0.9998	0.6775	0.7036	0.7291	0.6775	0.7036	0.7291
ES1	0.8222	--	--	--	0.1216	0.1462	0.1712
ES2	0.7477	--	--	--	0.1419	0.1501	0.1584
ES3	0.6206	0.2709	0.2964	0.3225	--	--	--

Chapter 6 Risk Profile and Risk Metric

Once quantified, RSDs provide probability and analysis of consequences for a given risk item. A figure of merit is needed to distill all this information for use as a basis of comparison. With such a metric, insights are possible into a variety of aspects of project risk. For example, whether a mitigation is likely to decrease risk and by how much; which decision (and associated expenditures) are more likely to reduce risk; or deriving a list of elements effecting risk the most.

Risk profiles are a natural outcome of RSDs. Much like Kaplan and Garrick championed the use of Farmer Curves (consequence versus frequency), ISPAR creates risk profiles in the form of exceedance probability curves as a way to describe the risk. An exceedance probability curve specifies the probabilities that certain level of loss will be exceeded. In our case, loss is utility. These curves are referred to as *risk profiles*.

Risk profiles are compared to a project baseline risk profile to determine a risk metric specific for a RSDs. The metric computed based on the shortfall, or area between the RSD curve and baseline curve as shown in Figure 6-1.

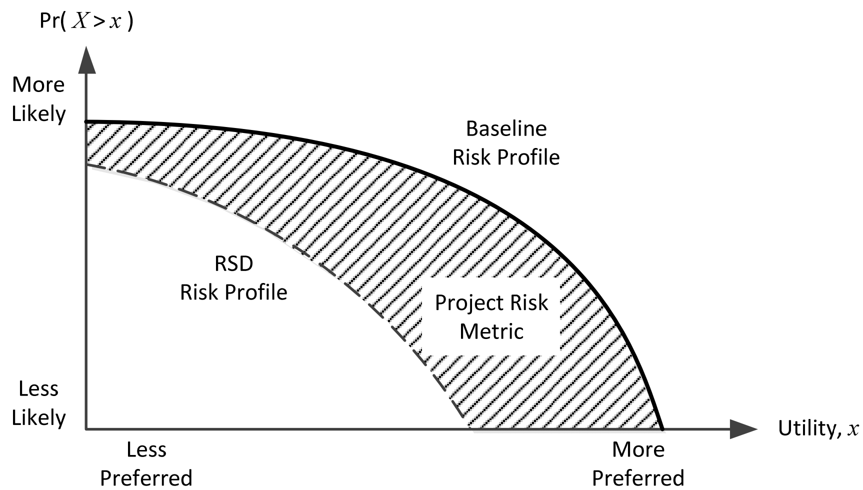


Figure 6-1. Utility risk profiles

This chapter discusses risk profile development and shows how risk metrics are computed.

6.1 Risk Profile Function

Risk profile are created starting with a set of ordered pairs of probability and utility values from a RSD. This probability mass function (PMF) is transformed into a cumulative distribution function (CDF) and then a complementary cumulative distribution function (CCDFs) which we call the *Risk Profile*. Risk profiles are plotted on two axes each ranging from 0 to 1[3]. More "risky" profiles are lower and left while less risky curves are higher and right. Intuitively, the baseline should be the farthest up and right.

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[3] Utility need not be represented on a 0 to 1 scale. ISPAR makes accommodations for any utility function.

6.1.1 Construction of a Risk Profile

This section addresses the development of risk profiles starting with output of RSD quantification procedures. A table of probabilities for each endstate is the input data needed. We consider the utility as the random variable with a finite number of distinct values, denoted here by x_i, with $i = 1, 2, \ldots, n$. We have a PMF of

$$f(x_i) = \Pr\,(X = x_i)$$

The CDF, $F(x)$, and CCDF, $R(x)$, are given by

$$F(x_i) = \sum_{j=1}^{i} f(x_j)$$

$$R(x_i) = 1 - F(x_i)$$

If utility random variables are continuous then $R(x)$ has an integral form

$$R(x) = 1 - \int_{-\infty}^{\infty} f(x)\,dx$$

One of the properties of CCDFs is that its integral is the expected value of the underlying distribution. For this application the limits of integration are $0 \to 1$.

$$EV[x] = \int_{0}^{1} R(x)\,dx$$

From this we can show that the shortfall between baseline and RSD (area between the curves) is the difference in expected utility.

6.1.2 Risk Profiles with Decision points

Presence of decision points represents different response mechanisms to an initiating event. Since they are not quantified, separate risk profiles emerge for each decision option. Only one of response is present at a time. Using data from the previous example, $F(x)$ and $R(x)$ are created for both decision cases. A superscript designates the decision points activated within the RSD.

Table 6-1. Utility PMF and CCDF

	"Do Nothing"		"Implement"	
x_i	$f(x_i)$	$R^0(x_i)$	$f(x_i)$	$R^1(x_i)$
0.6206	0.2964	0.7036	0.0000	1.0000
0.7477	0.0000	0.7036	0.1501	0.8500
0.8222	0.0000	0.7036	0.1462	0.7036
0.9998	0.7036	0.0000	0.7036	0.0000

These curves are plotted in Figure 6-2 to illustrate an improvement as a result of implementing mitigation *M1* via decision point (DP). Note that a baseline with no possibility of shortfall is assumed. Before computing a risk metric, one can visually determine a significant improvement. The left plot (solid) is akin to a risk statement and the right (dashed) is the same with a mitigation. But unlike a risk statement, these plots incorporate all three attributes and the PMs preferences for them.

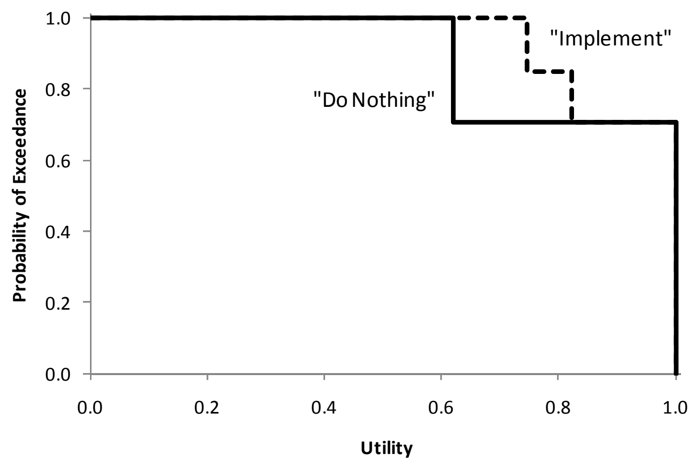


Figure 6-2. RSD risk curves showing mitigation effects

6.1.3 Comparison of Risk Profiles

A method of comparison is needed for PMs to make informed decisions of the differential risks. Comparisons must be made in a consistent manner that addresses not only the expected value, but also its variability and PM's preferences. Two questions need to be addressed in order to determine a metric for comparison purposes.

- Is using the area between CCDFs an appropriate, proven, and meaningful technique?
- What is the impact of this comparison when curves cross each other once, twice, or more?

Research into comparison methods of stochastic models yields a wealth of literature from financial, statistics, and decision theory communities. Several methods for comparing distributions are currently in use, including; mean, mean-variance, mean-critical probability, and stochastic dominance. Graves and Ringuest provide a tutorial paper where by various methods are applied to show their respective strengths and weaknesses. Among the methods reviewed, stochastic dominance is recommended (Graves & Ringuest, 2009).

Stochastic dominance (SD) first discussed in the early 1930s, but was not widely used until the publication of four separate papers in 1969 and 1970 (Hadar & Russell, 1969; Hanoch & Levy, 1969; Rothschild & Stiglitz, 1970; Whitmore, 1970). Since then hundreds of papers have been written extending the topic, see (Bawa, 1982; Levy, 1992). SD is used to predict a decision, preference or choice between given pairs of uncertain alternatives without knowing the utility function of the decision-maker. Its usefulness here is to show meaning for the use of the area under a CCDF.

Let us focus on second degree stochastic dominance (SSD). This is used when first-degree stochastic dominance (FSD) does not provide a clear choice, which occurs if two CDFs intersect. Given two alternatives A and B, with CDFs $F_A(x)$ and $F_B(x)$, A is said to dominate (less risky) B if

$$\int_{-\infty}^{z} [F_B(x) - F_A(x)]\, dx \geq 0,$$

for all z over x. This applies only under some assumptions about the unknown utility function, $u(x)$. Namely, when $u(x)$ increases with x, $u'(x) \geq 0$, and also when the decision-maker is risk averse, $u''(x) \leq 0$ for all x. The form of the equation is the area between CDFs and Müller and Stoyan have shown that these criteria also hold true for Survival Functions (Müller & Stoyan, 2002).

Graphically, we can use area between risk curves to indicate an alternative is more risky and another. Numerically, we can integrate the difference between CCDFs as a basis for the project risk metric.

6.1.4 Baseline Risk Profile

Project risk baselines are weighted consequence profiles that are used to measure risk performance throughout project life cycle. Often they include contingencies to accommodate uncertainty of unidentifiable but normally occurring costs, delays, and performance variations within a defined scope. This contingency is margin carried by a project and agreed to by all parties. Baselines are modified when there is a significant approved scope change that has cost and/or schedule implications and consequently changes the project's approved project budget.

Baselines are used to monitor, compare, and measure project performance throughout the life cycle. From our definition, risk is measured against a baseline to determine shortfall. In other words, if a project is managing its issues so that there is no probability of overrun, delay, or unmet performance requirements, there would be no risk. Relaxing this analogy, gives allows for a project that is managed within the limits of its cost reserve, schedule slack, and performance goal margin, we would also say that no risk has occurred.

Creating a baseline profile works the same way as outlined for RSDs. The project has an expected cost number ($0 loss) and some probability associated with other loss events. Initial cost models will typically provide an "S-curve", CDF, of the cost estimate. Margin (also known as management reserve) is calculated as a function of the expectation cost. Similar analyses are done for schedule and performance attributes. Same utility functions are applied and the resulting curve is the baseline risk profile, $B(x)$. The function is no different than any other risk profile except that it is the basis of comparison to determine the project risk metric.

Since the baseline can be modified due to contractual changes, so will $B(x)$. This means that the project risk metric can change even without a change in risk items. As the change in scope is accepted so is the risk associated with the change. As a practical matter, configuration control over $B(x)$ needs to be maintained as the project progresses.

6.2 Project Risk Metric

The goal is to develop a figure of merit for project risk that is consistent with our definition of project risk (see Chapter 2) and can be applied to show comparative differences among risk profiles. The project risk metric (*Rm*) is a quantified measure of shortfall as referenced from the project baseline risk profile.

There are few figures of merit used with PRM to communicate risk. Most are designed to capture a sense how much risk is present in a single risk item.

6.2.1 Counts

Since PRM does not provide a measure for total risk, PMs use the number of risk items to obtain a sense of risk within a project. This of course is not so much a measure of risk as it is a "punch list" for how much work is to be done. The number of "red" risk items must be worked to move to yellow or green. The more risk items in red the riskier the project.

6.2.2 Risk Figure of Merit

A most common figure of merit representing risk is:

$$Risk = Probability \times Consequence$$

The idea of multiplying probabilities and consequences is a well-established practice. This equation is nearly ubiquitous in PRM guidance documents. What is not well communicated however are the limitations of this construct so as not to produce misleading risk rankings. Several authors (Conrow, 2003; Cox, 2008; Elmaghraby, 2005; Williams, 1996) have written papers demonstrating mathematically and through examples how this happens. Many issues revolve around the use of ordinal values instead of probabilities. Another is blind faith in average expected value; "Be leery of crossing a stream that is only 4 inches deep on average." Some other metrics have been proposed with varying levels of acceptance (Ferguson, 2004).

Within a new PRM process called Project Risk Response Planning (P2RP), a metric is proposed that addresses deviations from a baseline for cost, schedule, and project scope (Seyedhoseini, Noori, & Hatefi, 2009). This index called the Scope Expected Deviation (SED) shows weighted ratios of time (T), cost (C), target specifications (Q) between success criteria (designated with 0) and the same given a risk item (designated with ‘). The SED equation is:

$$SED = 100 \times \left[t \cdot \left(\frac{T_0 - T'}{T_0} \right) + q \cdot \left(\frac{Q_0 - Q'}{Q_0} \right) + c \cdot \left(\frac{C_0 - C'}{C_0} \right) \right]$$

where: $(t + q + c) = 1$: weighting coefficients for time, quality, and cost

This particular approach to defining a metric fits well with the stated risk definition, involving the deviation from acceptance.

6.2.3 Risk Metric Calculation

Figure 6-1 shows a conceptual view of Rm. Algebraically, we show this as an integration of the difference of two profiles.

$$Rm_i = \frac{1}{k}\int_0^{max} [B(x) - R_i(x)\,]\,dx$$

where: *i* is any RSD identifier
max is the highest consequence value
k is a normalization factor

Earlier discussions about utility have shown a maximum value to be 1. However, while this is a typical practice it is not dictated by theory. Utility could be any finite range that is convenient for the analyst. To account for this, we define a normalization constant, *k*, that is the maximum area of interest:

$$k = x_{max} \cdot \Pr(x_{max})$$

Notice that when the utility function is set to a domain of $0 \rightarrow 1$, $k = 1$.

Using risk curves from our example yields results in Table 6-2.

Table 6-2. Example risk metrics

Decision	Rm
Do Nothing	0.1125
Implement	0.6399

6.2.4 *Rm* Characteristics

The *Rm* function must exhibit behavior consist with our expectation of how risk increases or decreases under certain cases.

- $Rm = 0$ if there is no risk
- $Rm > 0$ if a RSD has more risk than the baseline
- $Rm < 0$ if a RSD has less risk than the baseline

For this will examine the following sensitivity cases.

<u>Identical Risk Profiles</u>: Two identical profiles when the presence of a risk item does not change the baseline risk profile. Even though there is some probability that the project will incur loss, it is within margins previously agreed. Suppose $R(x) = B(x)$ for all x, then $B(x) - R(x) = 0$ for all x. Integrating yields $Rm = 0$.

<u>Risk Profile Larger Than Baseline</u>: Suppose a RSD risk profile is higher and to the right of the baseline. This means that for every x, the probability of exceeding that value is higher with the RSD profile than the baseline, meaning that its more likely to achieve x with the RSD than the baseline. The is the definition of FSD, $R(x) >_{FSD} B(x)$. $R(x) > B(x)$ means that $B(x) - R(x) < 0$ for all x. Integrating this function that is always negative yields $Rm < 0$.

<u>Risk Profile Smaller Then Baseline</u>: Suppose a RSD baseline is higher and to the right of the RSD. This means that for every x, the probability of exceeding that value is higher with the baseline profile then the RSD. $B(x) > R(x)$ means that

$[B(x) - R(x)] > 0$ for all x. Integrating this function that is always positive yields $Rm > 0$.

Intersecting Profiles at Only 1 Point: In this case we examine the situation where the risk profiles intersect as shown in Figure 6-3.

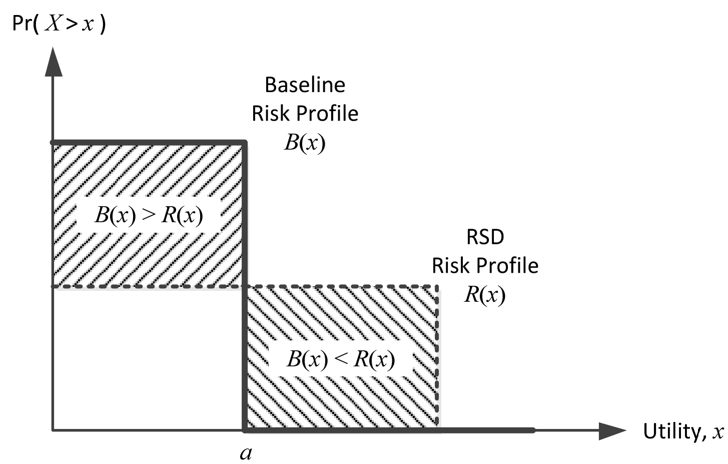


Figure 6-3. Intersecting risk profiles

This case is divided into three sub-cases; equal area on both sides of the intersection, area is greater on the high side, area greater on the low side. Let a be the intersection point of $R(x)$ and $B(x)$ such that

$$B(x) > R(x); \quad x < a$$

$$B(x) = R(x); \quad x = a$$

$$B(x) < R(x); \quad x > a$$

$$Rm = \int_0^a [B(x) - R(x)]\, dx + \int_a^{max} [B(x) - R(x)]\, dx \qquad \text{Eq 1}$$

When the intersection is placed such that the area low and high between the curves are equal the risk on either side balance each other for no net change in risk. We can see with the above equation the integrands will be equal magnitude but opposite signs. $Rm = 0$.

When the intersection is placed such that left side area is greater than the right side area, the risk should indicate that the RSD is more risky than the baseline. The first term is positive and large in magnitude while the second term is negative and small in magnitude. The net result is $Rm > 0$. When the intersection is placed with the right side having the greater area, $Rm < 0$. These can also be shown true if $R(x)$ and $B(x)$ exchange positions in Figure 6-3: $Rm = 0$, $Rm < 0$, and $Rm > 0$ respectively for the sub-cases. Note these results are consistent with the notion of SSD.

2 or More Intersections: With more intersections, the integral in Eq 1 is split the same way as above at each intersection. The sign will be positive where $B(x) > R(x)$ and negative where $B(x) < R(x)$. The differences sum across all the areas created to determine *Rm*.

Thus far, information from RSDs is transformed into risk profiles using probability calculations endstate utility functions. Risk curves can be compared and a figure of merit, *Rm*, has been introduced providing a tangible measure of risk. Chapters that follow, extend these concepts to derive a total project metric and importance measures to examine element risk contributions.

Chapter 7 Composite Project Risk Metric

Combining RSDs across an entire project provides a project-level risk profile metric to aid project analyses and risk driver rankings. The previous section defined a risk metric as the area between a risk profiles. This is incomplete for our purposes in that it is only a metric for a risk item and not for the entire project. Combining RSD risk profiles if the next step in the ISPAR process.

7.1 Combining Risk Profiles

Within PRAs, total risk is developed by gathering endstates across all the ESDs by assuming that initiating events happen one at a time and never concurrently. This greatly reduces complexity of the problem. In this application, we cannot assume independence. Things can go wrong and mitigations are implemented simultaneously. In addition, dependencies exist among root causes, pivotal events, mitigation actions, and the basic events that make up these logic models.

It is tempting to treat risk profiles as self-contained entities and combine them at that level through sampling or some other method[4]. However, there are two situations

[4] One method attempted involved OR-ing cutsets gathered by endstate values, constructing a histogram, and then a risk profile. The logic being that each cutset represents a path to a specific endstate and any combination of such cutsets would yield a new probability versus consequence curve.

that would make such a curve incorrect. First, combining endstates will not necessarily yield the same state but instead a very different endstate. Second, cutsets may be dependent on events from other RSD that do not show up in the original. Both these cases are amplified below. There may be other situations not addressed here. Combining risk profiles as entities will not produce an exact solution and so a model for integrating all RSDs is necessary.

The method for creating the project risk profile is to make a large *integrated project risk model* of RSD basic events in the form of an event tree (with decision points). Event trees were chosen here to maintain as much consistency with PRAs as possible, recognizing that other modeling techniques could be more efficient and easier to incorporate into software. This model is intended to be a tool for risk analysts and not a tool to be used by the PM or other team-members that own individual risk items. An Event tree allows us to work with logic and examine all paths that could possibly exist.

7.1.1 Endstate Combination

We start with two simple RSDs shown in Figure 7-1. If either α or β occurs then the result is consequence (utility) x_1; implied is consequence x_0 if neither occurs. Assume that risk items α and β are independent. Probabilities are computed at the endstates as shown using the event tree. Notice however, that should both occur the result could be x_1, or some function of x_1, such as summing the consequences.

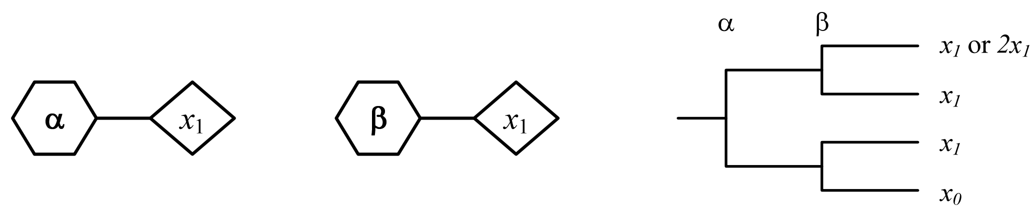


Figure 7-1. Independent RSDs

For illustration purposes, suppose that a project is worried about two separate tests, α and β. The failure of each would result in a delay of one month, x_1. The tests are not in the same schedule path so that failure of both still results in a delay of one month. By contrast, if both were on the critical path, failure of both tests would result in a delay of two months. Even though neither risk showed a potential for a two month slip the combination in context of the project schedule makes that a possibility. Attention must be paid to the context of paths through an event tree.

7.1.2 Cutset Combination

Cutsets may need to be altered in the presence of other RSDs. Take for instance the two following RSDs, Figure 7-2. Upon evaluating RSD-α we get a cutset show that the failure of *E1* yields on x_3 endstate. In fact, the failure of *E1* means x_3 endstate regardless of which risk item occurs (ignoring the endstate combination issue). For RSD-α, cutset α *E1* leads to x_1. In the presence of RSD-β however, *E1* does not guarantee that x_1 will be reached. *E2* must also be true otherwise the x_2 is a possibility. So in order to get the cutsets correct RSD-α must be evaluated with the cutsets from RSD-β.

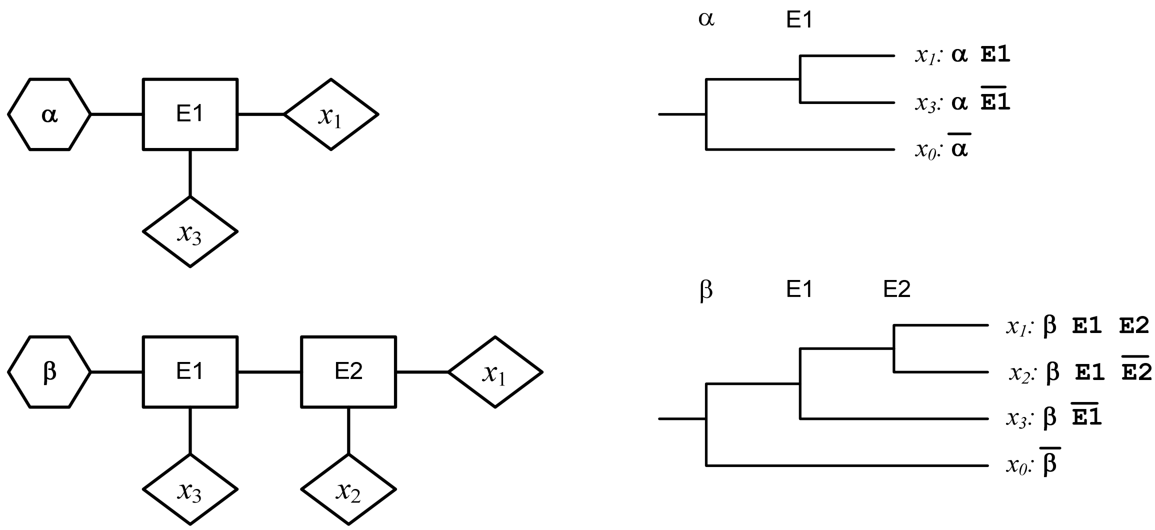


Figure 7-2. Dependent RSDs

The integrated event tree is shown Figure 7-3. Risk items and events are listed across the top. The tree structure to the left ensures that all the possible combinations are quantified. Each path stops at a labeled endstate corresponding to those shown in the figure above. Each endstate also shows the probability expression. The separate tree structures to the right of the double line illustrate the cutset reduction process for each consequence x_i. No ordering of the event tree events was imposed, although it is recognized that much efficiency could be gained by the order which they are placed.

A comparison of the cutset results from combining them as independent RSDs and within an integrated models reveals identical cutsets for endstate x_0, x_2, and x_3. Endstate x_1 shows significant differences rooted in interaction with event E1.

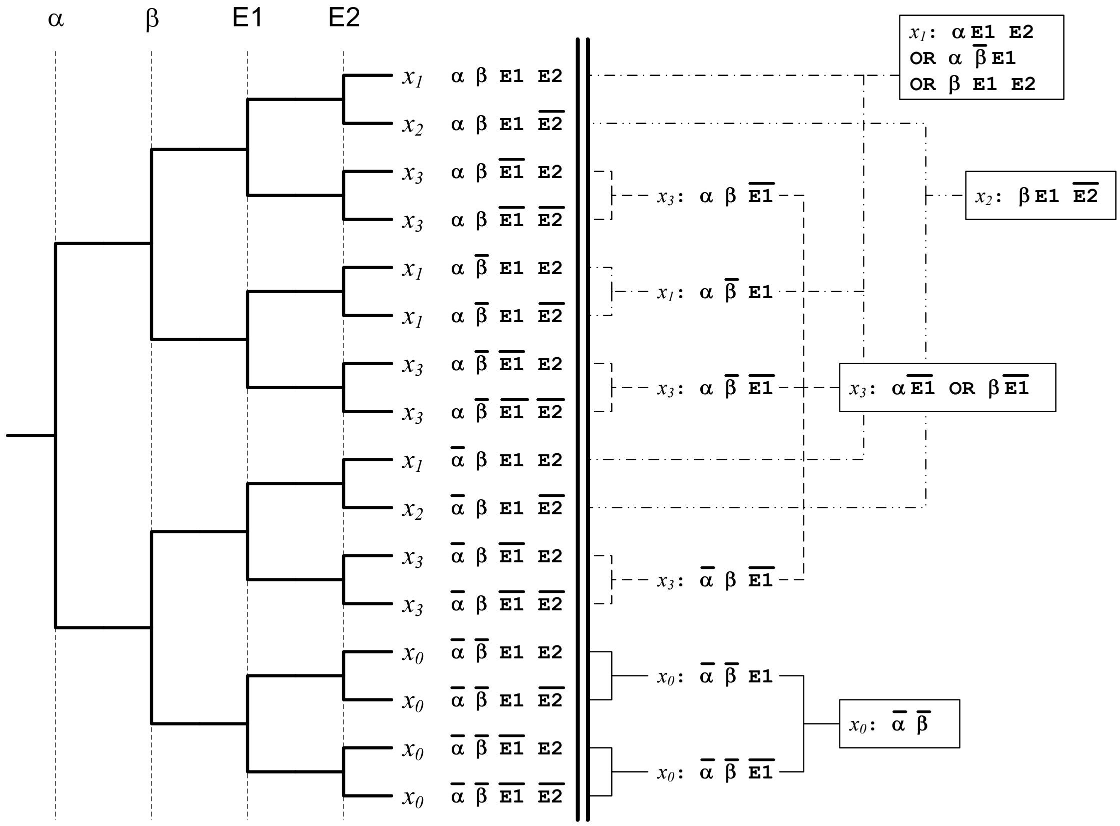


Figure 7-3. Integrated Project Risk Model

Table 7-1. Cutset comparison

	Cutsets	
Endstate	**Independent**	**Integrated**
x_0	$\overline{\alpha}$ $\overline{\beta}$	$\overline{\alpha}$ $\overline{\beta}$
x_1	α E1 β E1	α E1 E2 β E1 E2 α $\overline{\beta}$ E1
x_2	β E1 $\overline{E2}$	β E1 $\overline{E2}$
x_3	α $\overline{E1}$ β $\overline{E1}$	α $\overline{E1}$ β $\overline{E1}$

This quick example shows errors created by looking at RSDs independently. As more and more RSDs are added during the course of a project, this error becomes larger. The example also only addressed the cutsets at a pivotal event level, for completeness the same process must be followed at the basic event level.

When implemented in a model with many elements, the number of paths increases rapidly. To solve this path explosion problem software implementation of Binary Decision Diagrams can be used.

7.1.3 Composite Project Risk Profile

As RSDs are created they are incorporated into the integrated risk model. The intent is not to show this detail to management, but use it internally to the risk analysts workings and preparation. RSD risk profiles are combined to form one *composite project risk profile* (CPRP) as shown in Figure 7-4.

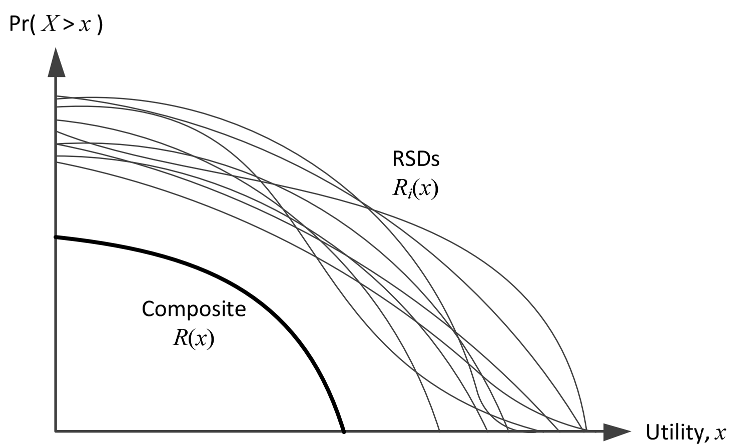


Figure 7-4. Composite Risk Profile

The key steps of process for creating a total project risk profile are:

Incorporate new information into integrated model: RSDs are continuously transferred into the integrated model at the basic event level. New risks are encountered and old risks are retired or accepted during a project. It is intended that a risk analyst keep this model up to date and provide information back to management. Most projects require this risk feedback at periodic management meetings already. One can easily envision that as new risks items are entered as RSDs, the total project risk profile will change position and shape. The amount of change, as measured by *Rm*, can be tracked and communicated. Other information must also be incorporated into the model. These include; decisions already made, events already occurred, and consequence model changes. As decisions are made or overcome by events (No Decision) the model structure changes as whole sections as pathways disappear. In addition, as more information becomes available about uncertainty, probabilities will change.

Remove illogical paths: Since the model takes into account all possible combinations as a default, there will be paths that cannot logically exist. This pass through helps to reduce the number of paths. More importantly, the credibility of the analysis improves if these impossible scenarios are not quantify and communicated outside the analysis.

Evaluate endstates: Endstates must be re-evaluated each time a new RSD enters the *integrated project risk model*. This may require interactions with the owners of other models for cost, schedule, and performance. The risk analyst will be able, based on the cutsets, what parameters are necessary for re-evaluation of those models. All utility functions are then applied.

Gather cutsets and reduce: As with any event tree model, a cutset reduction process must occur. These new cutset are then gathered for all identical consequences.

Quantify probabilities: With cutset associated with consequences, probabilities can be quantified. This will define the project level probability mass function, $f(x_i)$ discussed in Chapter 6.

Develop the risk profile: At this point the risk profile for the project is developed.

At this point the profile is treated just like any other risk profile to be compared to a project baseline.

7.2 Composite Project Risk Metric

With the risk profile created for the project, the process specified in Chapter 6 is used to determine a Composite Project Risk Metric (CPRM). CPRM is a function of the RSDs, their risk items, cutsets, basic event probabilities, and decisions which are traced through the model.

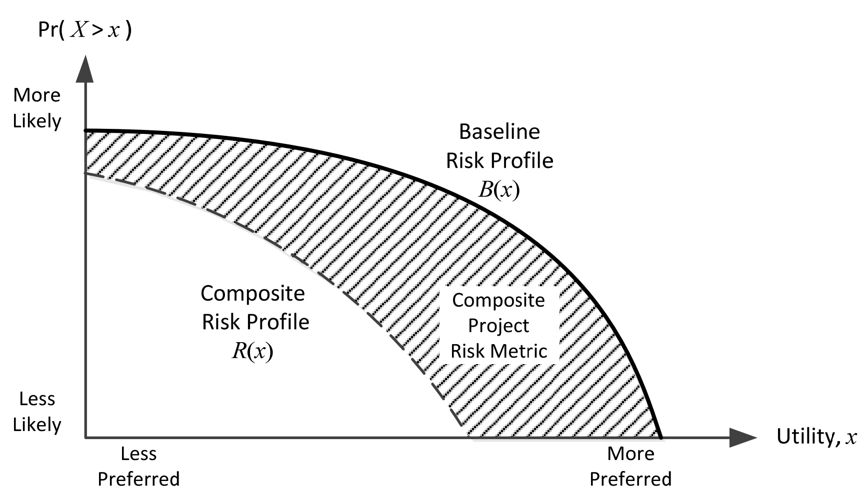


Figure 7-5. Composite Project Risk Metric

CPRM is a function of all the RSDs in the model. It encompasses a variety of potential endstates, combinations of events across RSDs, combination of endstates based on scenario-context, and the PM's preference and risk aversion. In essence it is the measure of total risk currently incurred by the project. This one measure can now be used to trend the overall risk performance throughout the project's life cycle. It will also be the bases of various importance measures (discussed later in Chapter 8) to explore relative contribution of risk items, events, decisions, preferences, and scenarios.

Neither *CPRM* nor *Rm* translate to a physical quantity. They are scalar quantities that represent a conglomeration of endstates, scenarios, probabilities, consequences, and preferences. There is no upper or lower limit to the quantity, but since it is calibrated to the accepted project risk baseline, there is meaning to zero. A value of zero means equivalency to the baseline.

7.3 Alternate Approach

Two approaches to derive *Rm* were explored. While not fully vetted the alternative approach offers some advantages. The current approach is consistent with how decision analysts apply *utility theory* to each scenario to derive a single number at each endstate. Risk profiles created from utility as shown in Figure 7-6 where the utility is compute at each endstate first, then gathered to create a risk profile and from that determine *Rm*.

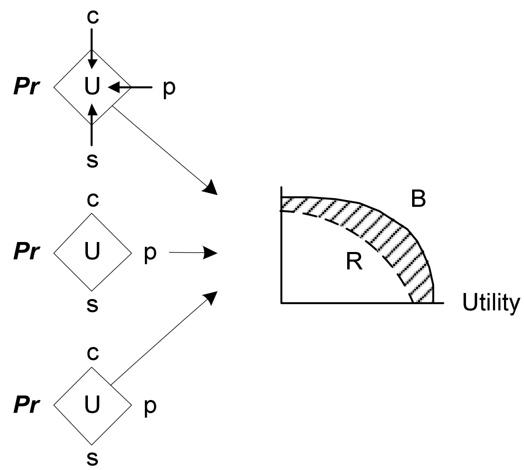


Figure 7-6. Risk metric is based on gathered utility values

An alternate approach applies attribute utility to a set of gathered endstates to form separate risk profiles for each attribute and subsequently to a risk metric for each, see Figure 7-7. A multi-attribute utility model would combine these attribute risk metrics to produce one composite metric. The benefit of this is approach is the separation of attributes and separate risk metrics so that management is provided insight into each. Importance measures and sensitivity analysis can focus on each. At this point, no further work has been done on this approach to see if it is logically and mathematically equivalent to the current approach.

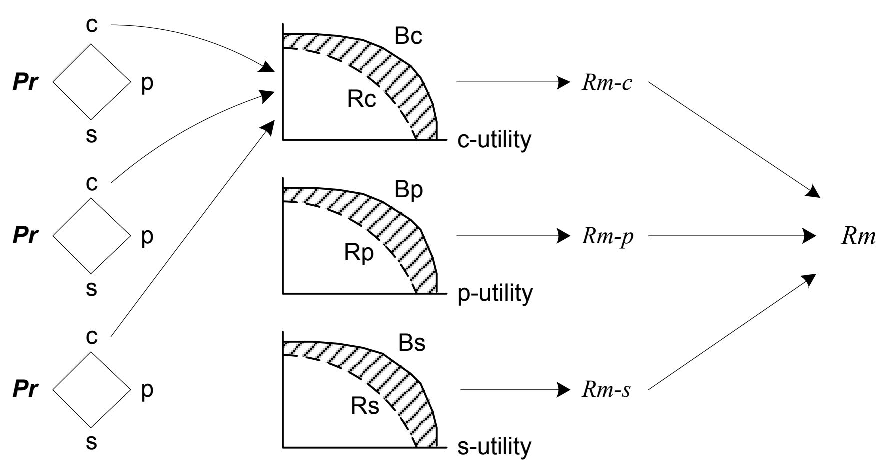


Figure 7-7. Risk metric is based on gathered consequence types

7.4 Quantitative Summary

In chapters 4-7 many moving parts to the process were discussed. Before proceeding with how to use the metrics, a review is in order. An identified risk item is described as a scenario in a RSD. RSD cutsets and endstates are determined and quantified using a project's consequence models, PM's preferences, and an organization's data repository. Ordered pairs of utility and probability create a PMF that is transformed into a CCDF risk profile. Risk profiles are compared to a baseline to compute *Rm*. Multiple RSDs are combined into an integrated risk model which determines the total risk profile. The total risk profile is also compared to the baseline to determine *CPRM*. Figure 7-8, illustrates the connections and relationships of various ISPAR elements.

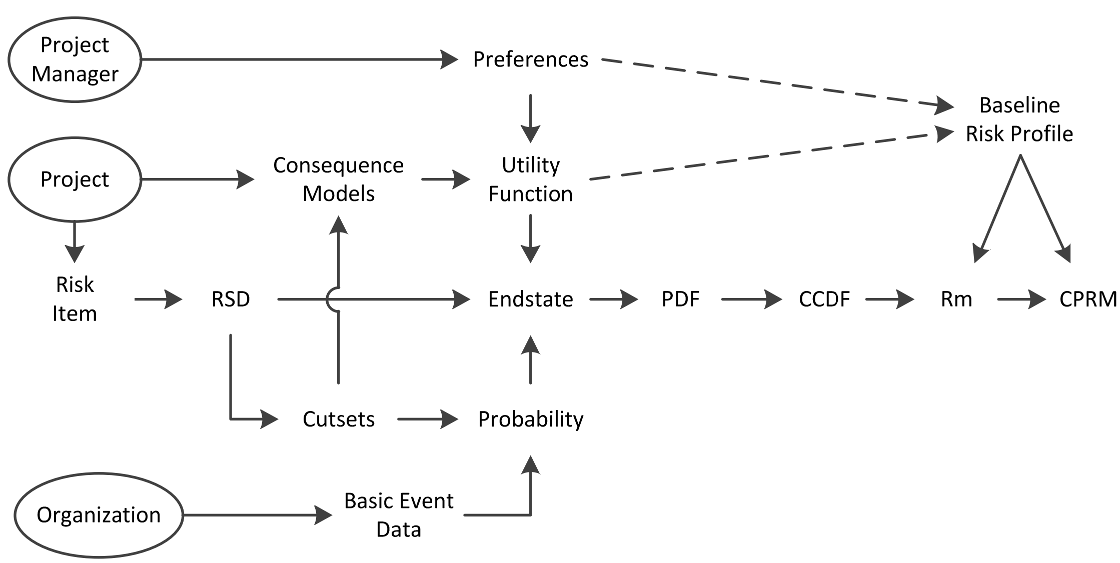


Figure 7-8. Quantification process overview

Chapter 8 Importance Measures

The ability to rank order project elements with respect to their risk significance is one of the most useful aspects of this methodology. It represents one of the major improvements over current PRM practices. In PRA parlance, values computed to perform rankings are called *importance measures* (IM).

Rm can certainly be used in ranking risk items. However, it provides value only when comparing RSDs with respect to other RSDs. It does not provide insights into the contribution of individual events or parameters to the total risk. *Rm* can be decomposed easily since all the constituent information exists in the model framework. With a database tool a risk analysts could easily answer questions about the percentage of risk attributed from any number of factors, such as type of risk items, type of consequences, decisions pending in near term versus long term, or dependant on vendors. Taxonomies for characterizing elements in the model can be developed to addressed any of these.

This chapter examines several importance measures currently used by PRA analysts and decision analysts for their use in this framework. There are four layers of metrics presented for; project, risk item, event, and decision.

8.1 Event Importance Measures

PRA analysts have created a set of IMs to evaluate risk contributions of any given item in a model. Most applications of importance measures are aimed at providing management insight into three broad areas: design or redesign optimization, test and maintenance strategy development, and daily configuration control (Van der Borst & Schoonakker, 2001). Several risk assessment texts contain detailed explanations and derivations of these (Bedford & Cooke, 2001; Hoyland & Rausand, 1994; Modarres, 2006; NASA, 2004; Vesely, Davis, Denning, & Saltos, 1983). These measures can also be applied to provide insights for a particular risk item and constituent elements.

While these measures can provide significant insight, they can also be misleading if applied improperly. Modarres cautions against the non-discriminate use of IMs noting that "formal importance measures are context dependent and their meaning varies depending on the intended application of the risk results" (Modarres, 2006). Van der Borst also stresses this point noting that a particular importance measure is dependent on the endstates of interest.

Consider a project system made up of *n* component events and let p_i denote the probability of success for each event *i* and let D_j denote the *m* decision points. We define two vectors, for probabilities $\mathbf{p} = \{p_1, p_2, \ldots, p_n\}$ and for decision points $\mathbf{D} = \{D_1, D_2, \ldots, D_m\}$. Then in accordance with previous chapters, *CPRM* is a function **p** of **D** denoted by

$$CPRM = f(\mathbf{p}, \mathbf{D})$$

At the RSD level *Rm* is also a function of probabilities and decisions and can be represented similarly.

With the logical construct of event trees and fault trees, cutsets are in the form of sum of products for event probabilities. For illustrative purposes, Wall simplifies the representation of total risk, *R*, using a linear equation (Wall & Worledge, 1996).

$$R = aP + b$$

This equation apportions cutsets based on the event of interest. So *aP* represents all cutsets containing event *P*. Parameter *b* represents all other cutsets. This formulation is enhanced to show the effect of **D** on total risk by splitting *aP* into a term containing cutsets (a_1P) without *D* and a term with *D* (a_2PD).

$$R = (a_1P + a_2PD) + b$$

The addition of term a_2PD represents those cutsets containing event *P* and decision point *D*. All other cutsets not containing event *P* are still represented in *b*. Since decision points are not quantified, a set of IMs will be generated for each event *P*. If no decision points are included in the a_1P, the *R* reduces to the original equation. The next sections apply various IMs and shows that they are consistent with their original intent.

8.1.1 Birnbaum

Birnbaum measures a component's importance by determining the rate of change in total risk of a system with respect to a elements rate of change in probability of occurrence.

$$IM_{Bn} = \frac{\partial R}{\partial P} = a_1 + a_2D$$

For a given event, a large IM_{Bn} means that a small change in an element's probability will result in a large change in system risk. A rank ordering of IM_{Bn} for the elements tells the analyst where risk is sensitive to minor changes. Another useful form of IM_{Bn} is the magnitude of risk change (Hoyland & Rausand, 1994):

$$IM_{Bn} = R(P = 1) - R(P = 0)$$

8.1.2 Risk Reduction Worth

Risk Reduction Worth (RRW) measures change in risk assuming an event of interest is perfect (will not fail). In other words it measures of how much improvement to a system can be made by fixing one event.

$$IM_{RRW} = \frac{R}{R(P = 0)} = \frac{a_1 P + a_2 PD + b}{b}$$

Since *D* is either 1 or 0, but yet un-quantified, we will get two RRW values. Should *D*=0, RRW reduces an expected expression. If *D*=1, all cutsets are treated identically to those in the first term, and again RRW reduces to an expected expression. If the event of interest is a decision point, we substitute *D* for *P*. There is no limitation in the model structure to prevent this representation.

8.1.3 Risk Achievement Worth

Risk Achievement Worth (RAW) is the inverse of RRW in that it measures improvement possible if no credit is taken for a given component. RAW is the change in risk assuming the component is not there.

$$IM_{RAW} = \frac{R(P = 1)}{R} = \frac{a_1 + a_2 D + b}{a_1 P + a_2 PD + b}$$

Since *D* is either 1 or 0, but yet un-quantified, we will get two RAW values. Should *D*=0, RAW reduces an expected expression. If *D*=1, all cutsets are treated identically to those in the first term, and again RAW reduces to an expected expression.

8.1.4 Fussel-Vesely

The Fussel-Vesely (FV) IM is a fractional contribution of a component to total risk. As before, *D* is either 1 or 0, but yet un-quantified, we will get two FV values. Should *D*=0, FV reduces an expected expression. If *D*=1, all cutsets are treated identically to those in the first term, and again FV reduces to an expected expression.

$$IM_{FV} = \frac{aP}{R} = \frac{a_1 P + a_2 PD}{a_1 P + a_2 PD + b}$$

If the metric is 0 there is no contribution from event *P*, if the metric is 1 then all the risk involves event *P*.

8.1.5 Discussion

Since *CPRM* is a function of basic event probabilities, the above IMs work when applied with respect to decision points. Decision points are treated as any other event in cutsets even though they are not quantified. *CPRM* is differentiable with respect to any decision point variable and therefore can and does work in this context. However, since decision point variables are not quantified IMs yield no numeric answer until they are given a value. The example below shows IMs calculated for both decision responses. Using the quantification example from Chapter 5, IMs are calculated (see Table 8-1) for both the "Do Nothing" case and the "Implement" case with respect to RSD *Rm*. Computations of these IMs with respect to one event is shown in detail below.

The resulting risk profile is a function. When the probability values are not quantified the expression for *Rm* is:

$$Rm = 1.52 \times 10^{-4} + ac(0.375 - 0.197\ \mathrm{DP} + 0.075\ d\mathrm{DP}) + b(0.375 - 0.122\ \mathrm{DP} + ac(-0.375 + 0.197\ \mathrm{DP} - 0.075d\mathrm{DP}))$$

where *a*, *b*, *c*, and *d* are the event probabilities. *DP* is the decision variable. When *DP* = 0, the *Rm* simplifies to:

$$Rm = 1.52 \times 10^{-4} + 0.375ac + b(0.375 - 0.375ac)$$

We can get expressions for *Rm* with *a* = 0 and *a* = 1.

$$Rm_{a=0} = 1.52 \times 10^{-4} + 0.375b$$

$$Rm_{a=1} = 1.52 \times 10^{-4} + b(0.375 - 0.375c) + 0.375c$$

The importance measures equations are used to get equations in terms the remaining variables. For example, IM_{Bn} is:

$$IM_{Bn} = Rm_{a=1} - Rm_{a=0} = c(0.375 - 0.375b)$$

Substituting probability values for *b* and *c* yields:

$$IM_{Bn} = 0.067$$

This process continues for the other IMs with *DP*=0 and *DP*=1 with respect to variable a. All steps are repeated for all the other variables. Notice that the DP point is no different than any other variable in the original *Rm* equation and can therefore be processed as well.

Table 8-1. Example IMs

DP=0	a	b	c	d	DP
Bn	0.067	0.311	0.261	0	-0.047
FV	0.494	0.419	0.494	0.000	0.000
RRW	1.973	1.721	1.973	1.000	1.000
RAW	1.108	3.371	2.855	1.000	0.576
DP=1	**a**	**b**	**c**	**d**	**DP**
Bn	0.032	0.222	0.124	0.011	-0.047
FV	0.407	0.519	0.407	0.000	-0.735
RRW	1.169	2.080	1.685	1.000	0.576
RAW	1.089	3.942	2.530	1.170	1.000

Another to way to look at the same information is to examine the rank orders based on these numbers. Table 8-2 shows the orderings with and without the mitigation action.

Table 8-2. Example IM rank orders

Bn		FV		RRW		RAW	
DP=0	DP=1	DP=0	DP=1	DP=0	DP=1	DP=0	DP=1
b	b	a, c	b	a, c	b	b	b
c	c	b	a, c	b	a, c	c	c
a	a	d, DP	d	d, DP	d	a	d
d	d		DP		DP	d	a
DP	DP					DP	DP

This section introduced various IMs used in traditional PRAs. It shows that IMs can be computed and used within this framework given the presence of decision points within the risk function. IMs provide numerical guidance about risk significance of events and conditions within a project. They identify common contributors appearing in multiple scenarios and cutsets and when ranked by risk significance they can drive testing and resource allocation.

IM_{RAW} is useful for estimating risk significant of equipment or process steps removed from a project flow while IM_{RRW} is useful for bounding benefits from proposed mitigation activities. IM_{FV} provides the fraction of a project's risk that involves the failure of a given event. IM_{Bn} represents the maximum spread in project risk when an event switches from the condition of perfect functioning to the condition of certain failure. A weakness of IM_{Bn} means that it completely depends on the model structure and not on an event's probability. However, when examining decisions, this criticism is moot since decision points do not carry an inherent probability. They only have meanings in the extremes (0 or 1).

Modarres cautions against the indiscriminate use of IMs, noting that their behavior may be affected by model structure and event probabilities (Modarres, 2006). IMs should be used to determine candidates for improvement or watched for trends.

8.2 Decision Point Importance Measure

One way to characterize the importance of a decision is based on the magnitude of potential change in *CPRM*. These decisions are conditioned on the likelihood of having to make a decision. Therefore, this importance measure is a function of both. Let R_0 and R_1 be expected values of *CPRM* given the decision D=0 and D=1 respectively and let P_d denote the probability from all cutset preceding the decision point D. The change in *CPRM* is normalized against the baseline (R_{BL}) to facilitate comparisons.

$$IM_{DP} = P_d \cdot \frac{(R_1 - R_0)}{R_{BL}}$$

Substituting the definition of IM_{Bn} we get:

$$IM_{DP} = P_d \cdot \frac{IM_{Bn}}{R_{BL}}$$

The measure is essentially the risk of the decision point. It contains the elements of likelihood and consequence. Since it is normalized to a baseline, all decision points can be compared among each other.

Let us examine the behavior of this measure. If there is no chance that the decision will be reached, $P_d = 0$, then the decision would not be important, $IM_D = 0$. If on the other hand $P_d = 1$, then the decision importance rests solely of the decision outcomes. If there is no difference between decision alternatives, $R_1 - R_0 = 0$, then again the decision is not important, $IM_{DP} = 0$. If the difference between decision alterative is large with respect to the baseline, then the decision could be important and therefore IM_D would be large and conversely a small difference could mean little importance.

We can also apply this same construct locally to get a sense of resources / performance at risk. For example, to get a sense of cost the computation would be

$$p_d \cdot \frac{EV_{cost}[D = 1] - EV_{cost}[D = 0]}{Baseline\ Cost}$$

Since the IM_{DP} is inherent to a decision point and normalized, values can be compared among decision points throughout the project. They can also be compared to the same decision point placed in a different place in the scenario. Let us explore this by moving the decision point in the example to before the pivotal event E1 as shown in Figure 8-1.

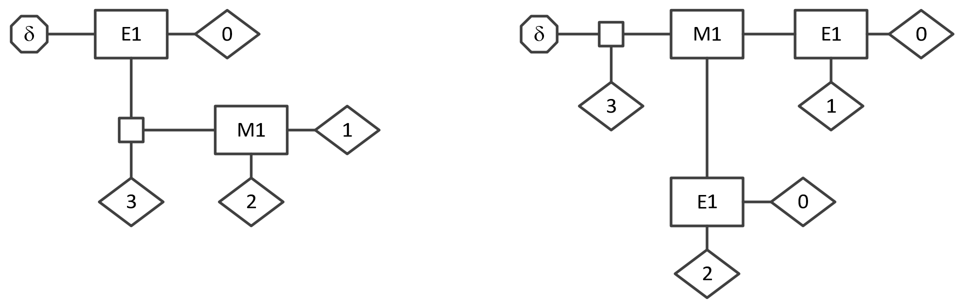


Figure 8-1. Example RSD with changing decision point

The cutsets change in response as does the structure of the RSD. When these two RSDs are analyzed the decision importance decreases with the move, see Table 8-3. The negative sign is an indication that *Rm* is larger with a "No" decision than an "Implement" decision.

Table 8-3. Example IM_D Results

	IM_{Bn}	P_d	IM_{DP}
Original	-0.0474	0.255	-0.0121
Moved	-0.0080	0.85	-0.0068

8.3 Time Importance

Time influences risk assessments in many ways. Exposure times are used to determine probabilities of component failure. Risk is often shown changing in time. Within projects, time influences the perception of risk. The closer an event or potential event is, the more conscious management becomes of its potential consequences. It is tempting to infuse time before a decision into importance measures with some justification. However, time is used in ordering only. The decision time horizon may increase the perception of risk by a PM, likelihoods, and endstates do not change. Some alternative may not be available due to a time constraint, but this is a matter of modeling choices no different than alternatives not pursued because they cost too much.

When ranking elements based on metrics or IMs, items with same or similar values can be ordered secondarily based on time.

8.4 Uncertainty Importance

Importance measures also exist for uncertainty. These metrics determine contributions of uncertainty of each element to total system risk uncertainty. The approach is similar to IM_{RAW} in that variability is set to zero and compared to base results. Modarres provides a survey of measures in use (Modarres, 2006).

Chapter 9 Implementation

Implementation of ISPAR is consistent with current PRM process and enhances information available to support projects decisions. PRM is a well established element of large project management efforts. Any hope of incorporating new ideas and frameworks requires that they seamlessly fold into existing processes. This chapter discusses areas where integration works well and where challenges still exit.

9.1 Working with Current Practice

Management has been biased toward simple (less resource intensive) PRM procedures. However identifying threats to meeting objectives and reducing wasted resources requires integration with all disciplines throughout a project and careful thought about all potential scenarios leading to unwanted endstates. Given historical performance of projects, the relatively few resources spent on PRM makes it one of the more cost efficient activities management can undertake. Specifically, understanding dependencies and uncovering hidden risk can lead to more effective decisions.

ISPAR methodology is designed to work in conjunction with current PRM process as shown in Figure 9-1. In Chapter 3, steps of this process were described. Notice that ISPAR replaces the "risk analysis" block while leaving other process steps intact. risk management planning activities are accomplished early in the project in order to secure appropriate level of resources. Risk identification processes used can and should continue as currently constituted. Checklists, brainstorming, and other techniques are required to determine risk items to be analyzed. Creating risk statements in now augmented by RSDs. The nature of risk assessment changes when the quantification portion is invoked. However, if only the RSDs are developed without quantification then risk assessment remains unchanged. Risk Handling is now treated as an integration activity with scenario development as mitigation actions are planned and become part of the RSD modeling. Risk monitoring activities (data collection, parameter tracking) feed RSD models using Bayesian updating techniques providing a capability to rethink upcoming decisions given the latest available information about causes and dependencies.

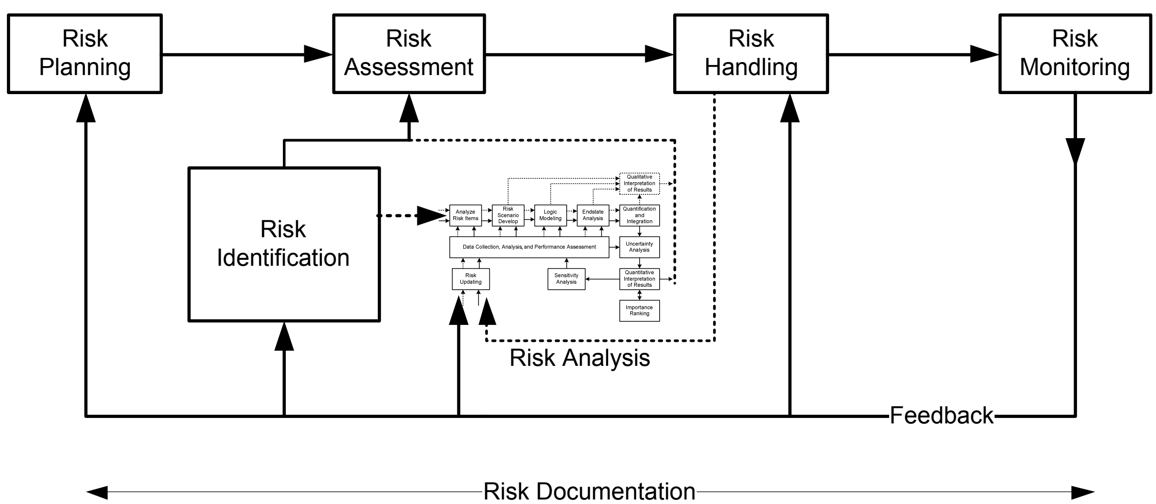


Figure 9-1. ISAPR integration with current PRM practices.

A major impact to risk management resources is a need to increase the skill level requirements of persons responsible for implementing PRM. No longer can they only be a database care-taker or meeting facilitator, but instead must be capable of performing risk scenario modeling, data collection and reduction, integrating consequence models, and communicating results and recommendations to management.

Risk analysts often hear statements similar to "since data is lacking, a risk assessment will tell you nothing." But this statement misses the point. It is the lack of data that leads to higher uncertainty and therefore risk. Risk assessments account for what is unknown and what impact that has on a project. The time to perform a risk assessment is when a project does not have all data. If all is known then management only has to fix problems already gone wrong with no need to worry about potential issues. PRA analysts and researchers have developed quantitative and semi-quantitative techniques to handle these situations and given that this methodology is based on PRA fundamentals, all these techniques can be effectively applied.

Projects may be unique, but this does not mean that constituent tasks are unique. Products also do not just appear. They are an evolutionary result of many projects and research. Data to support risk models can be adapted from the past given that events are decomposed to appropriate levels. Granted the application may not be identical, but similarity with past project plus the inclusion of uncertainty allows project analysts to infer data for the current project.

9.2 Risk Communication

Within a project context, management routinely presents status. Risk management is one of the subject areas often presented. One can argue that status meetings are part of risk management for organizations. Material presented herein, is not meant to be shared outside of the analysts work. So information has to be distilled to a set of meaningful information that provides insight into a project's current and future risk posture. Frank summarizes it this way; "The ability to clearly communicate risk issues, methods, and results with a high degree of credibility and in a way that is obviously targeted toward the overall success of the project becomes at least as important as the analysis itself" (Frank, 2008).

9.2.1 Risk Issue Presentation

We have shown that creating RSD provides a more robust view of scenarios and potential consequences than can be accomplished with a risk statement. Using RSDs as a communication vehicle also has carries the same advantages. Recognizing significant inertia behind using "if-then" risk statements, it is recommended that RSDs be shown together with risk statements. The statement can act as the focus of a PMs concern while RSDs show other circumstances at play and what work has occurred regarding mitigation, transfer, or acceptance.

RSDs provide a traceable, transparent, and documented support for decision rationale. All alternatives are laid out in front of management with pointers to all associated quantitative data.

This format lends itself well to providing status of all aspects of a risk item if so desired by a review team. RSDs can act as the basis for so called "burn-down" charts, discussed later in this chapter.

Appendix B contains RSDs from a current Johns Hopkins University Applied Physics Laboratory project. Tables show consequence for each endstate. These can be qualitative statements or outputs from consequence models. There is also a place to capture a narrative description of the context. Configuration control is maintained with a standard title block.

9.2.2 Risk Metric Presentation

Two risk metrics have been previously presented, *CPRM* for total project risk and *Rm* for risk items. *CPRM* is a useful measure to track as it embodies influences of all identified risk items, basic event data as currently known, and more importantly results of decisions. Used as a project level performance measure it can provide indications of a project's risk posture. *Rm* provides a basis of comparison among risk items as it measures the deviation from the baseline due to a single risk item.

These two metrics and their associated uncertainty distributions can be plotted over time. Current PRM practices have no equivalent to *CPRM* as a measure of total project risk and no way to show quantitatively the change in risk due to a single risk item, or the uncertainty about that either number. Since these numbers are computed with a model based on events and decisions, explanations for changes in *CPRM* can be easily explained. Currently the lack of experience using *CPRM* means that there is no validation about what value constitutes an acceptable risk. However, as more experience is gained and mapped to risk items and actual events, this concern will diminish.

9.2.3 Risk Matrix

One of the many reasons why current PRM practices persists in project management is the ease of communication with a risk matrix. Earlier we discussed their limitations with using it as an analysis tool. As a communication vehicle is works well.

So the key is to take this rich set of information and distill it to a presentation that is familiar and useful.

One way to put risk profiles on a matrix is to plot utility and likelihood as shown in Figure 9-2. Two risk items are plotted, black and white. Risk profiles are divided into segments of utility with its associated likelihood. How large a circle depends on the percentage allocated to that segments. So the black risk item has 95% of its utility within segment "1" and 5% in segment "2". Likewise, the white risk item has 5%, 20%, and 75% in segment "1", "2", and "3" respectfully. This representation keeps a look and feel of the risk matrix but indicates the spread within developed scenarios.

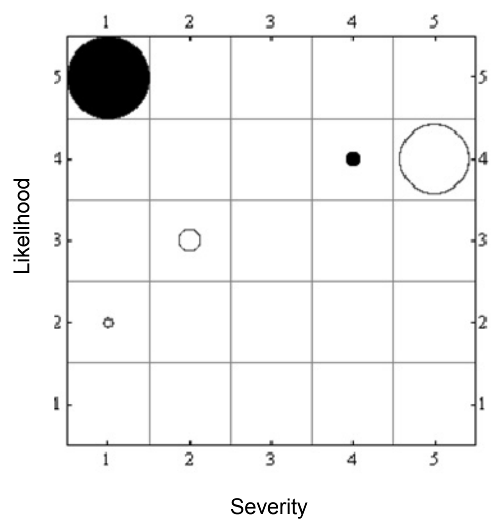


Figure 9-2. Enhanced risk matrix

However, the better alternative is to show the risk profiles.

9.2.4 Risk Profile Presentation

Even with the computation of *CPRM* and *Rm*, there is value in showing risk profiles. They provide a graphical representation of risk compared to a baseline. *CPRM* and *Rm* can be seen in the profiles since they are essentially normalized areas. It is often easier to gain a sense of where these metrics are most sensitive.

A quick examination of risk profiles with and without mitigation (see Figure 6-2) can tell one if the mitigation is likely to reduce risk significantly.

9.3 Feedback mechanisms

PRM feedback mechanisms are avenues to report on progress of mitigation activities. They are focused on actions created for mitigating the risk item at hand. The assumptions inherent with typical applications are that efforts to close a risk item are worth the resources to do so, that mitigations will succeed, and any movement is better than doing nothing. This approach is not very efficient when multiple risks are being worked simultaneously.

Based on the author's observations working in projects with PRM systems and with data collected for this study, after mitigation actions are completed, the associated risk item is deemed closed. If concerns still exist, another mitigation approach may be offered and pursued or more often another risk item is generated in the risk register. Data about successful or failed implemented mitigation actions is not captured to feed update probability estimates of the remaining risk items. Being a quantitative based approach, this framework can and should use this data to update the decomposed event types, i.e., basic events. This would not only benefit the current project but would be even more useful for the next.

A Bayesian updating methodology can easily be structured to support risk management systems and consequence models. Each event and mitigation action planned and recorded is fertile ground for a feedback loop. A system whereby data is collected to update existing probabilities and models is envisioned. With new data informing probabilities, ISPAR can be re-evaluated in time for the PMs monthly management briefings. With model runs occurring on a continuing basis, trends in risk performance can start to track mitigation successes and decision effectiveness.

9.4 Risk "Burn-down" Charts

A risk burn-down is a graphically representation of how risk is expected to decrease over time mitigation actions are implemented. Figure 9-3 illustrates a typical chart. The heavy line represents a plan considering mitigation steps and the layers represent priority zones found on a risk matrix. The idea is that a risk item will gradually move through a risk matrix from "High" to "Low". Notice here that risk level is combination of severity and likelihood. Often this combination is P×C, which is a flawed construct when dealing with ordinal scales. This representation suffers from the same limitations as a risk matrix, but perhaps more so since future actions planned are not analyzed for potential problems and therefore alternative scenarios are not considered.

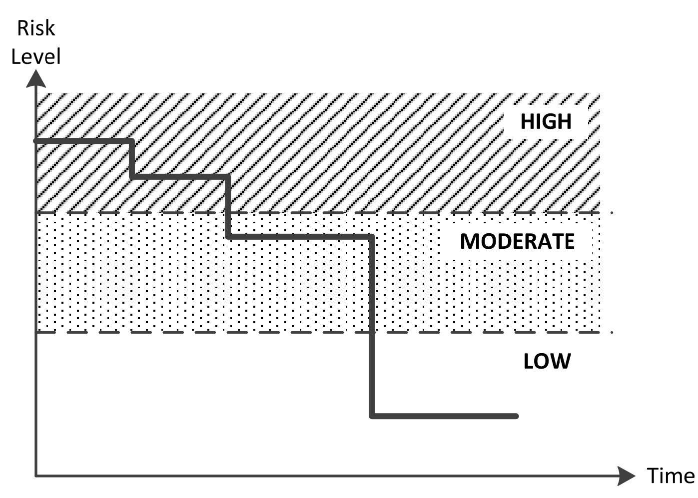


Figure 9-3. Risk burn-down chart

As actual events occur (mitigation actions or other), they are superimposed on this chart. The problem is that an event or step in a procedure does not relate to a score for risk reduction. An analyst is left to estimate the risk improvement with no basis.

Consider now a similar circumstance using ISPAR. We start with a RSD similar to examples used previous, see Figure 9-4. Notice, the mitigation action is now represented by 5 separate events (tasks). Failure of any one of them is a failure of the mitigation action. Next to the RSD is the "burn-down" chart of a risk reduction plan shown at *Rm* versus time. At $t = 5$, the mitigation will start, and for each subsequent time period a task will be accomplished. *Rm* values are recomputed with the planned completion of each task. This is done be setting the task probability to 1, meaning that once completed a task cannot fail to be completed. At this point the project has fully implemented to protection against an initiating event. *Rm* is not 0 since resources have been spent.

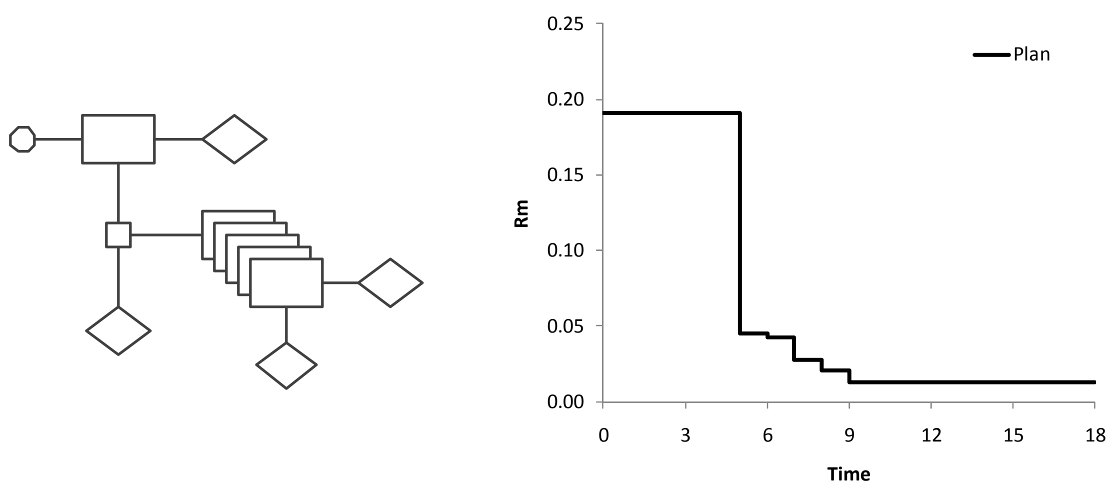


Figure 9-4. Burn-down chart, plan

At t = 3 however, the initiating event occurs (set to fail within the model). Following this event, the decision made to begin implementing mitigation tasks. By t = 5, the PM is showing chart Figure 9-5. The RSD indicates which events have occurred and the "burn-down" chart shows the corresponding change in *Rm*. *Rm* rose after the initiating occurred and dropped when the first task was accomplished. The PM is able show risk posture and reasons for changes. Also note that with a decision to implement tasking, an endstate is no longer reachable and so indicated with dotted lines on the RSD.

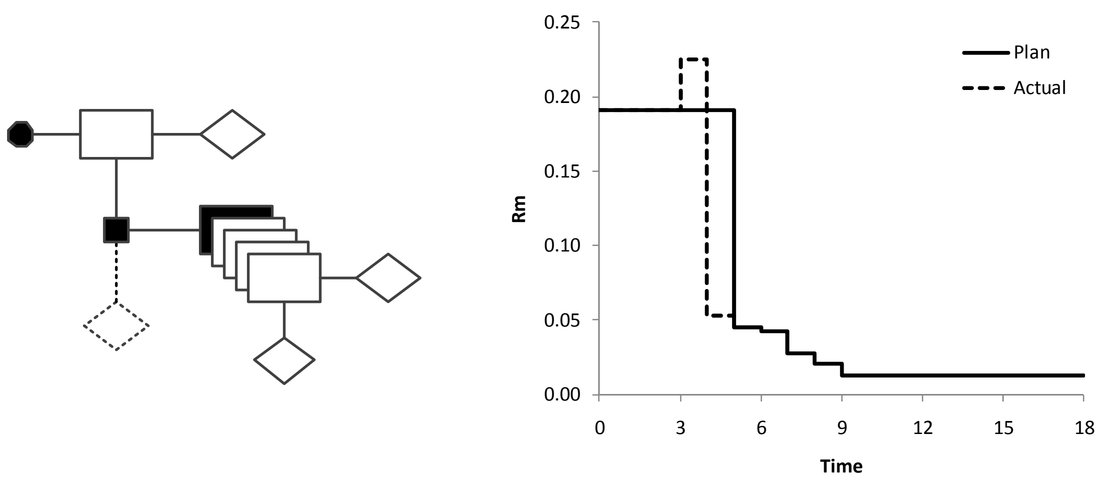
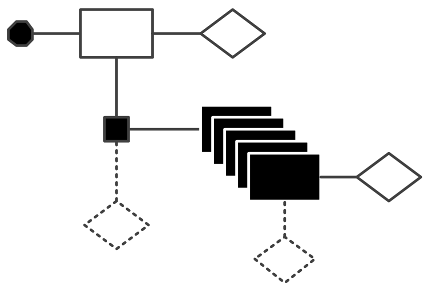


Figure 9-5. Burn-down chart, intermediate

At t = 6, tasking is completed under an accelerated pace rendering another endstate unreachable. *Rm* is lower. At t = 15, the occurrence of the initiating events is no longer possible and *Rm* drops to 0.



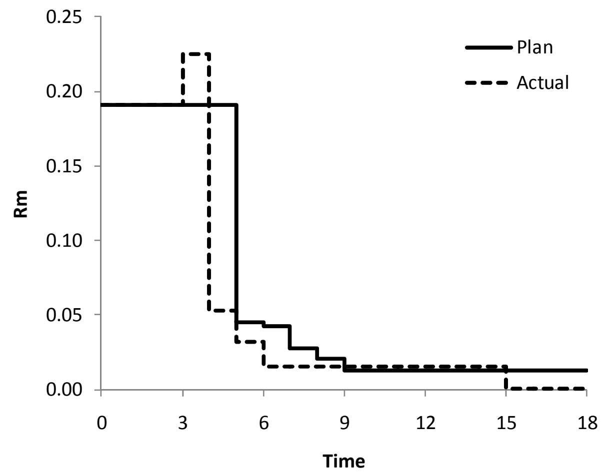


Figure 9-6. Burn-down chart, final

By tracking *Rm* on a periodic basis management can actively monitor project risk with respect to various events and activities. As we showed paths disappearing with time, other paths could just as easily appear given more information.

9.5 Residual risk

Even after mitigation actions have been implement, risk is still likely to exist, this is called *residual risk*. Current PRM practice is to disposition risk item in one of two methods:

<u>Closed</u> – a risk that will no longer be actively mitigated or handled. These are risk items that have been reduced to a level where the residual risk is considered negligible and further risk reduction activity is deemed unnecessary. Closure rationale is typically required before closure approved is granted.

<u>Accepted</u> – accepted risks have residual risk but continued efforts to prevent or mitigate are not deemed practical. Accepted risks will be reviewed periodically to reevaluate acceptance rationale and to assure that risk controls remain effective.

Residual risk is obviously still present for Open risk item as well.

Residual risk is rarely quantified. There are two reasons for this 1) there is no mechanism to compute and combine residual risk, and 2) residual risk is typically deemed negligible and therefore ignored. A concern arises when cumulative risk of hundreds of dispositioned risk items could be quite large. ISPAR computes residual risk both at the risk item level and for the total project in the form of *Rm* and *CPRM*.

Chapter 10 Fire Suppression System Example Project

Fire Suppression System (FSS) is a fabricated test platform used to illustrate the ISPAR methodology. It is based on a PRA example for a fire suppression system in (Modarres, 2006), and has been expanded to include the project design, installation and operations.

Risk items are identified and characterized using current Project Risk Management practices and also analyzed using this new method to show the advantages in the insight and amount of risk information that can be used by the management team. This is not meant to show optimum solutions of these particular management issues, but only to exercise the methodology. In fact, the type of contracts, incentives, and insurance provisions for sharing risk among parties would most likely have been put in place.

10.1 Project Description

The project is presented as a system with programmatic and technical descriptions. Programmatic environment and assumptions are presented along with descriptions of the baseline consequence models. Project descriptions include the system hardware and operational scenarios.

10.1.1 Programmatic Description

A fire suppression system is being acquired to extinguish all possible fires in a plant with toxic chemicals. This system must be installed before the unit is allowed to operate. Data provided by the insurance company estimates loss following levels of; minor damage ($1 Million), major damage ($92 Million), and catastrophic ($210 Million).

A company has been contracted to design and install the system. This contract is for $325,000 and a delivery date 24 weeks from contract award. The contractor's PM has been told by his management that his priorities are cost first, then schedule, and then performance of the system. The PM is under pressure to bring in cost and schedule on plan. He is generally cautious about making decisions that have large impacts to the company. With these considerations, utility function parameters are given in Table 10-1 for use with preference utility and multi-attribute utility equations presented in Chapter 6. Same assumptions about the independence of preference to each other are used here for simplicity.

Table 10-1. FSS utility functions

	Risk Aversion (β)	Weight
Cost	0.08	0.55
Delay	0.2	0.25
Pr Loss	5×10^{-5}	0.20

Risk items and quantification are first developed from a viewpoint of the contractor PM. Later the same data will be evaluated from the plant management perspective where the preferences are quite different. The plant management is extremely sensitive to schedule, then the performance of the system, while cost is nearly irrelevant. This discrepancy is because the plant's pressure is to get the unit in service producing revenue as soon as possible. The revenues generated dwarf the cost of this improvement.

10.1.2 System Description

Due to the unique nature of the chemicals, a special new technology sensor is required for operation in one location in the plant. This sensor will interface with an existing Detector / Alarm / Actuator (DAA) design. A third party vendor is developing the proprietary sensor based on experience designing and producing similar sensors.

FSS system design is shown in Figure 10-1, consisting of two physically independent water extinguishing nozzles designed such that each is capable of controlling all types of fires in the plant. Extinguishing nozzle 1 is the primary method of injection. Upon receiving a signal from the DAA device, pump 1 starts automatically, drawing water from the reservoir tank and injecting it into the fire area in the plant. If the second path is not available, the operators will call for help from the local fire department, although the DAA also sends a signal direction to the fire department. However, due to the delay in the arrival of the local fire department, the magnitude of damage would be higher than it would be if the local fire extinguishing nozzles were available to extinguish the fire.

Under all conditions, if the normal off-site power is not available due to the fire or other reasons, a local diesel generator, which is normally on standby, would provide electric power to the pumps. The power to the DAA is provided through batteries, which are constantly charged by the off-site power. Even if the AC power is not available, the DC power provided through the battery is expected to be available at all times.

Manual valves on the two sides of pumps 1 and 2 are normally open, and only remain closed when they are being repaired. The entire fire system and the generator are located outside of the main chemical reactor compartment, and the therefore not affected by an internal fire.

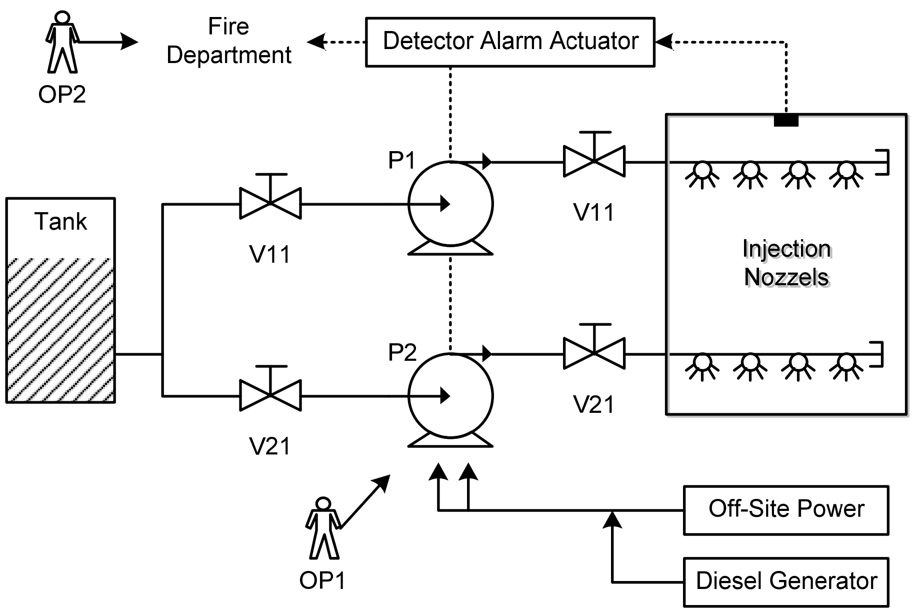


Figure 10-1. Example Fire Suppression System

10.1.3 Consequence Models

A contractor schedule and cost estimates have been approved by both parties as part of contract negotiations. Estimates are derived using the following models; a cost estimate based on a WBS roll-up, a CPM/PERT schedule, and a system PRA to determine expected loss. All have been set up as probabilistic models with Monte-Carlo simulations in Microsoft Excel with Palisades @Risk add-on. Simple triangle probability distributions are associated with each data element in the following consequence models.

The project schedule is shown in Figure 10-2. The simplified spreadsheet implements this PERT/CPM using standard equations to compute the critical path (Stewart, 1991). Solid bars in the schedule indicate that the task is on the critical path while the others are not. A Monte-Carlo simulation results in the probability of exceedance curve in Figure 10-3, with a mean of 24 weeks. This defines the schedule baseline.

This model is used to evaluate potential delays at a task level to produce the amount of delay of the final delivery date.

Project Duration 24.17

Description		Durn
Select Contractor	Critical	1.3
Deliver Building Plans	Critical	1.3
Develop System Layout	Critical	4.1
Design/Build/Test new DAA		8.3
PDR	Critical	0.2
Finish detailed design	Critical	4.1
CDR	Critical	0.2
Build-up Sub Assemblies	Critical	4.2
Install Piping	Critical	3.5
Install Fixtures		2.1
Inspection	Critical	1.1
Install Electrical Components		2.1
Inspection		1.1
Charge System	Critical	0.6
Pressure Test	Critical	0.8
Electrical Test	Critical	0.8
Communication Test		0.8
Review Test Results	Critical	1.0
QA Audit of Calibrations	Critical	0.6
Obtain County Approvals	Critical	1.2

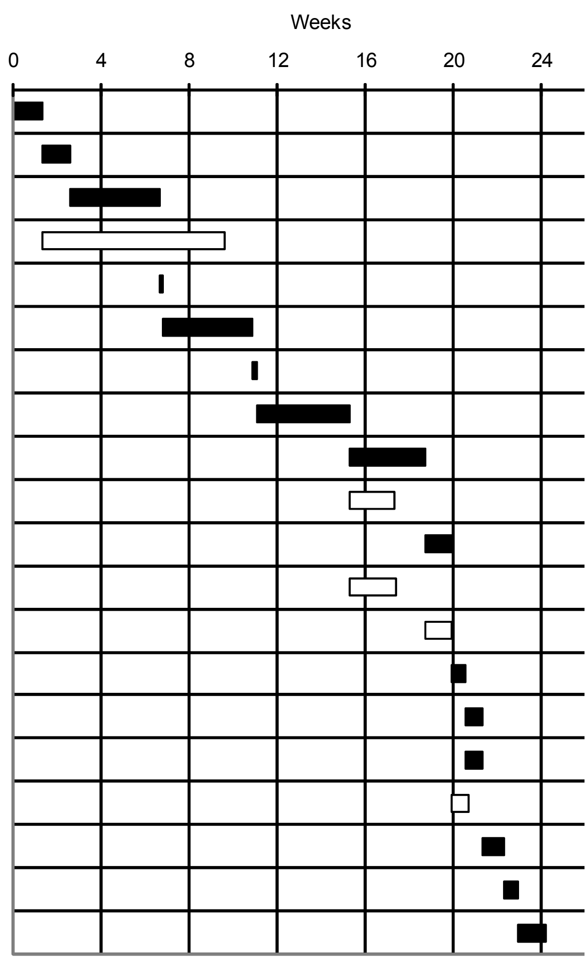


Figure 10-2. FSS milestone schedule

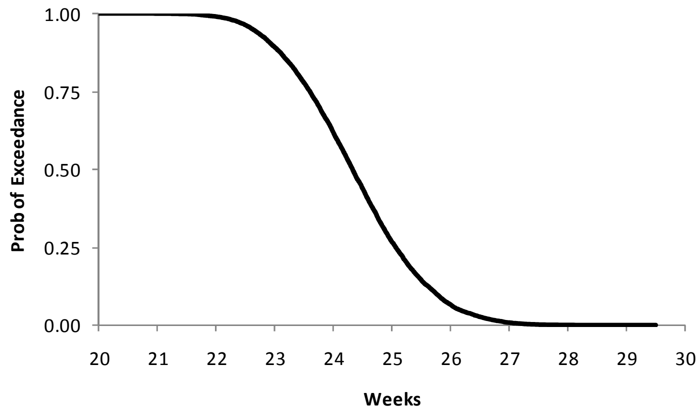


Figure 10-3. FSS estimated duration

A cost model based on a Work Breakdown Structure was employed to determine a cost estimate. The WBS and costs for each element is shown in Table 10-2 resulting in a spend plan shown in Figure 10-4. An estimate of just under $325K is produced along with its probability of exeedance distribution, see Figure 10-5.

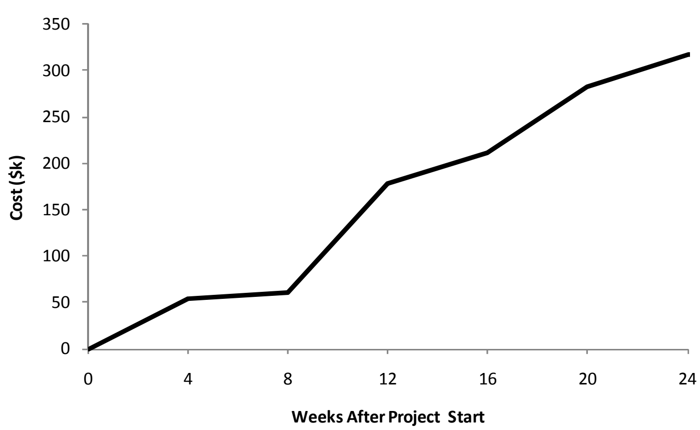


Figure 10-4. FSS spending plan

Table 10-2. FSS cost consequence model

Code	WBS Item	Wk4	Wk8	W12	W16	W20	W24	Total
1	Project Management	1	1	1	1	1	2	7.12
2	System Engineering	3	3	2	1	1	4	14.23
3	Fire Protection System							
3.1	Electrical							
3.1.1	Detector / Alarm / Actuator Device	50		25		25		101.67
3.1.2	System Wire Harness		1	3	3	2		9.15
3.1.3	Communication Hookup				0.5	1		1.53
3.1.4	Power Hookup				1	3		4.07
3.2	Mechanical							
3.2.1	Piping			5	5	5		15.25
3.2.2	Pumps				2	15		17.28
3.2.3	Valves			1	5			6.10
3.2.4	Injection Nozzles				2	10		12.20
3.2.5	Diesel Generator			75	5			81.33
4	System Support							
4.1	Construction Equipment			2.5	5	5	5	17.79
4.2	Logistic Support		1	1	1	1	1	5.08
4.3	Transportation			2	2	2	2	8.13
5	System Test & Inspection							
5.1	Test Equipment						4	4.07
5.2	Test & Inspection Coordination						6	6.10
6	Operational Support							
6.1	Spares						8	8.13
6.2	Training						5	5.08
	Monthly Totals	54	6	118	34	71	37	324

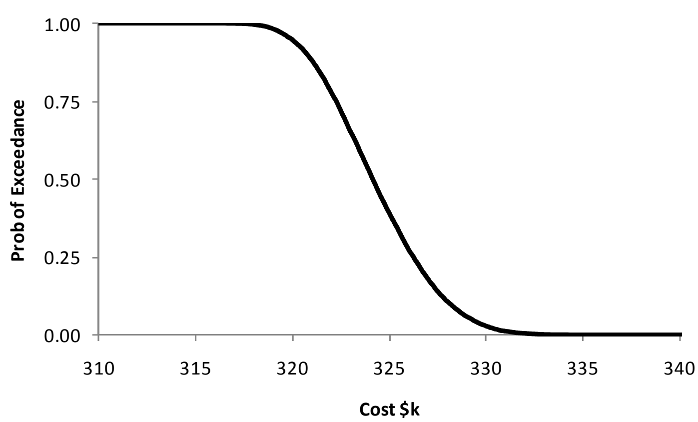


Figure 10-5. FSS estimated cost

The system model is a PRA consisting of one ESD shown in Figure 10-6, fault trees of each pivotal event, basic event probability data (Modarres, 2006). All endstate probabilities are conditioned given a fire in the unit. Table 10-3 lists all cutsets for the endstates as generated by SAPHIRE[5]. The single figure of merit is an expectation of loss given the loss profile in Table 10-4. The baseline is $896 with a probability of exceedance curve in Figure 10-7.

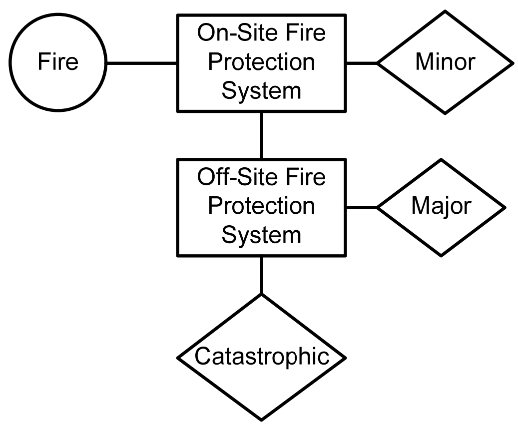


Figure 10-6. FSS system ESD

The preceding baseline consequence models are combined to produce the baseline risk profile in Figure 10-8 which yields a baseline *Rm* or 0.9738. All of these models are produced in projects as a matter of normal best practices. Even if a simulation is not run against the models, analyst's opinion about the estimate variances can be elicited to produce similar curves and input for the risk baselining process.

[5] SAPHIRE (*Systems Analysis Programs for Hands-on Integrated Reliability Evaluations*) is a probabilistic risk and reliability assessment software tool developed for the U.S. Nuclear Regulatory Commission (NRC) by the Idaho National Laboratory.

Table 10-3. FSS PRA cutsets

Catastrophic Endstate Cutsets		Major Endstate Cutsets	
Frequency per Year	**Events**	**Frequency per Year**	**Events**
1.789E-010	LFD, PUMPCCF	1.278E-006	PUMPCCF
7.100E-011	DAA, OP2	2.300E-007	P1, P2
3.221E-011	LFD, P1, P2	1.278E-007	OP1, P1
1.789E-011	LFD, OP1, P1	7.100E-008	DAA
9.940E-012	DAA, LFD	5.368E-008	P2, V11
7.515E-012	LFD, P2, V12	5.368E-008	P2, V12
7.515E-012	LFD, P2, V11	5.368E-008	P1, V22
7.515E-012	LFD, P1, V21	5.368E-008	P1, V21
7.515E-012	LFD, P1, V22	2.982E-008	OP1, V11
4.175E-012	LFD, OP1, V12	2.982E-008	OP1, V12
4.175E-012	LFD, OP1, V11	1.252E-008	V12, V22
1.753E-012	LFD, V12, V21	1.252E-008	V11, V22
1.753E-012	LFD, V11, V21	1.252E-008	V12, V21
1.753E-012	LFD, V12, V22	1.252E-008	V11, V21
1.753E-012	LFD, V11, V22	7.100E-009	TANK
9.940E-013	LFD, TANK	4.295E-009	DG, OSP
6.014E-013	DG, LFD, OSP	1.278E-010	N2, P1
1.789E-014	LFD, N2, P1	1.278E-010	N1, P2
1.789E-014	LFD, N1, P2	7.100E-011	N1, OP1
9.940E-015	LFD, N1, OP1	2.982E-011	N2, V11
4.175E-015	LFD, N2, V12	2.982E-011	N2, V12
4.175E-015	LFD, N2, V11	2.982E-011	N1, V22
4.175E-015	LFD, N1, V21	2.982E-011	N1, V21
4.175E-015	LFD, N1, V22	7.100E-014	N1, N2

Table 10-4. FSS probability of loss

Endstate	Loss ($)	Pr
Minor	1,000,000	7.08×10^{-4}
Major	92,000,000	2.04×10^{-6}
Catastrophic	210,000,000	2.75×10^{-10}

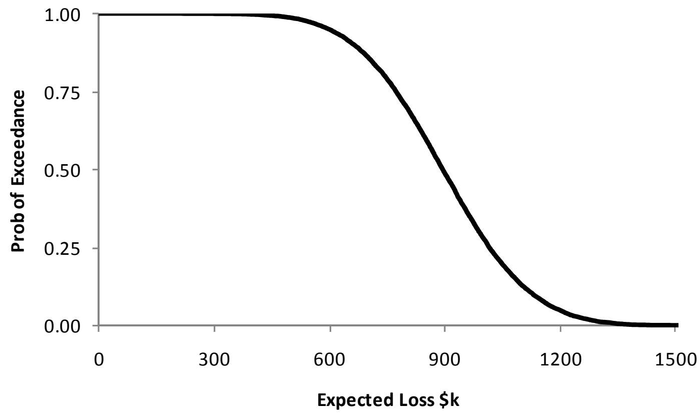


Figure 10-7. FSS expected loss

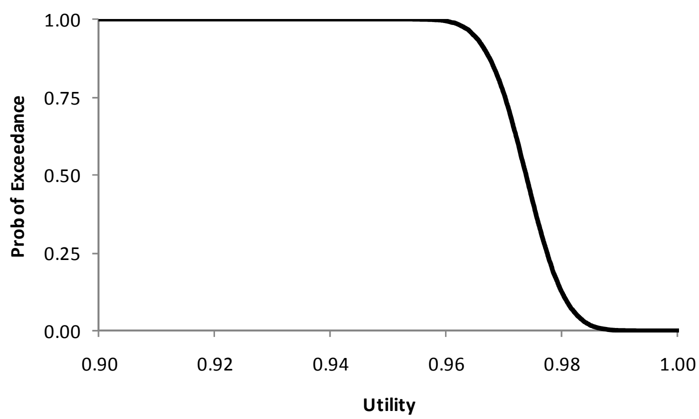


Figure 10-8. FSS baseline risk profile

10.2 Project Risk Management Using Current PRM Approaches

Normal procedures produced five identified risk items listed Table 10-5 that threaten successful completion of the project. Likelihood and consequence assignments reflect the best estimations of the contractor's management team. They were scored using values similar to those shown in Chapter 2. A risk matrix, Figure 10-9, determines priority levels for risk reduction.

Table 10-5. FSS risk register

#	Risk	Mitigation	Type	L	C
1	If sensor head cannot be built to match specific chemical signature, then the DAA will not be effective.	Use standard sensor head	Technical	1	5
2	If cost of materials continues to rise, then the project reserve will be eroded.	Purchase before design is approved	Cost	4	4
3	If site prep discovers an old chemical spill, the project will be delayed.	Move DG inside	Schedule	2	2
4	Industry alert concerning nozzle types potentially defective	None, use nozzles as is	Technical	1	3
5	If the new inspector (unfamiliar with plant specifics) does not approve of the previous informal agreements with past inspectors, then the project will slip.	Include inspector in design process	Schedule	3	1

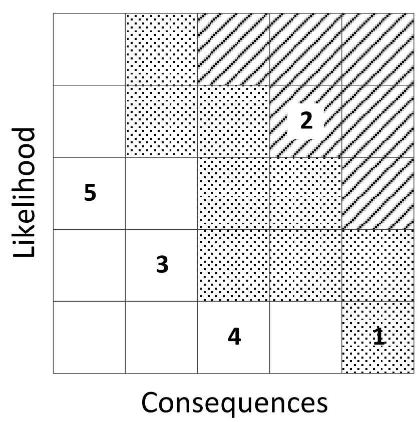


Figure 10-9. FSS risk matrix

Risk item #1 is based on technical information from the DAA vendor. Risk item #2 is written as a threat to cost with a consequence of $10k and supplier information about a high likelihood is easily identified as a threat to the PM's number one priority.

Risk items #2 and #1 get the most attention. Risk items 3-5 are deemed negligible and are essentially ignored.

Mitigation action plans developed for Risk Items #1 and #2 would be developed and implemented. Status of each risk item would be discussed at weekly/monthly reviews with management to show how these risks are under control.

10.3 Project Risk Management Using ISPAR Approach

This section uses risk information presented in the previous section and applies the ISPAR methodology as described in Chapters 3 - 8. RSDs are created for each of the five risk items. For simplification the analysis is performed at the pivotal event level. For each risk item risk profiles and risk metrics are shown with and without mitigation actions. A total project *CPRM* and risk profile are also presented. Risk item, event, and decisions are rankings using various importance measures.

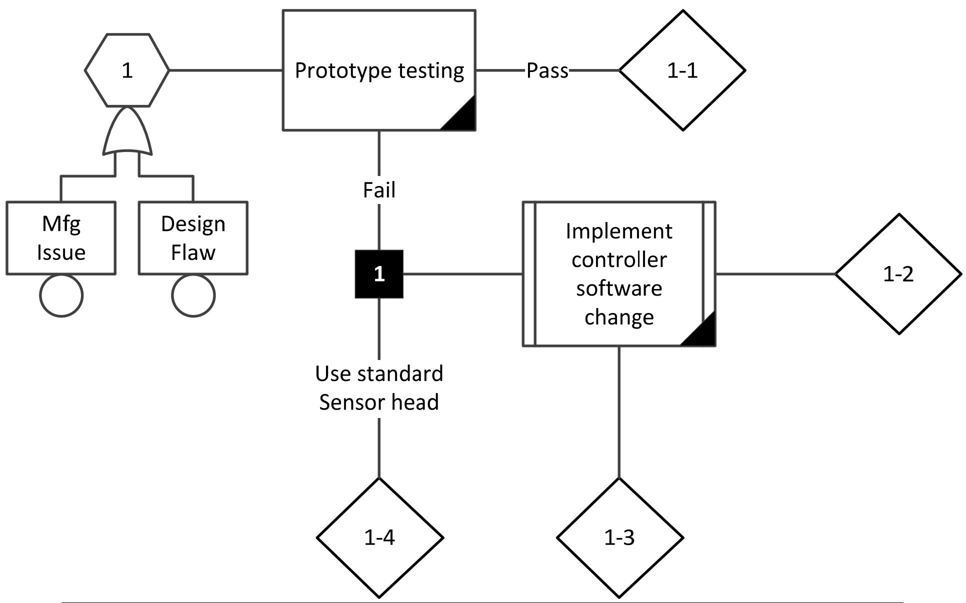
A note of quantitative convention, the *Rm* values are small so for readability they have all been multiplied by 10^6.

10.3.1 Risk Item Analysis

The following are descriptions of each risk item presented in the risk register. It is envisioned that the same identification procedures would be used to identify the risk items. So the point of departure between PRM and ISPAR would be the analysis of the risk items and the characterization of scenarios and event data.

Risk Item #1: Sensor Head Design

Risk item 1 is a concern about of the sensor head performance which can be either a manufacturing issue or a design flaw. The vendor does have in place a prototype test that catches 95% of all problems. A software change is an option costing $25K. The estimated 2-week delay of DAA will not affect the critical path. The engineers estimate the DAA failure rate will increase 25%, only 80% of potential issues can be addressed. However, using the standard sensor head would be an order of magnitude worse in this specified environment.



Endstate	Cost ($K)	Delay (weeks)	EV[Loss] ($)	Utility
1-1	0	0	896	0.9738
1-2	25	0	898	0.9726
1-3	25	0	954	0.9709
1-4	0	0	1537	0.9543

Figure 10-10. FSS risk item #1 RSD

Quantifying the RSD yields risk profiles for RI#1 with no mitigation and with mitigation as a result of decision point 1shown in Figure 10-11. Recall that up and right is better than down and left. One can easily see that implementing the mitigation will improve the situation. A result that should be intuitive, but now the amount of improvement is tangible, especially when examining *Rm* for each which yields an improvement from 2938 to 440 (smaller is better).

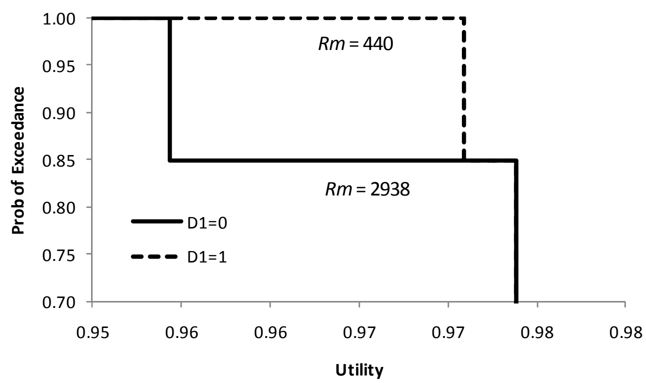
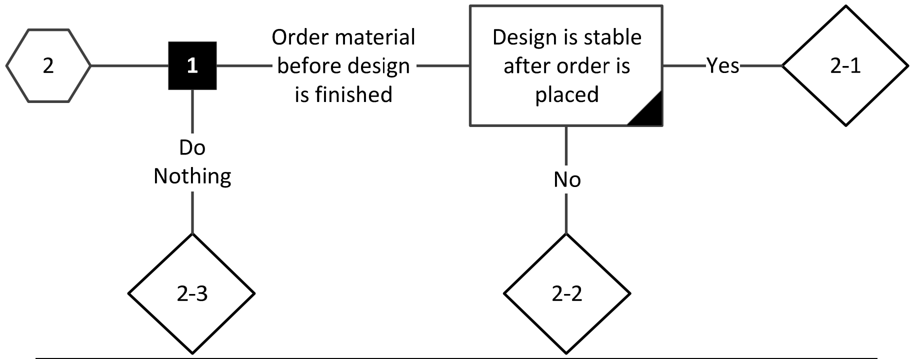


Figure 10-11. FSS risk item #1 risk profile

Risk Item #2: Cost Escalation

Information from suppliers and vendors indicate a 75% chance that costs will escalate by $10k across the board. Ordering material early runs the risk that the design will change and therefore $5k and 2 weeks will be lost. Historically a change in a design is an in-frequent event. However, risk items #1 and #3 have design changes as potential outcomes making endstates 2-1 and 2-2 dependent of those risk items.



Endstate	Cost ($K)	Delay (weeks)	EV[Loss] ($)	Utility
2-1	0	0	896	0.9738
2-2	5	2	896	0.9734
2-3	10	0	896	0.9763

Figure 10-12. FSS risk item #2 RSD

This risk is ranked as the only high risk on the risk matrix, due mostly to an over-reaction by the PM about his number one priority. The risk metric indicates that this is a much less significant risk than RI#1.

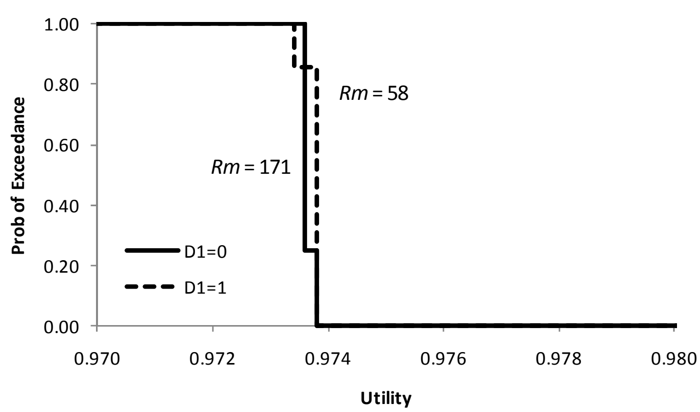
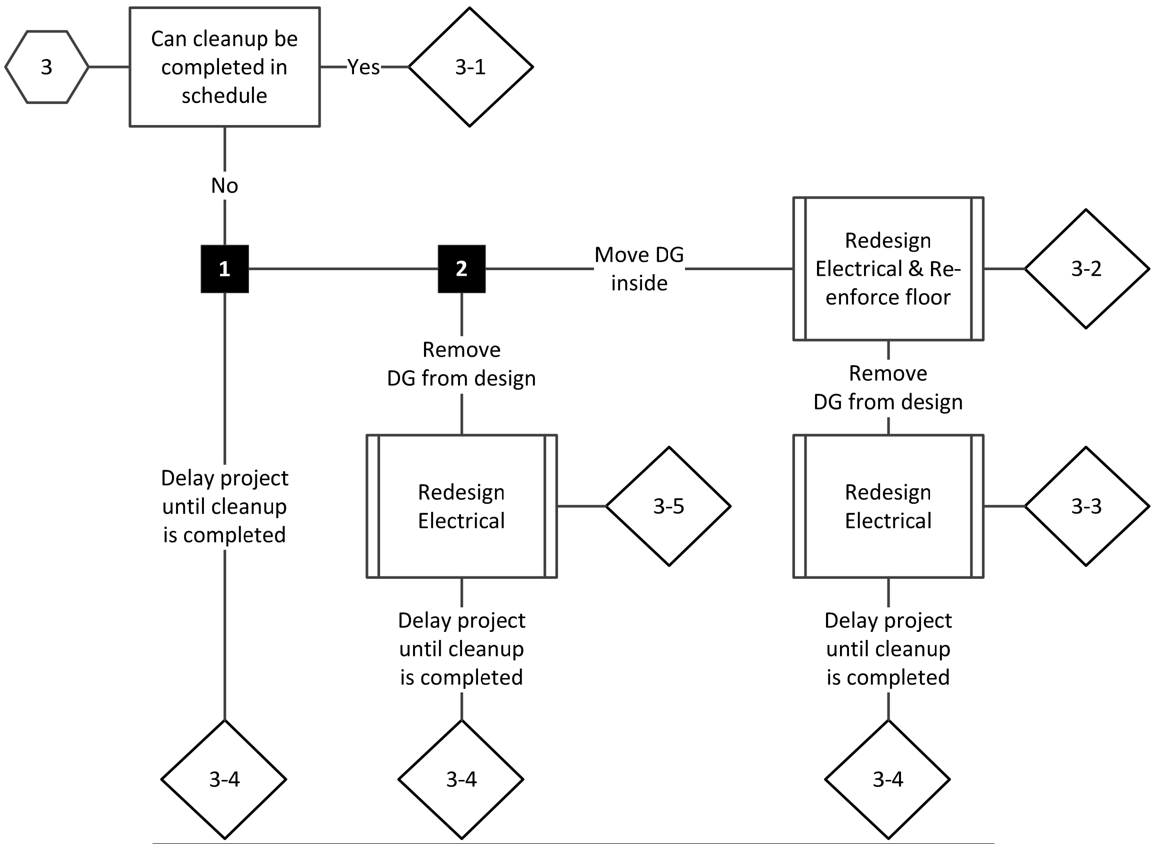


Figure 10-13. FSS risk item #2 risk profile

Risk Item #3: Chemical Spill Site

This initiator is a remote event, but the potential consequence could be large if a clean-up were to be required, costing $50k and 10 weeks delay. The site of concern is where the diesel generator is slated to reside. The alternatives would be to move the diesel generator inside or remove it from the design until a later date. Should these two alternatives fail the project would be forced to wait for the clean-up activity to be completed.



Endstate	Cost ($K)	Delay (weeks)	EV[Loss] ($)	Utility
3-1	0	0	896	0.9738
3-2	5	0	896	0.9737
3-3	6	1	903	0.9733
3-4	50	10	896	0.9599
3-5	1	0	903	0.9736

Figure 10-14. FSS risk item #3 RSD

The risk profiles show that either alternative will decrease risk and that there is no real distinction between the two.

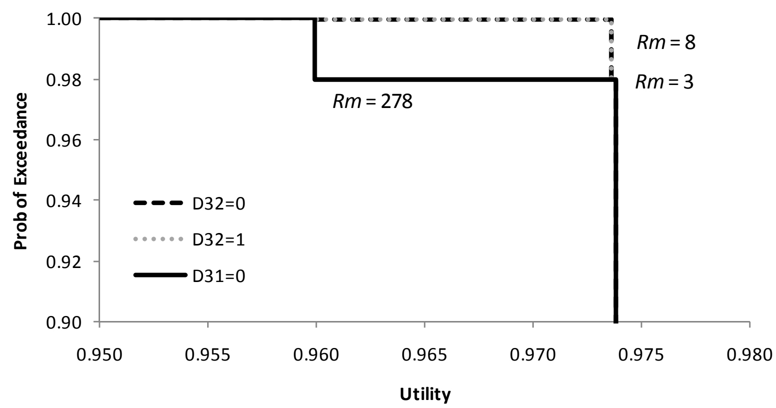
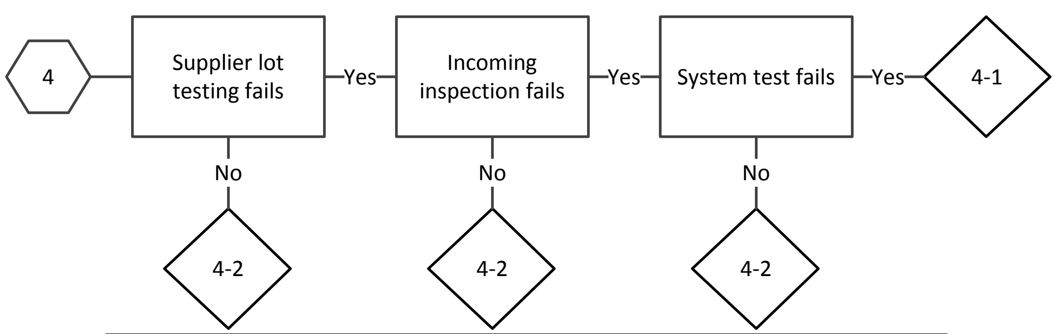


Figure 10-15. FSS risk item #3 risk profile

Risk Item #4: Injection Nozzle Defect

No mitigation is possible for a potential defect in the nozzles. The project must rely on a series of tests already scheduled. This type of defect is a latent failure that could remain until the system is called upon. The result here is a significant increase in the PRA expected loss value.



Endstate	Cost ($K)	Delay (weeks)	EV[Loss] ($)	Utility
4-1	0	0	896	0.9738
4-2	0	0	4954	0.8393

Figure 10-16. FSS risk item #4 RSD

Analysis shows the risk level to be quite high relative to the other risk items.

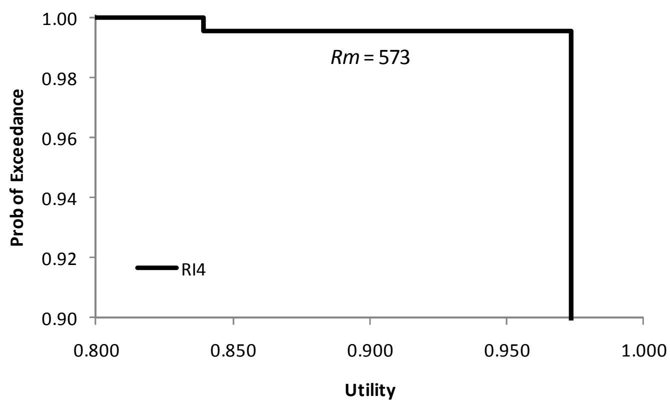
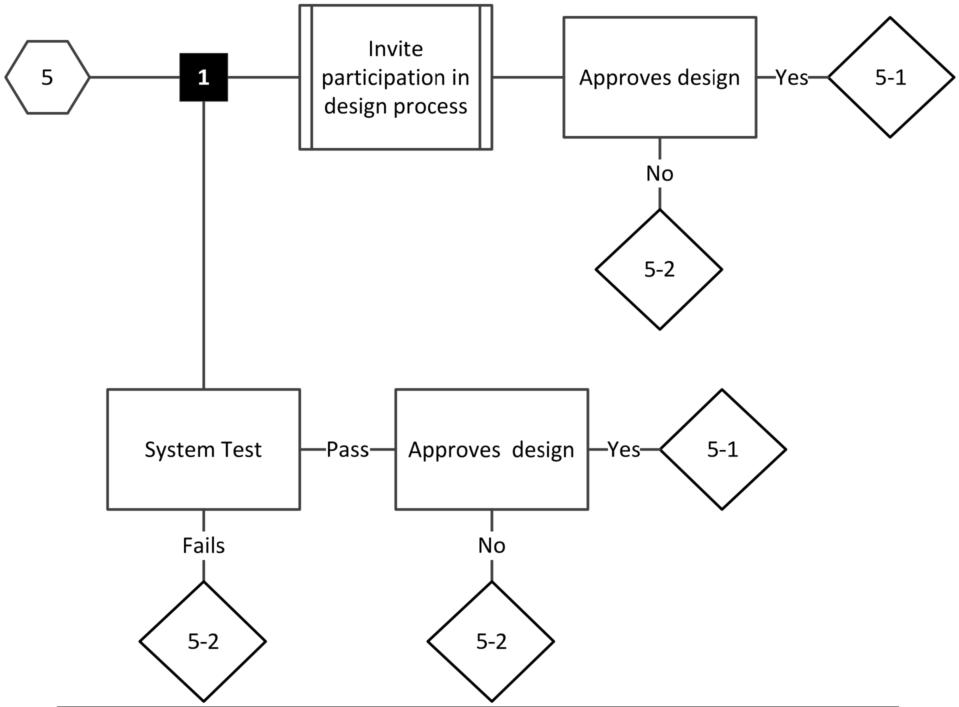


Figure 10-17. FSS risk item #4 risk profile

Risk Item #5: New County Inspector

There is always a chance that a new inspector unfamiliar with this plant would be assigned to the project. History shows that these inspectors are much more cautious and will not approve the design until a successful system test. However, if the inspector is part of the process early the likelihood improves. The system test event is the same event shown in RI#4, thereby creating a dependency.



Endstate	Cost ($K)	Delay (weeks)	EV[Loss] ($)	Utility
5-1	0	0	896	0.9738
5-2	10	4	896	0.9728

Figure 10-18. FSS risk item #5 RSD

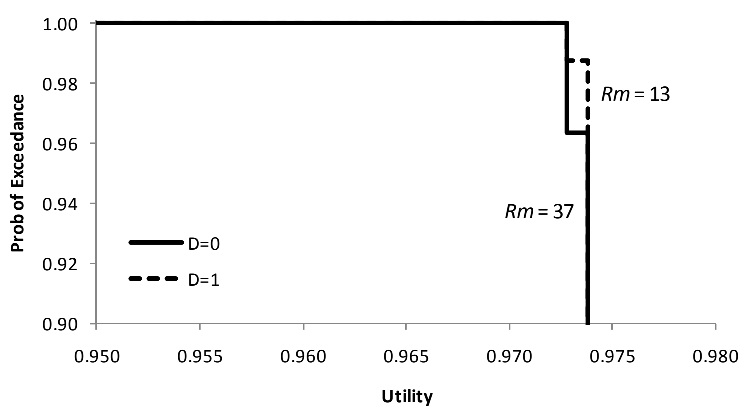


Figure 10-19. FSS risk item #5 risk profile

10.3.2 Risk Profiles

Some insights can be obtained by having all the risk profiles provided to the PM as shown in Figure 10-20. This graphical presentation shows RI#1 to be the largest threat while RI#2 and RI#5 have little significance. RI#3 and RI#4, thought to be negligible are indeed contributors. Other observations are that RI#1 has a large variation in the probability while the variation in RI#4 comes from consequences.

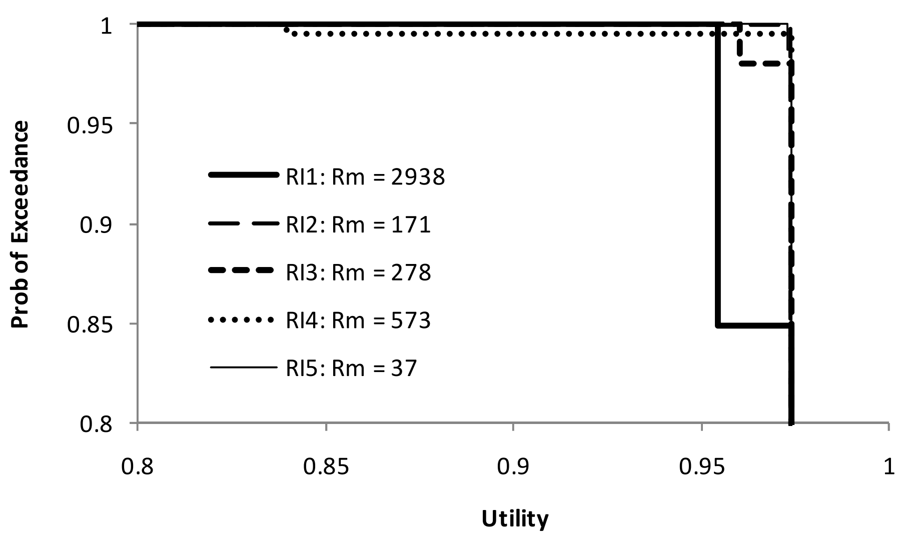


Figure 10-20. FSS risk profiles for all risk items

These profiles are combined to form a composite profile in Figure 10-21 and used to calculate *CPRM*. Notice that *CPRM* (4201) is not the sum of *Rm* (3997). That is because of the endstates combining in a non-linear fashion.

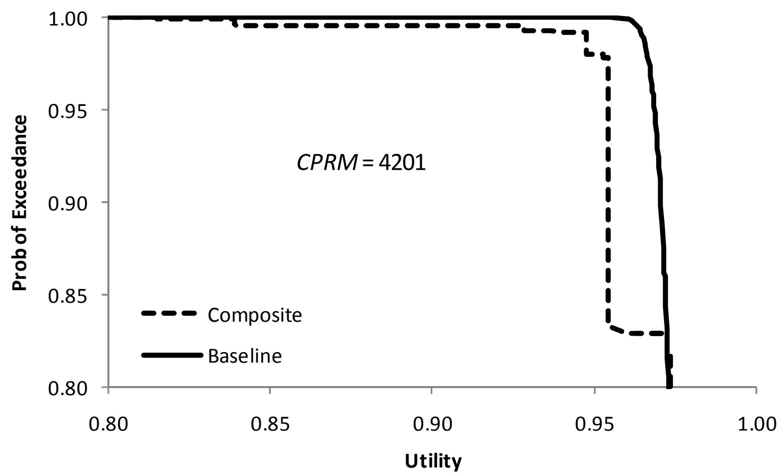


Figure 10-21. FSS composite risk profile

10.3.3 Risk Metrics

Each risk item has a *Rm* signifying its inherent risk if nothing is done to mitigate it. Notice that the priority ranking is different than that of the risk matrix. This difference is not just an artifact of this case study, but an example of how a scenario can provide insight to risk items.

Table 10-6. FSS risk metrics

Risk Item	Rm	Rm w/Mitigation	CPRM w/Mitigation
1	2938	440	2261
2	171	58	3908
3	278	D32=0; 8 D32=1; 3	3735 3729
4	573	573	4201
5	37	13	4162

Since, the basic events are populated with probability distributions (arbitrarily assigned triangular distributions), we also get distributions for *Rm* and *CPRM.* Monte-Carlo simulation results for *CPRM* yields a distribution shown Figure 10-22. Model output has been fit to a normal distribution with parameters μ = 4159 and σ = 5561. Recall that a risk metric is compared to a baseline, so we read this as the project having 77.5% chance of incurring a shortfall. If the PM implements all the mitigations, this number falls to 57.6%.

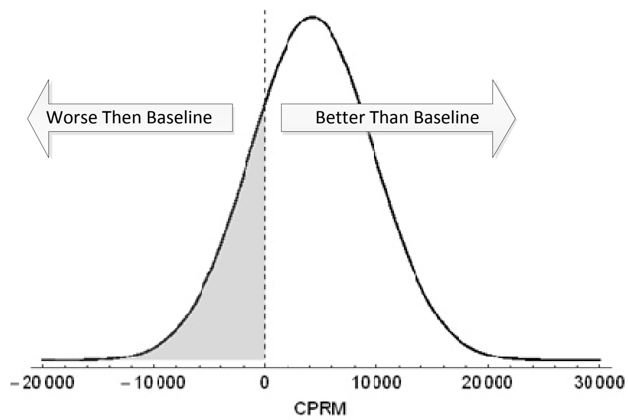


Figure 10-22. FSS CPRM distribution

This uncertainty is based on the variability in event probabilities only. We can extend the analysis by incorporating uncertainty in consequence models and by treating the baseline as uncertain. A latter case would be a comparison of overlapping distributions. This analytical capability shows the impact of assumptions on the total risk picture. It would allow for other types of alternatives to be considered, such as testing to reduce uncertainty. It also sets the stage nicely for data collection and monitoring feedback mechanisms to influence results through Bayesian updating.

10.3.4 Importance Measures

The previous section presented metrics by which the risk items could be ranked. Since the model is an integrated view of project risk, events and decisions can be rank-ordered and prioritized. From the importance measures in Table 10-7 and Table 10-8 the following priorities are established:

- Manufacturing defect in the new sensor head design
- Decision D11
- System test
- all three nozzle events (tied)

Table 10-7. FSS importance measures

	0	1	Bn	RRW	RAW	FV
Sensor manufacturing issue	20751	1280	19471	3.2820	4.9395	0.00078
Sensor Design flaw	5013	4185	828	1.0038	1.1933	0.00024
Test condition	4516	4185	331	1.0038	1.0750	0.00024
Software change	4201	4201	0	1.0000	1.0000	0.00024
Cost of material increase	4323	3824	499	1.0986	1.0290	0.00026
Design change after order	4201	4201	0	1.0000	1.0000	0.00024
Clean-up	8480	3726	4754	1.1275	2.0186	0.00027
Clean-up on schedule	6103	3726	2377	1.1275	1.4527	0.00027
Floor reinforcement	4201	4201	0	1.0000	1.0000	0.00024
Electrical redesign	4201	4201	0	1.0000	1.0000	0.00024
New Inspector	4380	4141	239	1.0145	1.0426	0.00024
Design approval	4553	4183	370	1.0043	1.0838	0.00024
Bad Nozzle	4302	3627	675	1.1583	1.0240	0.00028
Supplier test	4775	3627	1148	1.1583	1.1366	0.00028
Nozzle inspection	9371	3627	5744	1.1583	2.2307	0.00028
System test	9722	3588	6134	1.1708	2.3142	0.00028
D11	4201	2261	1940	1.8580	1.0000	0.00044
D21	4201	3908	293	1.0750	1.0000	0.00026
D31	4201	3735	466	1.1248	1.0000	0.00027
D32	4201	3729	472	1.1266	1.0000	0.00027
D51	4201	4162	39	1.0094	1.0000	0.00024

Table 10-8. FSS decision importance measure

Decision Point	Probability of Decision	IM_{DP}
D11	0.151	0.0696
D21	0.750	0.0523
D31	0.020	0.0022
D32	0.020	0.0022
D51	0.250	0.0023

This ranking is consistent using any of the importance measures. When we examine the decision importance measures we note confirmation that D11 is the most important, but unlike the other measures, D21 is the second most important. This fact is attributable to the probability having the make a decision being relatively high.

10.4 New Perspective

Suppose the contactor submits his risk items and metrics to plant management for review. Here ISPAR can take the same basic information about the scenarios, probabilities, and decisions and translate them through a different lens. Plant management is much more sensitive to schedule and system performance than to cost as shown in Table 10-9. In addition, they are much more risk averse to system performance. These values replace the contractors values and provide an indication of risk from their perspective.

Table 10-9. FSS plant utility functions

	Risk Aversion (β)	Weight
Cost	0.0004	0.05
Delay	0.1333	0.75
Pr Loss	0.0002	0.20

Upon re-running the model, *CPRM* = 4630, which is a higher level of overall risk. Risk level for the individual risk items also increased with one exception. RI#1, while still the highest, is quite a bit less than it is for the contractor. In addition, risk with mitigations are much higher than before. Notice, that RI#2 actually gets worse with its mitigation.

Table 10-10. FSS risk metrics

Risk Item	Rm	Rm w/Mitigation	CPRM w/Mitigation
1	2135	530	3016
2	686	692	4639
3	880	D32=0; 20 D32=1; 16	3777 3773
4	555	555	4630
5	397	141	4379

Changing preferences yields the following rank ordered list based on new importance measures.

- Manufacturing defect in the new sensor head design
- Probability of spill to be cleaned up
- System test
- Nozzle inspections
- Clean-up schedule

While the sensor head is still the top priority, the rest of the list is differs. Decision D11 is no longer in the top 5 while the spill events are now on.

A shift in decision importance has also occurred, see Table 10-11. D11 is still the most important, but D51 is the next. Notice, D21 is negative reflecting that its mitigation makes matters worse. Its absolute value is the smallest signifying that it is not important from the plant management perspective.

Table 10-11. FSS decision importance measure with new perspective

Decision Point	Probability of Decision	IM_{DP}
D11	0.151	0.0525
D21	0.750	-0.0015
D31	0.020	0.0037
D32	0.020	0.0037
D51	0.250	0.0136

This capability to substitute preference parameters means that different organizations can make independent assessments based on the same data. No censoring of low risk items needs to take place, which may filter risk significant events from a different perspective. In this case study, plant management and contractor can discuss differences in perceived risk and understand where there source. Specific risk items, events, decisions, assumptions, or parameters can be identified and resolved in a mutually beneficial manner.

10.5 Discussion

This case study of a Fire Suppression System Project illustrates how ISPAR could be used. It provides a more robust understanding of a projects risk posture by using scenarios to describe risk items and integrating them into a unified model. The risk item metrics provide a systematic, traceable, and defendable measure of relative risk magnitude and potential improvement.

Analysis shifts focus from status updates for mitigation plans to decisions to be made and specific future events. Focus is set on a sensor issue and the outcome of a system test as key issues. These are tangible items management can study and impact.

The ability to share data and apply separate criteria will increase understanding among partners in a venture. Relying less on ambiguous notions of a matrix location and more on event probabilities based on data and judgment; and consequence analyses sets stage for decisions based on quantitative risk information.

This example illustrates ISPAR's implementation through process and modeling. A premise was the ability to start with identified risk items using identical processes as PRM whether they be brainstorming or checklist techniques. Mitigation activities and plans are woven into risk scenarios from the outset as an integral process step. Rankings of risk items can be used identically as they are now, but much more information can accompany them as they are presented to management.

Finally, a word about this particular example application. The model exists as an Excel spreadsheet and enhanced using Palisade @Risk simulation add-on. Cost, schedule, and PRA models are in the spreadsheet alongside event tree representations of each RSD. The composite risk model lays out all combinations in a large tree structure. Care was taken to evaluate each path for effects on consequences. All *Rm*, *CPRM*, and IM results are produced within the spreadsheet. Working in this environment is labor intensive, but it does show promise for a real data and computational tool to implement this framework.

Chapter 11 Application

During this study access was provided to risk registers being generated for two projects. The first, Project #1, was a relatively small project designing and building a spacecraft sensor. Preliminary ideas for creating RSDs were tried. Lessons were learned and used to modify techniques and methodology for use in the next project application. Project #2 was a large scale spacecraft development effort that allowed full access to the risk database, risk manager, system leads, and the Project Manager. RSDs were developed for each risk item in a period of time. This chapter discusses the observations and lessons learned during these activities.

11.1 Small Project #1

Project #1 was an endeavor to design and build a scientific instrument that would be integrated with a larger suite of instruments for a future space mission. The instrument measures energy and angular distribution of various element atoms and other ions. Despite having many new engineering and science challenges to overcome, the project had an aggressive delivery schedule.

The project team consisted of 10-15 people; engineers, scientists, technicians, and managers. Our participation was limited to receiving data in the form of risk item entries. Since this effort was exploratory in nature, there was no expectation of further interaction. Risk data was used to create RSDs and to discover pros and cons of the process.

Surprisingly, the data was difficult to use. Both because of its form and its content. No database existed as a repository, instead we were given monthly briefing packages to the customer which contained a page or two listing that months current top ten risks. As such, the data showed only a one-line descriptor and an associated position on a 5x5 risk matrix. As a communication tool, this apparently worked well when risk items were fresh and being worked day-to-day, however, as an archive to be used for research after the fact, it was lacking.

Risk items tended to be problems currently plaguing the project and not future potential problems. Statements in the charts were status reports of how problems were being rectified. Unexpectedly, this was rather difficult to diagram when the mind set is focused on describing events and future interactions. Also diagramming deterministic relationships started to lose meaning. Upon reflection, difficulty stemmed from my view that RSDs needed probabilistic alternatives and decisions. When this emphasis was relaxed it became apparent that risk items with an initiator probability of one could not only be modeled but could be useful. This realization ultimately led to an understanding that RSDs were a convenient tracking and status tool.

An interesting aspect of project #1 was that it was closely coupled with 2 other projects. All three shared the same core design and resources, but were built to different quality assurance and documentation requirements depending on their intended mission. As one might expect, much of the risk was tied to these dependencies.

Experience working Project #1 lead to a strong sense that an integrated scenario-based systematic risk management methodology was needed. It also led to enhancements in process steps:

- Integrating a more robust form of project risk management requires a PM that fully believes in the effort and actively uses it as a way to manage the project.
- Sole reliance on the risk register makes it impossible to develop RSDs because by the nature of being " if-then" statements provide no other information exists about other alternatives on the table.
- Using risk matrix scales without any information as to how they were developed and/or calibrated only leads to a vague notion of the PM "feeling" of both severity and likelihood.
- Consolidate risks items as much as possible. Do not try to make a one RSDS for every risk item unless the dependencies are expressly shown. Risk items created as the program moves along can recreate the same risk many times.

11.2 Large Project #2

Project #2 is a large multi-year venture to design, build, launch, and operate a scientific mission to Earth orbit. The scope covers all mission aspects including, spacecraft, instruments, ground control center, data processing centers, and networks. Many organization within the prime contractor, as well as partner institutions and equipment vendors are contributing to this mission's success.

The PM was extremely helpful and gracious providing full access to the entire online risk register database, access to the risk manager, access to all risk board meetings, access to systems engineers, and system design leads.

11.2.1 Project #2 Risk Management Process

Project #2 has an active and robust risk management process in place. As documented in a risk management plan, "Risk management shall be implemented to ensure risk items are mitigated and/or resolved before they jeopardize the successful execution of the program, become major sources of rework, or lead to cost and schedule overruns." It is structured around several "risk boards" deliberating about area specific risk items and elevating them when resolution cannot be decided or implemented at that level. The process is implemented by a "risk manger" but ultimate responsibility for risk management belongs to the PM.

Project #2 classifies risk items using Table 11-1 through Table 11-3 to identify risk area, likelihood and severity. These charts are pulled from the project's Risk Management Plan. Guidance on the use of these charts is provided by the parent organizations Risk Management Procedure:

> Both scales are a bit subjective in both dimensions. Developing risk attribute categories and the risk severity table is complicated by fundamental differences between technical, programmatic, and safety risks, particularly with respect to likelihood values. Technical risks generally operate in a regime of less than one in a billion to perhaps a few percent. For instance, a technical risk that yields a 10% chance of on-orbit failure would generally be considered quite high. On the other hand, programmatic risks usually operate on a scale from about 1% to nearly 100%. This represents both the lower fidelity in estimating programmatic risks and the higher tolerance of programmatic risks.
>
> From the combination of likelihood and consequence is derived a severity indicated by color (green, yellow, red) that is roughly identified with low, medium, and high levels of concern. Green risks are generally not discussed or reviewed in reviews. Yellow denotes a significant concern

that requires deliberate and careful assessment, monitoring, with consideration of mitigation, and with awareness and buy-off at all level when the program/project reaches “go/no-go” decision points. Similarly, a red assessment is taken to mean “no-go” without mitigation. This does not mean stop the project immediately, but it does mean that an acceptable mitigation plan shall be part of the path forward, and that mitigation must reduce the color level to yellow or green.

Table 11-1. Project #2 risk type classification

Risk Classification	Description
Technical Risk	Product Risk - focused on technical performance of the product. This includes risks associated with meeting performance specifications, maintaining adequate margins, and ensuring acceptable quality. Process Risk - addressed development methods including design methods, analysis methods and limitations, design validation, fabrication, assembly, and verification and testing approaches. Performance Risk - addressed risk associated with satisfying on orbit objectives. These may be Instrument performance risk, life expectancy, availability and other issues that manifest themselves following deployment Safety - emphasizes the potential for damage or injury to personnel, facilities, project equipment or the environment posed by project development, deployment, and operations activities.
Schedule Risk	The uncertainties linked to the adequacy of time estimated and allocated for development and production of the system. Schedule risk is usually analyzed in terms of: (1) the risk that schedule estimates and objectives are inaccurate, and (2) the risk that program execution will fall short of schedule objectives as a result of failure to identify and mitigate risks.
Cost Risk	The potential impact of contractual and budgetary constraints, as well as the resources available for a particular project. Cost risk analysis, in general, examines (1) the risk that cost estimates and objectives are inaccurate, and (2) the risk that program execution will not meet the cost objectives as a result of a failure to identify and mitigate operational or development risks.
Programmatic Risk	Catch-all for risks that do not fall into the previous categories. Programmatic risks may be associated with project staffing, facility availability, the sponsor relationship, subcontractor relationships, legal action, the dynamic nature of institutional policies, priorities, and risk tolerance, as well as the overall project working environment.

Table 11-2. Project #2 likelihood scale

Likelihood	Safety	Technical	Cost/Schedule
	Likelihood of safety event occurrences	Estimated likelihood of not meeting mission technical performance requirements	Estimated likelihood of not meeting allocated Cost or Schedule requirement or margin
5 Very High	$P_s > 10^{-1}$	P_T > 50%	P_{cs} > 75%
4 High	$10^{-2} < P_s > 10^{-1}$	25% < P_T < 50%	50% < P_{cs} ≤ 75%
3 Moderate	$10^{-3} < P_s > 10^{-2}$	15% < P_T < 25%	25% < P_{cs} ≤ 50%
2 Low	$10^{-5} < P_s > 10^{-3}$	2% < P_T < 15%	10% < P_{cs} ≤ 25%
1 Very Low	$P_s > 10^{-6}$	0.1% < P_T < 2%	P_{cs} ≤ 10%

Table 11-3. Project #2 consequence scale

Consequence	Safety	Technical	Cost	Schedule
5 Very High	Death or permanent disabling injury	Loss of S/C, instrument, or P/L	Project cost overrun of greater than 20% of allocated	
4 Major	Severe injury	Loss of one or more Level-1 science requirements	Project cost overrun between 10% and 20%	Schedule slip greater than 3 months
3 Medium	Injury with lost work time	Major loss of capability of S/C or P/L	Project cost overrun between 3% and 10%	Schedule slip affecting critical path but not launch or post-launch critical event
2 Minor	Minor injury with no lost work time	Decrease in S/C or P/L capability/ margin, but all mission requirements met, or need for requirement definition or design/ implementation workaround	Project cost overrun between 1% and 3% of allocated	Schedule slip not on critical path
1 Minimal	Negligible safety impact	Negligible technical impact	Project cost overrun of less than 1% of allocated	Negligible schedule slip

One of the project's requirements is to report risk status to its sponsor monthly as stated in the plan, "The risk report consists of two viewgraphs, a Top 10 risk list and a Risk Matrix Report." Formats are specified in the Statement of Work.

Project #2 adopted use of a risk management database tool called Project Risk Information Management and eXchange (PRIMX). This tool was developed under a NASA contract. It combines risk identification, analysis, planning, tracking, control, and communication into a single, comprehensive environment that meets NPR 7120.5B and NPR 8000.4 requirements. The PRIMX database is organized into several levels, with the top level being the Project; levels below that include Instruments, Spacecraft, and Ground Operations.

11.2.2 RSD Development

All risks in the project database were examined although only a few were subjected to creating RSDs. For a period of four months during the design phase (April - July 2010), RSDs were developed in parallel with normal risk management process. During this time 28 new risk items were entered into the system. These can be found in Table 11-4 (see Appendix B for more complete entry information) along with the risk registry entries. Entries and examples are redacted and modified under an agreement with the project for publication purposes. At the time of this writing over 225 risk items are in the database.

Table 11-4. Project #2 risk registry

ID	Title	Statement	L	C	Type
160	Nutation Damper Leak	If the nutation damper leak is not resolved in a timely manner, then the beginning of spacecraft I&T will be delayed.	2	2	Sched
161	Instr-H HV Part Failures	If the HV parts are not qualified for flight use, then the delivery of the full unit (with the high voltage board) will be delayed.	2	2	Sched
162	PSE HW Schedule Slip	If the PSE hardware continues to slip schedule then the hardware will be late to system I&T.	5	3	Sched
163	SSPA Part Leakage	If the SSPA amplifier part can not be made resistant to flux, solvent, and moisture degradation and long-term reliability ensured, then SSPA delivery schedule will be impacted.	1	4	Sched
164	Meeting Spin Balance Requirements	If our spin table is not used for final processing and checkout of the Observatory at the launch site, then uncertainty will be introduced into the spin balance measurements before launch.	2	2	Tech
165	PDU Op Amp Interface Qualification Test	If the op amp interface qualification test fails then the PDU flight build schedule will be impacted and PDU telemetry measurements will be degraded.	1	2	Sched
166	Radiation and Charge Monitoring	If additional spacecraft radiation and charge monitoring data is not available on-orbit then spacecraft model correlation and anomaly resolution will be difficult to achieve.	1	2	Tech
167	SSPA DC/DC Converter Burn-in Failure	If the purchased in-stock DC/DC converter cannot be used for flight, then SSPA schedule will be impacted.	2	2	Sched
168	PDU Flight Part Delivery	If PDU flight parts currently on order do not arrive in time to replace non-flight parts installed to allow board-level processing and test, then there will be a schedule impact.	2	3	Sched
169	Use of Bond Wire in SA Substrates	If the use of bond wire in some of the SA substrates is accepted, then the wires will become magnetized in space and will influence the Instr-M measurement results.	1	2	Tech
170	Instr-M Hybrid Delivery	If the hybrid boards are late, then the delivery of Instr-M units to the Spacecraft for I&T will be delayed.	1	3	Sched
171	Instr-M Detector Procurement and Delivery	If the solid state detector assemblies are delayed then the Instr-M instrument will experience delays that will impact the delivery schedule.	3	3	Sched
172	Instr-E DFB FPGA Verification	If the Instr-E DFB FPGA design verification and flight FPGA programming is not complete by July 2010, then Instr-E will deplete all of its funded schedule reserve and the Project I&T schedule will be impacted.	1	3	Sched

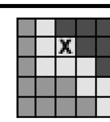
ID	Title	Statement	L	C	Type
173	SSPA Schedule Slip	If the SSPA continues to have part availability and fabrication issues, then there will be a critical-path schedule impact.	1	2	Sched
174	Part x Life Test Failure	If the part x failure investigation results in a rejection of remaining lot of parts, then there will be a XCVR receiver delivery impact.	2	3	Sched
175	Instr-R Waiver 006 Technical Risk - Pin gold thickness	If Instr-R uses pins/sockets with less than the minimum plating thickness of 50 microinches, a failure of a pin may occur.	1	2	Tech
176	I&T Staffing Shortage	If the I&T staffing shortage continues with no relief, system-level I&T scripts will not be ready when needed, and there will be a schedule impact.	1	3	Sched
177	Instr-R Resource Conflict with another mission	If the other program schedule moves to the right then Instr-R resource conflicts will occur affecting mission critical path.	1	3	Sched
178	Instr-R Mechanical Part Fabrication	If all Instr-R mechanical parts are not available when required, and have to be fabricated or ordered, then there will be a schedule impact.	2	3	Sched
179	Magnetometer Team Resources	If sufficient resources are not available to the magnetometer development effort to allow it to respond to additional work identified at another mission CDR, then the Instr-F magnetometer effort will incur schedule delays.	2	2	Sched
180	Instr-F Filter Tin Whiskers	If the existing filter flight parts cannot be used as is and require rework involving disassembly and reassembly of the filter cans, schedule will be very severely impacted.	2	3	Sched
181	Use of DC/DC Converters in the IEM	If the root cause of the unit failures is not resolved before flight part installation, then additional failures are possible.	1	3	Tech
182	IEM Flight Model 2 Schedule Slip	If the IEM flight mode 2 continues to have part availability, fabrication, and acceptance test issues, then there will be a critical-path schedule impact.	5	3	Sched
183	XCVR Schedule Slip	If the XCVR continues to have part availability and fabrication issues, then there will be a critical-path schedule impact.	5	3	Sched
184	PDU Flight Model 2 Schedule Slip	If the PDU flight model 2 experiences part availability and fabrication issues, then there will be a critical-path schedule impact.	1	2	Sched
185	Lot Jeopardy Parts Fail Qual Testing	If hardware being fabricated and/or tested use parts released on lot jeopardy, and those parts fail qualification testing, then there will be a schedule impact.	1	3	Sched
186	Spare Parts Not Available for Hardware	If spare parts (either mechanical or electrical) are not available to meet fabrication/rework needs, then there will be a schedule impact.	1	3	Sched

ID	Title	Statement	L	C	Type
187	IEM Test Team Staffing	If the IEM test team is not sufficiently staffed to work both flight box qualifications in parallel then the IEM delivery schedule will be impacted.	2	3	Sched
188	Instr-F Late Delivery to Observatory I&T	If the Instr-F suite is delivered late to the Observatory, guidance & control test schedule will be impacted which will impact the launch date.	2	3	Sched

As a risk was entered into the database, information was taken along with more extensive discussions with project personnel to create an RSD with alternative paths, mitigations, and decisions. The goal of this activity was three fold; 1) to determine feasibility of drawing RSDs in real time instead of risk statements, 2) to gain an understanding of the resources required, and 3) determine the value of such an activity constrained to qualitative assessments.

RI-160 was previously discussed in Chapter 4 as case study 1. Another example RSD is illustrated here, RI-161; Instrument-H High Voltage part failures, is one such risk item. Figure 11-1 shows the database entry and the corresponding RSD created is in Figure 11-2.

ID: RI-161



Title: Instrument-H HV Part Failures

Statement: If the HV parts are not qualified for flight use, then the delivery of the full unit (with the high voltage board) will be delayed.

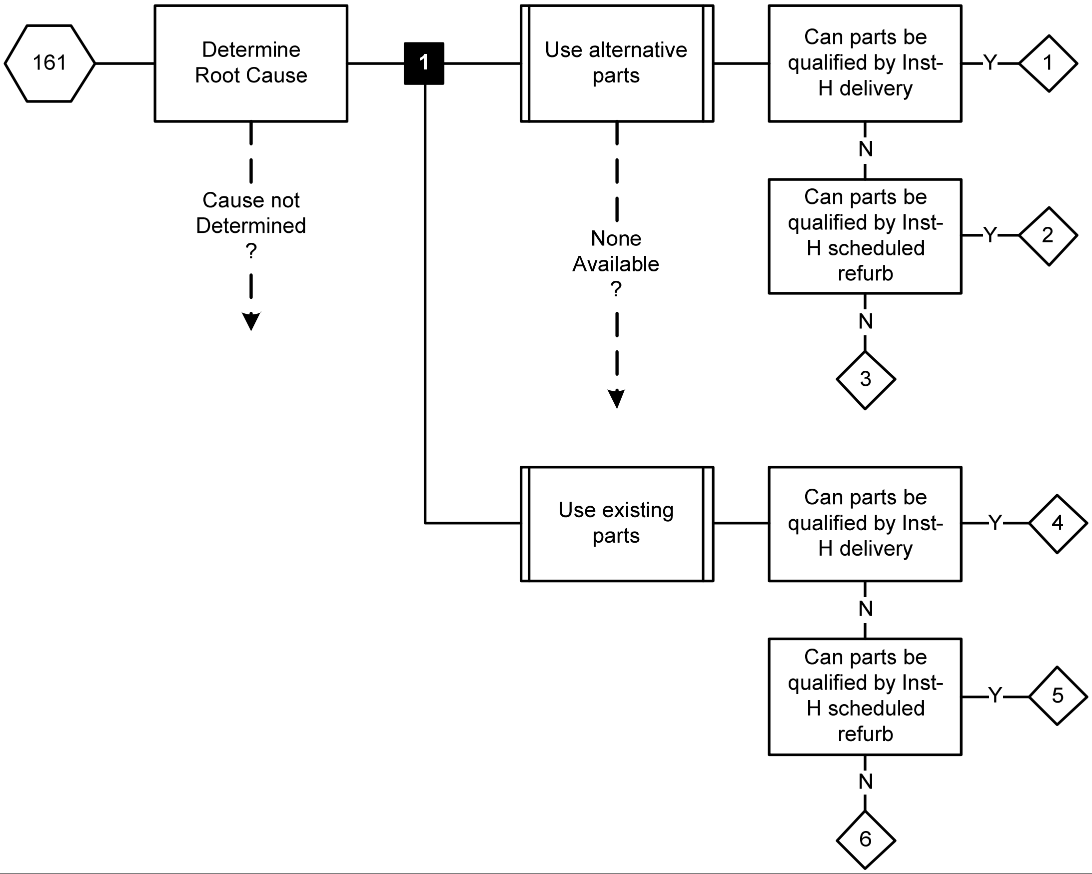
Context: Eleven optocoupler parts are used in each Inst-H on the high voltage power supply board. Vendor-S uses these part on 2 other sponsor missions. Recent HV failures on those programs have occurred. The 2 failure types on those programs were broken bond wire and LED lifting from the substrate. In addition, inspection of Inst-H parts found 2 parts appeared to have weak bonds as evaluated by x-ray and another had LED lifting.

Likelihood: 4 **Consequence**: 3 **Timeframe**: Near Term; up to 3 months

Class: Schedule **Area**: Science Instruments **System/SubSys**: Instr-H

Risk Owner: xxx **Area Lead**: xxx **Risk Status**: Open **Risk Action**: Mitigate

Figure 11-1. Project #2 RI-161 risk item entry



Endstate	Cost	Delay	Loss of Mission
1	x% increase of parts	Baseline	Approx baseline
2	x% increase of parts + delay cost	Refurb date	Approx baseline
3	x% increase of parts + delay cost	Late for I&T	Approx baseline
4	Baseline	Baseline	Baseline
5	Delay cost	Refurb date	Baseline
6	Delay cost	Late for I&T	Baseline

Figure 11-2. Project #2 RI-161 RSD

Included in the figure is an endstate legend which describes qualitatively the state the project would be in if it reached this point. It is a qualitative representation aimed at providing more information about the risk item so that likelihood and consequences scores can be assigned. There is still a need for a narrative description of the context for the risk item. Any recent history and pertinent data is valuable for the process.

Despite having two mitigation options identified in the database, two questions were uncovered regarding what to do if:

- root causes are not definitively identified - No answer was immediately forthcoming by the engineer, so the question was left as is to inform the PM that it is still potentially open ended.
- what happens if alternative parts are unavailable. The presumption was that existing parts would be used, but the engineer did not have the span of authority to make that call. Again its left as an open item to bring attention.

From a larger perspective, the thought process investigating questions about failure or off-nominal mitigation actions is not pursued. Identifying them leads to a more robust view of issues.

11.2.3 Observations and Insights

During the process of examining the risk items a number of observations were made regarding the nature of risk items with respect to PRA scenarios. These observations point to the benefits of having an integrated, scenario-based systematic process for analyzing risk items across multiple organizations and throughout the project life cycle.

- Early in the program risk items were general and vague as to what the real issues were. For example, RI-006 states "Given the current understanding of the science investigation concepts, requirements, and constraints, there is a possibility that the design solution space will not converge without changes in one or more of these areas." This particular risk item had no mitigation assigned to it and eventually was closed when a design was developed. RI-035 states "If mission cost growth beyond allocated reserves occurs, then mission descopes will be taken" and illustrates a general concern with no hard data or alternatives (as written in the risk item) to consider.

- Multiple risk items are open for the same issue. The lack of flexibility in describing multiple scenarios forces the project to create and manage several items. RI-010 and RI-011 illustrate this point, their respective risk statement are: "Given that Principal Investigators will require a higher data rate than given in their updated proposals, there is a possibility that additional, strategically located, Ground Stations will be required which will impact Phase E cost." and "Given the uncertainty in the availability of ground stations, it is possible that the average daily data return requirement cannot be met." Additional ambiguity sets in with the type of risk assigned. Both are labeled as technical risks, but clear implications can be seen on cost and schedule.

- One can see when the PM took over. The nature of the risk items changed as did their specificity.

- 30% (8 of 28) of risk items entered are problems. Meaning that an initiator has already occurred. They are entered as risks because the next event in the scenario is still uncertain or because the eventual severity is still unknown.

- RI-164 is interesting because the consequence is not a change in cost, schedule, or LOM. Instead, the result is an increased uncertainty in a measurement to be taken; in particular uncertainty in spin balance characteristics of the spacecraft.

- Some risk items were identified because an important event was getting closer. Nothing had changed about the event and it carried the same amount of risk as it had months prior. The only thing that had changed was the perception of risk. RI-203, was opened stating "if IEM #2 uncovers issues during EMC testing, then IEM #1 will … need to be modified." This test was not newly added to the schedule, it has been there since the beginning. The change is that this test was only six weeks away and modifying any unit would be an issue. Opening this risk items was not prompted by a new discovered condition or event; or a change to likelihood or severity.

- Risk items have been previously entered. Risk items are not explicitly duplicated, instead they are restated with different outcomes or with a different scope. The first is a procedural byproduct when conditions or events no longer fit the risk statement as written, a new risk item is opened. Sometimes this is accompanied by closing the original risk item. Second, a new risk item is a subset scenario of an existing risk item, but since there is no way to track it (with its new detail), a new item is opened. Third, a new risk items is opened due to off-nominal conditions in a previous risk item. Fourth, repeating or sustained underlying issue is reported by writing risks against different symptoms. RI-176 is a staffing issue, as are risk items 042, 066, 110, and 187. In addition, risk items 177 and 179 might be related as staffing could be root cause for these.

- External events are captured. Risk items 171, 177, and 179 are events that the project cannot affect, but their impacts will cause problems. The project is using this system to proactively address influences from outside the program.

Observations regarding development of RSDs were also captured. One of the first questions asked by management was how much would this cost to implement, time and budget. Time to create a RSD is longer than typing a risk narrative. However, this superficial view of the process is misleading. A majority of time is spent understanding various scenarios that can spawn from an initial event. This time is the same whether the end product is a sentence or a diagram. My experience and those of colleague engineers is that a lot of time is spent simplifying and making risk statements politically palatable, striking a balance between voicing a concern but not over-emphasizing potential undesired outcomes. "This will be useful, it's how I think. It's confining to put a whole process into one sentence." commented one of the lead engineers. With RSDs, tempering the potential outcomes is a natural outcome of the probability cutset analyses.

Budget requirements would be similar for a qualitative implementation. Essentially maintaining diagrams instead of, or in addition to, a narrative database would not require a different skill set. A quantitative implementation of ISPAR however, would require a risk analyst skilled in modeling techniques, data analysis, utility function generation, and risk communication.

An additional item needed for implementation would be a tool set to develop RSDs under a configuration protocol; create, gather, combine, and calculate cutset; and compute risk metrics and importance measures.

Early in 2011, a meeting was held with the Project #2 technical management team. At the meeting were the PM, lead mission engineer, lead systems engineer, and the risk manager. Progress and qualitative results were presented. The discussion focused around a question posed to them; is the process of creating RSD useful? Response from the team was encouraging. As a process tool and a communication vehicle the RSDs were received well and the team agreed on the value of a couple aspects. First, identifying dependent events among risk items. This suggests that at a minimum, for qualitative assessments, cutsets should be generated for analysis. The PM found particularly interesting the paradigm of including all possible alternative and decision points in the diagrams. He mentioned that being able to "see" the decision *apriori* would be help in his management activities for planning and budget/schedule discussion with the sponsor. The risk manager took exception to a system that would have the project "think through so many activities that far into the future." Without prompting the PM chimed in with "isn't that kinda the point."

The systems engineer, responsible for the spacecraft risks, had trouble seeing a concrete connection to the existing process saying "How do I take this and put it on a 5x5?" This suggests that a procedure to distill qualitative scenario and consequence information into appropriate ordinal values would help with non-quantitative implementations.

Perhaps the common perception that ISPAR is a labor intensive activity prompted the mission engineer to say "I can't see doing this for all risks." This suggests that a screening procedure may be needed. This would have to filter low-consequence, low-probability, independent risk items. Perhaps, given project history within an organization, this filter can be tuned based on how "routine" risk items are typically handled.

The meeting ended with perhaps the best encouragement of all when the PM asked "Are you developing a tool for this?"

Chapter 12 Discussion

The initial premise was that current PRM practices were not up to state-of-the-art standards for risk assessments. Four main areas stood out; PRM is not scenario-based, PRM does not integrate risk items or consequence types, PRM does quantify risk items to form a total project risk picture, and PRM does not address management's risk posture or preferences. ISPAR is a framework to correct these shortcomings by adopting methods and techniques from PRAs and DAs. Some new procedures or modifications were required to integrate the entire framework. As discussed in Chapter 2, many of the methods used in the proposed methodology were first developed to assist in technical risk assessments and decision analyses. They have been incorporated to solve particular shortfall and are identified in the table.

This study expands the field of risk assessment in several key areas for project risk management and probabilistic risk assessments. ISPAR creates a framework to treat a project as a system for analysis, a system that includes development, fabrication, fielding, operations, and the product. Both stochastic events and non-stochastic decisions are essential modeling elements.

Profound shifts in PRM mindset are required. Project risk management can no longer be viewed as a simple repository of everyone's concerns. Instead, PRM is an analytical tool requiring skill and a level of sophistication in order to model scenarios, data, uncertainty, and metrics. The change in PRM scope and depth of analysis must be commensurate with the PM's span of responsibility and the project's magnitude.

Risk is now a project level trait with risk items in combination, instead of several independent undesired events. Project risk is defined as a shortfall in achieving goals with constraints. It is measured against a baseline. Risk items are scenarios of off-nominal events or conditions propagating through a project causing multiple effects, not a cause with one specific effect limited to one type of consequence. Inherent process responses to events must be actively reflected in these scenarios as well as alternative choices available to the PM. Alternatives must be viewed with their potential costs not just as optimistic get well plans.

This systematic process requires data to support risk item modeling efforts instead of relying on group consensus assignments for likelihood and severity. Data at a basic event level is more readily available than data for a risk item since basic events are not unique to a given project. For instance, while a risk item may be concerned with schedule delay of a new technology, component life tests or conformal coating processes are not. Sophisticated Bayesian techniques support the inclusion of judgment and expertise.

In order to make this new framework viable, several technical issues were addressed to incorporate ingredients from current state-of-the-art methodologies. Assumptions and boundary conditions were explored to ensure compatibility with proven techniques. The following sections detail contributions of this work in combining separate methodologies and creating new techniques to solve some the challenges of this integration.

12.1 Scenario-Based Risk Items

A scenario-based view of risk items provides a richer context for project decisions involving risks. RSDs allow project personnel to articulate pivotal events that exist between initiator and end effect, alternative courses of action, decisions required, and a range of potential impacts. The act of decomposing a risk item, diagramming decisions, and populating them with the best information at hand support the decision-making process.

Scenario-based risk assessments and decision analyses have been in existence for years, but have not adopted for PRM. The creation of a hybrid ESD / DT allows an analyst to examine the impact of decision on risk as an inherent parameter of a risk model. PRAs are currently used to assess probabilities of alternatives. In this sense, they support decision analysis. As discussed in Chapter 2, decision trees often model top level events, but do not typically examine cutsets at lower levels for dependencies, common cause failure modes, or single point failures. The combination enhances both methodologies. Facilitating this integration is that both use a consistence probability calculus framework and set of assumptions. From a PRM perspective this combination adds capability not found in current practice.

Scenarios are represented by RSDs are meant to augment and replace "If-Then" statements as the preferred method of documenting risk items. Decomposing risk items into more than initiator and endstate allows development of procedures for probability assignments using data collection and expert elicitation in a far more rigorous, traceable, and defendable manner.

Within this study, scenario-based techniques have been applied to several examples and to a spacecraft development project. Examples show that specific conceptual constructs will work. RSDs creation was shown to be feasible in its implementation.

12.2 Integrated Assessments

Integration provides a systematic treatment of both project and product with successful combination of consequence models to produce a multi-faceted view of project risk. The PRA domain is expanded into the project management arena, increasing insights provided to project managers and demonstrating versatility of PRA to the project management research community. Risk analyses are presented to management for a variety of reasons, but ultimately, they are to inform decision-makers of all appropriate information needed to make a decision if and when the time comes.

PRAs have supported DA in the past with endstate probabilities providing input to decision tree chance nodes. Here decisions are an integral part of the modeling process. Risk depends on the decisions needed and decisions depend on the risk analysis.

Central to integrating the two risk assessment methods has been showing how RSDs integrate with decision trees, decision trees with fault trees, and the methodology with various system risk assessment styles. This also includes the calculus for new risk scenario models containing decision points, common cause analysis, dependency of multiple risk scenarios occurring simultaneously, and calculations with some basic events appearing on either side of decision points.

PRM rarely addresses various types of impacts from a risk item simultaneously, instead opting to address only a type deemed to be the worst-case. This framework unifies cost and schedule risk models with system risk models. Consequence models are analyzed given the same set of circumstances in the form of cutsets that determine model configurations at endstates. Output from these models are combined using well established multi-attribute utility techniques thereby providing an endstate with a single value (and its distribution) based on common inputs. This allows existing consequence models to operate in their own unique environment without interference.

This new risk management framework explicitly accounts for items that greatly impact the probability of project success, such as dependencies (PRM assumes independence of risks items), uncertainty (aleatory and epistemic uncertainties), and decision points (needed for managers to interact with analysis).

12.3 Quantitative Assessment

PRM uses consequence × probability to rank order individual risks based on ordinal scores. ISPAR quantifies risk in a metric *CPRM* that is a composite of all risk items, decisions, and consequence types. This metric also has an associated uncertainty. Since *CPRM* is a function of the model's logic structure and event probabilities, it can be used to derive risk contributions from any event or decision in the models. Popular importance measures are shown to be valid within this framework and to provide a set of tools for PRM heretofore not available.

Within the realm of PRM, risk items exist and progress simultaneously. A basic assumption in PRA is that initiating events are independent. Accident sequences occur and propagate relatively quickly and so only one ESD can occur at a time. This allows analysts to simplify the computations. A brute force methodology was developed to combine all cutsets into one composite model for all endstates.

This leads to another modeling challenge, endstate compounding. Endstates' computations are dependent on the path taken to get there. A methodology was devised to examine the paths and recomputed the consequences.

Data collection for project basic events can be collected and analyzed with the benefit of updating the ISPAR risk models using standard Bayesian techniques. In addition, the system is available to quantitatively assessment expert opinion under a Bayesian framework as data supporting basic events. This transforms PRM from a committee based consensus building effort to one where defendable analysis is used throughout.

12.4 Risk Aversion and Preferences

Finally, while decision analysis specifically addresses a decision-makers preferences, PRM does not. This leads PMs to lose credibility in risk results, arbitrarily reassigning scores, or self censoring the information. An approach is employed to adjust consequence model results for PM's own risk aversion and preferences. This has some nice side benefits. A systematic controllable methodology provides a much more consistent response from decision-makers. It also nullifies many of the effects of "groupthink" influences on decisions.

When managers from different perspectives enter, they bring their own set of biases and preferences. This system can exchange utility functions, allowing the same data to flow but to yield different results based on a different context or perception. These differences result from changes in scope of responsibility or authority, changes in organizational or personal priorities, etc.

12.5 Summary of Contributions

This methodology makes contributions to Project Risk Management in two areas. First, it provides a new paradigm for PRM by integrating various elements and processes expanding the analytical capability heretofore not available. Second, several new techniques, methods, and metrics were developed to fill the gaps created by the integration effort.

The scope of PRM is expanded by integrating development of a project with performance and operation of a product into one system for analysis. Previous practice limited risk analysis to development activities, while system operations and performance were analyzed separately. In this work, traditional PRA methods are combined with decision analysis concepts providing a more robust view of the project risk landscape. It explicitly addresses project controls (i.e., decisions) available to PMs. Collapsing all consequence types into a single value through the use of utility functions allows PMs to examine all aspects simultaneously. Finally, integrating all risk items into a single model expands the view of risk from *item-by-item* to *total-project* perspective. Overall, PRM is thereby integrated with state-of-the-art risk assessment methodologies.

Table 12-1. Project risk management gap analysis

Gap Description	Solution Source: PRA	Solution Source: DA	Solution Source: New/Mod	Solution
Scenario-based Assessment				
Only one potential outcome at a time	●			Scenario-based ESD
Severity assigned as worst-case	●	●		Scenarios present a variety of outcomes
Decisions not addressed			●	Hybrid ESD/DT
No common cause to risk posture	●			CCF analysis
Event dependencies not addressed	●			Scenarios/FTA modeling
External event dependencies	●			Events or initiator
Lacks accounting for root causes of risk item	●			Failure logic decomposition
Integrated Assessment				
Treats project and product risks separately			●	Project/product system definition
Treats cost, sched, and perf separately	●	●		Multi-Attribute Utility theory
Consequences are not modeled	●	●		Existing model integration
Consequence independent of path			●	Endstate compounding methodology
Risk item dependencies not addressed	●			ET/FTA style analysis framework
Risk items treated as independent events			●	Modeling does not require assumption of independence
Off-nominal mitigations not addressed			●	ESD modeling style
Quantitative Assessment				
Total project risk not computed	●		●	*CPRM*, *Rm* created
Ordinal scales can introduce errors	●	●	●	Risk profiles
Probabilities estimates for entire risk item	●	●		Decomposition
Lacks risk contribution rank ordering	●		●	PRA Importance Measures
Uncertainty not addressed	●	●		Integral part of both
Feedback and status are qualitative	●	●		Bayesian techniques updates risk based on data collection
Risk aversion & Preferences				
Decisions not addressed		●	●	Modified to handle decisions in cutsets
Decision ranking not determined			●	Decision Importance Measure
Group dynamics influence process Assignments by committee Groupthink voting schemes can be irrational	●	●		Systematic risk assessment methods
Cannot integrate risks up and down organization without censorship (editing)			●	Utility function substitution

As a result of defining this new methodology, several shortfalls of current PRM practice were uncovered. Table 12-1 provides a summary list of many identified shortfalls along with an indication of how each one was addressed. Solutions used within this framework originated either from PRA, DA, or newly created or modified in this research. The table also indicates a solution to the particular shortfall.

Many of the contributions, while new for PRM, are not new from a risk assessment perspective. Listed here are only those items newly created or modified for use within this methodology.

- Risk Sequence Diagrams are a hybrid of Event Sequence Diagrams and Decision Trees. The combination allows examinations of scenarios in the presence of decisions. Heretofore, PRAs have supported decision trees by quantifying the potential outcomes, assuming a decision, but decisions have not been imbedded into the scenarios. The necessary algorithms for solving cutsets with the inclusion of non-stochastic events are developed and validated.

- The common assumption in system PRA methods, where scenario initiators are considered to be mutually exclusive, is often not valid for PRM where risk scenarios are occurring simultaneously. Therefore a modeling framework is developed that incorporating basic events from all risk item scenarios.

- Endstate compounding is addressed to capture the correct combination of system configurations in determining an endstate consequence value. Gathering endstates as one would in traditional PRAs can lead to incorrectly quantifying the magnitude of consequences when the consequence models are non-linear.

- Risk metrics for the entire project and for risk items is developed. The metrics combine information about likelihoods, consequences, and PM preferences into a single value consistent with the definition of project risk.

- Decision importance measure is introduced to rank order decisions. This measure provides a scale value combining decision impacts with the potential of having to make the decision. Decisions can be compared across the project and across risk mitigation actions.

Chapter 13 Future Work

This study is a foundation on which to continue building project risk management techniques and infrastructure. Continuing use of scenario-based assessments will increase management's understanding, communication, and decisions about project risk. These building block integrate system and project; PRA and DA; cost, schedule, and performance consequence models; and qualitative and quantitative techniques under the same assessment methodology. Other techniques and tools can be integrated to expand capability. Figure 13-1 illustrates a development roadmap spawning from the methodology presented here.

I envision a computer tool, a modeling environment, that allows an analyst to develop RSDs in a graphical interface. RSDs would be translated to logic models producing information required for qualitative assessments of cutsets and dependencies. Logic would feed a quantitative engine that incorporates datasets of event histories (industry and organizationally specific), expert judgment, and preferences to produce risk metrics at every level of a project. Further, automated information exchange with consequence models would facilitate communication throughout a project across organizational boundaries.

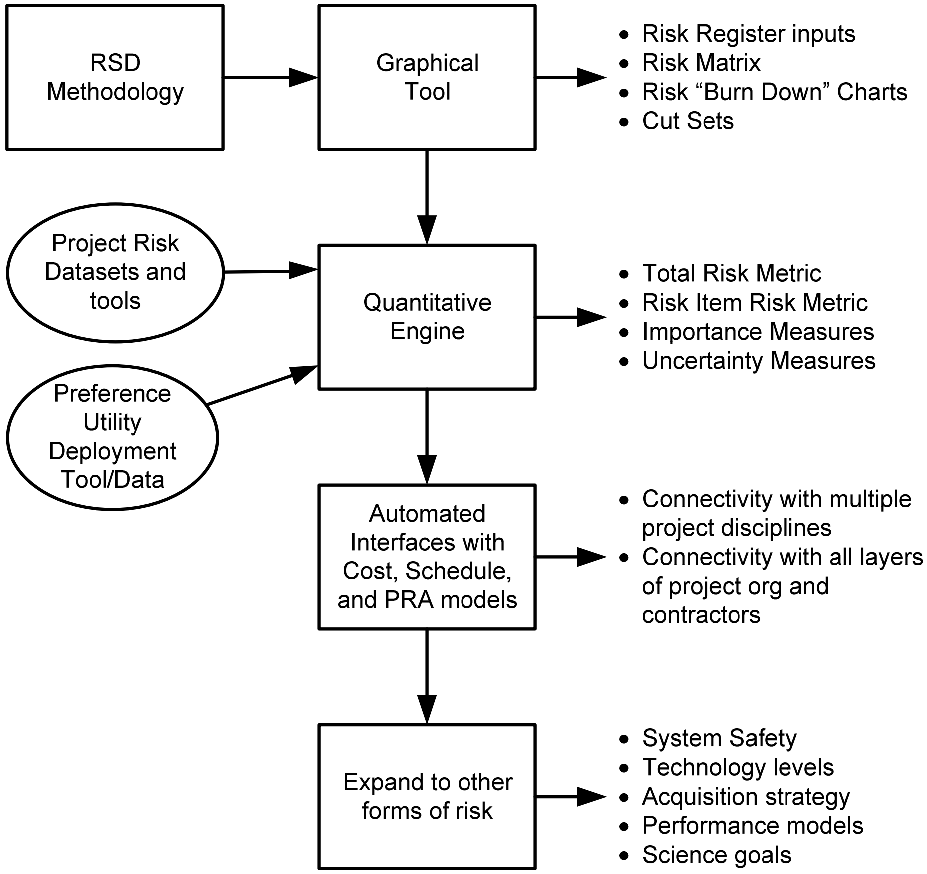


Figure 13-1. Roadmap of future work

Within this study a few process steps were discussed where supporting algorithm development could increase capability and efficiency. One such area is the creation of composite logic models incorporating pivotal and basic events. Branch and path explosion problems have been addressed elsewhere concerning expansion of binary trees. An efficient algorithm is needed to keep up changing nature of a project as decisions are made and outcomes of stochastic events becoming known. Each change alters model structure. One such research project is underway to create an environment where a risk can be continually updated in order to reflect current status of the risk posture. Specifically, as decisions are made and risk events either manifest or are made negligible, the model will allow reflection of these facts and will update the integrated risk posture.

The endstate combination process, which at this point is labor intensive, is another candidate. Perhaps a rule-based algorithm integrated with a consequence model exchange protocol could be employed.

Handling time in this framework has only been briefly discussed. There is much potential for incorporating event horizons to events and decisions. Risk as a function of time would then be an inherent characteristic of scenarios and models. It could also greatly facilitate "burn-down" charts and monitoring aspects of this implementation. There are also aspects of time versus risk perception that could be addressed including time dependent utility functions for managers.

While this study has focused exclusively on project risk, there is potential for application to system safety processes. System safety as a discipline possesses many similar characteristics of PRM, not the least of which is the use of a 5×5 matrix. Shifting to a scenario-based assessment has shown to be invaluable in other safety dominated industries like nuclear power and chemical processing, but a full embrace of quantitative assessments in system safety is elusive. This may be a compromise platform from which to start a discussion. Another more detailed process to explore is the practice of writing waivers and deviations against requirements and standard operating procedures. Each carries risk and could couple with other deviations.

Recently, models have been developed to include influences of organizational factors with system models. They are implemented as Bayesian Belief Networks that sit in parallel with a systems modeling logic to change event probabilities. This could also be integrated with ISPAR to accommodate influences of organizational preferences and constraints, culture, contract types, project environment (commercial or government), or type of work.

Finally, this study has been resolute in stating this is not for predicting decisions. Decisions are left as model variables and not quantified. Information about decisions is provided to inform decision-makers about their importance. However, optimization algorithms could be a fertile research area. More interesting could be decision-makers' behavioral responses to such a system.

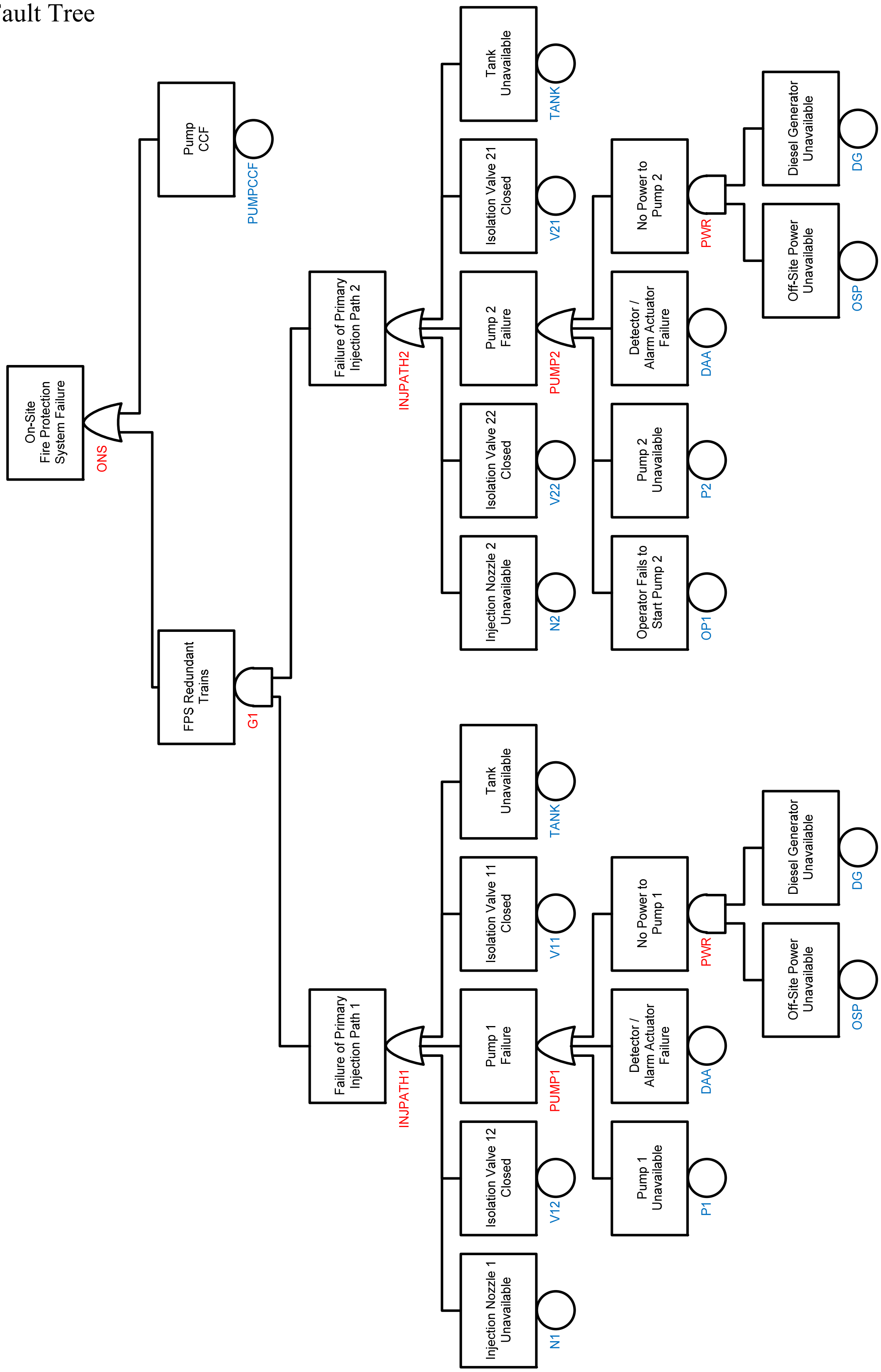
ISPAR sets the foundation to move PRM into employing state-of-the-art risk assessment techniques.

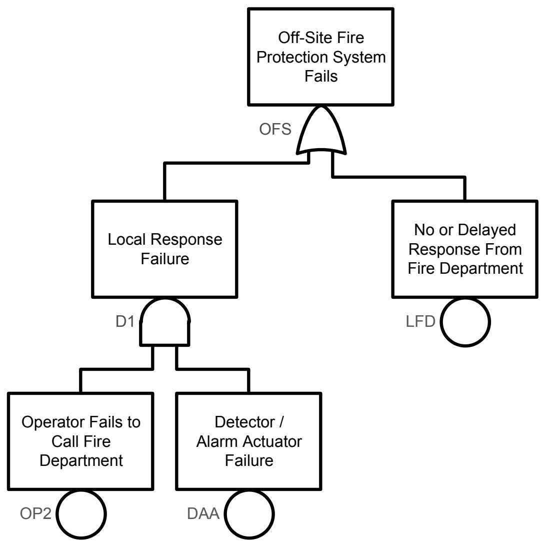
Appendix A. Fire Suppression System Example Data

FSS Schedule Detail

ID	Description		Durn	Precedence Matrix																			ES	EF	LS	LF	Slack
1	Select Contractor	**Critical**	1.3	**1**																			0.00	1.27	0.00	1.27	0.00
2	Deliver Building Plans	**Critical**	1.3	1	**2**																		1.27	2.53	1.27	2.53	0.00
3	Develop System Layout	**Critical**	4.1		1	**3**																	2.53	6.60	2.53	6.60	0.00
4	Design/Build/Test new DAA		8.3	1			**4**																1.27	9.60	2.53	10.87	1.27
5	PDR	**Critical**	0.2			1		**5**															6.60	6.80	6.60	6.80	0.00
6	Finish detailed design	**Critical**	4.1					1	**6**														6.80	10.87	6.80	10.87	0.00
7	CDR	**Critical**	0.2				1	1	1	**7**													10.87	11.07	10.87	11.07	0.00
8	Build-up Sub Assemblies	**Critical**	4.2				1			1	**8**												11.07	15.23	11.07	15.23	0.00
9	Install Piping	**Critical**	3.5								1	**9**											15.23	18.73	15.23	18.73	0.00
10	Install Fixtures		2.1								1		**10**										15.23	17.33	16.63	18.73	1.40
11	Inspection	**Critical**	1.1									1	1	**11**									18.73	19.87	18.73	19.87	0.00
12	Install Electrical Components		2.1				1				1				**12**								15.23	17.37	17.23	19.37	2.00
13	Inspection		1.1									1	1		1	**13**							18.73	19.87	19.37	20.50	0.63
14	Charge System	**Critical**	0.6											1			**14**						19.87	20.50	19.87	20.50	0.00
15	Pressure Test	**Critical**	0.8														1	**15**					20.50	21.30	20.50	21.30	0.00
16	Electrical Test	**Critical**	0.8				1									1	1		**16**				20.50	21.30	20.50	21.30	0.00
17	Communication Test		0.8				1								1	1				**17**			19.87	20.67	20.50	21.30	0.63
18	Review Test Results	**Critical**	1.0															1	1	1	**18**		21.30	22.30	21.30	22.30	0.00
19	QA Audit of Calibrations	**Critical**	0.6																		1	**19**	22.30	22.93	22.30	22.93	0.00
20	Obtain County Approvals	**Critical**	1.2											1	1	1						1	22.93	24.17	22.93	24.17	0.00

Fault Tree


On-Site Fire Protection System Failure
ONS
Pump CCF
PUMPCCF
FPS Redundant Trains
G1
Failure of Primary Injection Path 2
INJPATH2
Failure of Primary Injection Path 1
INJPATH1
Tank Unavailable
TANK
Isolation Valve 21 Closed
V21
Pump 2 Failure
PUMP2
Isolation Valve 22 Closed
V22
Injection Nozzle 2 Unavailable
N2
No Power to Pump 2
PWR
Detector / Alarm Actuator Failure
DAA
Pump 2 Unavailable
P2
Operator Fails to Start Pump 2
OP1
Diesel Generator Unavailable
DG
Off-Site Power Unavailable
OSP
Tank Unavailable
TANK
Isolation Valve 11 Closed
V11
Pump 1 Failure
PUMP1
Isolation Valve 12 Closed
V12
Injection Nozzle 1 Unavailable
N1
No Power to Pump 1
PWR
Detector / Alarm Actuator Failure
DAA
Pump 1 Unavailable
P1
Diesel Generator Unavailable
DG
Off-Site Power Unavailable
OSP


Off-Site Fire Protection System Fails
OFS
Local Response Failure
No or Delayed Response From Fire Department
D1
LFD
Operator Fails to Call Fire Department
Detector / Alarm Actuator Failure
OP2
DAA

Risk Data		Input
Sensor manufacturing issue	DAA_SNS_MFG	0.85
Sensor Design flaw	DAA_SNS_DSGN	0.98
Test condition	DAA_TEST	0.95
Software change	DAA_SW	0.8
Cost of material increase	COST_INCR	0.75
Design change after order	DSGN_CH	0.05
Clean-up	SPL	0.1
Clean-up on schedule	SPL_SCHED	0.8
Floor reinforcement	FLOOR	0.99
Electrical redesign	ELECT_RED	0.99
New Inspector	INSPTR	0.25
Design approval	APV|OLD	0.95
Design approval w/new	APV|NEW	0.8
Bad Nozzle	NOZZ_BAD	0.85
Supplier test	NOZZ_SUP	0.5
Nozzle inspection	NOZZ_INSP	0.9
Nozzle system test	NOZZ_SYS	0.9

Appendix B. Project #2 Risk Sequence Diagrams

Project #2 Risk Item Registry

RI#	Title	Likelihood	Impact	Classification
1	Project lifecycle cost at ICR	3	4	Unspecified
2	Test Risk #1	3	4	Unspecified
3	Phase A Requirements Development Duration	4	1	Cost
4	Test	2	1	Unspecified
5	Star Tracker Radiation Hardness and functionality at operational spinrates	3	3	Unspecified
6	Spacecraft concept convergence	1	2	Unspecified
6	Spacecraft concept convergence	1	2	Unspecified
7	Electrostatic & Electromagnetic Cleanliness	2	1	Cost
8	Accommodation of data collection and downlink requirements	4	3	Technical
9	Rad-hard parts availability	1	3	Schedule
10	Additional Ground Stations to Increase Downlink	5	3	Unspecified
11	Availability of Ground Stations	1	5	Technical
12	Observatory Robustness	1	5	Technical
13	Space Weather Broadcast Requirements	3	2	Technical
14	Attitude knowledge pointing requirements	1	3	Technical
15	Burst mode concept	3	1	Schedule
16	Science investigation team staffing levels	2	3	Schedule
17	Upgrades to 18m	1	1	Cost
18	Bldg. 21 Construction completion date	1	3	Cost
19	PRIO Fabrication Cost Risk	2	3	Schedule
20	TRIO-A Availability	2	1	Cost
21	Integral Systems, Inc. could be sold	3	2	Unspecified
22	Harness Shielding for EMC	5	2	Technical
23	Rad-hard star tracker/scanner for spinning spacecraft	2	3	Technical
24	On-Orbit Spin Rate	1	3	Technical
25	Instr-R MCP Mount	1	4	Cost
26	Nutation Dampers	2	3	Cost
27	Instr-E Detector Procurement	3	2	Schedule
28	DDD Mitigation Implementation Risk	1	3	Schedule
29	xxx chip-scale packaging in RF Subsystem	1	3	Schedule
30	Early Long Lead Procurements	1	1	Cost
31	Mission Cost Cap	2	2	Cost
32	Low Power Margin	1	3	Technical
33	45 Day Commissioning	4	5	Unspecified
34	Instr-E Data Sharing	1	3	Technical
35	Instr-H Time of Flight Electro-optics	2	4	Schedule
36	IT Security Clause	3	2	Programmatic

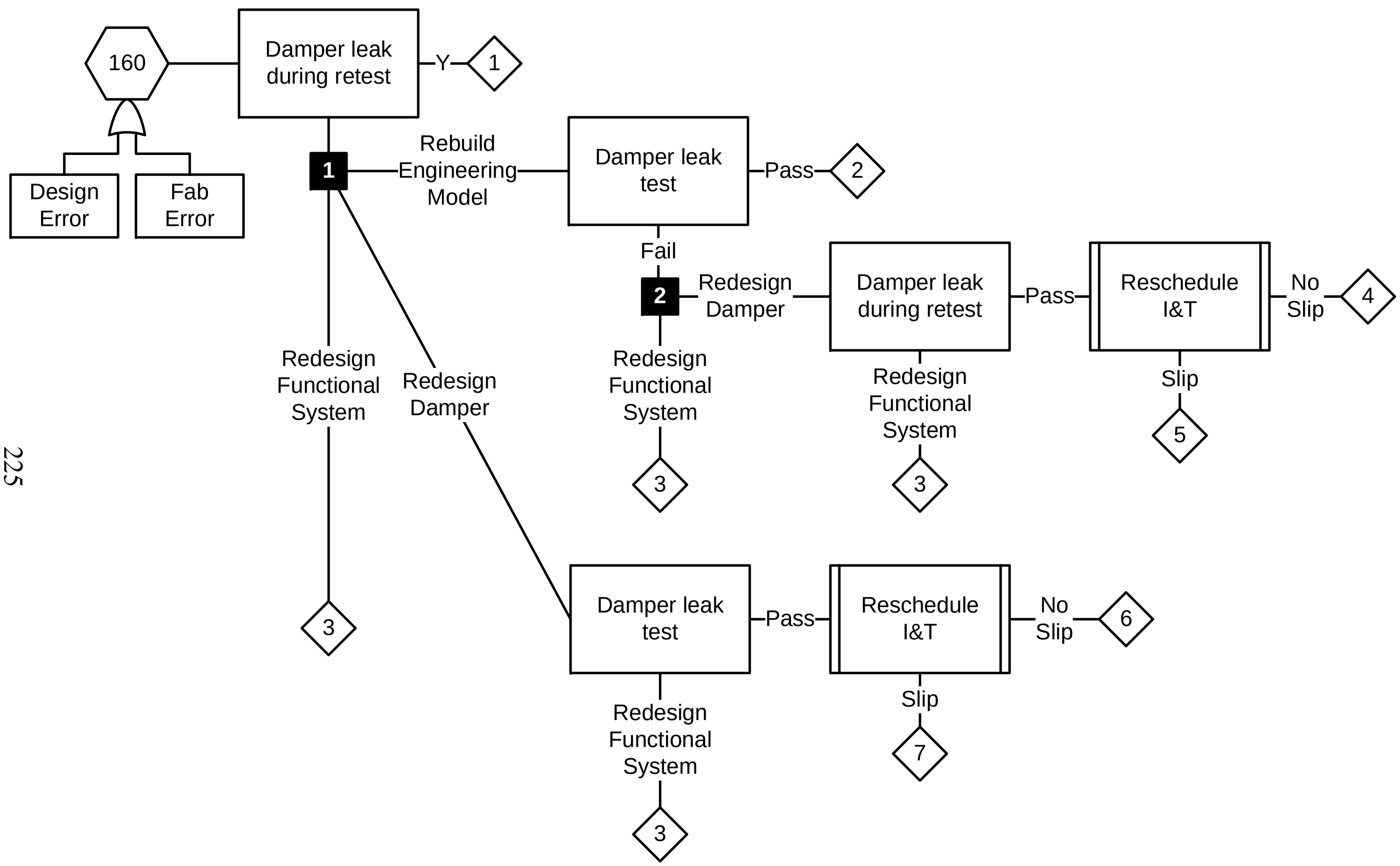
RI#	Title	Likelihood	Impact	Classification
37	Earned Value Implementation Cost	1	1	Cost
38	Solid State Detector Design	3	3	Technical
39	Transceiver Co-Development	1	1	Cost
40	Instr-E and Instr-H Susceptibility to Materials Activation	1	3	Technical
41	Instr-E Particulate Contamination Environment	2	2	Schedule
42	Staffing	3	3	Schedule
43	Instr-RP Detector Procurement and Delivery	1	3	Schedule
44	SBC/SSR Procurement Schedule Delay	4	3	Technical
45	Magnetometer Software Classification	2	3	Schedule
46	Project Use of Actel	1	3	Schedule
47	Acoustics Testing	2	4	Safety
48	Spin Table Availability	1	2	Cost
49	S/C Fit in Thermal Chambers	1	2	Cost
50	Cmd/Tlm/1PPS Signal Interface Resolution	2	3	Technical
51	xxx Part Availability	1	1	Schedule
52	Project Schedule	5	5	Schedule
53	PDU Development	2	3	Cost
54	Instr-E1 Reserves	5	1	Cost
55	Instr-E2 Reserves	3	1	Cost
56	Instr-E Reserves	5	1	Cost
57	Instr-R Reserves	5	1	Cost
58	Processor Board Cost	5	2	Cost
59	SSR Development Cost	5	2	Cost
60	Undefined Space Asset Protection Requirements	3	1	Cost
61	Instr-E Thin Wire Approach	1	4	Schedule
62	Propulsion Subsystem Cost	3	1	Cost
63	Observatory Materials Acceptability	1	2	Schedule
64	Inter-Organizational Communications Issues	1	4	Programmatic
65	Prohibited Connectors per EEE-INST-002	1	5	Technical
66	Spacecraft Staffing	1	2	Schedule
67	Phase B Flight Hardware Procurements	1	1	Schedule
68	IEM Sun Sensor Interface Changes	2	3	Schedule
69	Redundancy of DC Magnetometer Measurements	2	4	Technical
70	IT Security Compliance	1	4	Schedule
71	Instrument PDR Schedules	2	3	Schedule
72	Other Mission Conflicts with APL 18m Antenna Usage	1	3	Schedule
73	Instr-E Spin Plane Boom Damping	2	3	Schedule
74	Low Power Margin	3	3	Schedule
75	Low Mass Margin	3	3	Technical
76	Funding Delay	1	3	Schedule

RI#	Title	Likelihood	Impact	Classification
77	Redundant Magnetometer Data Path	1	4	Technical
78	IT Security Clause	1	1	Schedule
79	Vendor xx Deliverables	3	3	Schedule
80	IEM DC-DC Converter Procurement	3	3	Schedule
81	PAF Size Change	1	3	Cost
82	Science Instrument Team Late Invoicing	1	2	Schedule
83	Instr-M Thermal Design	3	3	Schedule
84	Simulator May Require PSE	3	1	Cost
85	Adequate Estimate of Phase C/D Direct Cost	3	1	Cost
86	Subcontracted Component Procurement Costs	5	1	Cost
87	Increased Labor Costs Affect Mgmt Reserve	3	1	Cost
88	Power Converter for Transceiver	1	2	Schedule
89	Vendor xxx Connector Schedule Delay	2	3	Schedule
90	Staffing for Instr-E	2	3	Schedule
91	Soldering Process	1	3	Schedule
92	Launch Vehicle Selection	2	3	Schedule
93	Transceiver Prohibited Connector	2	5	Technical
94	Increased Usage of Plastic Parts	3	1	Cost
95	Component Engineering Costs	1	1	Cost
96	Fabrication Facility Loading	2	3	Schedule
97	Observatory Robustness	1	3	Technical
98	Observatory EME Testing	1	3	Technical
99	Instr-E Prohibited Connector	4	2	Schedule
100	Propulsion ICD Delivery	2	3	Schedule
101	Early Structure Fabrication	2	1	Schedule
102	Transceiver DSP Slice Connector	1	3	Schedule
103	Instr--E Connector Delivery	3	2	Schedule
104	Implementation of TRIO Functions Totally Within IEM	2	3	Schedule
105	Instrument Compatibility Tests	1	3	Schedule
106	Simulator not delivered to MOPS by I&T start	1	2	Schedule
107	Instr-M Quality Mgmt System	2	3	Schedule
108	Additional Fault Protection Testing	2	3	Schedule
109	Box-Level Mechanical Design Issues	1	4	Cost
110	Additional vendor-xxx Oversight Labor	1	2	Cost
111	Commissioning Timeline	1	3	Schedule
112	DC-DC Converter Hermeticity Issue	3	2	Schedule
113	Charging of Solar Cell Coverglass with Coating	5	2	Technical
114	IEM vendor-xx Connector Tolerancing and Alignment	2	3	Schedule
115	Demonstration of Functionality of Transceiver Firmware for Qualification Model	4	3	Schedule
116	XCVR Use of Mini-Circuit Non-Standard Parts	1	3	Schedule

RI#	Title	Likelihood	Impact	Classification
117	Flight Propellant Tank Availability	2	2	Schedule
118	PWB Fabrication Before CDR	4	1	Cost
119	Provided Separation Hardware	1	1	Cost
120	Instr-E System Interface Maturity	1	3	Schedule
121	XCVR Qualification Program	2	3	Schedule
122	IEM Engineering Model Fabrication and Test	3	2	Schedule
123	xxx Costs Higher Than Expected	5	1	Cost
124	Spurious Emission Temperature Testing	3	2	Technical
125	Solar Panel Laydown Design and Development	2	3	Schedule
126	Qualification of Hypertronics Flight Connectors	4	3	Schedule
127	Instr-H Detailed Design of the Door	2	3	Schedule
128	Instr-M ASIC Design/Delivery/Testing	2	2	Schedule
129	Completion of Instr--M EM2 End-to-End Testing	3	3	Schedule
130	Instr--E Flight Drawing Release Status	2	2	Schedule
131	Instr-H HVPS Additional Mechanical Board Support	2	2	Schedule
132	Instr-RP Stress Test in Beam with FPGA Code	3	2	Schedule
133	End-To-End Test of the Instr--M Low Energy Electron Analyzer	2	2	Schedule
134	Instr-M LVPS Design Updates	1	2	Schedule
135	xxx Design Completion	1	3	Schedule
136	PGS Subsystem Drawing Release	2	3	Schedule
137	Ground Station Upgrade Funding	3	1	Cost
138	XCVR FPGA Utilization	1	2	Schedule
139	Pressure Transducer Delivery	3	3	Schedule
140	Search Coil MLI Standoff Requirements	2	2	Technical
141	IEM vendor-xxx Connector Solder Process	3	3	Schedule
142	PRIO Test Risk	3	3	Schedule
143	PDU Fuse Board	2	2	Technical
144	Flight Fabrication	1	3	Schedule
145	Development Delay	1	3	Schedule
146	Instr-RP Instrument Performance	2	3	Schedule
147	XCVR RCVR Crystal Filter Delivery	2	3	Schedule
148	Support Reliability	3	1	Cost
149	PDU Flight Board Fabrication	2	3	Schedule
150	Instr-M Preamp Board TVAC Anomaly	2	2	Schedule
151	Titanium Exoneration	1	3	Schedule
152	Air Force C-17 Cost	1	1	Cost
153	IEM & XCVR FPGA Rework	1	4	Schedule
154	Completion of Vendor-xx Qualification Program	1	1	Schedule
155	Instrument Management Reserve	5	1	Cost
156	Propulsion Subsystem Delivery	1	3	Schedule

RI#	Title	Likelihood	Impact	Classification
157	Mission-YY Environmental Test Failures – Instr-R impacts	2	3	Schedule
158	Umbilical Connector Delivery	2	3	Schedule
159	Instr-H Diode Multiplier String	1	4	Technical
160	Nutation Damper Leak	2	2	Schedule
161	Instr-H Part Failures	2	2	Schedule
162	PSE Hardware Schedule Slip	5	3	Schedule
163	SSPA Part Leakage	1	4	Schedule
164	Meeting Spin Balance Requirements	2	2	Technical
165	PDU Op Amp Interface Qualification Test	1	2	Schedule
166	Radiation and Charge Monitoring	1	2	Technical
167	SSPA - DC/DC Converter Burn-in Failure	2	2	Schedule
168	PDU Flight Part Delivery	2	3	Schedule
169	Use of Bond Wire in SA Substrates	1	2	Technical
170	Instr-M Hybrid Delivery	1	3	Schedule
171	Instr-M Detector Procurement and Delivery	3	3	Schedule
172	Instr-E FPGA Verification	1	3	Schedule
173	SSPA Schedule Slip	1	2	Schedule
174	Part xx Life Test Failure	2	3	Schedule
175	Instr-R Waiver 006 Technical Risk - Pin gold thickness	1	2	Technical
176	I&T Staffing Shortage	1	3	Schedule
177	Instr-R Resource Conflict with JEDI	1	3	Schedule
178	Instr-R Mechanical Part Fabrication	2	3	Schedule
179	Magnetometer Team Resources	2	2	Schedule
180	Instr-E Filter Tin Whiskers	2	3	Schedule
181	Use of DC/DC Converters in the IEM	1	3	Technical
182	IEM FM2 Schedule Slip	5	3	Schedule
183	XCVR Schedule Slip	5	3	Schedule
184	PDU FM2 Schedule Slip	1	2	Schedule
185	Lot Jeopardy Parts Fail Qual Testing	1	3	Schedule
186	Spare Parts Not Available for Hardware	1	3	Schedule
187	IEM Test Team Staffing	2	3	Schedule
188	Instr-E Late Delivery to Observatory I&T	2	3	Schedule
189	Loss of Fluxgate Instr-M Data	1	4	Technical
190	Propulsion Module Delivery	2	3	Schedule
191	HVPS Redesign To Alleviate Discharge	1	2	Technical
192	Instr-E delivery requires the replan I&T need date	3	1	Cost
193	Instr-H delivery requires the replan I&T need date	3	1	Cost
194	Instr-RP delivery requires the replan I&T need date	3	1	Cost
195	Instr-R delivery requires the replan I&T need date	3	1	Cost
196	Low Voltage Sense (LVS) False Trip	1	2	Technical

RI#	Title	Likelihood	Impact	Classification
197	Battery Overcharge Due to Saturation of PGS Shunt	2	2	Technical
198	Pressure Transducer High Current Mode	1	1	Technical
199	Latent Damage from EM Zap Testing	1	4	Technical
200	Use of State Of The Art (SOTA) Resistors	1	1	Technical
201	Black Paint	1	3	Technical
202	IEM Card Precision Oscillator	1	1	Technical
203	IEM FM1 Shortened EMC Testing	1	3	Schedule
204	Instr Interface Testing	3	3	Schedule
205	Solar Cell Interconnect Failures	3	3	Schedule
206	Remanufacture of Flight Bobbins	2	3	Schedule
207	High Electron Transfer Board for Instr-MS	1	3	Schedule
208	Detector Rework for Instr-M	4	3	Schedule
209	Instr-R Capacitor Replacement	3	3	Schedule
210	Launch Flow Planning	5	1	Schedule
211	Instr-M Detector Pin Retention Issue	2	4	Schedule
212	Flight Hardware EMC Testing Resources	2	3	Schedule
213	Low Project-Level Schedule Reserve	3	4	Schedule
214	PSE Vibration Failure	3	4	Schedule
215	IEM FM1 Anomaly Investigation	4	4	Schedule
216	Instr-H Delivery To I&T	5	3	Schedule
217	Instr-ES Delivery To I&T	2	3	Schedule
218	Instr-E1 Delivery To I&T	3	3	Schedule
219	Instr-RP Delivery To I&T	3	3	Schedule
220	Instr-R Delivery To I&T	3	3	Schedule
221	Instr-E Cost Growth	3	3	Cost
222	Ground Offset High Current Fault on LVDS Interfaces	1	3	Technical
223	Instr-M Proton Telescope Detectors	3	2	Technical
224	Jackpost Torque Issues	2	3	Schedule
225	Instr-M Delivery To I&T	4	4	Schedule



DESCRIPTION

If the nutation damper leak is not resolved in a timely manner, then the beginning of spacecraft I&T will be delayed

Context: The nutation damper experienced a leak during a cold soak cycle on the EM. This leak puts the reservoir design in question, and will require some level of redesign. Since the nutation dampers are required to be installed to the spacecraft prior to the beginning of I&T, this redesign and retest must be completed in a timely manner to maintain schedule and not delay the beginning of I&T.

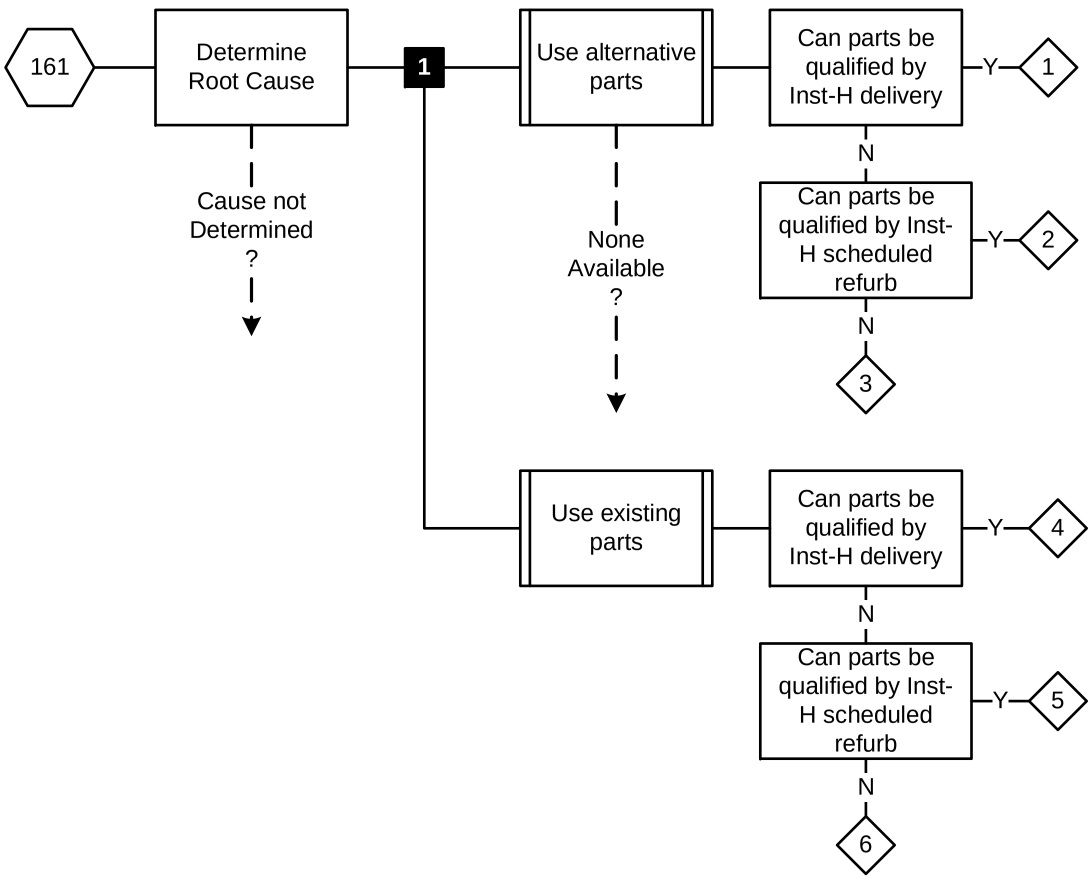
ES	Cost	Delay	LOM
1	BL. No add'l cost	No impact to crit path	BL w/higher uncert
2	Minimal add'l cost	No impact to crit path	BL
3	Large $ impact	Large slip on crit path	Unk. across subsys'
4	$ redesign + 2 test cost	No impact to crit path	~BL
5	$ redesign + 2 test cost	Med slip	~BL
6	$ redesign + 1 test cost	No impact to crit path	~BL
7	$ redesign + 1 test cost	Med slip	~BL

Risk Sequence Diagram

TITLE: RI-160: Nutation Damper Leak

FILENAME: RSD-160B.VSD

PAGE: 1



DESCRIPTION

If the HV parts are not qualified for flight use, then the delivery of the full unit (with the high voltage board) will be delayed.

Context: Eleven optocoupler parts are used in each Instr-H on the high voltage power supply board. Vendor-S uses these part on 2 other sponsor missions. Recent HV failures on those programs have occurred. The 2 failure types on those programs were broken bond wire and LED lifting from the substrate. In addition, inspection of Instr-H parts found 2 parts appeared to have weak bonds as evalued by x-ray and another had LED lifting.

ES	Cost	Delay	LOM
1	x% incr of parts	BL	~BL
2	x% incr of parts + delay cost	Refurb date	~BL
3	x% incr of parts + delay cost	Late for I&T	~BL
4	BL	BL	BL
5	Delay cost	Refurb date	BL
6	Delay cost	Late for I&T	BL

Risk Sequence Diagram

TITLE: RI-161: Instr-H HV Part Failures

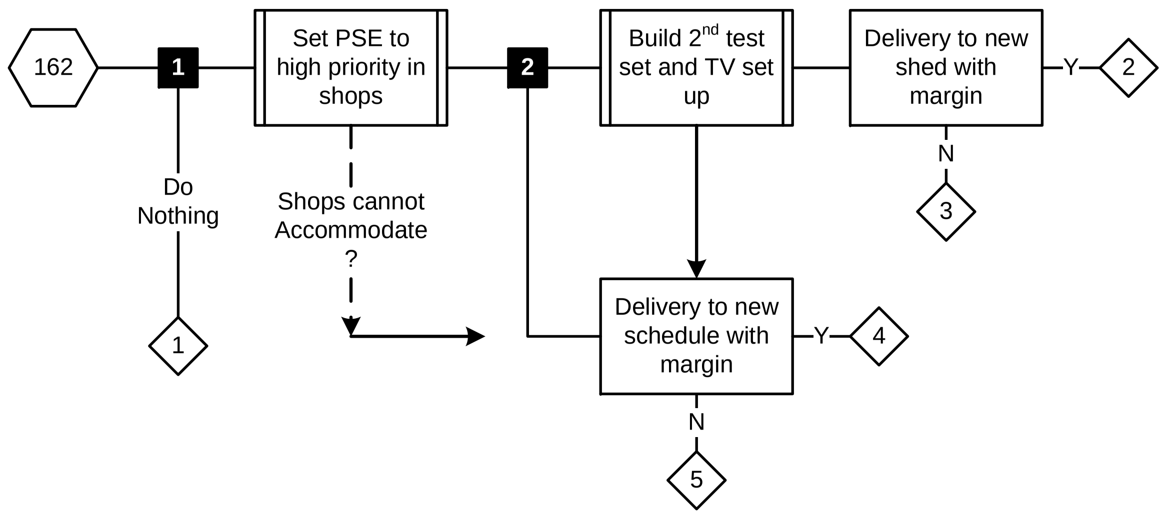
FILENAME: RSD-161.VSD

PAGE: 1

DESCRIPTION

If the PSE hardware continues to slip schedule, then the hardware will be late to system I&T.

Context: PSE hardware funded schedule reserve has deteriorated at a fast pace with many months before delivery.



ES	Cost	Delay	LOM
1	$ of delay	X weeks	BL
2	$ of new test sets	No impact to crit path	BL
3	$ of new test sets + delay	Y weeks to crti path	BL
4	BL	No impact to crit path	BL
5	$ of delay	z weeks to crit path	BL
6			

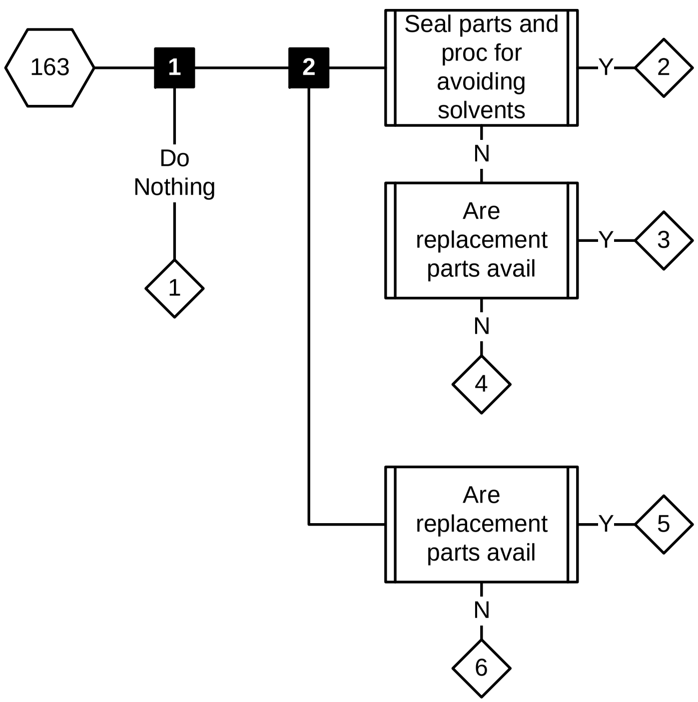
Risk Sequence Diagram

TITLE

RI-162: PSE hardware schedule slip

FILENAME RSD-162A.VSD

PAGE 1



DESCRIPTION

If the SSPA amplifier part can not be made resistant to flux, solvent, and moisture degradation and long-term reliability ensured, then SSPA delivery schedule will be impacted.

Part packaging has been discovered to allow leakage. Need to ensure that corrosive materials, cleaning/assembly solvents, or moisture will not affect power amplifier performance. On two breadboard units, corrosive flux had entered the part during the assembly process. After ~1,000 hours of successful operation, both units failed.

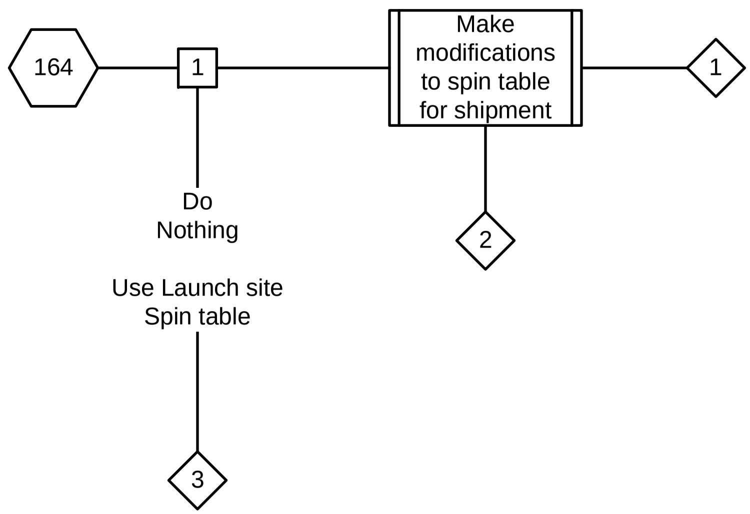
ES	Cost	Delay	LOM
1	BL	BL	LOM close to 1.0
2	Minimal add'l cost	1 mo slip	~ BL
3	Add'l $ sealing + new parts	Med slip	~ BL
4	Sealing $ + redesign effort	Significant slip	~ BL
5	$ replace parts	Med slip	~ BL
6	Redesign effort	Significant slip	~ BL

Risk Sequence Diagram

TITLE: RI-163: SSPA Part Leakage

FILENAME: RSD-163.VSD

PAGE: 1



ES	Cost	Delay	LOM
1	Mod & ship costs	--	--
2	“	--	--, incr mass uncert
3	--	--	“
4			
5			
6			
7			

DESCRIPTION

If the local spin table is not used for final processing and checkout of the observatory at the launch site, then uncertainty will be introduced into the spin balance measurements before launch.

The local spin balance table is far superior to the Launch Site facility spin table. We will conduct initial spin balance of each observatory on the local table, and should conduct the final spin balance of each observatory on the local table as well. This will also allow the mission to spin balance without propellant in the tanks, making the spin balance effort no longer hazardous. In order to be able to use the local spin table, the program needs to make the spin table portable for transport to the launch site.

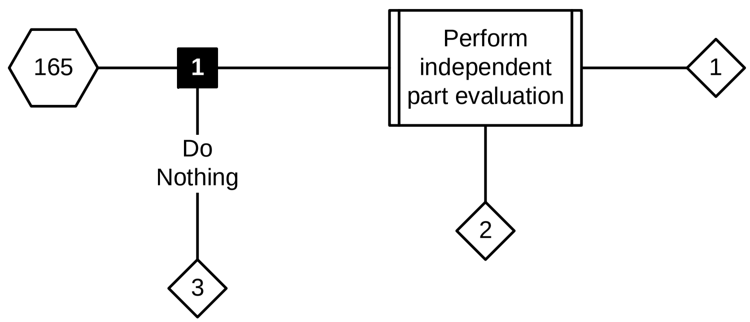
Risk Sequence Diagram

TITLE

RI-164: Meeting Spin Balance Requirements

FILENAME RSD-164.VSD

PAGE 1



ES	Cost	Delay	LOM
1	Increase cost of testing	< 1wk, no crit path impact	--
2	Cost of testing, replace parts	“ + reorder time	--
3	--	~ 3wk to PDU	--

DESCRIPTION

If the op amp interface qualification test fails then the PDU flight build schedule will be impacted and PDU telemetry measurements will be degraded.

The PDU utilizes xxx op amps to amplify telemetry signals for current and voltage. These signals will be present as the PDU powers up and also during PDU off-pulsing. It is not clear on the xxx data sheet under what conditions it is allowable for an input to be present when the part is unpowered. The manufacturer has indicated that they believe the configuration of the op amp in the PDU is acceptable but recommended testing as additional confirmation of this. Qualification testing is being performed to confirm that the op amp configuration does not cause device overstress. If the test fails, then 2 resistor values will have to be changed and a resistor must be added to each RC slice. This change will slip the PDU schedule, and as a secondary effect will degrade the voltage and current measurements made by the PDU, and degrade LVS performance.

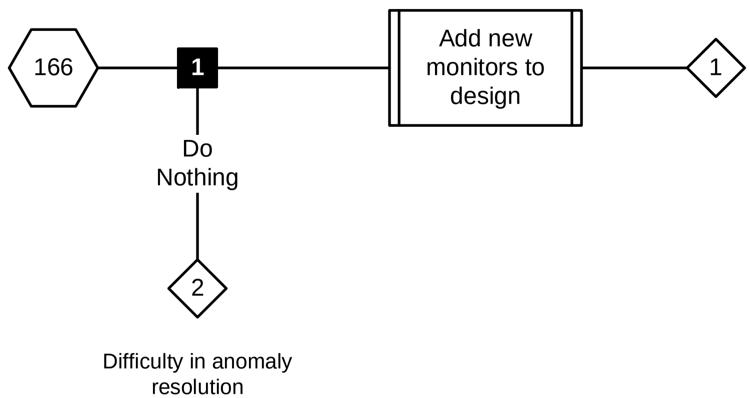
Risk Sequence Diagram

TITLE

RI-165: PDU Op Amp Interface Qualification Test

FILENAME RSD-165.VSD

PAGE 1



DESCRIPTION

If additional spacecraft radiation and charge monitoring data is not available on-orbit then spacecraft model correlation and anomaly resolution will be difficult to achieve.

Spacecraft radiation and charge models cannot rely solely on science instrument data for correlation. In addition, on-orbit anomaly resolution will be difficult without accurate measurements of radiation and charge conditions impacting the spacecraft. The addition of simple and inexpensive monitors will add value to resolving both of these spacecraft issues.

ES	Cost	Delay	LOM
1	Cost of design, test, mass	~ 1 mo, no crit path impact	--
2	--	--	Small increase
3			

Risk Sequence Diagram

TITLE

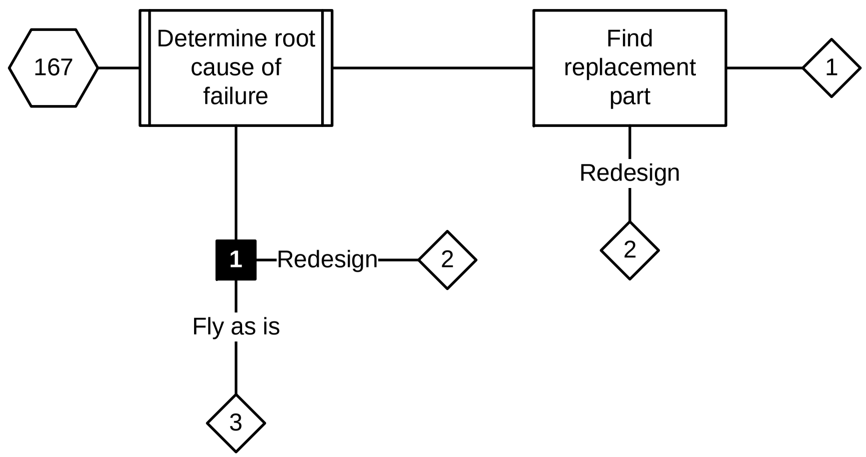
RI-166: Radiation and Charge Monitoring

FILENAME	PAGE
RSD-166.VSD	1

DESCRIPTION

If the purchased in-stock DC/DC converter cannot be used for flight, then SSPA schedule will be impacted.

Context: Vendor xxx experienced a failure on one device during DPA of three converters. Investigation showed that an output tantalum capacitor had blown on a life test sample (a full Class K screening regime and 1,000 hours of operation at accelerated conditions) which had been used for DPA / RGA evaluation. Part used in RF Solid State Power Amp with implications of affecting other series used on IEM DC/DC converter board.



ES	Cost	Delay	LOM
1	Small increase for parts	--	--
2	Huge cost of design	Several weeks	~ BL
3	--	--	Incr λ, small overall impact

Risk Sequence Diagram

TITLE

RI-167: SSPA - DC/DC Converter Burn-in Failure

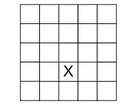
FILENAME

RSD-167.VSD

PAGE

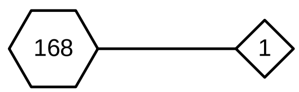
1

DESCRIPTION



If PDU flight parts currently on order do not arrive in time to replace non-flight parts installed to allow board-level processing and test, then there will be a schedule impact.

Context: Some PDU flight parts that have TBD as their delivery date. PDU board-level testing will continue by putting untested parts on the board, then potentially swapping them out later in the flow.



ES	Cost	Delay	LOM
1			
2			
3			

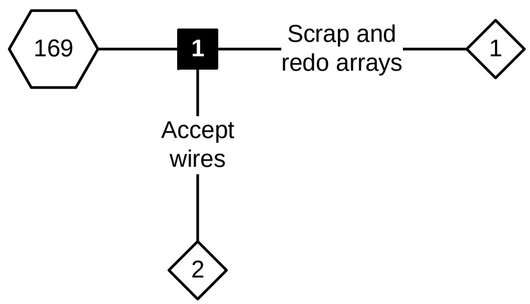
Risk Sequence Diagram

TITLE

RI-168: PDU Flight Part Delivery

FILENAME RSD-168.VSD

PAGE 1



ES	Cost	Delay	LOM
1	Slight increase	2 wks	--
2	--	--	--
3			

DESCRIPTION

If the use of xxx bond wire in some of the SA substrates is accepted, then the wires will become magnetized in space and will influence the Instr-M instrument measurement results.

Context: The SA substrate contractor, installed xxx bond wire in some of the SA substrates. It deviates from the yyy bond wire material specified in the process spec. The xxx is more likely to get magnetized in space and, as a result, will influence the Instr-M measurement results. Science Team should be able to filter out the measurement contributed by the xxx bond wires.

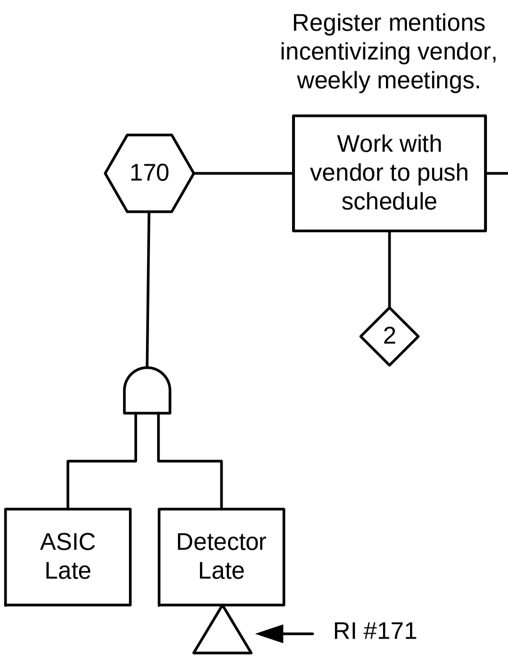
Risk Sequence Diagram

TITLE

RI-169: Use of xxx Bond Wire in SA Substrates

FILENAME RSD-169.VSD

PAGE 1



DESCRIPTION

If the hybrid boards are late, then the delivery of Instr-M units to the Spacecraft for I&T will be delayed.

Context: Building the hybrid boards is a complex activity with a subcontractor. After the initial build, the ASICs are placed on the hybrid and then the hybrids are screened and life tested. Any delays in fabrication, placement of the ASICs or screening will cause schedule delays.

ES	Cost	Delay	LOM
1	Incentive cost	--	--
2	“	Significant delay	--
3			

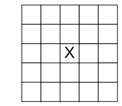
Risk Sequence Diagram

TITLE: RI-170: Instr-M Hybrid Delivery

FILENAME: RSD-170.VSD

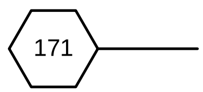
PAGE: 1

DESCRIPTION



If the solid state detector assemblies are delayed then the Instr-M will experience delays that will impact the delivery schedule.

Context: A number of NASA programs are using the same vendor for detector procurement; given that vendor xxxx has a limited capacity of manufacturing these detectors, a delay for Instr-M is possible if vendor xxx cannot deliver on time.



See # 170

ES	Cost	Delay	LOM
1			
2			
3			

Risk Sequence Diagram

TITLE

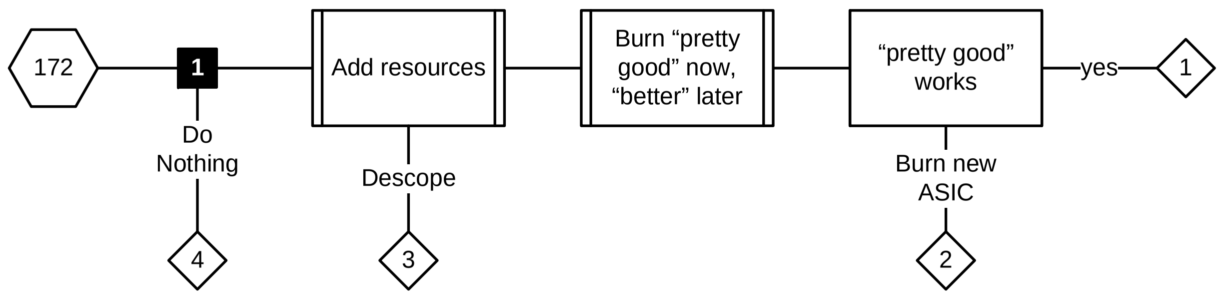
RI-171: Instr-M Detector Procurement and Delivery

FILENAME	PAGE
RSD-171.VSD	1

DESCRIPTION

If the Instr-E DFB FPGA design verification and flight FPGA programming is not complete by July 2010, then Instr-E will deplete all of its funded schedule reserve and the Project I&T schedule will be impacted.

Context: Verification of the DFB FPGA has taken longer than planned. It has moved onto the Instr-E delivery critical path and continued delays are resulting in use of Instr-E's funded schedule reserve.



ES	Cost	Delay	LOM
1	Slight increase	--	--
2	Additional ASIC cost	Slight	--
3	--	--	Lower functionality
4	Potential rework cost later	Potential significant later	Potential LOM
5			

Risk Sequence Diagram

TITLE

RI-172: Instr-E DFB FPGA Verification

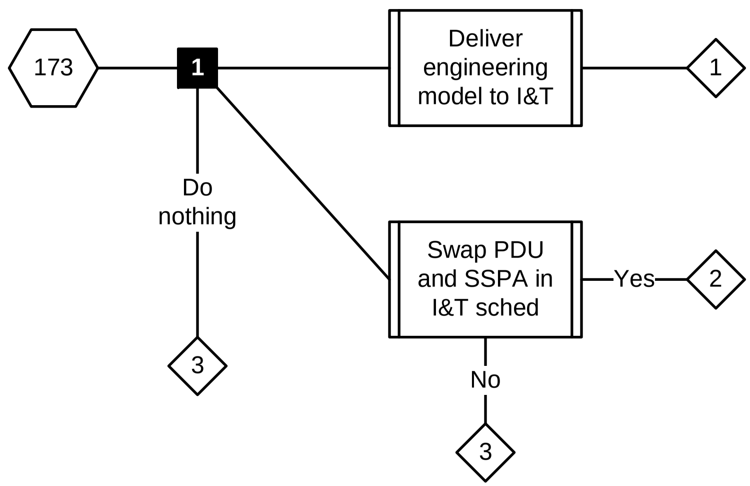
FILENAME RSD-172.VSD

PAGE 1

DESCRIPTION

If the SSPA continues to have part availability and fabrication issues, then there will be a critical-path schedule impact.

Context: The SSPA has under 10 days slack to its delivery to I&T. In addition, since RF is one of the last subsystems to be integrated there is no easy way to delay their delivery without schedule impact.



ES	Cost	Delay	LOM
1	--	Delay may be later	Greater uncert
2	--	--	--
3	--	Significant	--

Risk Sequence Diagram

TITLE: RI-173: SSPA Schedule Slip

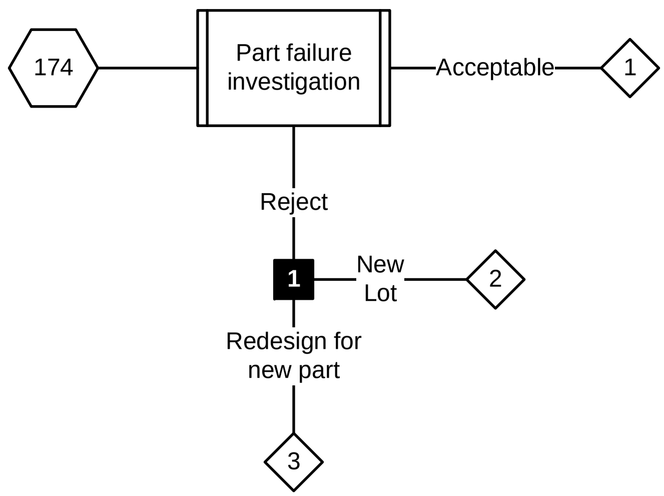
FILENAME: RSD-173.VSD

PAGE: 1

DESCRIPTION

If the part x failure investigation results in a rejection of remaining lot of parts, then there will be a XCVR receiver delivery impact.

Context: Test lab communicated results of a life test failure. One piece out of 22 failed post-life test electrical measurements; catastrophic continuity failure.



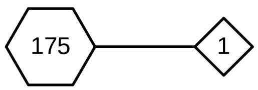
ES	Cost	Delay	LOM
1	--	--	--
2	--, covered by vendor	--	--
3	Redesign and replacement	Few weeks	--

Risk Sequence Diagram

TITLE: RI-174: Part x Life Test Failure

FILENAME: RSD-174.VSD

PAGE: 1



Only description is to accept a waiver

DESCRIPTION

If Instr-R uses pins/sockets with less than the minimum plating thickness of 50 microinches, a failure of a pin may occur.

Context: Waiver 006A was approved which allows use of the identified pins & connector sockets with less than 50 microinches of plating. Expected mate/demate cycles less than 10 times. An FMEA concluded the loss of 1/6 th of the energy field of view is the worst case open circuit effect. Risk of using these was determined to be low.

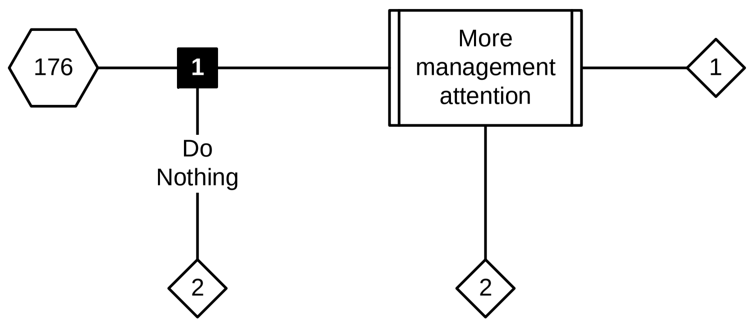
ES	Cost	Delay	LOM
1	Cost of failure	--	Risk increases
2			
3			

Risk Sequence Diagram

TITLE: RI-175: Instr-R Waiver 006 Technical Risk - Pin gold thickness

FILENAME: RSD-175.VSD

PAGE: 1



DESCRIPTION

If the I&T staffing shortage continues with no relief, system-level I&T scripts will not be ready when needed, and there will be a schedule impact.

Context: System-level I&T scripts may not be done in time since 9 I&T staff are “loaned” to the subsystems for box-level testing and not available for I&T procedure work. Group supervisors are hesitant to hire additional staff since they have a staffing cliff early next year.

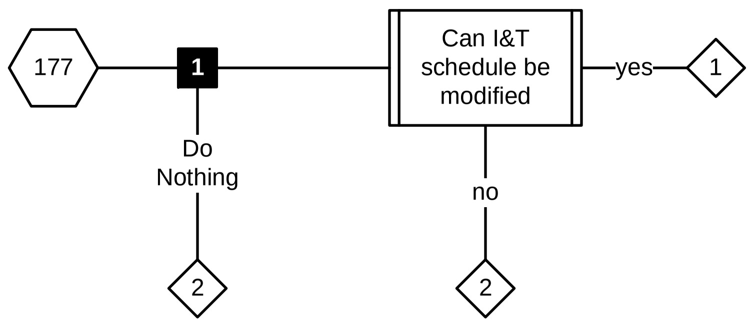
ES	Cost	Delay	LOM
1	Cost of mgt	--	--
2	?	Significant	--
3			

Risk Sequence Diagram

TITLE: RI-176: I&T Staffing Shortage

FILENAME: RSD-176.VSD

PAGE: 1



DESCRIPTION

If xxx program schedule moves to the right then Instr-R resource conflicts will occur affecting mission critical path.

Context: The Instr-R program cost and schedule was estimated assuming that the xxx program would be the lead in design, test and documentation. If these activities are not complete before Instr-R needs them, then Instr-R will have to assume leadership and more funding will be required. In addition, the same personnel and facility resources are required for both programs so the schedule may be impacted.

ES	Cost	Delay	LOM
1	--	--	--
2	--	Significant	--
3			

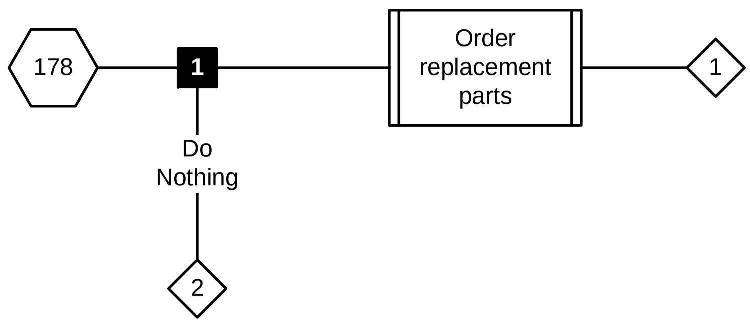
Risk Sequence Diagram

TITLE

RI-177: Instr-R Resource Conflict with another mission

FILENAME RSD-177.VSD

PAGE 1



DESCRIPTION

If all Instr-R mechanical parts are not available when required, and have to be fabricated or ordered, then there will be a schedule impact.

Context: Tracking of mechanical parts has been difficult due to Instr-R being closely coupled with xxxx program. It is unclear whether a) all of our parts have been ordered and b) xxx program has taken any of our parts for their use. Some of these items are long-lead items because they are made out of copper-tungsten. While there are usually work-arounds for parts that we do not have in stock, then work-arounds cause schedule delays and complexity in process and documentation. For items where there is no work-around, day-for-day schedule delays may ensue.

ES	Cost	Delay	LOM
1	Cost of new parts	~ wks, not crit path	--
2	--	~ month, not crit path	--
3			

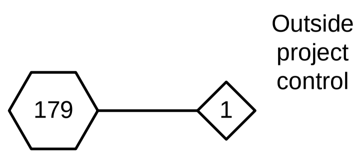
Risk Sequence Diagram

TITLE

RI-178: Instr-R Mechanical Part Fabrication

FILENAME RSD-178.VSD

PAGE 1



DESCRIPTION

If sufficient resources are not available to the sponsor instrument development effort to allow it to respond to additional work identified at the Mission-YY CDR, then the Instr-M effort will incur schedule delays.

Context: The Mission-YY Instr-M design received a number of significant action items during its CDR that require a moderate redesign effort. Even though the Project #2 Instr-M design is simpler in design requirements, their designs are paralleled. Some of the Mission-YY design issues would have been encountered at our CDR. The sponsor team is actively working to resolve the action items, however this will take additional unscheduled resources. If the redesigns can not progress in a timely manner for Mission-YY, this will have an impact on Project #2.

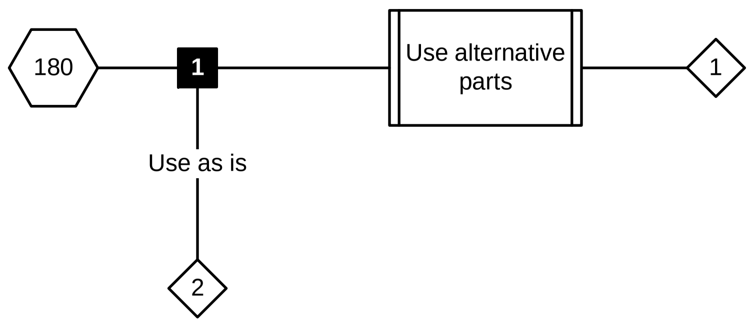
ES	Cost	Delay	LOM
1	--	Moderate delay	--
2			
3			

Risk Sequence Diagram

TITLE: RI-179: Instr-M Team Resources

FILENAME: RSD-179.VSD

PAGE: 1



DESCRIPTION

If the existing filter flight parts cannot be used as is and require rework involving disassembly and reassembly of the filter cans, schedule will be very severely impacted.

Context: In early June, Instr-E received data from the vendor that the required pre-tinning of leads on parts had not taken place in the assembly process. This means that these filters may be at risk for tin whisker growth. If the mitigation path is to open the filter cans and do mitigation (Echofoam and or RTV) then schedule will be impacted very significantly.

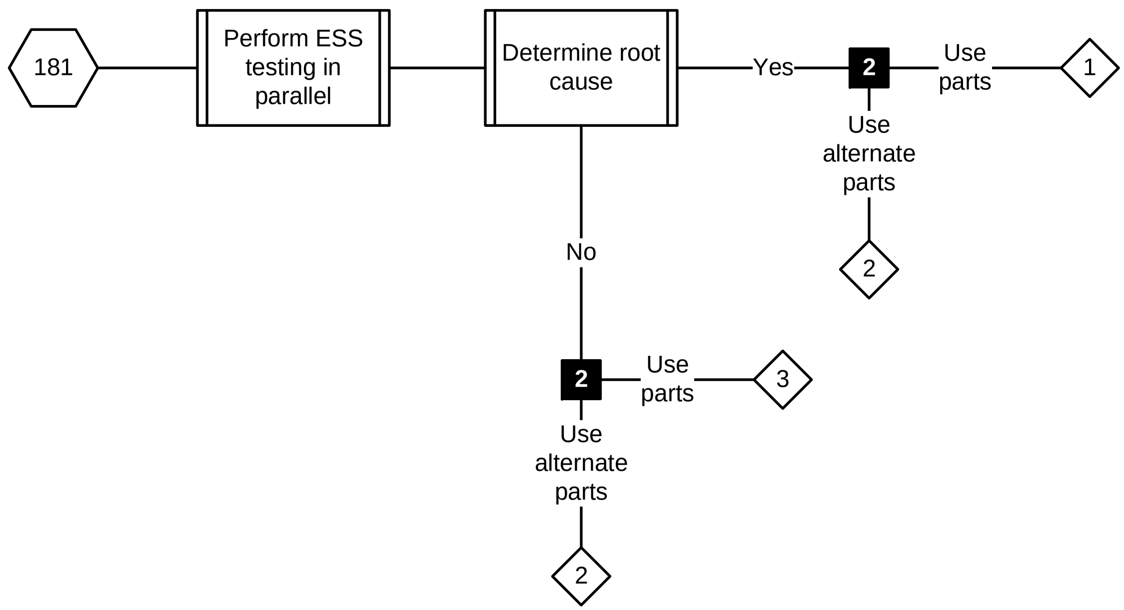
ES	Cost	Delay	LOM
1	Slight increase	Slight delay	--
2	--	--	Reliability decrease
3			

Risk Sequence Diagram

TITLE

RI-180: Instr-E Filter Tin Whiskers

FILENAME	PAGE
RSD-180.VSD	1



DESCRIPTION

If the root cause of the unit failures is not resolved before flight part installation, then additional failures are possible

Context: A failure was found in an xxx Converter part that was being screened for use in the SSPA. Investigation showed that an output tantalum capacitor was blown on a life test sample. This part is used in the RF SSPA assembly. A similar xxx converter is used in the IEM DC/DC Converter and initially there was concern that this failure could affect all xxx converter parts. No root cause established for blown output tantalum capacitor on a life test sample.

ES	Cost	Delay	LOM
1	--	--	--
2	Cost of parts	Reorder parts	--
3	--	--	Higher uncert

Risk Sequence Diagram

TITLE

RI-181: Use of DC/DC Converters in the IEM

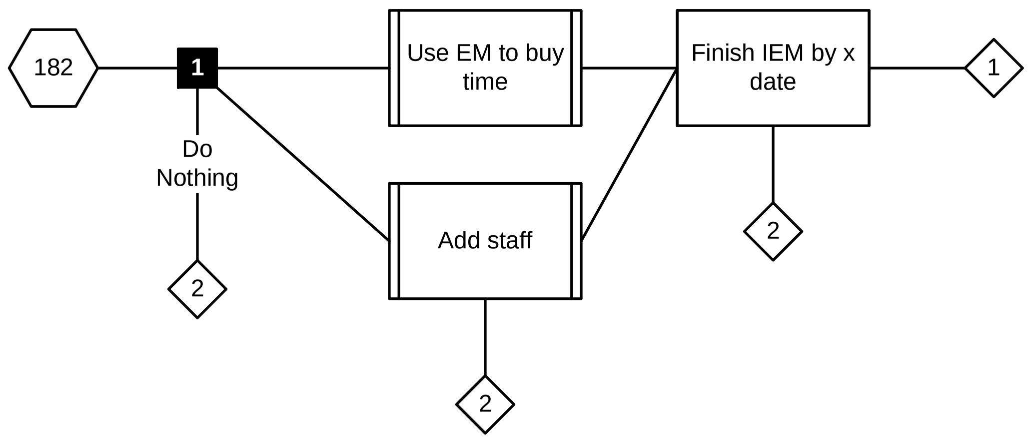
FILENAME RSD-181.VSD

PAGE 1

DESCRIPTION

If the IEM Flight Model 2 continues to have part availability, fabrication, and acceptance test issues, then there will be a critical-path schedule impact.

Context: IEM is at -8 days reserve and it can not be pushed later in the I&T schedule.



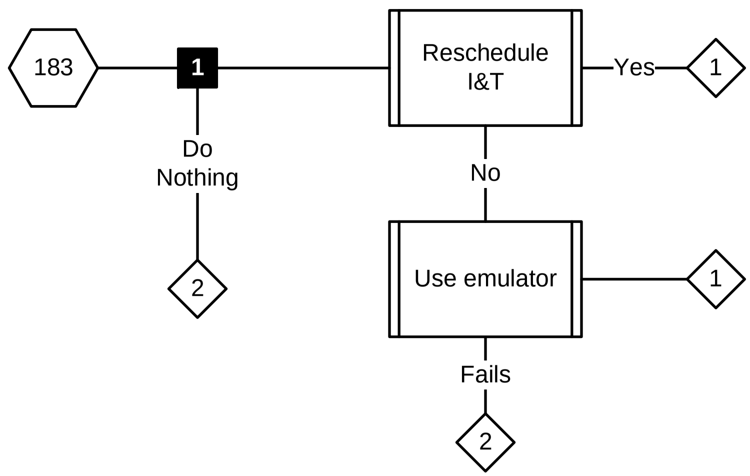
ES	Cost	Delay	LOM
1	--	--	--
2	--	Sig, on critical path	--
3			

Risk Sequence Diagram

TITLE
RI-182: IEM Flight Model 2 Schedule Slip

FILENAME
RSD-182.VSD

PAGE
1



DESCRIPTION

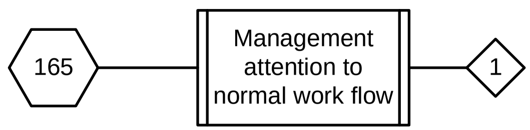
If the XCVR continues to have part availability and fabrication issues, then there will be a critical-path schedule impact.

Context: The XCVR has -6 days on Radio 1 and -2 days on Radio 2 for its delivery to I&T. In addition, since RF is one of the last subsystems to be integrated there is no easy way to delay their delivery without schedule impact.

ES	Cost	Delay	LOM
1	--	--	--
2	--	Significant	--
3			

Risk Sequence Diagram

TITLE	RI-183: XCVR Schedule Slip
FILENAME	RSD-183.VSD
PAGE	1



DESCRIPTION

If the PDU Flight Model 2 experiences part availability and fabrication issues, then there will be a critical-path schedule impact.

Context: Decision made to rebuild the PDU FM2 Relay/Capacitor slice (will be S/N 004). All the RDDs that were done against s/ns 001 & 002 will either have to be revised to add s/n 004, regenerated exclusively for s/n 004, or will need ECNs released to cover the changes.

ES	Cost	Delay	LOM
1			
2			
3			

Risk Sequence Diagram

TITLE

RI-184: PDU Flight Model 2 Schedule Slip

FILENAME

RSD-184.VSD

PAGE

1

Appendix C. Worked Example Code

Example RSD δ

This mathematica code is the quantitative implementation of RSD example from Chapters 4 - 8.

```
<< RiskSeqDiagrams`
```

```
eslb = {"BL", "ES1", "ES2", "ES3"};
```

■ RSD quantification at the pivotal event level

Data for pivotal events is computed from fault trees in Figure 5 - 3.

```
δ = 0.847;
E1 = 0.29637;
M1 = 0.15085;
```

Endstate expressions from RSD

```
esBL = (1 - δ) + δ (1 - E1);
es1 = δ E1 DP (1 - M1);
es2 = δ E1 DP;
es3 = δ E1 (1 - DP);
{{eslb⟦1⟧, esBL}, {eslb⟦2⟧, es1},
  {eslb⟦3⟧, es2}, {eslb⟦4⟧, es3}} // TableForm
```

```
BL     0.748975
ES1    0.213158 DP
ES2    0.251025 DP
ES3    0.251025 (1 - DP)
```

Apply DP = 0 or DP = 1 to get columns for Table 5 - 1.

```
DP = 0;
presD0 = {esBL, es1, es2, es3};
DP = 1;
presD1 = {esBL, es1, es2, es3};
```

```
t51 = Table[{eslb⟦i⟧, presD0⟦i⟧, presD1⟦i⟧}, {i, 1, 4}];
Print[]
Print["Table 5-1"]
Print[TableForm[t51,
  TableHeadings → {None, {"Endstate", "Do Nothing", "Implement"}}]]
Print[]
```

Table 5-1

Endstate	Do Nothing	Implement
BL	0.748975	0.748975
ES1	0.	0.213158
ES2	0.	0.251025
ES3	0.251025	0.

```
Clear[esBL, es1, es2, es3, DP, δ, E1, M1, presD0, presD1];
```

■ RSD quantification at the basic event level

Computations are displayed symbolically for RSD δ. The cutset are generated at the basic event level and are consistent with figure 5-4.

```
cutsetx0 = ((1 - a) (1 - b)) + ((1 - b) a (1 - c));
cutsetx1 = (1 - b) a c DP (1 - d);
cutsetx2 = (b DP) + ((1 - b) a c DP d);
cutsetx3 = (b (1 - DP)) + ((1 - b) a c (1 - DP));
```

Define probabilities.

```
pres = {cutsetx0, cutsetx1, cutsetx2, cutsetx3}
```

```
{(1 - a) (1 - b) + a (1 - b) (1 - c), a (1 - b) c (1 - d) DP,
 b DP + a (1 - b) c d DP, b (1 - DP) + a (1 - b) c (1 - DP)}
```

```
DP = 0;
presD0 = pres;
DP = 1;
presD1 = pres;
Clear[DP];

a = 0.82;
b = 0.15;
c = .21;
d = 0.001;

t52 = Table[{eslb⟦i⟧, presD0⟦i⟧, presD1⟦i⟧}, {i, 1, 4}];
Print[]
Print["Table 5-2"]
Print[TableForm[t52,
  TableHeadings → {None, {"Endstate", "Do Nothing", "Implement"}}]]
Print[]
```

Table 5-2

Endstate	Do Nothing	Implement
BL	0.70363	0.70363
ES1	0	0.146224
ES2	0	0.150146
ES3	0.29637	0

Consequence definition. Each set contains {cost, delay, Loss}

```
escq = {{0, 0, 0.01}, {100, 25, .01}, {125, 30, .5}, {2000, 10, 0.9}};
```

Cost Utility function

```
chigh = 2500;
clow = 0;
crav = 1 / (.5 (chigh - clow))
```

$$uc[cx\_] := \frac{Exp[-crav\ (chigh - cx)] - 1}{Exp[-crav\ (chigh - clow)] - 1}$$

```
FullSimplify[uc[x]]
```

0.0008

$1.15652 - 0.156518\, e^{0.0008\, x}$

```
esx = uc[escq⟦All, 1⟧];
```

```
t53 = Table[{eslb[[i]], escq[[i, 1]], esx[[i]], presD0[[i]], presD1[[i]]}, {i, 1, 4}];
Print[]
Print["Table 5-3"]
Print[TableForm[t53, TableHeadings →
   {None, {"Endstate", "Consq", "Utility", "Do Nothing", "Implement"}}]]
Print[]
```

Table 5-3

Endstate	Consq	Utility	Do Nothing	Implement
BL	0	1.	0.70363	0.70363
ES1	100	0.986964	0	0.146224
ES2	125	0.983539	0	0.150146
ES3	2000	0.381281	0.29637	0

Schedule Delay Utility function

```
dhigh = 50;
dlow = 0;
drav = 1 / (.8 (dhigh - dlow))
```

$$ud[dx\_] := \frac{Exp[-drav\ (dhigh - dx)] - 1}{Exp[-drav\ (dhigh - dlow)] - 1}$$

```
FullSimplify[ud[x]]
```

0.025

$1.40155 - 0.401551\, e^{0.025\, x}$

Loss of Mission Utility function

```
lhigh = 1;
llow = 0;
lrav = 1 / (.25 (lhigh - llow))
```

$$ul[lx\_] := \frac{Exp[-lrav\ (lhigh - lx)] - 1}{Exp[-lrav\ (lhigh - llow)] - 1}$$

```
FullSimplify[ul[x]]
```

4.

$1.01866 - 0.0186574\, e^{4.\, x}$

Multi-Attribute Utility function

```
ut[list_] := 0.3 uc[list[[1]]] + 0.5 ud[list[[2]]] + .2 ul[list[[3]]]

esx = Table[ut[escq[[i]]], {i, 1, 4}];

t54 = Table[{eslb[[i]], esx[[i]], presD0[[i]], presD1[[i]]}, {i, 1, 4}];
Print[]
Print["Table 5-4"]
Print[TableForm[t54, TableHeadings →
   {None, {"Endstate", "Utility", "Do Nothing", "Implement"}}]]
Print[]
```

Table 5–4

Endstate	Utility	Do Nothing	Implement
BL	1.	0.70363	0.70363
ES1	0.986964	0	0.146224
ES2	0.983539	0	0.150146
ES3	0.381281	0.29637	0

■ Risk Profile

```
Clear[a, b, c, d, DP]

pdfδ = SortBy[Table[{esx⟦i⟧, pres⟦i⟧}, {i, 1, 4}], First]
ccdfδ = Ccdf[pdfδ]
rmδ = 1. − AreaCalc[ccdfδ]

{{0.381281, b (1 − DP) + a (1 − b) c (1 − DP)}, {0.983539, b DP + a (1 − b) c d DP},
 {0.986964, a (1 − b) c (1 − d) DP}, {1., (1 − a) (1 − b) + a (1 − b) (1 − c)}}

{{0, (1 − a) (1 − b) + a (1 − b) (1 − c) + b (1 − DP) + a (1 − b) c (1 − DP) +
    b DP + a (1 − b) c (1 − d) DP + a (1 − b) c d DP}, {0.381281,
   (1 − a) (1 − b) + a (1 − b) (1 − c) + b DP + a (1 − b) c (1 − d) DP + a (1 − b) c d DP},
 {0.983539, (1 − a) (1 − b) + a (1 − b) (1 − c) + a (1 − b) c (1 − d) DP},
 {0.986964, (1 − a) (1 − b) + a (1 − b) (1 − c)}, {1., 0}}

1. − 0.0130359 ((1 − a) (1 − b) + a (1 − b) (1 − c)) −
 0.00342521 ((1 − a) (1 − b) + a (1 − b) (1 − c) + a (1 − b) c (1 − d) DP) − 0.602258
   ((1 − a) (1 − b) + a (1 − b) (1 − c) + b DP + a (1 − b) c (1 − d) DP + a (1 − b) c d DP) −
 0.381281 ((1 − a) (1 − b) + a (1 − b) (1 − c) + b (1 − DP) +
     a (1 − b) c (1 − DP) + b DP + a (1 − b) c (1 − d) DP + a (1 − b) c d DP)

pdfD0 = SortBy[Table[{esx⟦i⟧, presD0⟦i⟧}, {i, 1, 4}], First];
pdfD1 = SortBy[Table[{esx⟦i⟧, presD1⟦i⟧}, {i, 1, 4}], First];
ccdfD0 = Ccdf[pdfD0];
ccdfD1 = Ccdf[pdfD1];
rmD0 = 1. − AreaCalc[ccdfD0];
rmD1 = 1. − AreaCalc[ccdfD1];

a = 0.82;
b = 0.15;
c = .21;
d = 0.001;

t61 = Table[{pdfD0⟦i, 1⟧, pdfD0⟦i, 2⟧,
    ccdfD0⟦i, 2⟧, pdfD1⟦i, 2⟧, ccdfD1⟦i, 2⟧}, {i, 1, 4}];
Print[]
Print["Table 6–1"]
Print[TableForm[t61, TableHeadings → {None, {"Utility",
      "f Do Nothing", "R Do Nothing", "f Implement", "R Implement"}}]]
Print[]
```

Table 6-1

Utility	f Do Nothing	R Do Nothing	f Implement	R Implement
0.381281	0.29637	1.	0	1.
0.983539	0	0.70363	0.150146	1.
0.986964	0	0.70363	0.146224	0.849854
1.	0.70363	0.70363	0.70363	0.70363

```
t62 = {rmD0, rmD1} // TableForm
```

```
0.18337
0.00437773
```

```
Clear[a, b, c, d, DP]
```

Importance Measures

```
imδ = {};
```

Birnbaum

Applied as $\frac{d\,\mathrm{Rm}}{d\,\theta}$, where θ is the parameter of interest

```
im = ImBirnbaum[rmδ, #] & /@ {a, b, c, d, DP};
AppendTo[imδ, im];
```

Fussell - Vesely

Applied as $\frac{d\,\mathrm{Rm}}{d\,\theta} \times \frac{\theta}{\mathrm{Rm}}$, where θ is the parameter of interest

```
im = ImFV[rmδ, #] & /@ {a, b, c, d, DP};
AppendTo[imδ, im];
```

Risk Reduction Worth

Applied as $\frac{\mathrm{Rm}}{\mathrm{Rm}(\theta = 0)}$, where θ is the parameter of interest

```
im = ImRRW[rmδ, #] & /@ {a, b, c, d, DP};
AppendTo[imδ, im];
```

Risk Achievement Worth

Applied as $\frac{\mathrm{Rm}(\theta = 1)}{\mathrm{Rm}}$, where θ is the parameter of interest

```
im = ImRAW[rmδ, #] & /@ {a, b, c, d, DP};
AppendTo[imδ, im];
```

```
a = 0.82;
b = 0.15;
c = .21;
d = 0.001;

DP = 0;
Print["DP = 0"]
Print["Importance Measures"]
Print[TableForm[imδ,
  TableHeadings → {{"Birnbaum", "Fussell-Vesely", "Risk Reduction",
     "Risk Acheivement"}, {"a", "b", "c", "d", "DP"}}]]
Print[]

DP = 1;
Print["DP = 1"]
Print[TableForm[imδ,
  TableHeadings → {{"Birnbaum", "Fussell-Vesely", "Risk Reduction",
     "Risk Acheivement"}, {"a", "b", "c", "d", "DP"}}]]
Print[]
```

DP = 0

Importance Measures

	a	b	c	d	DP
Birnbaum	0.110441	0.512176	0.431247	0.	−0.178992
Fussell-Vesely	0.493876	0.41897	0.493876	0.	0.
Risk Reduction	1.9758	1.72108	1.9758	1.	1.
Risk Acheivement	1.10841	3.37416	2.85791	1.	0.0238738

DP = 1

	a	b	c	d	DP
Birnbaum	0.00232752	0.0142157	0.00908841	0.000501348	−0
Fussell-Vesely	0.435971	0.487093	0.435971	0.000114522	−4(
Risk Reduction	1.77296	1.94967	1.77296	1.00011	0.(
Risk Acheivement	1.0957	3.76019	2.64008	1.11441	1.

```
Clear[a, b, c, d, DP]

ImBirnbaum[rmδ, a]
```

0. + (0.375323 − 0.375323 b) c

```
ImFV[rmδ, a]
```

(a (0. + (0.375323 − 0.375323 b) c)) /
(0.000152284 + 0.375323 b + 0.375323 a c − 0.375323 a b c)

```
ImRRW[rmδ, a]
```

(0.000152284 + 0.375323 b + 0.375323 a c − 0.375323 a b c) /
(0.000152284 + 0.375323 b)

ImRAW[rmδ, a]

$(0.000152284 + 0.375323\, b + 0.375323\, c - 0.375323\, b\, c) / (0.000152284 + 0.375323\, b + 0.375323\, a\, c - 0.375323\, a\, b\, c)$

RiskSeqDiagrams.m

```
(* Mathematica Raw Program *)

StepPlotData[list_] :=
      (* Produces all the points to draw a discrete cdf *)
      Module[{i = 1, nlist},
            nlist = {};
            While[i < Length[list],
                  AppendTo[nlist, {list[[i, 1]], list[[i, 2]]}];
                  AppendTo[nlist, {list[[i + 1, 1]], list[[i, 2]]}];
            i++];
            AppendTo[nlist, {list[[Length[list], 1]], 0}];
            nlist
      ]

AreaCalc[list_] :=
      (* Computes the area under a ccdf *)
      Module[{i = 1, area = 0},
            While[i < Length[list],
                  area = area + (list[[i + 1, 1]] - list[[i,
1]])*list[[i, 2]];
            i++];
            area
      ]

Ccdf[list_] :=
      (* Creates a complementary cumulative density function *)
      Module[{i = 2, cum = 0, prsum, nlist},
            prsum = Total[list[[All,2]]];
            If[list[[1, 1]] == 0,
                  nlist = {{list[[1, 1]], prsum - list[[1, 2]]}},
                  nlist = {{0, prsum}, {list[[1, 1]], prsum - list[[1,
2]]}}
            ];
            cum = list[[1, 2]];
            While[i < Length[list] + 1,
                  cum = cum + list[[i, 2]];
                  AppendTo[nlist, {list[[i, 1]], prsum - cum}];
            i++];
            nlist
      ]

ImBirnbaum[eq_, elem_]:= Simplify[D[eq, elem]]

ImFV[eq_, elem_] := Simplify[D[eq,elem]*(elem/eq)]

ImRRW[eq_, elem_] := Module[{eq1},
      eq1=eq /. elem -> 0;
      Simplify[eq/eq1]
]

ImRAW[eq_, elem_] := Module[{eq1},
      eq1=eq /. elem -> 1;
      Simplify[eq1/eq]
]
```

```
PrOR[list_]:= 1-(Times @@ (1-# & /@ list))

GatherCutSets[list_] :=
      (* Gather Cutsets and OR them together *)
      Module[{i, n, m, l1, l2, lans = {}, lans1 = {}},
            l1 = GatherBy[list, First];
            n = Length[l1] + 1;
            For[i = 1, i < n, i++,
                  l2 = l1[[i]];
                  m = Length[l2];
                  AppendTo[lans, { l2[[1, 1]], PrOR[l2[[All, 2]]]}];
            ];
            lans
      ]
```

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