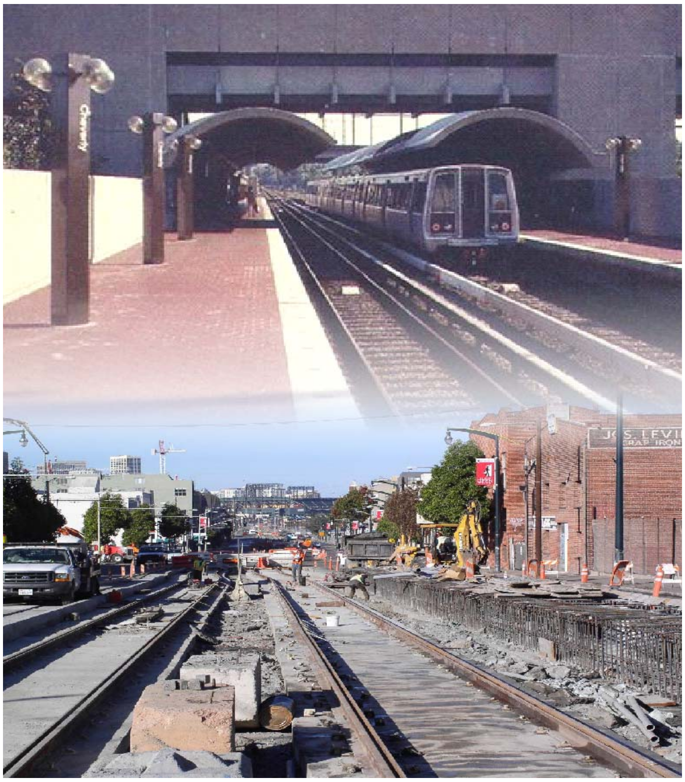

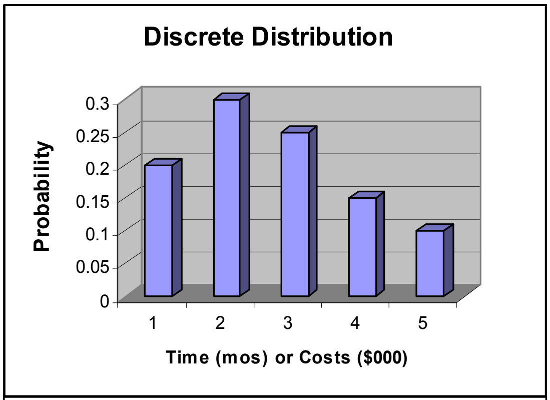

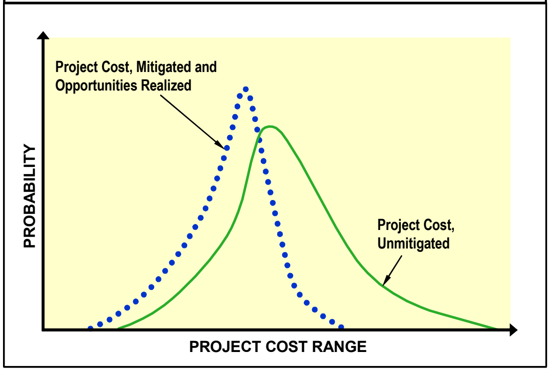

Risk Analysis Methodologies and Procedures

Prepared for: Federal Transit Administration
United States Department of Transportation
Washington, DC 20590

Contract No: DTFT60-98-D-41013

Project No: DC-03-5649

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Date: June 2004

FEDERAL TRANSIT ADMINISTRATION
PROJECT MANAGEMENT OVERSIGHT

Contract No. DTFT60-98-D-41013
Project No. DC-03-5649
Work Order No. 6

Risk Analysis Methodologies and Procedures

Prepared by
Parsons Transportation Group
in association with
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June 2004

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Acronyms

BCE	Baseline cost estimate
CDF	Cumulative distribution function
CLT	Central limit theorem
CMGC	Construction manager/general contractor
DBOM	Design-build-operate-maintain
FFGA	Full funding grant agreement
FOSM	First-order second-moment
FTA	Federal Transit Administration
IGA	Intergovernmental agreements
LRT	Light rail transit
MC	Monte Carlo
PDF	Probability density function
PE	Preliminary engineering
PMF	Probability mass function
PMO	Project management oversight
PMOC	Project management oversight contractor
PMOOG	Project management oversight program operating guidance
YOE	Year of expenditure

Executive Summary

Risk analysis is the systematic evaluation of uncertainty about the scope, cost, and duration of a project. This uncertainty is in the form of risks that a project could encounter during the course of its development, from planning through construction. It can also be in the form of unknown opportunities for improving the cost and schedule prospects for a project.

Traditionally, project owners have accounted for the possible impacts of risks by establishing contingencies, or add-ons, to a base project cost or base project duration. Contingencies typically are single-value allowances and set using simple rules of thumb (e.g., 10 percent of the base cost when setting a budget). Risk analysis provides an analytical basis for establishing allowances that account for the likely risks to a project; the allowances reflect defensible estimates of likely risk costs and durations. A probabilistic risk analysis uses concepts of probability to model uncertainties affecting project cost and schedule. It does not lead to a revised single-value allowance for project uncertainty, but identifies a likely range of costs or durations that bracket potential risk cost or schedule impacts. The likelihood of a project being completed within budget and on time will depend upon what level of potential risk impacts a project owner chooses to accept when setting budget and schedule allowances. Information from risk analysis supports other project budgeting and scheduling activities, such as value engineering and strategic planning. Risk analysis can also be a tool for better communication and more cost-effective project management.

This report describes procedures for performing risk analysis, which consists of two parts:

- **Risk assessment**, which includes identification and evaluation of risks in terms of their likelihood of occurrence and their probable consequences, and
- **Risk management**, which involves taking cost-effective actions to reduce risks and to realize opportunities.

Risk assessment begins with a critical review of the project's scope, cost, and schedule. The purpose is to determine whether they are reasonable, accurate representations of the project. The review establishes base project conditions with the cost and schedule stripped of all contingencies. A comprehensive list of risks that would add costs or time to the base project is identified and quantified. Quantification is in terms of the likelihood of each risk occurring and the potential cost and duration impacts. These impacts can be expressed as discrete values or a continuous range of values between certain limits.

Independence in the review of base conditions and for risk identification is desired to avoid any potential bias that a project owner might bring to the assessment. However, substantial owner involvement is important for several reasons, including the specific, thorough knowledge the owner can provide and the desire for buy-in to the risk analysis process and findings. One way to balance these competing objectives is to use a facilitated expert panel or workshop, composed of outside specialists and owner staff.

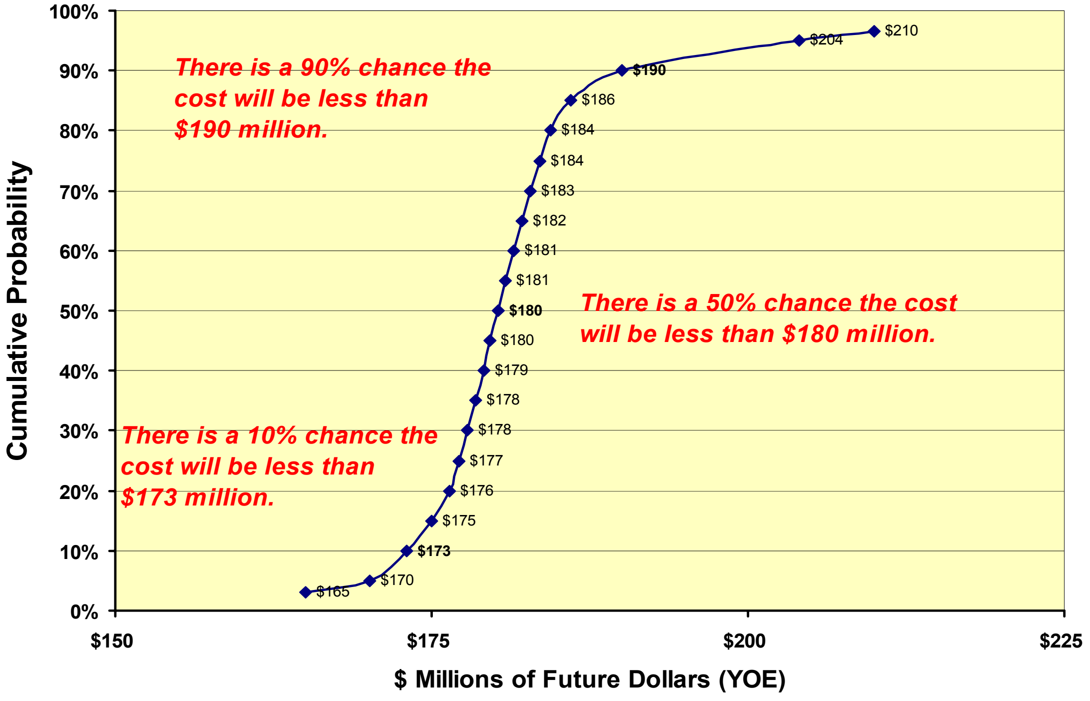
When risks have been appropriately quantified, they are analyzed for their effects on total project or major project component cost and duration. Risks and risk impacts can be characterized as single-value estimates (deterministic values) or probability distributions (probabilistic values). Probabilistic characterization of risks is recommended since it offers a valid statistical basis for representing uncertain or random events.

Depending upon the nature of risks and the desired outcomes of the analysis, risk cost and schedule impacts can be evaluated independently or together—in an integrated fashion. The disadvantage of independent evaluation is that the interrelationship of cost and schedule cannot be determined. Integrated analysis converts duration impacts to cost impacts through escalation. It is more difficult technically, however, to evaluate cost and schedule together and may not be necessary in all cases depending on the nature of the significant risks to a project. Analytical tools are available to assist in integrated analysis. Technical expertise is advised to help model risk relationships, including dependencies among risks and project components.

Combining validated base project costs and durations with accurately characterized risk costs and durations gives a defensible estimate of the total project cost and duration. Figure E-1 is an example of the estimated cumulative distribution of probable cost for a hypothetical public transit project.

Figure E-1 Cumulative Distribution of Cost

(Cumulative Distribution Function for Hypothetical Project)



There is a 90% chance the cost will be less than $190 million.

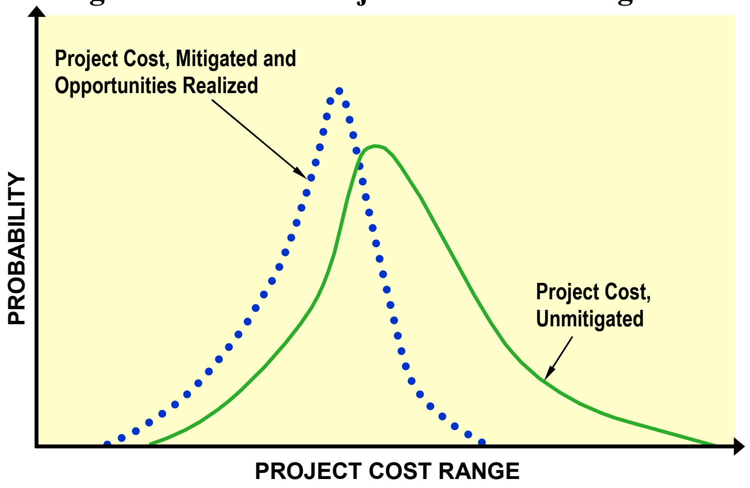
There is a 50% chance the cost will be less than $180 million.

There is a 10% chance the cost will be less than $173 million.

Probable cost ranges, such as shown in Figure E-1, allow project owners to evaluate whether a project budget, including contingency, is likely to be adequate to avoid cost overruns. If under the 50-percentile probable cost, the project is more than likely to experience an overrun. The contingency could be increased to support a project with a higher likelihood of successfully meeting the budget.

Using information from risk assessment, a project owner can evaluate measures to mitigate cost and schedule risks. Effective **risk management** will reduce impacts and make it more likely the project will be on time and within budget without the owner having to make additional contingency allowances. Effective risk mitigation will improve a project's probable cost (see Figure E-2). Proposed risk mitigation is documented in a risk management plan. This becomes the project owner's action plan for effectively minimizing risk impacts to a project.

Figure E-2 Total Project Cost with Mitigation



Risk analysis has value at all phases of project development and for both small and large projects. The preferred approach for risk analysis could vary depending upon phase or size but is not necessarily a function of either. The approach, including analysis methods, should be based on the project owner's objectives, available information, desired outcomes, and the different types of risks potentially facing a project.

Project owners will find risk analysis a valuable source of information about a project and the risk management plan an important management tool. FTA perceives risk analysis as important in the oversight of federally funded major investment projects.

Table E-1 is a summary of the recommended steps for risk analysis of public transit projects.

Table E-1 Recommended Approach to Risk Analysis

Risk Assessment

1	Establish objectives for risk analysis and expected outcomes.	***Prepare***
2	Identify resources available and resources required; scale effort in proportion to expected benefits.	
3	Perform comprehensive review of base project scope, cost and schedule to validate reasonableness. Review should include independent experts to ensure objectivity.	
4	Establish the project’s base cost and schedule (base excludes contingencies that are not specific allowances for known but unquantified project elements). Risks costs and risk delays are added to the base.	
	Products: Project Scope, Cost, and Schedule Review (report on reasonableness and accuracy of scope, cost and schedule of project) *Estimate of Base Project Costs and Durations (table of adjusted base costs and durations allocated to project components)*	
5	Establish a comprehensive and non-overlapping list of possible risks to the project.	***Identify***
6	Ensure all project components (major activities, contract units) are evaluated for risks and opportunities. Opportunities represent actions or measures that could reduce costs and delays as opposed to risks that increase costs and delays. Use an expert panel/workshop to develop risk list--the project risk register; including an unbiased facilitator is advised. Participation by project owner in this and other steps of risk analysis is important.	
	Product: Long List of Risks/Draft Risk Register	
7	Quantify risks in terms of their likelihood of occurring and their potential costs and delay impacts when they do occur. Risks reflect uncertainty and typically exhibit a range of values; therefore, they are appropriately characterized as probability distributions.	***Quantify***
8	Estimate cost and schedule (i.e., duration) impacts of risks. Use data on+C29 risk impacts from similar projects, relevant owner experience, expert judgment to establish the range of values for risks (e.g., optimistic/low impact, most likely impact, pessimistic/high impact).	
9	Identify correlated project components, that is, activities whose costs or durations move together in response to a risk event.	
10	Document estimated risk impacts on individual project components in the risk register.	
	Product: Completed Risk Register	

Table E-1 Recommended Approach to Risk Analysis, continued

11	Select the appropriate analysis method for estimating impacts of multiple risks on the project cost and/or schedule. This involves combining risks impacts (probable costs, probable durations) to obtain the risk cost or delay to a project. The method will depend upon the objective: ●Evaluate risk cost impacts to the base project cost [Independent cost analysis] ●Evaluate risk delay impacts to the base project schedule [Independent schedule analysis) ●Evaluate risk cost and delay impacts to the base project [Integrated cost and schedule analysis]	**Assess**
12	Use non-simulation or simulation (e.g., Monte Carlo) analysis methods for combining risk and base costs or schedule durations; either is appropriate but non-simulation methods prove difficult when multiple, complex risk impacts and correlations exist.	
13	Use simulation analysis methods to assess combined effects of risk cost and duration impacts on total project cost and schedule.	
14	Rank risks by the magnitude of their effect on total project cost or duration, i.e., how much the project cost or duration changes when risk occurs.	
15	Review analysis results with expert panel/workshop participants and project owner management.	
	Products: Ranking of Major and Minor Risks *Assessment Results (risk plus base costs and/or durations; probabilistic estimates of total project cost and/or duration)* *Risk Assessment Report (summary and findings of Prepare, Identify, Quantify, Assess)*	

Risk Management

16	Prioritize risks for mitigation: unacceptable risks; high cost, high likelihood risks. Mitigation must be cost-effective; use benefit-cost assessments to determine if mitigation is worthwhile.	**Mitigate**
17	Allocate risks to parties best able to manage/mitigate them. Contract documents and alternative procurement methods offer means for distributing risks.	
18	Prepare a risk management plan describing risk mitigation strategies, responsible parties, likely costs and benefits, additional implementation requirements.	
19	Monitor performance of mitigation measures; reevaluate risk mitigation strategies as appropriate to improve outcomes.	
20	Document program and lessons learned for application on other projects and/or for the benefit of others.	
	Products: Priority Ranking of Risks for Mitigation *Risk Mitigation Register* *Benefit-Cost Assessment of Risk Mitigation Costs* *Risk Management Plan (attachment to Project Management Plan and Risk Assessment Report)* *Lessons Learned and Other Documenation on Risk Management Strategies (developed from risk analysis process)*	

1. Introduction

1.1 Background

The public transportation industry has a mixed history of success in delivering projects within budget and on schedule. Major projects too often come in significantly over budget, which normally equates with being late in completion as well. There may be many causes for disappointing performance. The reasons seldom matter, however, when the news reaches the public. The lasting impression is almost always negative. And this makes it harder to garner support for the next proposed improvement.

Avoiding overbudget and late projects whenever possible is highly desirable. One way is to be more realistic in estimating project costs and timelines when projects are in planning and design, that is, before they are scheduled to begin construction. A better understanding of what circumstances and events could lead to cost growth and schedule delays will help. Then, proper allowances can be made for problems likely to arise prior to, during, and even after construction.

The Federal Transit Administration (FTA), which participates in the funding and, consequently, the oversight of most major public transit projects in the U.S., is both concerned about the total costs (and schedule delays) of new transportation projects and dedicated to providing technical assistance to help address the problems. The current FTA Strategic Plan includes vision strategies for improving public transit performance and specific goals to work with project owners in applying management practices that will help them implement successful rail, bus and other projects.

One such management practice is project risk analysis. Risk analysis is the systematic evaluation of risks, or uncertainties, facing a project. It actually has two components – risk assessment and risk management – explained in more detail in subsequent sections. Risk analysis, applied to public transit projects, is the focus of this report.

1.2 Risk Analysis Compared to Traditional Methods

A project's cost and schedule duration can be estimated in three basic ways:

1. Total cost or total duration, each a single value that implicitly includes both known and uncertain or unspecified values.
2. Base cost or duration plus a specified contingency, where the base covers all known values and the contingency is an "add-on" allowance for uncertain or unspecified values.
3. Base cost or duration plus itemized risks, which also explicitly includes all knowns in the base but delineates uncertain values into risks, which are quantified and added to the base.

Cost and schedule estimating for public transit projects has traditionally adopted the second method, although sometimes the single value estimate is used for projects at the conceptual level of development. The drawback of project estimates derived by either of the first two methods is that there is no quantification of the uncertain costs and durations that are inherently part of a project until construction is complete. A contingency is based on many stated and unstated assumptions, without establishing any confidence level for its value.

Risk analysis proposes that a project's cost and duration be established using the third method or, if an estimate is to include a contingency, that the adequacy of the contingency be validated using risk analysis. The benefit of systematic evaluation of project risks is that a project owner can be more confident that appropriate cost and schedule allowances have been established, and as a result, the project is more likely to be completed on time and within budget.

This report explains in detail the rationale for risk analysis of public transit capital projects. The emphasis is on probabilistic methods for evaluating risks– as this approach provides an effective way for modeling uncertain events – and describes the procedures a project owner should follow to carry out the process. FTA believes, once undertaken, risk analysis will be seen as an invaluable source of information about a project's scope, cost, and schedule. Transformed into an action plan for mitigating significant risks to a project, risk analysis becomes an important management tool. From its own perspective, FTA views risk analysis as a critical element in the oversight of federally funded projects.

2. Purpose

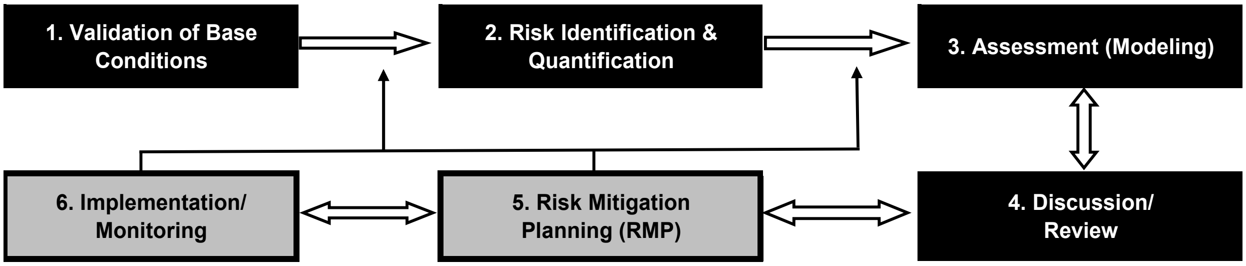
This report is intended to complement FTA's guidance on risk assessment and mitigation procedures for major capital projects (Project Management Oversight Program Operating Guidance Number 22—PMOOG#22). That guidance has emerged following FTA decision to undertake formal risk analyses of several major transit projects beginning in 2002. Relevant recommendations of this report will be incorporated into PMOOG#22 as it is updated to provide direction in risk analysis procedures and reporting to both local agencies undertaking major capital projects and contractors in FTA's project management oversight (PMO) program.

There are various approaches to risk analysis. This report describes the recommended approach for performing risk analysis of public transit projects. It outlines the basic steps of the process and discusses procedures for both identifying and characterizing risks and for evaluating risk impacts on a project's cost and schedule. While an overall approach to risk analysis is recommended, various analytical procedures for evaluating risk impacts are proposed and it is left to the entity undertaking risk analysis to select the preferred methods. This is because no single analysis method necessarily works best on all projects all of the time. The preferred method depends upon the desired outcomes—or objectives—of risk analysis and the conditions that exist. Guidelines are provided that will allow project sponsors[1] to select the analysis method best suited to a specific set of conditions.

The risk analysis process involves six basic steps. These are shown in Figure 2-1. For purposes of discussion, the convention is to divide these steps into two parts:

- The first involves identifying risks to a project and describing their potential impacts relative to a base set of conditions—boxes 1 through 3 in Figure 2-1. Base conditions refer to the scope, cost, and schedule for a project before allowances are made for unknown or as yet undefined circumstances—contingencies in the terminology of the design and construction industry. The first component also includes review of findings with parties involved in the risk analysis process—box 4—and establishing who would be responsible for mitigating impacts of significant risks. In this report, steps 1 through 3 are referred to as *risk assessment*.

Figure 2-1 The Risk Analysis Process



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[1] In this report, project sponsors refer to the project owner, FTA, and other entities (e.g., states, cities) that fund and oversee projects. The project owner is typically the operating entity that constructs a project.

- The mitigation of risks, which involves development and implementation of a risk management plan (box 5) and monitoring outcomes (box 6), is the second component of the process. In this report, steps 5 and 6 are referred to as *risk management.*

Risk assessment and risk management combined are referred to as risk analysis. As the boxes and arrows in Figure 2-1 indicate, risk analysis involves ongoing reassessments of risks and the effectiveness of risk mitigation. During the course of project development, as new risks become apparent or circumstances change and alter the character of previously identified risks, it is important that the potential impacts be assessed systematically.

An important aspect of risk analysis is when and how the process should be performed. The approach, including analytical methods used, may differ somewhat depending upon the project type or project phase, but its use can add value at any point in project development: from conceptual planning, to preliminary engineering (PE), to final design, and even during or after construction.

This report's format for presenting information is as follows:

- Section 3 provides an overview of risk analysis. It should be useful especially to individuals who want to understand the process and its potential benefits but do not need to become immersed in technical issues.
- Section 4 is a technical discussion of approaches to risk assessment: identifying project risks, their likelihood, probable costs, and schedule impacts. Probable costs and schedule impacts are important to quantify at both the detailed project activity level and the overall project level.
- Section 5 is a discussion of risk management, including the development and implementation of risk mitigation measures. A sound risk management plan, as stressed throughout this document, is important for realizing the benefits of the risk analysis
- Section 6 summarizes key concepts of, and best practices for, risk analysis.
- A list of references and related documentation on risk analysis concludes the main body of the report.
- Technical appendices follow the list of references. They include (A) glossary of terms; (B) risk checklist; and (C) risk assessment examples, including specific analytical procedures for combining base and risk costs for a project.

3. Understanding Risk and Overview of Risk Analysis Process

Main Points:

- *Project uncertainty includes both risks (adverse events) and opportunities (unrealized benefits).*
- *Risk assessment and risk management defined.*
- *Objective is to better understand project risks and opportunities and to quantify potential cost and schedule impacts.*
- *Findings inform the budgeting and scheduling process and support value engineering.*
- *Participants should have a range of appropriate skills and represent management and technical disciplines; unbiased expertise is critical.*
- *Before undertaking a risk assessment, identify the approach that best suits the study objectives and can be carried out with the resources and information available; avoid common mistakes.*

3.1 Risk and Definitions

Most people intuitively understand **risk**. Generally it is consistent with, in the words of Webster's Seventh New Collegiate Dictionary, the "possibility of loss or injury; a dangerous element or factor." Risk has a strongly negative connotation by this definition. In the context of risk analysis of public transit projects, risk is normally used to indicate a potentially adverse circumstance, expressed mainly in terms of causing undesired cost growth or time delays.

However, risk analysis is not to be focused entirely on potentially adverse circumstances. Just as there may be uncertainties that could negatively affect a project owner's ability to implement a project on time and within budget, there may be uncertainties that have been overlooked and which could provide opportunities to achieve faster project implementation at lower cost. For example, a simplified design or innovative construction technique could reduce the cost of materials and construction labor. These opportunities, or potential benefits, can offset (not to be confused with mitigate) risk impacts. The risk analysis process should identify opportunities to exploit as well as adverse circumstances to avoid or minimize, when implementing a project. During risk assessment, it is important to identify specific circumstances that may hurt or help a project.

For purposes of discussion, when referring to risk analysis, the intent is to incorporate the identification and evaluation of opportunities as well as risks although the term risk will be predominantly used.

There are various sources of risks to public transit projects. They include

- Socio-political risks
- Financial risks
- Planning and design risks
- Environmental concerns
- Right-of-way acquisition
- Permitting requirements
- Third party agreements
- Technology applications, availability, and reliability
- Procurement requirements (vehicles, civil facilities, systems equipment, materials)
- Construction risks, including maintenance of traffic, changed conditions, utilities and subsurface conditions, *etc*.
- Other risks, such as acts of God (weather, etc.) and changes in regulatory conditions or market conditions.

Some risks are not under direct control of the project owner and are referred to as *external risks*. These often fall under the socio-political risk category, sometimes are financial risks, and also include "other risks" such as weather and changing market conditions. Risks that are largely under the control of, or can be influenced by, actions of the owner are referred to as *internal risks*. Among the latter are risks in the planning, engineering, construction, and direct management of projects. It is, of course, important to understand the types of risks facing a project and who can influence their likely occurrence or their likely outcomes.

A **risk event** is the specific occurrence of a risk or the potential for a specific occurrence. For example, the possibility of encountering more than expected water inflow in a tunnel project or being sued over construction equipment noise impacts is a risk event. Each event carries a potential impact on cost and schedule and can affect construction means and methods.

Risk assessment has been defined previously to be the identification and evaluation of risks or risk events in terms of their likelihood of occurrence and their probable consequences. Likelihood of occurrence and the associated consequences can be expressed qualitatively or quantitatively. If risks can be quantified, it is easier to comprehend their effects on a project and determine whether resources—time, money, or other resources—can be cost-effectively applied to positively influence risk events. As an example, for both the risk of excessive water inflow into the tunnel and of a lawsuit over construction noise, the risk assessment should quantify the likelihood of the event happening and the likely costs and schedule delays if it does occur.

Risk management is making decisions to influence risks and, ultimately, taking cost-effective actions to reduce adverse risks and to realize opportunities. The process involves preparing an action plan that prioritizes risks, identifies the underlying causes of risk events, and describes ways to change the likelihood of risk events and their potential costs and schedule impacts. This action plan is referred to as the **risk management plan**, probably the most important tangible result of the overall risk analysis process.

Risk mitigation planning is another term used to describe risk management, although, again, it has the connotation that all risks are adverse and to be avoided. As an example, an action plan to mitigate excessive tunnel water would involve more geotechnical investigations to reduce the probability of being surprised by excessive water inflow and to prepare for high inflows in specific locations. To forestall a lawsuit over environmental noise, additional measurements of ambient noise levels near construction sites might be warranted and special measures specified in the contractor's scope of services, such as time restrictions on the use of heavy equipment or additional precautions to muffle equipment noise. In each case, the possible cost and schedule impacts that could result if the risk event occurred would be weighed against the costs of mitigation measures—essentially a benefit-cost comparison. This information would support a management decision on whether it was preferable to accept or to mitigate the risk.

Appendix A includes a list of terms used in this report along with their definitions.

3.2 Objectives and Expected Results of Risk Analysis

Risk analysis is intended to offer a systematic, cost-effective approach for evaluating project uncertainty. The process provides valuable information about a project. It is an important oversight tool for project sponsors, such as FTA, who fund major capital improvements. Risk analysis becomes an important management tool for project owners when results are used to reduce project uncertainty through the mitigation of significant risks.

Besides providing a better understanding of uncertainties that could affect project cost, schedule, scope, and quality, risk analysis offers other benefits. Among these are

- Improved communication among members of the project team
- Improved external communication, which is important for educating the public and other interested parties about the project
- Better understanding of the project delivery process, including timelines and phasing, procedural requirements, and potential obstacles
- More realistic estimates of individual component costs and durations, therefore more reasonable expectations of total project cost and duration
- Better understanding of the project contingency, whether it is sufficient, and for what it may need to be used
- Information support to other project or agency activities, such as value engineering and strategic planning
- Potential to improve the project budget and scheduling processes, possibly for the immediate project in development but certainly for future projects.

Among the many valuable items of information that can be generated by risk analysis are:

- Probabilistic estimates of project cost and schedule, considering all uncertainties (including risks).
- Prioritized list of cost and schedule risks, including assessment of their likelihood of occurring and their cost and schedule impacts if they do occur.
- Estimates of individual risk costs and their potential effects on project component schedules.

- Estimates of risk effects on the total project cost and overall schedule.
- Prioritized risk mitigation strategies, including their estimated implementation costs and cost/schedule savings, summarized in a risk management plan.

Cost and schedule estimates are in the form of a probable (i.e., likely) range of costs and a probable range of durations, respectively. This reflects the fact that a project's cost and schedule incorporate uncertainties surrounding its implementation: both will vary depending upon the occurrence of risk events and any uncertainties in the base project cost and base schedule. The last information item listed, a risk management plan, can only be developed if risks have been identified and quantified.

FTA has specified that project oversight contractors participating in risk analyses of New Starts projects prepare certain forms of documentation in addition to that listed above (see PMOOG#22). Included among FTA required documentation are background reports on (1) data sources, (2) the reasonableness and accuracy of information on the project scope, schedule and budget, and (3) draft and final risk analysis reports, inclusive of risk mitigation strategies. Project owners who independently undertake risk analyses will also benefit by requiring that this documentation be included among the key deliverables.

3.3 Timing of Risk Assessments

Project uncertainty changes over time. As the definition of a project advances, the level of uncertainty typically diminishes. This is intuitively logical. FTA has divided the project development process into five phases. These are shown in Figure 3-1 along with certain major milestones that demarcate when a federally funded project advances from one phase to the next. The classification provides a convenient way to characterize the state of planning and design, as well as other information about a project.

Projects in systems planning and alternatives analysis generally have more unknowns than projects in preliminary or final design. The alignment and modal specifics might not even be resolved in the conceptual phases. Projects moving through final design and into construction, in contrast, would be expected to have a comprehensive set of engineering drawings, operating assumptions, and cost detail. There could still be substantial uncertainty about certain aspects of a project well advanced in design, but most physical characteristics of the project will have been settled.

Project risks similarly change. The *number* of risks faced by a project would be expected to decrease as design detail advances to eliminate or avoid potential problems that are discovered. Risks also are reduced as policy makers take steps to shore up support for and clear environmental and other obstacles to project implementation.

Depending upon the phase of project definition, the *types* of risks also will likely change. Projects in planning often must address political concerns (socio-political risks), funding uncertainty (financial risks), environmental issues, and lack of public consensus on project characteristics (planning risks), among other risks. Projects in preliminary engineering or final design will focus more on risks in resource quantities and costs of construction (design and construction risks). If a project's estimated total cost is thought of not in terms of a single dollar value but as a potential range in costs – a range that reflects the potential effects of risks (and opportunities) – the potential range in costs would be expected to narrow over time and converge upon a most likely value. This is shown in Figure 3-2.

Figure 3-1 FTA New Starts Project Development Process

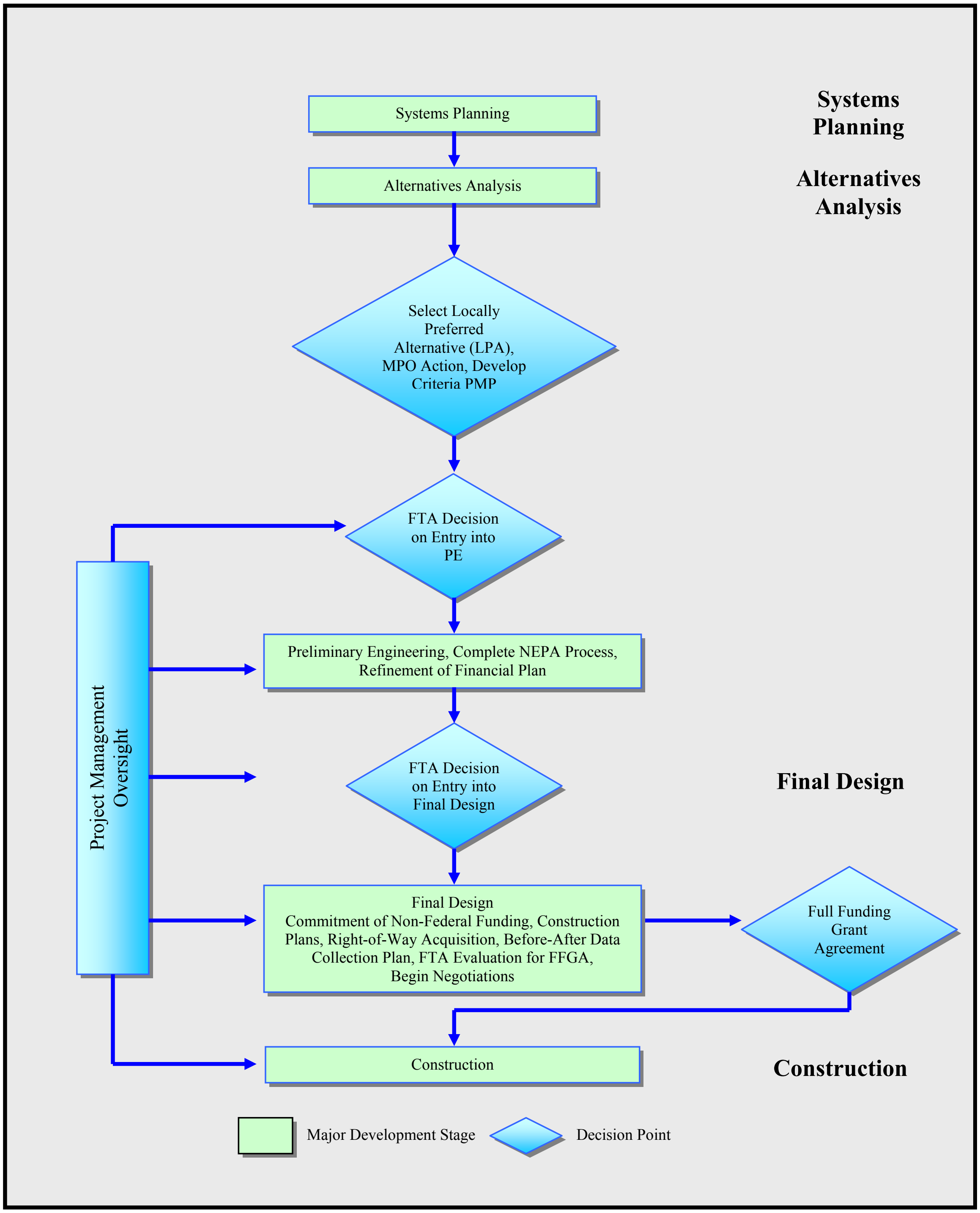
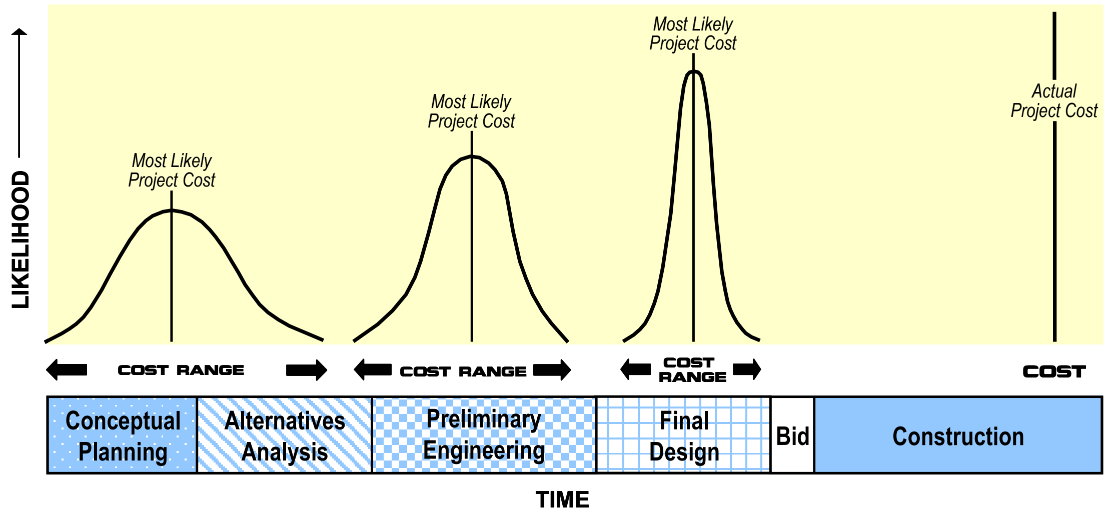


Figure 3-2 Project Cost and Uncertainty Over Time



3.3.1 Current FTA Requirements

FTA's current policy is that projects under consideration for New Starts funding, formalized in the approval of a full funding grant agreement (FFGA), will be subject to risk analysis. This generally means the analysis will be performed when the project has completed preliminary engineering (PE) and entered final design, or is at the 30 percent or greater level of design completion. (FFGA applications usually are not received until a project is at the 60 percent design level.) FTA considers this time critical because the federal government is evaluating a major funding decision and wants a high level of confidence that the project budget and schedule are achievable and the scope is not likely to change.

This does not mean final design is the preferred time to conduct risk analysis. If there are major project issues during conceptual planning or new uncertainties encountered during construction itself, these are equally suitable times to subject a project to evaluation of these specific risks. FTA encourages (and has sponsored) risk analysis at other phases of project implementation. In fact, FTA has concluded that risk assessments performed during PE will provide major benefits to FTA and project owners alike and establish a foundation for follow-up risk assessments during final design.

Table 3-1 offers a summary of the considerations, including objectives and benefits that apply to risk analysis at various phases of project development. Project sponsors should decide when to conduct risk analysis on a project-specific basis and after a careful evaluation of whether the objectives can be realized.

Table 3-1 Conditions Influencing Risk Issues and Risk Analysis Objectives

Project Phase	Status	Typical Risk Issues	Objectives for Risk Assessment	Expected Outcomes
Alternatives Analysis/ Conceptual Design	• Focus is on general alignment and mode • Project details not defined, environmental reviews incomplete • Funding possibly not committed • Public support uncertain; order-of-magnitude cost estimates • General implementation timeline	• Fatal or significant environmental, economic impacts • Funding uncertainty • Uncertain political and public support • Competing interests and competing projects • Costs relative to ridership/other benefits	• Identify implementation challenges--political, public acceptance, approvals • Better define a reasonable project approval and implementation schedule • Quantify advantages/disadvantages of different modes, alignments • Establish order-of-magnitude costs by mode, alignment • Identify major design and construction risks	• Better understanding of environmental, engineering, and construction issues facing each project alternative • Identification of major risks associated with each mode and alignment • Order-of-magnitude risk costs and possible total cost range for each mode, alignment
Preliminary Engineering	• Environmental reviews approaching completion (Record of Decision) • Initial approvals received but long term funding commitments still to be determined • Project definition in the form of engineering design approximately 30 percent complete • Cost estimates based on industry data and for aggregated activities • High cost and schedule contingencies	• Changes to project scope and budget • Costs of environmental compliance • Appropriate procurement methods • Changes in design requirements • Technical uncertainties • Market conditions, exchange rates, inflation • Funding uncertainty	• Identification, quantification and likelihood of major scope, budget and schedule risks for all major project components • General definition of base costs, risk costs, and total probable project costs • Risks of alternative design concepts, procurement methods	• List of major project risks • Reasonable estimate of risk costs and probable total project costs and duration • Long list of risk mitigation strategies • Preliminary risk management plan, focused on design and constructability risks
Final Design	• Project scope, cost and schedule well defined • Minor open issues since all cost and design detail well advanced • Construction approvals, including permits, agreements, not yet final	• Changes to project scope and budget • Errors or omissions in quantities, inaccurate unit prices • Changes in design requirements • Market conditions, exchange rates, inflation • Permit requirements • Delays in final approvals (agreements, sign-offs, grants/funding)	• Identification, quantification and likelihood of all identifiable scope, budget and schedule risks for all project components • Detailed definition of base costs, risk costs and total probable project costs • Validation of reasonableness of contingencies and allowances in project budget and schedule	• List of major critical risks; prioritization of risks based on impacts to total project cost and duration • Estimate of risk costs and probable total project costs and duration • Costs/benefits of risk mitigation strategies • Risk management plan, focused on mitigation of unacceptable risks to project owner
Construction	• Design complete; project defined • Commitments (funding, policy) in place • Construction in progress	• Contractor performance, construction quality • Final permitting, right-of-way acquisition • Unanticipated site/working conditions • Field design changes • Construction safety • Contractor coordination • Cash flow	•Targeted assessment of construction problems, causes and potential cost/schedule impacts • Identification and systematic evaluation of possible corrective actions	•Analysis of specific problem(s) •Costs/benefits of possible corrective actions •Corrective action plan that will allow project sponsors/owner to maintain (or recover) schedule and avoid cost overruns

Projects in **conceptual design** (systems planning and alternatives analysis) lack detailed cost and engineering detail. Risk analysis to identify construction quantity and unit cost risks would not be appropriate. But the process would, for example, help planners better understand basic implementation issues, general schedule issues, and major design and construction risks associated with the alternatives and modes/alignments under consideration.

Projects in **preliminary engineering and final design** would share many of the same objectives and expected outcomes when subjected to risk analysis. The major difference is in the level of detail, in risk identification and quantification, and in the definition of risk mitigation strategies. Confirmation that construction quantities, unit costs, and schedule are accurate would be one objective of both preliminary engineering and final design since the accuracy of the project budget is now a paramount concern. The level of contingency to cover realized risks also needs to be validated.

Projects in the **construction phase** would benefit from risk analysis targeted on specific existing or potential construction problems. The risk management plan would be focused on specific corrective actions to address these problems. The project owner will want to establish a plan that maintains or recovers the schedule and avoids cost overruns.

3.3.2 Implications of Alternative Project Delivery (Procurement) Methods

Risk analysis must be adapted to support the special requirements of new project delivery methods. Different types of procurement methods, other than the traditional design-bid-build method, are becoming increasingly common on public transit projects. These alternative methods pose new challenges to how we view risks. It is worthwhile to consider how project delivery methods can affect the objectives and appropriate timing for risk analysis.

Contracting methods are varied but for purposes of this discussion fall into four basic categories:

Traditional procurement—

- **Design-bid-build**, where the owner completes the project design, prepares and issues bid packages, and awards a construction contract to the preferred bidder (e.g., lowest cost) who constructs the project and turns it over to the owner when completed.

Alternative procurement methods—

- **Design-build**, where the contractor is responsible for completing the project design, after the owner has progressed it to possibly the 30 or 60 percent level, and then constructing the project. The project is then turned over to the owner to operate.
- **Design-build-operate-maintain (DBOM)**, wherein the design-build contractor, for a specified period, is also responsible for operating and maintaining the project it constructs.

- **Construction manager/general contractor (CMGC)**, sometimes referred to as construction manager at risk, is, as the name implies, where the traditional scope of services of the construction manager is combined with that of the general contractor in a single contract. The CM/GC firm is typically selected early in design and supports the owner (and its design consultants) in developing design drawings and preliminary cost estimates. A guaranteed maximum price for construction is negotiated with the owner at the close of design. The CM/GC may self-perform work and also subcontract work. It manages construction on behalf of the owner.

Under design-bid-build and CMGC procurements, the project owner has full control of the implementation process at least up to awarding construction contracts. The owner can undertake risk analysis at any phase in the process up to construction and, depending on the contractual relationship with a contractor, participate in risk analysis during construction itself (e.g., in an arrangement similar to partnering). If the objective is to establish a reasonable project contingency for the construction program, then it makes sense to undertake a comprehensive risk analysis later in final design, for example when the design is at least 60 percent complete.

Under alternative procurement methods where the contractor assumes other responsibilities besides construction, owner control becomes more removed or certainly becomes less direct as the project advances. Consequently, the timing and scope of risk analysis are not quite as flexible. Project owner-initiated and directed risk analysis is probably not as effective during the latter stages of final design, under the design-build and DBOM procurement approaches, after contractor bids have been requested, for example. The advantage of risk analysis undertaken prior to solicitation of bids is that the owner obtains a better understanding of how risks might be allocated between itself and the design-build or DBOM contractor.

Figure 3-3 Timing of Risk Analysis for Differing Procurement Methods

	PROJECT PHASE			
Contracting Method	**Conceptual Design***	**Preliminary Engineering**	**Final Design**	**Construction**
Design-Bid-Build	🔵	●	◍	⊙
Design-Build	🔵	●	⊙	⊙
Design-Build-Operate-Maintain	🔵	●	⊙	⊙
Construction Manager/General Contractor	🔵	●	◍	⊙

* Includes FTA systems planning and alternatives analysis.

🔵 Preliminary risk assessment based on conceptual cost and schedule data

● Comprehensive risk assessment based upon all the detailed information collected up to the point of analysis

◍ Follow-up / updated risk assessment based upon most current design, cost, and schedule information.

⊙ Targeted risk assessment on special problems based upon all available information

Figure 3-3 summarizes one perspective on the timing and extent of risk analysis appropriate for differing procurement methods.

Alternative procurement methods present several other challenges besides the preferred timing for risk analysis.

- Design-build and DBOM contracts tend to be large, encompassing a sizeable portion of work. To ensure full disclosure of risks and accuracy in estimating potential risk impacts on total project cost and duration, design-build and DBOM components should be disaggregated to a comparable level of detail as for other project components.
- Project components to be assigned to the design-build or DBOM contractor are often viewed as having lower risks to the owner. They require the same scrutiny as all other components.
- If risk analysis is undertaken post contract award, the types of risks to the project owner change. The owner is in a contractual relationship and an important element of risk identification will be on contract liabilities. In many respects this situation also exists when construction contracts have been issued under traditional procurement methods. However, the owner will have entered in the design-build or DBOM relationship without having fully specified the design and technical specifications, i.e., with less project information.

It is important to note that the general analytical approach to risk analysis does not change in response to different procurement methods. It may be appropriate to follow different approaches depending on the information available, including the risk issues, and the objectives for risk analysis. However, with the exception of risk analysis conducted post construction contract award, these are independent considerations.

3.4 Participation in Risk Analysis

Subsequent sections of this report deal with the specific steps, including analytical methods, involved in conducting risk analysis. In short, the process involves intensive scrutiny of all aspects of a project from all reasonable perspectives. A range of disciplines – technical, management, and policy – is needed to make the process successful. The project owner normally should be an active participant and represented in as many disciplines as possible. Circumstances may arise where a completely independent risk assessment is proposed, however. The owner's level of involvement might then be limited to providing project information and reviewing results.

3.4.1 Risk Assessment

3.4.1.1 Key Areas of Expertise

The identification and quantification of risks will draw upon individuals with a solid understanding of current project status and future issues. Their backgrounds should offer experience relevant to the types of risks potentially facing a project at its current phase of development (refer to Table 3-1). For a project in planning and conceptual design, expertise is important in the overall project implementation process, funding, environmental and public policy issues, and broad-based engineering. Expertise in the technical disciplines is less important since the design, schedule, and cost estimating issues would also be general. This expertise should be independent of the project team's in the corresponding field; independent perspectives are critical for unbiased assessments.

For a project well along in design and approaching construction, more focused expertise is useful, including in the areas of project management and construction management, design in all relevant disciplines (civil, structural, geotechnical, systems, etc.), cost estimating, right-of-way, permitting, finance, and project controls such as scheduling and budgeting.

Figure 3-4 provides a list of the key disciplines to be included in the risk analysis process at the various phases of project development. Not all possible disciplines are listed. Depending upon the circumstances, other additional expertise may be desired, such as in public policy and political/institutional issues or in specialty services. The former could be required at any phase of project implementation, of course; the latter is more likely to be required late in final design or during construction to provide targeted assistance with a special problem.

Figure 3-4 Key Expertise for Risk Analysis by Project Phase

Discipline	Conceptual Design*	Preliminary Engineering	Final Design	Construction
Implementation Planning	●	●	○	
Environmental Planning	●	●	○	○
Funding/Approvals	●	●	○	
Project Management	●	●	●	●
Engineering	●	●	●	●
Civil, Structural, Systems		○	●	●
Architectural Design		●	●	○
Cost Estimating	○	●	●	●
Scheduling	○	●	●	●
Budgeting/Controls		○	●	○
Real Estate	○	●	●	○
Construction Management/Oversight			●	●
Constructibility/Contractor			○	●
Operations	●	●	●	●
Other Technical (e.g., Legal, Permitting, Procurement)	○	●	●	●
Risk Facilitation	●	●	●	○

* Includes FTA systems planning and alternatives analysis.

● Highly desirable

○ Desirable but optional depending upon circumstances

The risk facilitation discipline is critical at all stages to ensure that the process generates consistent, accurate, and defensible results. It is especially important if an expert panel or workshop approach is employed as a way to bring together the recommended expertise. When well coordinated, the workshop has been demonstrated to be a very effective way to evaluate risks. It offers a convenient, acceptable forum for individuals to share ideas.

3.4.1.2 Key Individuals

One or more individuals can carry out the facilitation function. Preferably the facilitator is independent—from the project and from the owner or other project participants. A comparable model is the independent facilitator of value engineering.[2] As discussed in Section 4, one method for carrying out risk identification and quantification is to convene key expertise in workshops where brainstorming and intense discussions are used to establish a priority listing of significant project risks. The workshop facilitator coordinates the workshop (not necessarily being the leader), eliciting comments, summarizing conclusions, and providing expert advice on process and technical matters such as how to represent risk impacts.

The project owner needs to have direct involvement in risk assessment. The project manager should actively participate in all phases of risk analysis and project owner executive staff should follow the process closely. It is highly desirable that top level decision-makers be involved at the beginning and at the end of the process.

Other technical resources may be in-house or obtained through contractors (e.g., consultants) or a combination thereof. Outside participants are often desirable to fill voids in desired expertise and to provide independent, objective assessments. Objectivity and the avoidance of conflicts of interest are paramount in the risk assessment process.

Based upon lessons learned from recent transit risk assessments, one of the most important of other technical resources to include is an experienced project engineer or project developer. Someone who has put together a complex project and preferably seen it into or through the construction period is invaluable for understanding project risks that technical staff or policy people may not appreciate. This individual has the “picture window” view of the world, which allows the sorting out of significant issues from the myriad details of project implementation. The experienced project engineer/developer complements the owner’s project manager. If at all possible, he or she should be completely independent from the project, thus coming from the outside or a separate part of the owner’s organization.

Participating agencies and substantially affected agencies should also be represented in the process. The areas of expertise of individuals from these agencies would reflect the interests—financial, technical, and other— the agencies have in the project.

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[2] Value engineering is the systematic review of a project design and implementation program to identify and eliminate unnecessary costs. It is usually undertaken by a panel of objective, independent technical experts and facilitated by an experienced third party.

3.4.2 Risk Management

Risk assessment concludes by prioritizing risks according to their potential impacts on cost and schedule. Risk management, an extension of risk assessment, begins with planning ways to mitigate high priority, unacceptable risks.

3.4.2.1 Key Areas of Expertise/Key Individuals

Many of the same disciplines involved in identifying and quantifying risks, from Figure 3-4, need to be represented in risk mitigation planning. As the term risk management implies, however, this is most importantly a management activity—and responsibility. Management staff of the project owner are thereby the key individuals.

Balanced perspectives are needed to avoid biased assessments as to the cost-effectiveness of a proposed risk mitigation measure. Decisions will be made about which of the prioritized risks a project owner feels it can cost-effectively mitigate and what level of resources, if any, should be directed to mitigating adverse risks. The main product of the risk management—the risk management plan—is really an action plan.

Political and organizational issues are acknowledged to come into play when mitigation measures involve money or affect individuals. This is another reason to have the same decision-makers involved in both risk assessment and risk management. Buy-in to cost-effective mitigation will be easier if individuals understand the process.

3.4.2.2 Risk Allocation

There are various ways to mitigate risks. Risks identified early in the project development process can often be dealt with through better planning and design. Management action is key. Opportunities exist to modify the project scope to avoid certain risks, for example, modifying an alignment to bypass a problem area or changing design guidelines to ensure higher standards for construction.

As a project approaches the construction phase, much of risk mitigation is through risk allocation between the project owner and contractors in fair and carefully prepared contracts. A construction contract is the owner’s prerogative; many risk issues can be addressed through contract terms. Effectively allocating risks requires special skills, among them contract negotiation and contract writing. These areas of expertise are possibly a unique requirement of risk management and can be added to the list of disciplines in Figure 3-4.

Where risks cannot be acceptably mitigated through better planning and design, risk allocation, or other actions, increasing project contingency allowances (or providing for a project reserve) might be warranted. By adding to the contingency, the project owner acknowledges—and insures against—the potential adverse effects of unmitigated risks.

3.5 Summary of Issues to Consider for Risk Analysis

In conclusion, it is useful to reiterate several things project sponsors need to consider when initiating risk analysis.

- *Avoid bias in assessing risks and their impacts*. A project owner is often inclined to believe that its project scope, schedule, and budget are solid and is not affected by the risks associated with other similar projects. This is especially the case late in design when a lot of time and money have been invested in project development. Another potential source of **project owner bias** is a reluctance to acknowledge the potential for not just technical problems but management shortcomings on a project.

  A fully independent risk analysis will largely avoid the potential for bias among project advocates but has several drawbacks. Project owner buy-in may be difficult. Without being a close participant, the owner will not fully understand how project information has been used to establish risks and their impacts; understandably, the owner will be less accepting of findings. The owner could view the process as biased—with the independent reviewer not being objective.

  Another drawback to the fully independent analysis is that reviewers lack the intimate knowledge of the project necessary to identify and quantify real risks. Facts are often in dispute, and consensus must be reached with the project owner on a reasonable interpretation of circumstances that could lead to a significant risk event. That foundation must be built before risk impacts can be assessed. Otherwise, analytical results can be questioned. Having independent reviewers and an objective facilitator as part of the risk assessment team (similar to value engineering), complementing the project owner's resources, is the recommended option.

- *Be realistic about available expertise to support risk analysis*. In addition to the need for objectivity, there is a need for a range of expertise. This is another reason for bringing in outside participants.

- *Assess the available approaches to risk analysis against the established objectives and the project's requirements.* The objectives for risk analysis, including desired information, should be the primary consideration in selecting an approach. The types of risks that face a project (e.g., cost, schedule, or a combination thereof) are also important.

- *Objectives for risk analysis may differ by project phase*. Projects in conceptual planning will have order-of-magnitude costs, at best. Analytical methods offering a fine level of cost or schedule information are probably not needed. The emphasis should be on major risk identification and then mitigation through changes in the overall design and in the implementation program for a project.

- *Avoid some of the common mistakes others have made in performing risk assessments:*
  - Not validating whether the base project scope, cost, and schedule are reasonable.
  - Using inappropriate or error-prone analytical methods.
  - Targeting mitigation resources on risks that will not provide much 'bang for the buck.' Mitigation should be designed to cost effectively reduce or eliminate major risks.

- *Use the risk analysis process to obtain a better understanding of a project; focus on outcomes.* As important as the analysis steps and proper analytical methods are, the process itself has value. It provides a powerful means for communicating to project participants the effects of potential adverse events. It can serve in educating the project sponsors and other stakeholders on what can go wrong. Project sponsors are able to better understand the potential difficulties of project implementation and the critical interrelationships among project components.

  The ultimate objective is an implementable risk management plan. The analytical approach used to get to that point can vary as long as it is sound and defensible.

4. Approaches to Risk Assessment

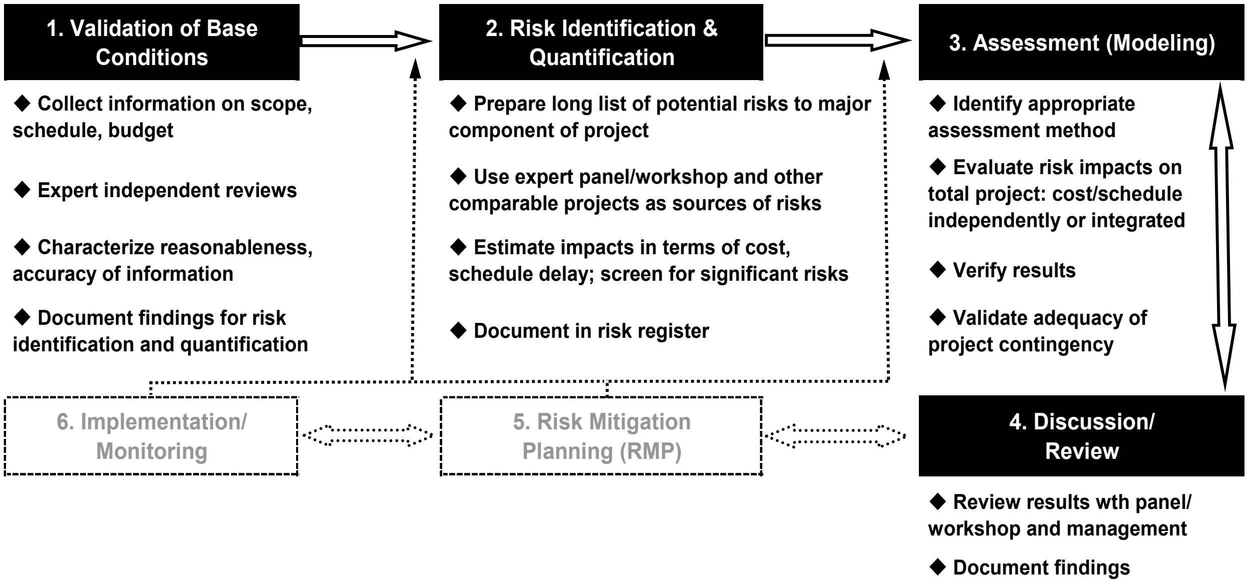
Main Points:

- *Basic steps of risk assessment explained.*
- *Validation of scope, cost and schedule reasonableness is a precondition for conducting a risk assessment.*
- *Base costs represent costs stripped of all contingencies except for any allowances that cover actual (but unquantified) elements of the project.*
- *For risk identification, begin with an all-encompassing list and then screen to those most critical to the project. Critical is generally defined in terms of cost or schedule but other considerations can apply.*
- *Experience provides the best source of data. Peer group analysis is valuable.*
- *Non-simulation analytical methods are often satisfactory if dealing with conceptual risk analysis. They are not well suited for capturing effects of cost and schedule risks in combination.*
- *Simulation methods allow simultaneous analysis of cost and schedule risks.*
- *Non-simulation and simulation approaches to modeling risks are compared.*
- *Apply tests of reasonableness to validate results of risk assessment.*

4.1 Basic Steps of Risk Assessment

Risk assessment has been defined to include the first four steps of Figure 4-1. The process begins with a validation of the base project's scope, schedule and cost; includes identification, quantification, and modeling of risks; and concludes with findings for review by project sponsors. Findings would include a ranked list of risks and their contributions to total project cost and schedule variance.

Figure 4-1 Risk Assessment



The relative importance of each of these steps will vary. The resources to be applied can similarly vary. Both are a function of project characteristics and the objectives when undertaking a risk analysis. An important aspect is that the process is iterative, involving feedback of information that prompts a reevaluation of risks and their potential effects.

4.2 Step 1: Validating Base Scope, Costs and Schedule

When analyzing the potential effects of risk and uncertainty, a project is divided into two parts. The first element is the base project, which is described by the

1. Adopted project **scope**, documented in detail in the engineering planset and/or in the approved environmental document
2. Project **base cost**, which is the cost excluding add-on contingencies to cover unknowns (or risks)
3. Project **schedule**, which is the best estimate of the likely durations of project components, from inception to the start of revenue service.[3]

The second element of the project includes the uncertainties that could add to (or, in turn, subtract from) the scope of the project, the cost of the project, or the time to complete the project. This is the element of project risk.

Figure 4-2 shows this relationship from the perspective of project costs. Base costs tend to be large and relatively well defined. Risk costs tend to be smaller than base costs and can vary considerably. Total cost is simply the sum of these two cost elements. Costs are shown as distributions since, in risk assessment, both elements are uncertain. Even base costs of a project include some level of uncertainty; no two individuals would likely agree on an exact dollar number even if all assumptions were held in common.

The concept that there are a base scope, cost, schedule and add-on risk elements is central to risk assessment. The concept is actually not that much different from traditional cost and schedule development. There is a base cost and schedule—the engineer's best estimate before cost and time contingencies are applied—and there are the cost and schedule contingencies, which added together give the total estimated project cost and its total estimated duration.

Engineer's Estimate *plus* Contingencies = Total Cost or Schedule Estimate

One important distinction is the engineer's cost and schedule are typically point (or single-value) estimates as are contingencies when translated from a percentage allowance to actual dollar costs or time durations.

The first step in risk assessment is to establish the reasonableness of the base scope, cost, and schedule. Without a solid base, it is difficult to quantify the impacts of risks. A base with "holes" or inaccuracies may be indicative of major risks—in the design, in

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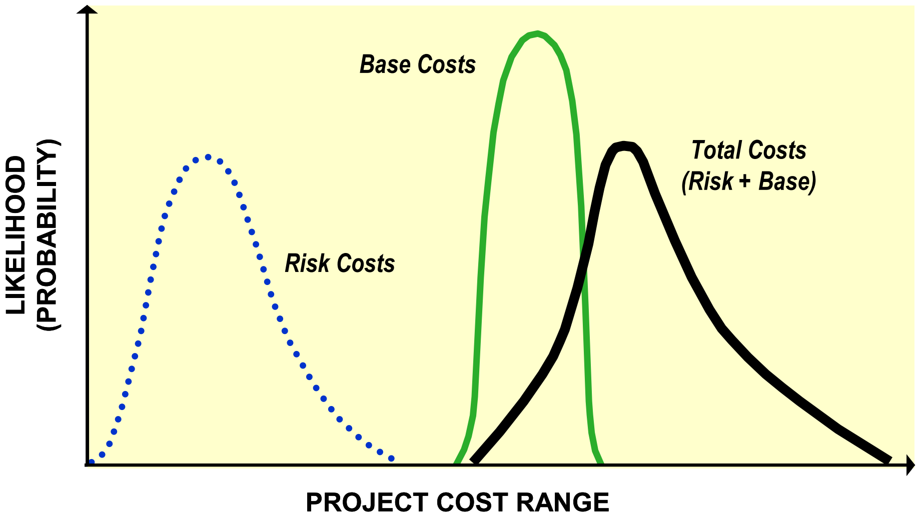
[3] The term component is used to describe generically the baseline cost estimates, contract units, or work activities that form a project.

the quantities used to build up the design, or in the prices of the quantities. Such uncertainties should be captured in the risk element of a project. Starting out with too low or too high a base cost, for example, will translate into an inaccurate estimate of total project cost no matter how accurate the assessment of risk costs. The same holds for the project schedule.

Figure 4-2 Risk, Base, and Total Project Costs



The review of base conditions should “fix" the base as appropriate. The base cost and schedule are then a reasonably accurate picture of how the project would be implemented assuming everything goes right and according to plan.

The main activities in the review include the following:

1. Remove all “true” contingencies from cost estimates and schedules. Usually contingencies assigned to project components are explicitly identified, but they may actually be provisions for a combination of circumstances. The base conditions reviewer should understand what is included in any contingencies. If a contingency or a portion thereof is really an allowance for items certain to be included in the project design but not quantified at the time of the estimate, the allowance represents part of the base. The contingency should be split accordingly and the design allowance component not removed from the base.
2. Check plans, base costs, and base schedules for completeness and general accuracy. On large projects, sampling of items is recommended. The base conditions review is not intended as an independent engineer’s check of the project cost and schedule. Generally, that level of effort would be prohibitive, at least for large projects.

   Sampling methods can vary, from random sampling of data items to stratified sampling. One reason for stratifying is that certain project activities may warrant more scrutiny than others because of their potentially significant effects or their critical relationships to other project activities. Applied to risk analysis, Pareto's Law would suggest about 20 percent of project components will generate about 80 percent of the major risks on a project.[4] It is reasonable to focus on activities with inherently the most uncertainty and the greatest potential effects on overall project success. Evaluation of other project activities can be limited to check on their overall reasonableness.

3. Prepare an objective estimate of costs and time durations that should be added to or subtracted from the initial base. This yields a revised base. General consensus on this new base is recommended.

Things to focus on as part of this process include the following:

Scope—

- Consistency of the project portrayed in the planset with that in the environmental document and record of decision/finding of no significant impact, if issued
- Quantities in the design and their correspondence to the quantities in the cost estimate

Costs—

- Sources of data
- Dates of data
- Escalation assumptions

Schedule—

- Time dependencies among project components
- The project network and activities on the critical path (i.e., the steps in project development and their durations that set the minimum time in which a project can be completed)
- Additional time allowances (i.e., float) for activities
- Overall mechanics of the schedule.

Specific guidance is helpful for individuals performing technical reviews of a project's scope (i.e., design), cost, and schedule. Guidance will help reviewers focus on the main concerns and lead to uniformity in reporting—and thus in the interpretation—of findings. Direction to the reviewers might be in the form of a checklist or template. Figure 4-3 is an example of a template used on a light rail project to organize reviewers' comments. It asked for a qualitative scoring of the quality of project documentation. The template is the summary page of a multiple page form. A more detailed comment template was provided for each project element listed in the first column (e.g., design, schedule). The detail for a template or checklist would vary depending upon phase of a project, including the level of design.

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[4] Originally an empirical "rule of thumb" proposed by Vilfredo Pareto that 20 percent of the population earned 80 percent of the income. "Pareto's Law" has been expanded to similarly characterize the sources of significant variation, problems, costs, etc. in large and complex systems.

Figure 4-3 Base Conditions Review Template: Summary

*Scoring Criteria

5 - Better than would be expected at the stated level of design.
4 - Consistent with expectations at the stated level of design.
3 - Consistent with expectations at the stated level of design with minor exceptions.
2 - Consistent with expectations at the stated level of design with major exceptions.
1 - Inadequate for representing the stated level of design.

Please use the above criteria as a guideline for rating each of the Items in the checklists.

Definitions and Examples			
Contract Section or Unit			
Description		Light Rail Transit Line 1	
Reviewer		John Doe	
Date		31-Jan-04	
Document	**Item**	**Comment** *(Example of items to consider in review and comments; make special note of uncertain or unclear items, including quantity and unit cost variance from base.)*	**Score 1- 5***
Design	Constructible	Room for shoring, barriers, temporary supports; maintenance of traffic requirements; space for laydown or equipment to operate.	
	Cost Effective	Materials, structural members	
	Complete	Equipment.	
	Correct	Consistent with Design Criteria; Consistent with ROD	
Drawings	Complete	Notes, dimensions	
	Clear	Line work	
	Cross Referencing	Work by others consistent with contract definition; details and sections	
	Consistent	Uniform line work, symbols and text.	
	Correct	Abbreviations, spelling; numbers	
Specifications and Contract Conditions	Scope Defined	Consistent with contract definition; work by others clear.	
	Consistent	Consistent terms used, such as "construct", "furnish and install", "includes", "consists of", etc.	
	Complete	All work covered and cross referenced	
	Correct	Correct references to standards and other specification sections	
	Pay Items	Cross references to spec sections; payment for procurement vs. installation; measurable units; final quantities	
Schedule	Work Sequencing	Access to work areas; requirements for moving equipment	
	Maintenance of Traffic	Work durations and time restrictions	
	Utility relocation	Implications of advance utility relocation or other prior work	
	Right of way	Implications of property to be purchased in advance of construction	
	Other	Implications of work performed by other contractors	
Cost Estimate	Unit prices	Consistent with bid list	
	Quantities	Accuracy and potential for upward change	
	Contingencies	Consistent with level of detail and potential for cost increases; broken down by category	
	Allowances	Consistent with specs and contingencies	
	Escalation	Consistent with contract duration and period of execution.	

4.2.1 Timing and Method of Base Conditions Review

The validation of base conditions should be completed in advance of beginning formal risk identification and quantification. A comprehensive, objective base review requires time. One way to achieve objectivity is to involve individuals not intimately part of the project. In certain FTA-sponsored risk assessments, documentation was distributed to outside experts who provided input based upon their experience or by checking against industry data or information from other projects. In other assessments, a peer group review of base assumptions and scope, cost, and schedule information was conducted. The group included project owner staff.

The most practical time and method for the base conditions review will depend on the circumstances. Quality of data has a considerable bearing on the merits of an independent review completed in advance of risk identification. If scope, cost, and schedule information is readily available, well organized, and complete, an independent review in advance of risk identification has value. If information is not of good quality, there are considerable drawbacks to such a base review. Even experts in their fields will have difficulty understanding key elements of the project and characterizing the reasonableness and accuracy of the information. The process can become inefficient as clarifying information must be secured in order for the review to proceed. Under such circumstances, the recommendation is to limit the independent base conditions review.

Lack of quality data probably foreshadows risks to a project, possibly unpreparedness or inexperience of the project owner, poor quality of plans, or other problems. The reasons need to be explored as part of the risk assessment process.

For the risk assessment to proceed, as sound as possible information about the base project must be obtained. Often it is best to work with project owner staff (or designates) who are knowledgeable about the project to clarify the assumptions used in developing total project costs and the overall project schedule. Meetings with the project owner and its representatives to obtain better information can be incorporated into the risk identification and quantification process.

4.2.2 Level of Detail for Base Conditions Review

FTA guidance recommends that scope, cost, and schedule reviews include detail to at least each of the proposed major contract units or line item grant activities for a project. For projects seeking award of an FFGA, these equate to baseline cost estimate (BCE) categories. FTA suggests that scope, cost, and schedule issues and identified risks are traceable to this level.

If some of the categories are large, as may be the case with certain grouped construction components, BCEs should be broken down into a finer level of detail. Component roll-up to a specific BCE should be clear. As a rule of thumb 20 BCEs or components would be recommended for organizing an assessment of a large project, and probably no more than 50 (with a possible exception for megaprojects). A smaller project might be characterized by fewer than 20 BCEs or components. There is no exact rule. BCEs, contract units, or components simply provide an organizational framework for the analysis. A reasonable level of detail is necessary.

On projects in conceptual design, no BCE structure is likely to be designated. In fact, a fine level of detail for scope, cost, and schedule reviews probably is not as useful for projects in planning as it would be for projects well along in design. Another rubric for organizing the base conditions review and for assigning risks must be substituted. FTA has developed a project cost database that probably provides an acceptable level of detail (see Booz-Allen & Hamilton, "Heavy Rail Transit Capital Cost Study Update." Federal Transit Administration, Washington, D.C., 2004; Booz-Allen & Hamilton, "Light Rail Transit Capital Cost Study Update." Federal Transit Administration, Washington, D.C., 2003; and Booz-Allen & Hamilton, "Light Rail Transit Capital Cost Study." *UMTA-MD-08-7001,* U.S. Dept. of Transportation, Washington, D.C., 1991.). The main categories in the database are the following:

- Guideway and Track Elements
- Stations, Stops, Terminals, Intermodal
- Yards, Shops, Administrative Facilities
- Sitework and Special Conditions
- Right-of-Way, Land, Existing Improvements
- Systems
- Vehicles
- Soft Costs (design, project administration, insurance, start-up, etc.)
- Finance Charges
- Contingency

These are now FTA's standard cost categories for capital projects. Cost estimates are to be organized consistent with this framework. As a project advances in design and towards grant award, cost detail is added and ultimately translated into BCE or contract unit costs.

4.3 Identifying and Quantifying Risks

4.3.1 Risk Identification

The second step in risk assessment is identifying the risks that could affect the base scope, cost, and schedule (Figure 4-2, Step 2, Risk Identification and Quantification). These changes are also quantified, both in terms of their likelihood of occurrence and their likely, or probable, impacts.

Identification of risks should not be initially constrained. A long list of every conceivable scope, cost, or schedule risk to a project is better than a short list of detailed risks. The long list can have overlapping risk areas; risks are later screened and refined to become more focused on project components. If attempting to proceed immediately to a short list, it is quite possible areas of potential project uncertainty will be overlooked.

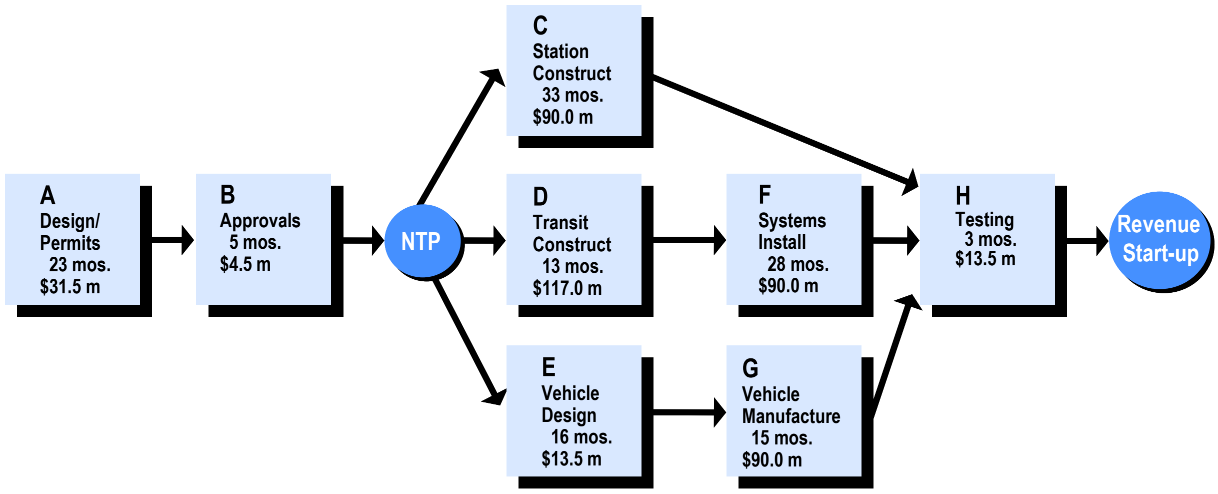
4.3.1.1 Mapping Risks to Project Components

It is nonetheless helpful to think about risks in terms of the major project components, discussed in Section 4.2.2. This traceability of risks to major components is important in understanding how individual risk events can affect the budget and schedule—not just at the overall project level but also at the levels at which design and construction contracts are managed. Organizing and tying risks to these levels is important for effective risk management through design modifications and procurement contracting (see Section 5).

A convenient way to associate risks with components is to develop a network of the project. The network should identify the sequence of major components and their relationships. The network can be summary level, grouping smaller and closely related items into a single component. To help understand time and cost relationships, the durations and estimated cost for major components might be included. Thus the network becomes a summary cost and schedule model. An example of a summary network is shown in Figure 4-4. The project is conceptualized as a light rail line, running at-grade and aerial, along public and private rights-of way. It has eight major components. Two milestones – “notice to proceed with construction/procurements” and “initiation of revenue service” – are shown. The durations and costs given represent averages. They are the base schedule and the base costs for the project.

Figure 4-4 Example Project Network: At-grade and Aerial Light Rail Transit

Base Cost [$450 M Current] and Schedule [72 Months]



The component network assists in understanding big picture relationships on a project. Schedules and engineering designs become very detailed as projects advance from conceptual into preliminary and final design. Information can become overwhelming or at least difficult to evaluate for individuals at the project management level. The network establishes an appropriate level of project detail for definition of risks.

Another way to map risks to project components is to list in tabular format the major components of a project and assign risks accordingly. This is actually the suggested format for describing risks, their likelihood of occurrence, and their potential costs and schedule impacts when the risk identification has progressed to the point where screening and quantification of significant risks can begin. This description of risk is called the *risk register*, discussed in Section 4.3.2.

4.3.1.2 Sources of Information on Risks

The best sources of information from which to build a long list of risks are findings from the validation of base conditions and data on other similar projects. Outside experts will be able to draw on other project experience. Research into similar projects may be possible. The experience database is currently limited because systematic risk analysis is relatively new to transit. With more projects performing risk assessments, and with free exchange of data through FTA or on the Internet, the database is growing.

Findings from the base conditions review should include all the questions and concerns of the expert reviewers. These translate into potential risk issues. For instance, if design drawings are found to be missing certain important details normally expected in the planset at the stated level of design, there is the potential risk that design errors or omissions could exist and affect the quality of the project, including the construction bid documents. If there is uncertainty about the unit costs or quantities incorporated into the engineer's cost estimates, there is risk to the budget established from the engineer's cost estimate and possibly a greater likelihood of contractor changes due to differences in actual versus design quantities.

All of these objective sources of information should be reviewed to identify risks to the project. Subjective data provide a secondary source of information on risks. Subjective data would include expert opinion, or judgment, based on experience. A project owner may be able to offer both direct experience and subjective data. The expert panel or workshop approach is another way to elicit discussion and identification of risks. Section 3 identified the various disciplines and key individuals to include as participants. The expert panel or workshop provides a convenient forum in which to quantify likely impacts of risk events.

4.3.1.3 Risk Checklists

As part of risk identification, checklists provide useful guidance and help ensure that all major areas of possible risks to a project have been addressed. In FTA's Project Management Oversight Program Operating Guidance #22, a checklist for preliminary engineering, final design, and FFGA scope, schedule and cost reviews is included as Appendix A. The list highlights review criteria for projects reaching each milestone; these translate into potential risk issues.

FTA's "Risk Assessment in Fixed Guideway Transit System Construction" (Ali Touran, Paul Bolster; and Scot Thayer, Report No. FTA MA-26-0022, Federal Transit Administration, Washington, DC, January 1994), includes a checklist developed from "the owner's point of view." Another list is provided in "Management of Project Risks and Uncertainties" (Publication 5-8 of the Construction Industry Institute, Cost/Schedule Controls Task Force, October 1989). This was developed from the contractor's perspective. A combined risk identification checklist from these two sources is included at the end of this report, in Appendix B.

The long list of potential project risks will vary with the size and complexity of the project. Experience demonstrates that risks for a major transit investment (not a megaproject) ought to number on the order of 50 to 75 items. Many more than that would indicate too much detail in risk definitions or too many incidental, insignificant risks are included in the list. Experience also indicates that significant risks warranting further scrutiny for possible mitigation will be a subset of the long list.

Table 4-1 provides an example of types of risks that might be identified as part of the example project depicted in the network of Figure 4-4.

Table 4-1 Types of Risks on Combined At-grade and Aerial Light Rail Transit Project (Figure 4-4)

1. Permit Requirements/Intergovernmental Agreements Schedule
2. Governmental/Regulatory Agency Approval Schedule
3. Design Changes Late in Final Engineering or During Construction
4. Real Estate Cost and Availability
5. Utility Locations and Conditions
6. Market Conditions
7. Light Rail Vehicles Price
8. Systems Equipment (Power, Signals, Controls) Installation and Test Schedule
9. Contractor Performance
10. Owner Costs for Project Management

4.3.2 Risk Register

Once identified, risks need to be documented. Descriptive information about their likelihood of occurrence and their potential impacts on major project components when they do occur is critical for assessing how unmitigated risks could affect total project cost and duration. FTA guidance recommends establishing a risk register to capture this information. The risk register is an evolving document. It is a database for characterizing risks and is updated as more information is generated about risk impacts. Some risks might fall out of the register while others are added or modified over time. It can be carried forward and used as an information tool during risk mitigation planning.

Table 4-2 is an example of a risk register, describing 10 specific risks for the hypothetical light rail project with the general types of risks listed in Table 4-1. The first five columns summarize information that would be obtained as part of risk

Table 4-2 Example of Risk Register Detail (For Hypothetical Eight-Component Light Rail Project)

ID	Risk/Opportunity	Description of Issue	Affected Project Component	Correlation Among Dependent Components	Probability of Risk Occurring	Risk Cost		Risk Duration	
						Distribution	Expected Value[1]	Distribution	Expected Value of Delay[1]
Risk 1.	**Permitting and Interagency Agreements:**	Permits required from approval agencies could be delayed; intergovernmental agreements between grantee and other agencies might not be concluded on schedule.	**A. Design & Permitting** **D. Transit Construction**	Positive between Cost and Schedule (i.e., Duration) of Both Components A & D	25% (0.25)	Triangular *(see Fig 4-5 "C")*	A. $ 2.2 m D. $21.6 m	Triangular *(see Fig. 4-5 "C")*	A. 7 mos. D. 4 mos.
Risk 2.	**FFGA Approval:**	Grantee documentation of readiness to enter into full funding grant agreement negotiations with FTA might require further revisions, thereby delaying the anticipated FFGA approval date.	**B. FFGA Approval**		10%	No Significant Effect	No Significant Effect	Discrete *(see Fig. 4-5 "A")* 1 mos.= 50% 2 mos.= 30% 4 mos.= 20%	2 mos.
Risk 3.	**Station Design:**	Changes in stations features could occur late in final design and/or during early construction due to community concerns, requiring additional design effort and delaying start of certain construction activities.	**C. Station Construction**	Positive between Cost and Schedule (Delay=Higher Costs	30%	Exponential *(Fig. 4-5 "F")*	$10.0 m	Lognormal *(Fig. 4-5 "E")*	5 mos.
Risk 4.	**Right-of-Way Cost and Availability:**	Property costs are uncertain and possibly higher than anticipated; the acquisition schedule, including obtaining of construction easements, could be extended.	**D. Transit Construction**	Positive between Cost and Schedule	50%	Lognormal *(Fig. 4-5 "E")*	$30.0 m	Lognormal *(Fig. 4-5 "E")*	6 mos.
Risk 5.	**Utility Relocations:**	Locations of certain utilities are unknown and their relocation could be required.	**D. Transit Construction**		20%	Lognormal *(Fig. 4-5 "E")*	$5.0 m	Uniform *(Fig. 4-5 "A")*	6 mos.
Risk 6.	**Changing Market Conditions:**	The construction market is changing, with bid prices on similar work components on other projects varying considerably. Procurement costs for major project components could be higher than estimated.	**C. Station Construction** **D. Transit Construction** **E. Vehicle Design** **F. Systems Installation** **G. Vehicle Manufacture**	Positive among Costs of Components C-G	100%	Normal *(Figure 4-5 "D")*	C. $4.5 m D. $5.9 m E. $0.7 m F. $4.5 m G. $4.5 m	No Significant Effect	No Significant Effect
Risk 7.	**Light Rail Vehicles Price:**	With vehicles likely to be supplied by firms based outside the U.S., prices could fluctuate significantly in response to changing dollar exchange rates.	**E. Vehicle Design** **G. Vehicle Manufacture**	Positive between Cost and Schedule of Both Components E & G	10%	Lognormal *(Fig. 4-5 "E")*	E. $ 2.0 m G. $20.0 m	Lognormal *(Fig. 4-5 "E")*	E. 4 mos. G. 4 mos.
Risk 8.	**Systems Equipment Integration:**	Problems installing and testing of complex systems equipment and controls (signals, communications, tractions power, fare collection, etc.) could add to costs and delay the revenue operations date.	**H. Testing**	Positive between Cost and Schedule	50%	Lognormal *(Fig. 4-5 "E")*	$5.0 m	Lognormal *(Fig. 4-5 "E")*	6 mos.
Risk 9.	**Contractor Incentive Payment:**	Construction contract for primary general contractor includes an incentive payment of $10 million if work is completed ahead of grantee's base schedule.	**H. Testing[2]**		50%	Single Value	$10.0 m	No Significant Effect	No Significant Effect
Risk 10.	**Grantee Administrative Costs:**	Should project construction be extended, grantee administrative costs, including costs for construction management and design support during construction, will increase proportionately.	**H. Testing[2]**	Directly Proportional to Delay if Project Duration Over 72 Months	100%	Multiplicative[3]	Months of Delay X $0.5 m per Month	No Significant Effect	No Significant Effect

[1] Calculated or simulated expected value for individual risk event; does not account for possible effects of correlations with other components/risks, escalation effects, etc.

[2] Impacts assigned to final project component although the risk does not only apply to Testing component.

[3] Estimated project duration is 80 months. Total Admin. Cost Calculated as (80+Months Delay)/80 X Base Administrative Cost

identification. The last five columns summarize information generated, when possible, as part of risk quantification, discussed in the following section.

Risks included in the risk register should be comprehensive and non-overlapping. The 10 risks in Table 4-2 would be considered a partial list of potential uncertainties facing the example project. Non-overlapping means risks should be distinct and not have the same impacts on project cost or duration. This is important to avoid doublecounting of risk costs or schedule delays. An example of overlapping risks would be if structural requirements for facilities were likely to change due to a revision in city standards and to reflect the state's proposed seismic criteria. The cost impacts of each are not independent if the city and state requirements are alike. Similarly, if the changes require added design effort with a potential delay to the engineering schedule, the time required might not be additive but best represented by the effort to meet one or the other. Such risks and risk impacts should be combined in the risk register.

4.3.3 Quantifying Risks

Once all perceived risks to a project have been identified, their potential impacts are quantified – in terms of costs and time impacts.

As this report has argued, risks are part of the uncertainty surrounding a project. They are typically not fixed values; rather, each risk represents a range of possibilities. We in fact express risks in terms of likelihoods—how likely they are to occur and how likely they are to have "x" cost or "y" time impacts. Likelihoods are expressed mathematically as probabilities; therefore risks can be defined mathematically by probability of occurrence (frequency) and the probable costs and probable time durations when they do occur.

The risk register of Table 4-2 includes an estimate of "Probability of Risk Occurring" for each risk and an estimate of the cost and duration impacts associated with a risk. Some risks have a range of possible costs and durations impacts, reflecting uncertainty about their magnitude. Expected cost and duration impacts can be calculated from the following:

$$\text{Expected cost or duration impact} = \text{Probability of occurrence} \times \text{Estimate of cost or duration impact} \qquad \textit{Eq. 4-1}$$

To characterize risks in this manner, individuals responsible for identifying and quantifying risks must think in terms of probabilities. As background to how risks can be quantified in the risk register and for detailed assessment, some of the basic concepts of probability are summarized in the following section.

4.3.3.1 Probability Basics

Probability is about the study of uncertainty. Theory of probability provides a methodology for quantifying the likelihoods of various random events. ***Probability of an event*** is expressed with a positive number between 0 and 1. For event E_i , $P[E_i]$ denotes the probability of event E_i and we have:

$$1 \geq P[E_i] \geq 0 \qquad \textit{Eq. 4-2}$$

Also, total probability of all elementary outcomes is 1.0, *i.e.,*

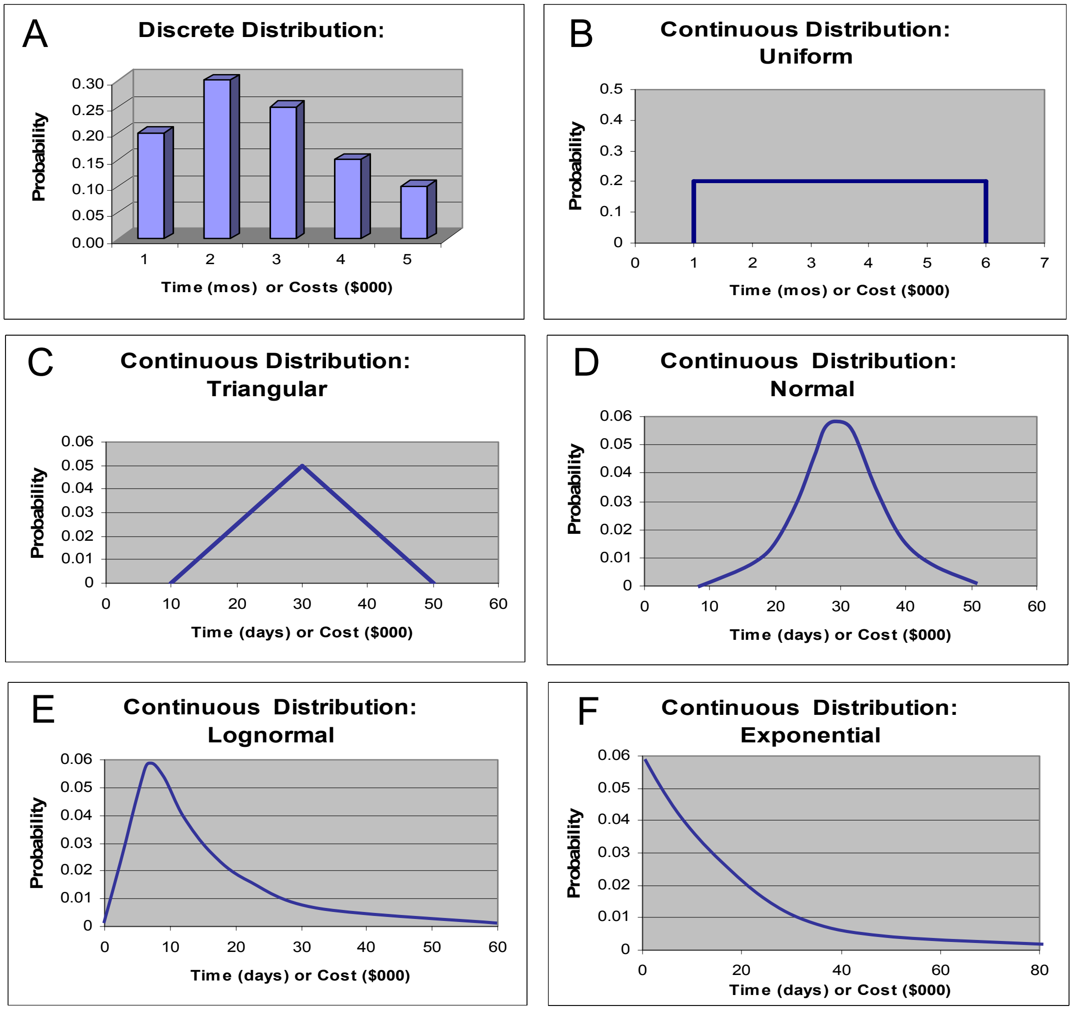
$$P(A) + P(B) + P(C) + P(D) = 1 \qquad \text{Eq. 4-3}$$

In Eq. 4-3, A, B, C, and D are probabilistic events that collectively define all the possibilities. Their total probability adds up to 1.0.

Engineering applications usually deal with numerical experiments. A **random variable** is obtained by assigning a numerical value to a probabilistic event. As an example, the probability that a project can be finished in 10 months is 0.4, and the probability that the duration would be 11 months is 0.6. Numerical values (in this case, durations) are assigned to a probabilistic event (i.e., completion of project).

Probability distributions are used to show the range of possible values for a random variable. Examples are shown in Figure 4-5. A **probability mass function** (PMF) expresses the probability of any particular value of a finite set of possible values being true (Figure 4-5, subfigure "A". A PMF is used when a random variable can be modeled as a discrete function.

Figure 4-5 Probability Distributions for Quantifying Risk Impacts



A **probability density function** (PDF) expresses the relative likelihood of any particular value of an infinite set of possible values being true (Figure 4-5, subfigures "B" through "F") The PDF is used when the random variable can be modeled as a continuous function. There are some convenient distribution "forms" (e.g., triangular, normal, lognormal, or exponential, among others) for special cases.

A **cumulative distribution function** (CDF) expresses the probability of being less than or equal to (i.e., not exceeding) any particular value, either discrete or continuous, as shown in Figure 4-6.

Figure 4-6 Cumulative Distribution Functions (Discrete and Continuous)

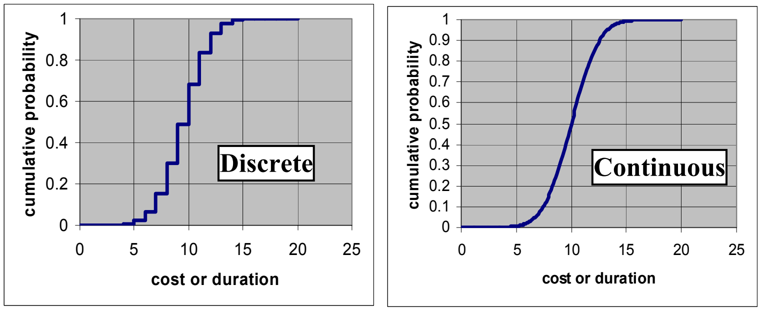
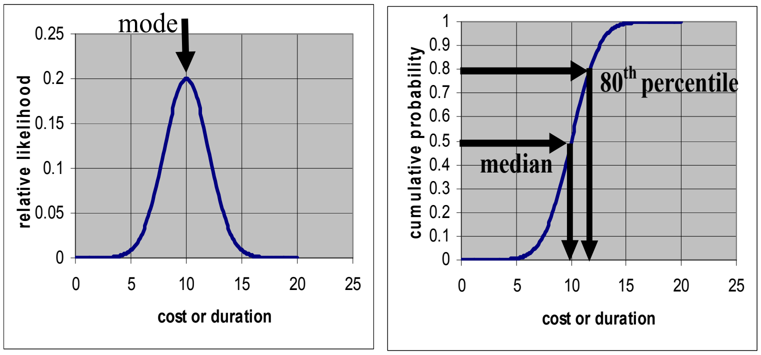


Figure 4-7 Mode and Median of Probability Distributions



The **mode** of the distribution is the most likely value (i.e., peak of the PDF or PMF) and is shown in Figure 4-7.

The **median** is the 50-percentile value, also shown in Figure 4-7 for a cumulative distribution.

The **mean** or "expected value" of the distribution is the probability-weighted average value (centroid).

The **variance** of the distribution is a measure of its spread about the mean. A large variance is an indication that the data is dispersed further from the mean, while a small variance is an indication that most data is centered close to the mean.

The **standard deviation** is simply the square root of the variance.

Correlation is the linear relationship between two variables, which can be expressed in terms of a "correlation coefficient" that ranges from –1.0 to +1.0. As an example of positive correlation, two construction activities that can be affected by inclement weather will be both delayed. An example of negative correlation is the movement of stock market with interest rate. As the interest rate *increases*, it is generally accompanied by a *decrease* in the price of stocks.

4.3.3.2 Commonly Applied Probability Distributions Describing Risk Impacts

Risk impacts are expressed as discrete or continuous probable outcomes within a specified range, for example, with lower and upper limits for costs and/or time. The distributions are often simplified, reflecting the limited "data points" available from objective or subjective information or to be consistent with the level of accuracy that can be expected in the risk quantification effort.

For instance, information may be available on the occurrence of a risk event, say ground failure, its cost and resulting delay, on another project with similar ground conditions to an owner's project. But it would be difficult to be very specific and estimate a detailed defensible statistical distribution of that same risk event occurring on the owner's project. It would nevertheless be a risk worth assessing. Simple risk distributions are easier for individuals to comprehend and to accept as reasonable approximations of what could happen. This is especially important if risk identification and quantification are carried out by an expert panel or in a workshop with several participants. These experts should be able to estimate an optimistic, most likely, and pessimistic impact for a specific risk event. In some instances, additional detail on the range of impacts can be offered.

Probability distributions are simply a convenient way to represent this detail, and they lend themselves to statistical analysis. The type of probability distribution should be chosen (e.g., by the lead analyst) to best reflect the perceived range of impacts of a risk event. Some common distributions used to characterize risks are shown above in Figure 4-5.

a. Discrete Distribution. The discrete distribution, distribution "A", reflects a case where certain specific outcomes are considered likely with differing probabilities. Perhaps the risk impact is months of delay to a construction contract if an approval or permit is delayed.

b. Uniform Distribution. The uniform distribution in "B" represents the case where a maximum and minimum can be set for impacts; however, the likelihood of any value occurring within that range is the same. In other words, due to lack of better information or because of the nature of the event, the analyst has no preference for a value between the minimum and maximum values. As an example, the delay impact of a certain risk factor has been estimated to be between one and six months. In this case, the analyst could not be any more specific in the estimate due to lack of information about the nature of the delay.

c. Triangular Distribution. Where the analyst expects that the risk factor is more likely to have a specific value between its two extreme points, then a triangular distribution can be used to model the risk. As an example, in distribution "C" of Figure 4-5, while the delay may range between 10 and 50 days, its most likely value is estimated as 30 days. In other words, the scale of the y-axis is an indication of likelihood of the value of the random variable. In each case, the area under the curves should be equal to 1.0.

d. Continuous Distribution. Adding more known or estimated data points to a distribution allows refinement in depicting the actual distribution of impacts. A continuous function, as in distributions “B” through “F” of Figure 4-5, could be used to represent this greater wealth of information on risk impacts. A continuous distribution such as “E” or “F” is skewed with the range of impacts extending far to the right. It represents a very common characteristic of risks’ impacts: there is the likelihood, increasingly small but real, that impacts could be extreme. Take for instance, a tunneling activity where the boring machine potentially encounters unexpected subsurface conditions that dramatically reduce its productivity. The cost impacts would be proportional to the delays, which could be extensive.

In the risk register of Table 4-2, various distributions have been assumed to represent risk impacts. More detail on the rationale for selecting those distributions as well as their specific attributes – such as the range of values, including the mode, mean, and standard deviation – are explained in the examples of Appendix C. Using the example project illustrated in Figure 4-4, “Permitting and Interagency Agreements” risks, which affect both the design and construction components of the example project, are estimated to have a 25 percent likelihood of occurring (0.25 probability) and would adversely affect costs and schedule for both component A, Design and Permitting, and component D, Transit Construction. The impacts were estimated to be best represented by a triangular distribution. The expected value of the risk impact on both project components has been estimated. The cost impact to Design and Permitting, for example, is estimated to be $2.2 million when the risk occurs; the schedule impact is to extend the duration of this component on average seven months.

As another example, “Changing Market Conditions” risks (number 6 in Table 4-2) are assumed to affect the costs of all construction and procurement activities, with a 100 percent probability of occurrence. The range of impacts was best represented by a normal distribution in each case. Using component C, Station Construction, as an example, costs were estimated to increase on average $4.5 million relative to the base. Market conditions risks were determined not to affect the vehicle and construction schedules.

Expected values for risk impacts, or the average cost or delay of the risk when it occurs, have been calculated using probability concepts. The estimates represent the impact of the risk event on the affected components. More than one risk event can affect risk costs or duration impacts to a project component. Project schedule impacts depend on whether the component is on the critical path. If not, the increase in component duration associated with a risk event probably does not translate into an increase in total project duration. Methods for analyzing individual risk impacts on total project cost and duration are discussed in Section 4.4, Risk Assessment Methods.

4.3.4 Screening for Significant Risks

When risk identification is complete and risks quantified as best as possible given the available information, the long list of risks should be screened to a shorter, manageable list of significant risks. Significance can be determined using thresholds for potential cost or schedule impacts. In a large project, risks with the potential to add $500,000 or possibly $1,000,000 in costs or four or more weeks of delay to the project might be designated significant. Unacceptable risks should also be carried forward for further analysis. Lesser risks should not be ignored, however. These minor risks could still affect the project cost and schedule. It is often reasonable to combine them into one composite cost or schedule risk and assign a likelihood (based upon the estimated underlying probabilities of occurrence preferably) and a range of impacts.

4.4 Risk Assessment Methods

4.4.1 Overview

Quantifying cost and schedule risks starts with the risk register. If the register is prepared correctly and carefully, it provides a summary of various risk events and their cost and schedule impacts. Risk assessment (Step 3 in Figure 4-1) is the process of combining these identified risks in a defensible mathematical approach to arrive at the combined effect of these risks on the total project cost and schedule (or on a major project component's cost and schedule). Risk costs and durations quantified in the risk register are added to the base project to obtain estimates of the total project cost and duration. The exercise is not one of simple summation, as noted previously. Risk impacts are characterized as random variables following various probability distributions. Adding probability distributions together requires use of statistical methods.

While the analyst has flexibility in modeling the total cost and schedule, he or she has to ensure that no important item has been overlooked and that each risk event can be traced to its origin in the risk register. In this way, the process of validation becomes easier and more efficient.

There are various approaches to estimating the impacts of risks on a project's cost and duration. The proper approach depends to a large extent on the purpose of the assessment and several factors:

- Outcomes of interest, such as total project or contract cost in current dollars or in escalated year of expenditure (YOE) dollars; schedule to completion or to reach certain milestones; rate of expenditure (cash flow); and so forth.
- Desired accuracy and defensibility of results, including the level of uncertainty in predictions and the degree of independence required.
- Budget and schedule available for doing the predictions, as well as the ability of those doing the predictions. Some analysis methods may require special skills and tools.
- Information available. Assessment methods must be consistent with available data.

4.4.2 Possible Approaches

Risk assessment approaches can be described as combinations of the following:

- Project cost and duration can be determined as **single-values**[5] or in terms of a **range of possible values** ("probabilistic" values). A probabilistic approach quantifies the uncertainty and allows confidence in various values to be determined, although it

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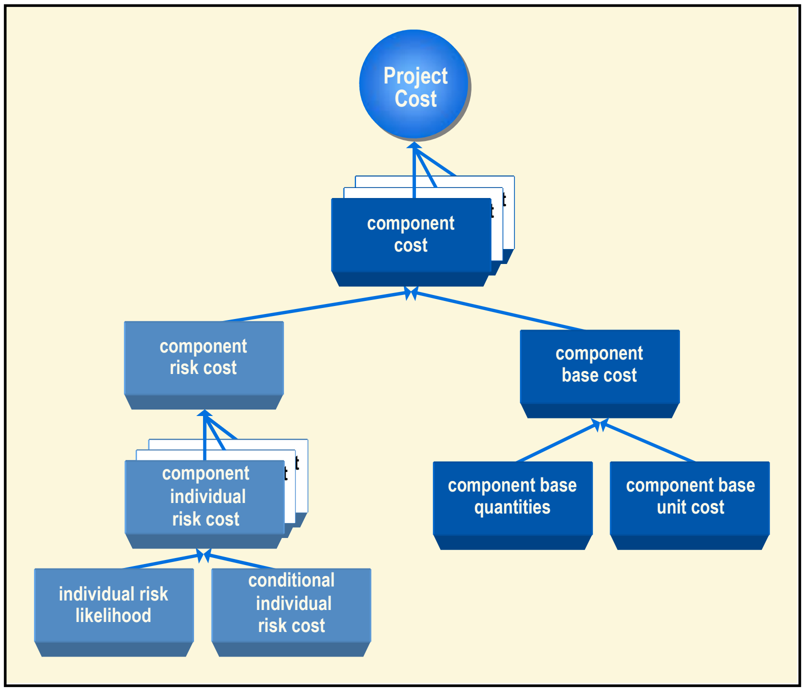
[5] Or "deterministic" values. This report generally uses the term single-value.

requires more effort and skills. If estimated probabilistically, project cost and duration can be determined either by **"non-simulation"** or by **"simulation"** methods, although non-simulation methods may not be practical in some cases.

- Project cost and duration can be estimated at the "total project" level[6] or determined by analyzing the various components that constitute the project cost and schedule and adding the components together to obtain a total project cost and duration. This is referred to as **decomposition**, which consists of (1) identifying project components to various levels of detail, (2) estimating project component costs and durations, and then (3) combining those estimates. The increased resolution from decomposition allows for more accuracy and defensibility in the results.
- If broken down to the component level, project cost and duration can be determined **independently** or in an **integrated** fashion. Independent determinations add component costs together to estimate the total project cost and similarly add component durations together to estimate the total project duration. Costs do not incorporate schedule impacts directly except to the extent that components are estimated in YOE dollars and summed in this form. Integrated assessments of cost and schedule risks account directly for the effect of time on costs; cost escalation is determined directly. Thus, the project cost estimate includes schedule impacts.

Figure 4-8 Levels of Detail for Project Cost Estimation



The issues of decomposition, integration and risk itemization can be illustrated in Figures 4-8 through 4-10. As shown in Figure 4-8, the project cost is determined separately from the project schedule to various levels of detail. Project cost is the sum of component costs which, in turn, can be estimated directly or as the sum of a base cost and risk costs.

Previous sections of the report have identified typical cost components of a project, such as fixed facilities, vehicles, systems, real estate, project management, and other components. Section 4.3 discussed the process for identifying the base and risk costs of individual project components.

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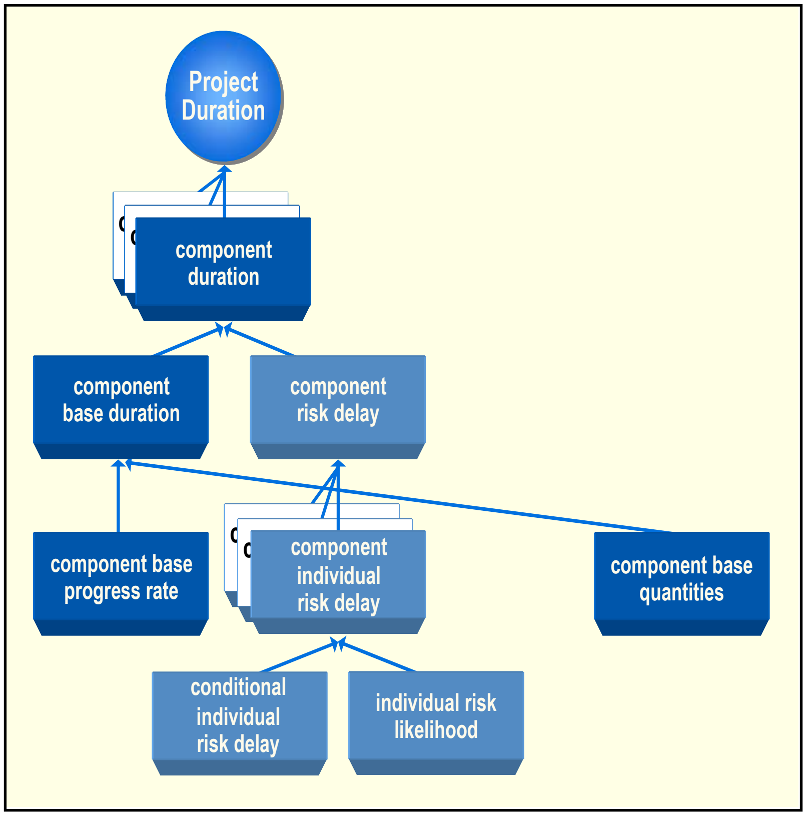
[6] As an example, if the project is "X" miles long and assumed to cost "Y" dollars per mile, the total cost would be X*Y=Z dollars. The project's duration could be estimated similarly, for example, the sum of the months for design and the months for construction.

Project durations can be similarly determined, as shown in Figure 4-9. A project's duration can be estimated as a function of the durations of components (i.e., the sum of the durations of critical path components). Each component's duration can be estimated directly or determined as the sum of a base duration and a combined risk delay. Finally, individual risk delay for a component can be estimated directly or determined as a function of its estimated likelihood of occurrence and its estimated conditional delay.

Figure 4-9 Levels of Detail for Project Duration Estimation



Project cost and duration can also be determined in an integrated fashion to various levels of detail, as illustrated in Figure 4-10. Cost and durations can be determined in the same way as they are independently, as in Figures 4-8 and 4-9. However, the same or compatible components risks are used for both cost and schedule. Connecting costs to durations allows for escalation, cash flow, and other indirect schedule-related costs to be determined.

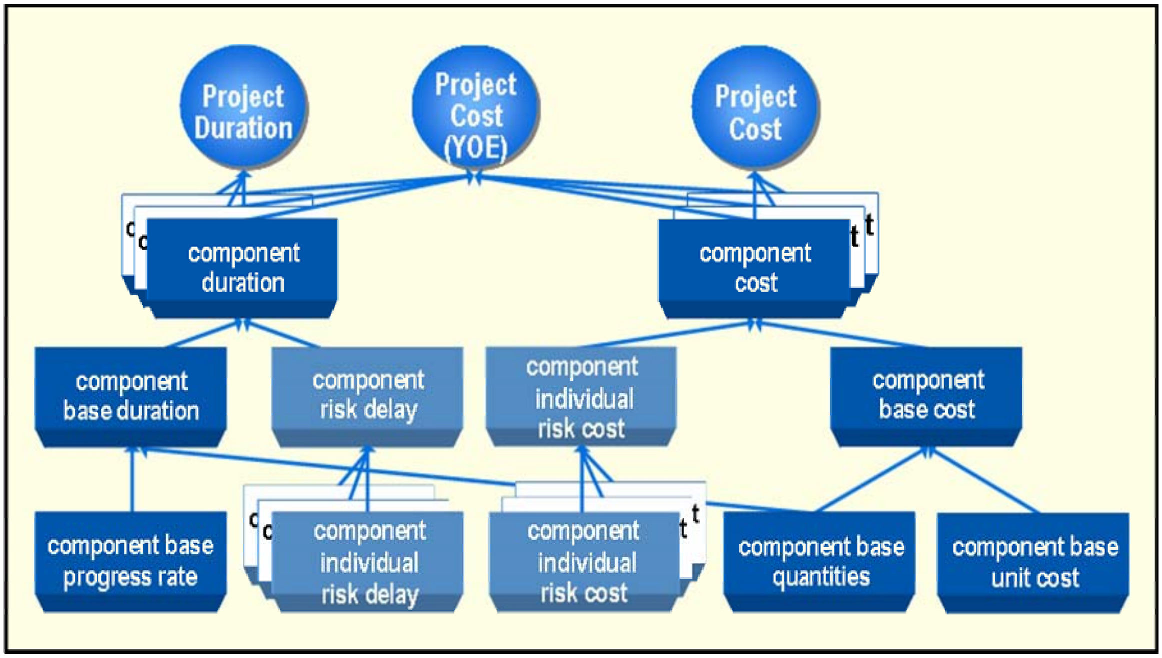
This report has proposed that project cost and schedule estimates be decomposed—to components and to each component's associated risk costs and risk durations. This is the level of information recommended for the project risk register, shown in Table 4-2.

Also, the main emphasis of this report is probabilistic risk analysis. Therefore, the discussion of assessment approaches for combining risk and base costs and durations into estimates of total project cost and duration focuses on decomposed, probabilistic methods.

4.4.3 Probabilistic Estimates

As opposed to single-value estimates, which are based on various assumptions that may or may not be true, probabilistic estimates consider all possibilities. The basic probabilistic approaches in risk assessment are discussed below.

Figure 4-10 Levels of Detail for Integrated Cost and Schedule Estimate



Regardless of the approach, uncertainties in total project cost and duration are determined as a function of uncertainties in the estimates of various underlying parameters. In the context of risk analysis, these are component risk costs and durations and component base costs and durations. Uncertainties in a particular cost or duration can be assessed directly, using accepted statistical methods if adequate data are available. Uncertainties can also be assessed subjectively, consistent with all available information, or as a function of other parameters. This report proposes developing sufficient information on risk and base component costs and durations for statistical analysis of their impacts on total project cost and duration.

This information gathering and analysis effort can be significant, however. To reduce effort, the uncertainty in a few of the most important parameters might be estimated and then extrapolated to others (statistical sampling). Or, the uncertainty in minor parameters, for example risks determined to have a low likelihood of occurrence and modest impacts when they do occur, can be combined into one parameter and assessed in that form.

Both single-value (deterministic) and probabilistic estimates follow the same basic approach. The estimate is prepared by estimating cost of various components and combining these costs in an appropriate way (either by adding them up or combining the costs using other mathematical relationships as appropriate). The main difference in a probabilistic estimate is that it explicitly considers the fact that some cost components are not single values but a range of values modeled using appropriate statistical distributions. The mathematics of combining these components consists of dealing with ranges of data rather than single data values. Addition, subtraction, multiplication, and other mathematical operations have to be performed on data ranges, and require the use of probability theory.

In certain instances this mathematical manipulation becomes unwieldy and intractable due to the complexity of the problem. The only logical way to perform the analysis is to *simulate* the data according to statistical distributions specified in the model and combine these sampled values using the deterministic approach. Each time that the distributions are sampled, a total cost and schedule are calculated deterministically. By repeating the process of sampling the distributions and calculating the total cost and schedule a sufficient number of times (usually a few thousand times), a distribution for cost or schedule can be obtained. This distribution then provides all possible values for total project cost or duration and identifies their probabilities.

In the following subsections, non-simulation probabilistic estimates and then simulation approaches for estimating total project cost and schedule impacts are discussed.

4.4.3.1 Non-Simulation Methods

Non-simulation methods for determining the uncertainty in project costs and/or duration consist primarily of the following:

- *First-Order Second-Moment (FOSM) methods* (see Appendix C). These methods are appropriate for determining the uncertainty in project cost in current dollars only. They are only partially appropriate for determining the uncertainty in project duration and even less appropriate for determining the uncertainty in project cost and schedule together (e.g., including project cost in YOE dollars).
- *Probability tree.* This method can be used to transform individual risks, each with a conditional expected value impact and a probability of occurrence, into a probability distribution for collective risks. However, probability trees become impractical with even moderate numbers of risk events because the total number of possible outcomes increases exponentially with the number of risk events.

Only FOSM methods are discussed in this report.

A non-simulation method can be used for determining the uncertainty in project cost in terms of current dollars, where the cost is made up of various uncertain, correlated parameters. There are major limitations to the use of non-simulation methods. When cost can be modeled as the sum of several components, one can use the Central Limit Theorem to obtain the distribution of the total cost. The total cost would follow a normal distribution and the mean and variance can be calculated by summing up means and variances of individual cost components. An example application is provided in Appendix C1 and some of the limitations of this approach are described.

A non-simulation method can be used with any approach for determining the uncertainty in project schedule if the critical path is “stable,” that is, doesn’t change. In this case, the total project duration is simply the sum of the durations of all the critical path components, similar to project costs except that only a subset of the components is considered. If the critical path is not stable (i.e., the float for non-critical path components might be exceeded, causing a different critical path), the various percentiles (and thus the mean) of project duration will be underestimated. An example of this approach is the well-known PERT approach, discussed in detail in Appendix C3.

It is currently not feasible to use a non-simulation method with an integrated cost and schedule approach to determine the uncertainty in project cost and schedule.

4.4.3.2 Simulation Methods

Simulation methods for determining the uncertainty in project costs and duration consist primarily of Monte Carlo (MC) simulation. These methods are generally appropriate for determining the uncertainty in project cost (in current dollars only), the uncertainty in project duration, and, with effort, the uncertainty in project cost and schedule together (e.g., including project cost in YOE dollars). In a Monte Carlo simulation, the modeler samples statistical distributions representing random variables (mainly cost or duration in risk assessment) using a digital computer.

In recent years several software companies have marketed specialized software that allow the user to perform Monte Carlo simulation on a critical path method (CPM) network or a cost estimate spreadsheet. Most of these programs allow the user to define activity durations, costs, or resources (such as labor hour requirements, *etc.*) as random variables. Assume, for instance, that the user has defined all risk costs as random variables by specifying a distribution type and also possible ranges or distribution parameters. The simulation software generates random numbers for these costs according to specified distributions and calculates the total cost. This process is repeated hundreds or thousands of times, each usually called an iteration or realization. The number of iterations depends on the confidence intervals desired for the results. Each iteration produces a single value for total project cost. These values can then be organized into a histogram for total project cost. Using this histogram, a probability density function (PDF) and a cumulative distribution function (CDF) for total cost is compiled. These distributions can then be used to assess the probability of project cost overrun beyond the project's established budget. It can also be used to determine reasonable amounts of cost contingency for the project.

Schedule risk impacts are similarly evaluated using simulation software, although total project duration is a function of the time required to complete only those components on the critical path. Thus, software must calculate the critical path through the project schedule during each iteration in addition to the impacts of schedule risks. Appendix C4 provides an example of evaluating schedule impacts using Monte Carlo simulation.

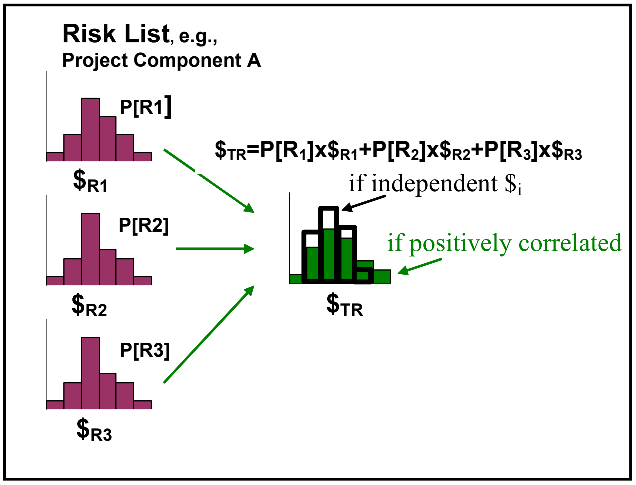
To determine costs, software such as Excel^{TM} with @RISK^{TM} or CrystalBall^{TM} can be used with any estimating method.

For schedules, software such as MSProject^{TM} with @RISK^{TM} or Risk+^{TM}, or Primavera^{TM} with Monte Carlo^{TM} can be used. Alternatively, if a schedule model can be developed in a spreadsheet, Excel with @RISK or CrystalBall can be used to simulate risks directly.

4.4.3.3 Decomposed, Independent Project Cost and Schedule Estimates

a. Independent Cost Estimate. Just as a project is likely to face multiple risks, individual project components can have multiple risks potentially affecting their costs. To obtain the total project cost, which is the combined risk and base costs of all components, the costs of individual components must be determined. This is done by combining the relevant risk costs of a project component and adding the total to the component base cost. Figure 4-11 shows schematically this concept of combining risk costs at the component level. $P[R_1]$, $P[R_2]$, and $P[R_3\}$ are the probabilities of risks R_1, R_2, and R_3 occurring. $\$_{R1}$, $\$_{R2}$, $\$_{R3}$ are the cost impact of those risks if they occur. $\$_{TR}$ is the expectation of total risk costs. Note that the combined risk cost affecting component A is a function of probabilities of occurrence of each risk factor.

Figure 4-11 Risk Costs Combined



An important consideration is the potential for correlations among risk events, which can significantly affect the results. If correlations are ignored, then the spread of the outcome distribution is generally underestimated, as indicated in the figure. There are various analytical methods for dealing with correlations, and software now available for risk analysis makes it convenient to specify the desired relationships among risks.

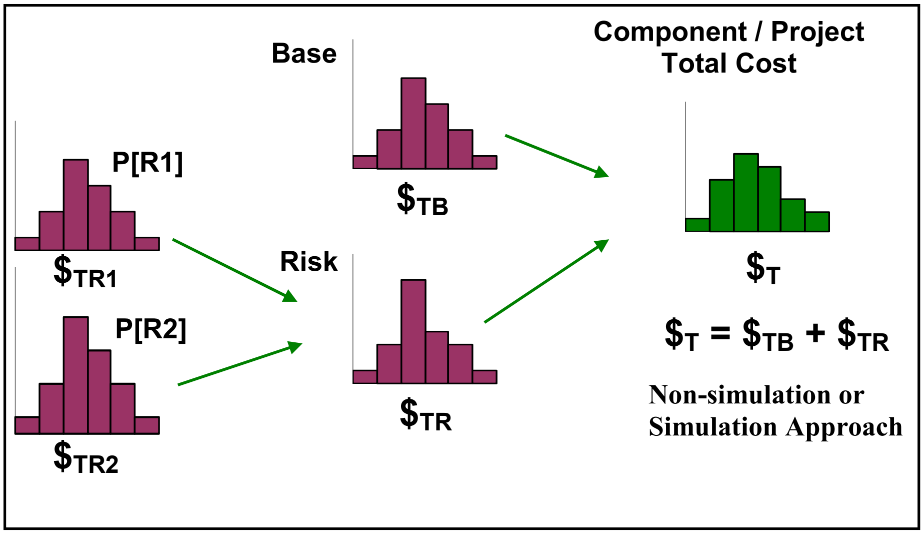
It may be possible to simplify combining risk distributions, at this or other levels, by ignoring the range of uncertainty if it is relatively insignificant. As an example, if $\$_{R1}$ is relatively small, its expected value instead of its cost distribution can be used. This also applies to combined risk distributions and base costs distributions, if the latter are estimated to follow a probability distribution (i.e., have some level of uncertainty) rather than being a single-value estimate.

As shown in Figure 4-12, individual component costs are simply the sum of combined risk costs and the base cost. The schematic also depicts the process for determining the project's total cost and duration, since it is the sum of all component base and combined risk costs.

Uncertainties in the base and in individual risk costs, which in turn are due to uncertainties in whether each risk will occur and if so its cost impact, have been translated into uncertainties in project component costs and project total cost. In Figure 4-12, for example, P[R1] and P[R2] are the probabilities of Risk 1 and Risk 2 occurring, respectively. $\$_{TB}$ and $\$_{TR}$ are base and total risk costs, respectively. The combined risk cost can be estimated from the following:

$$\$_{TR} = P[R1] \text{ x } \$_{TR1} + P[R2] \text{ x } \$_{TR2}$$

Figure 4-12 Uncertainty Analysis for Base plus Risk Costs



As an example of independent cost risk analysis, an assessment was performed of the hypothetical at-grade and aerial light rail transit project described in the project network of Figure 4-4 and with the 10 risks listed in the risk register of Table 4-2 (seven of the identified risks are actually cost risks independent of schedule risks). The steps and detailed results of the analysis, using simulation methods for combining risk and base costs to obtain total project cost, are described in Appendix C2. The example project has a base cost of $450 million in current dollars (the base was assumed to be a single-value, i.e., deterministic). Adding risk costs results in the total project cost distribution shown in Figure 4-13.

The mean (or expected value) of project cost at completion is approximately $500 million. The cost could range below and above that level, with varying likelihoods. An optimistic total project cost, represented by a 10 percent probability in the cumulative distribution function for the project cost, would be $453 million (i.e., risk cost impacts are incidental; see Appendix C2 for details on estimated costs by percentile). A pessimistic total project cost, represented by 90 percent probability in the cumulative distribution function, is estimated to be $553 million (i.e., risks add over $100 million to the base project cost).[7] All costs are expressed in current (2004) dollars.

Costs can be escalated to anticipated year of expenditure (YOE). This would be done by evaluating the project schedule and determining the midpoint of expenditure for each major project component, then escalating current costs by a selected rate of cost growth. In the example project, the annual rate of cost growth is assumed to be 3 percent a year. Just over three years into the future would be midpoint of construction for an 80-month construction schedule. This would result in a mean project cost YOE of approximately

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[7] Another way to interpret the 90 percentile cost is that there is a 90 percent likelihood that the cost will be this value or less at completion. There is only a 10 percent chance of budget overrun. For the 10th percentile cost, in contrast, there is a 10 chance that the final cost will be less than this value and 90 percent chance of overrun.

$554 million. Figure 4-14 shows the estimated cumulative distribution function for YOE costs. The optimistic project cost is approximately $500 million and the pessimistic cost is $607 million.

Figure 4-13 Results of Independent Cost Assessment
for Hypothetical Light Rail Project ($450 M Base Cost)

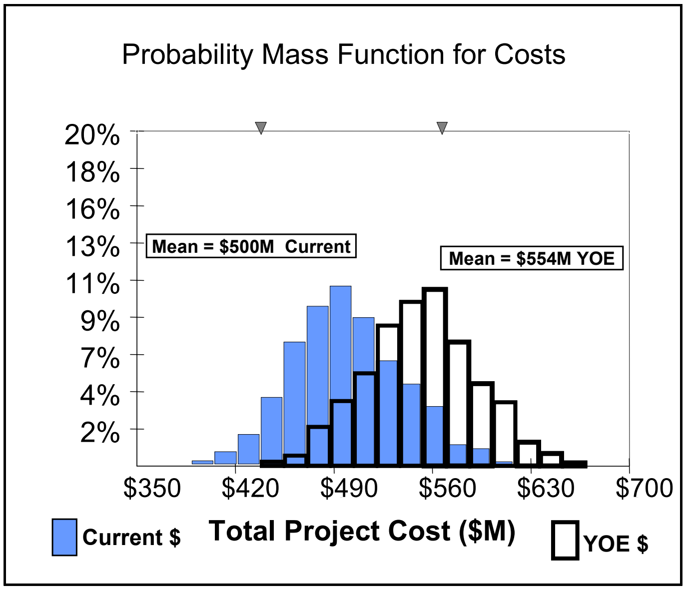
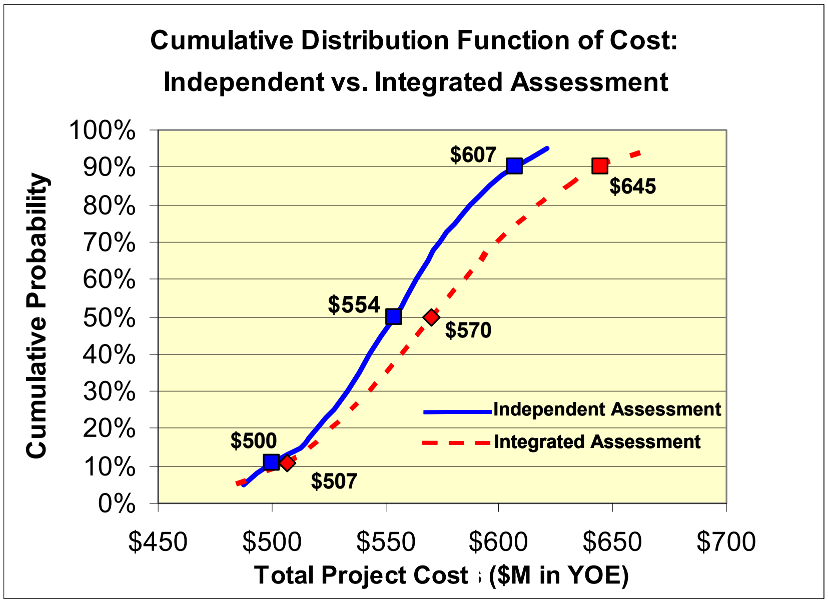


Figure 4-14 Results of Cost Risk Assessment in YOE
for Hypothetical Light Rail Project ($450 M Base Cost)

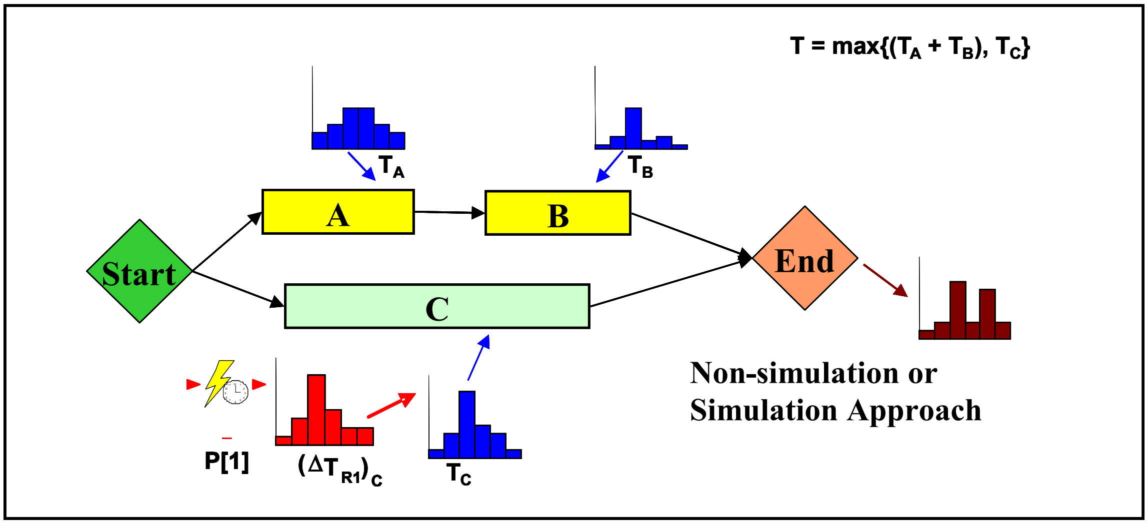


b. Independent Schedule Estimate. Assessment of risk duration impacts on total project cost is similar to risk cost assessment. Risk impacts to component durations are determined. Correlations among risk durations and component durations need to be considered the same as for correlations among costs. Risk and base durations are combined to give total component duration. Component durations are combined to estimate the total project duration—or the schedule. Total project duration is also a probability distribution, following from the fact that component durations are uncertain as a result of risk impacts.

This is shown schematically in Figure 4-15. Each component of the simple network has an associated distribution for the time it will likely take to complete the component. This duration is comprised of risk duration impacts and the scheduled base duration. For simplification, only Component C is depicted as including risk impacts, but most project components could experience schedule risks that add to base durations.

The important distinction with duration impacts is that they adversely affect total project duration only if they extend the critical path for project completion. An increase in the duration of a component will translate into an increase in project duration if the component is on the critical path and schedule float, for this and other critical path components, is consumed. Float is the additional time allowance in a component, or within a sequence of components, not considered part of the minimum time to complete the activity.

Figure 4-15 Uncertainty Analysis for Base plus Risk Durations



Another consideration in assessing risk duration impacts on total project duration is that the critical path can change if risk impacts increase the time to complete a previously non-time critical component. The minimum time to complete the project may now include the expected duration for this activity. Schedules are dynamic, and analysis approaches must be flexible to account for both direct and indirect consequences of changes in the project critical path. Some analysis tools are not flexible, and it is up to the analyst to carefully evaluate results and anticipate when these changes might occur.

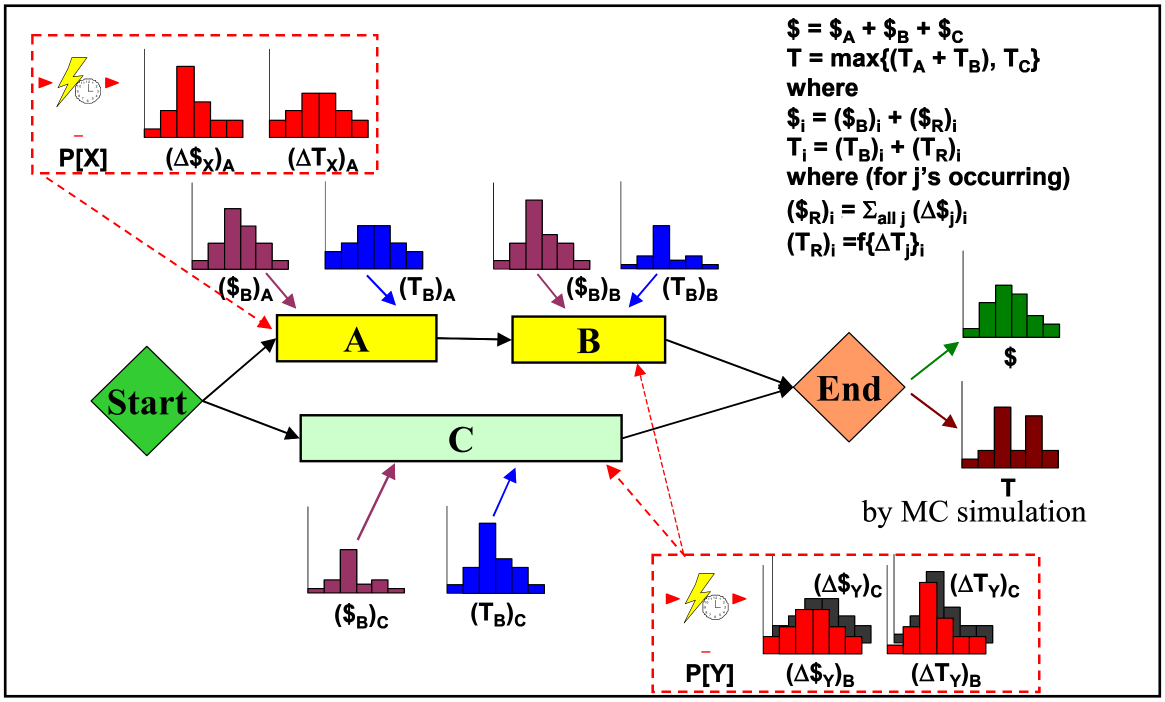
Appendices C3 and C4 analyze risk impacts to a project schedule using the PERT and Monte Carlo simulation methods, respectively.

4.4.3.4 Decomposed, Integrated Cost and Schedule Estimates

For integrated assessment of risk impacts on total project cost and duration, the same risks and components as applied in independent cost and schedule analysis can be used. Uncertainties (and possible correlations) in the cost and duration of each component combine to produce uncertainties in total project cost and duration as well as escalated project costs. The benefit of the integrated approach is that escalation is incorporated directly in the assessment of total project cost, and the effects of component schedule delays are translated not just to probabilistic estimates of project duration but to improved estimates of escalation costs. Escalation is not set deterministically (as function of the midpoint of construction, for example) but is dynamic in response to the changes in component durations from risk events. A probabilistic estimate of total project cost should be more accurate, therefore, when component duration risks are significant.

As with independent cost and schedule assessments, a base plus itemized risk approach is used to estimate the cost and duration of each project component. In Figure 4-16 risk items X and Y have probabilities of occurrence of P[X] and P[Y]. Risk X has an impact on component A while Risk Y has an impact on components B and C, as shown. Total project cost ($) and total project duration (T) are a function of base and risk factors. By explicitly considering individual risk events, instead of combining them first, many of the correlations in component cost and durations are automatically dealt with.

Figure 4-16 Integrated Cost and Schedule Uncertainty Analysis



Simulation methods are necessary to analyze cost and duration impacts in an integrated fashion for a project of any complexity. Correct and careful structuring of the relationships among costs and durations, in particular possible correlations, will ensure a higher level of accuracy and defensibility of results.

As an example of integrated cost and schedule risk analysis, an assessment was performed of the light rail transit project described in the project network of Figure 4-4 and with the 10 risks listed in the risk register of Table 4-2. The steps and detailed results of the analysis, using Monte Carlo simulation for combining risk and base costs to obtain total project cost and total project duration, are described in Appendix C5. The example project has a base cost of $450 million in current dollars (the base was deterministic). Adding risk costs results in the total project cost distributions shown in Figure 4-17 and total project duration distribution shown in Figure 4-18.

The mean project cost in current dollars is estimated to be \$509 million, or risks add approximately \$59 million to the base project cost. The optimistic project cost (10th percentile) is estimated to be \$453 million and the pessimistic project cost (90th percentile), \$568 million, both in current dollars (see Appendix C5 for details). In YOE, mean total project cost would be approximately \$574 million, with an optimistic cost of \$507 million and pessimistic cost of \$645 million.

Figure 4-17 Cost Results of Integrated Cost and Schedule Assessment
for Hypothetical Light Rail Project (\$450 M Base Cost)

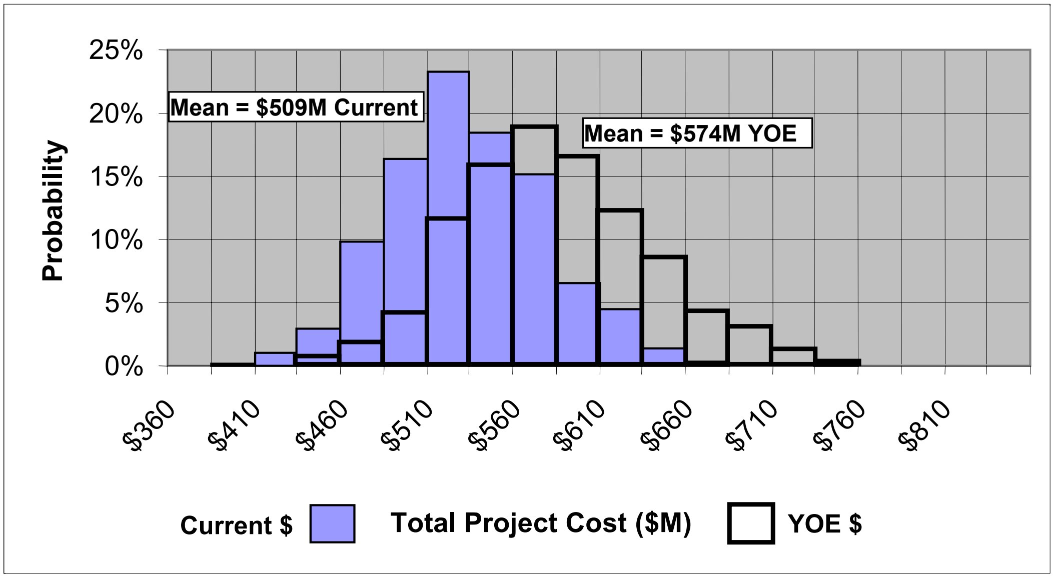


Figure 4-18 Schedule Results of Integrated Cost and Schedule Assessment
for Hypothetical Light Rail Project 72 Mos. Base Duration)

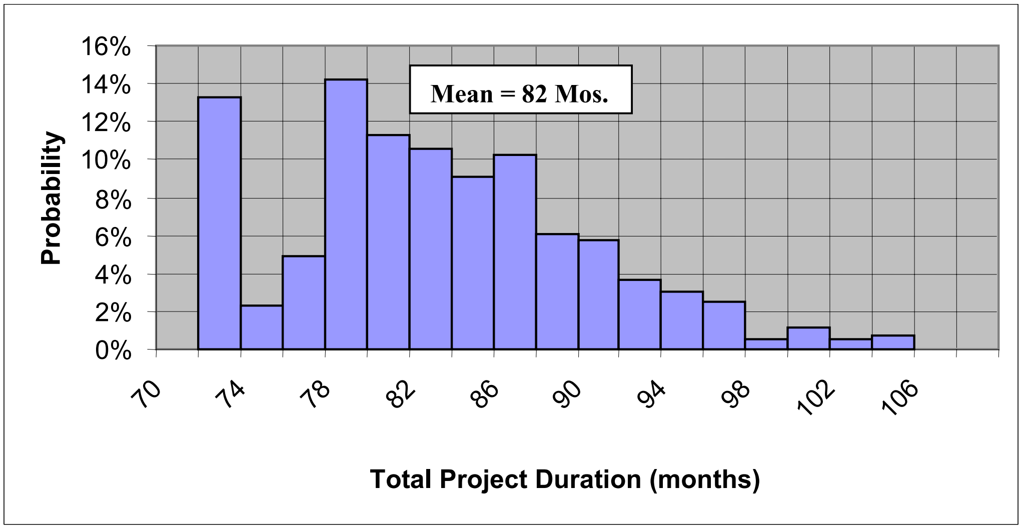


Figure 4-14, previously shown, compares the cumulative distribution function of the integrated cost assessment with that of the independent cost assessment. The total cost curve resulting from the integrated assessment of risks has a flatter slope than that of the independent assessment (and higher estimated project costs at, for example, the 50th and 90th percentiles) because schedule delay impacts on cost have been explicitly included in the integrated case.

The eight-component project network of Figure 4-4 has a base duration of 72 months. In the integrated assessment of project duration, the mean (or expected value) duration is 82 months, or risk impacts add on average 10 months to the base schedule. The estimated optimistic completion duration (10 percentile) is 72 months and the pessimistic completion duration (90 percentile) is 91 months (Appendix C5).

It should be noted that the assessment results for project duration are essentially the same whether project duration is evaluated independently of cost impacts or in an integrated fashion when simulation methods are used. The potentially significant difference in results between the two approaches is in costs when risk duration impacts are large and affect cost escalation.

4.4.4 Verification of Simulation Results Using Non-simulation Approaches

It is important that the risk analyst understands the underlying theoretical concepts of simulation. Simulation is a facilitator; it allows the analyst to solve complex probabilistic problems and arrive at approximate solutions. The degree of approximation depends on several factors such as the reliability of the computer's random number generator and the number of simulation runs performed. Simulation will always generate an answer—but that does not necessarily mean that the answer is right. It is important to be able to test and validate simulation results.

As a starting point, the results should be logical. Consider a simple example consisting of the summation of three random variables. Each random variable has a range. Obviously, the range of their sum cannot be outside the boundaries calculated by simply adding low and high ends of these variables.

One common way to ascertain the reasonableness of simulation results is to check the outcome using non-simulation techniques. An example of these techniques was briefly discussed earlier under *first-order-second moment* (FOSM) methods in Section 4.4.3.1. In this approach, the analyst may have to simplify the risk assessment model in order to use a non-simulation approach to verify the results. If the model can be reconfigured such that the final result—total project cost or duration—is the sum of a number of random variables, the mean and variance of the result can be calculated and compared with the simulated values of mean and variance. If there is considerable difference between the results, this would indicate possible inconsistencies or errors in the simulation.

Another common approach is to calculate an upper limit for the variance of the sum of random variables. If several of the random variables are correlated (with correlation coefficients ranging from 0 to 1), then an upper bound for the variance can be calculated by assuming that all correlated variables are *perfectly correlated* (correlation coefficient = 1). The total variance can be calculated using first-order-second moment methods and compared with the simulated variance. In such a case, the simulated variance should be *less than* the calculated variance. Appendices C2 and C4 illustrate the process of validation of simulation results in greater detail.

4.4.5 Contingency Analysis in Probabilistic Approach

One of the main differences between probabilistic and single-value estimates is that, in the traditional single-value estimates, a contingency budget is calculated based on experience with similar projects in the past. One of the more common methods of budgeting for contingency is to consider a percent of the total estimated project cost (e.g., 10 percent), based on previous experience with similar projects.

A more detailed approach is to assign various percent contingencies to various parts of the budget. In this approach, the riskier components of a project may get a higher percentage for contingency. As an example, consider a tunneling project. The contingency level for underground construction activities and tunneling (considered risky and hard to estimate accurately) might be set at 15 to 20 percent while the contingency level for the rest of the project might be established at 5 to 10 percent. In either approach, however, it is not possible to establish a desired level of confidence that the contingency will provide against cost overruns.

The probabilistic assessment of project costs recommended in this report provides a method for establishing project budgets with varying levels of confidence against cost overruns. In the case of a project budget that has been established with a specific contingency, subjecting the project to probabilistic risk assessment offers a means for determining whether the contingency is likely to be adequate.

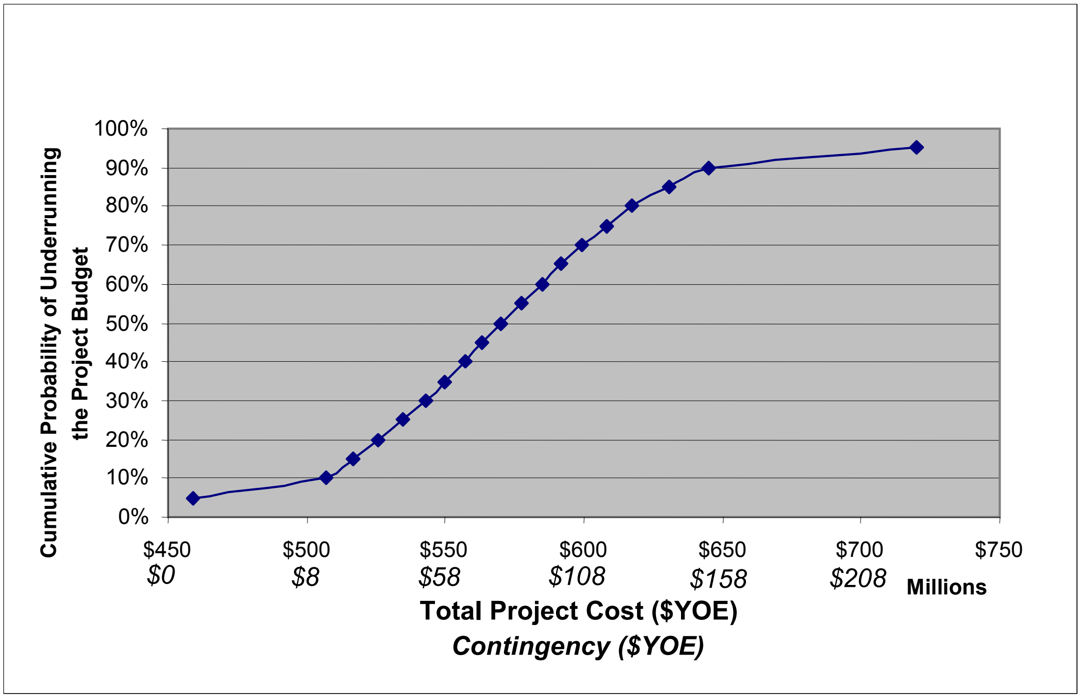
In a probabilistic approach, the project cost is estimated as the sum of base and risk costs. The base cost represents an expected cost for the project assuming none of the major potential risks will affect the project. The risk costs represent the potential impacts of project uncertainties—what in traditional project budgeting is normally covered by the contingency. The combined effect of risks is a random variable with a statistical distribution that, when added to a project's base cost, will result in a total project cost that is also a random variable. This range of values for total project cost follows a probability distribution, as in Figures 4-13 and 4-17, which can be evaluated mathematically. Statistically valid conclusions can be drawn about the range in project costs.

Using the total cost distribution (YOE$ histogram, Figure 4-17) for the eight component hypothetical light rail project described in Figure 4-4, a cumulative distribution function (CDF) can be calculated by summing up values. This is shown in Figure 4-19.

As shown, total project cost ranges from approximately $450 million to $750 million. There is a 50 percent chance that a budget around $575 million would be sufficient to meet project cost needs. This equates to a project having a contingency of $83 million on a base project cost of $492 million YOE ($450 million escalated 3 percent for three years). Some project sponsors may be uncomfortable with such level of confidence. Sponsors may want to have 80 percent confidence that the project will not suffer from a cost overrun. In such a case, a budget of approximately $620 million would be required. The corresponding necessary contingency has increased to $128 million.

As compared with the single-value approach, project sponsors have the added benefit of knowing what level of protection they are "buying" against potential cost overruns. This will help in establishing realistic budgets for various projects with various levels of complexity while being consistent in providing adequate contingencies against potential overruns. Exactly the same concept can be used for establishing schedule contingencies.

Figure 4-19 Cumulative Distribution Function of Total Project Costs



4.4.6 Evaluation: Advantages and Disadvantages of Assessment Approaches

Project cost and schedule analysis can be developed to various levels of detail (both in breadth and depth). The advantages and disadvantages of the various possible approaches can be summarized as follows:

- *Probabilistic* versus *single-value.* In the probabilistic approach, the confidence level in estimates is known, but it requires more effort and skill.
- *Decomposed (into components)* versus *non-decomposed (big picture).* Better accuracy and defensibility are achieved by decomposing and prioritizing components; but more effort and skills are needed compared to the non-decomposed approach.
- *Integrated cost and schedule* versus *non-integrated cost and schedule.* Better accuracy and defensibility for schedule and cash flow or cost escalation are achieved but additional effort and skills are needed for analysis.
- *Itemized risk plus base assessments* versus *contingency plus base assessments* versus *total assessments.* Better accuracy and defensibility (especially regarding

correlations) is achieved by itemizing risks and calculating their combined impacts; this will allow prioritization of risks, but more effort and skills are needed for a successful risk assessment.

The value and effort of each method are also affected by the following:

- Level of detail and completeness
- How it is conducted (e.g., collaborative versus independent)
- Defensibility of experts and data
- Documentation / reporting
- Budget and time available
- Expertise and information available
- Accuracy requirements.

4.5 Summary and Recommendations

Section 4 describes the process of risk assessment, which involves the validation of the base scope, cost, and schedule for a project; identification of risks to the base scope, cost, and schedule; quantification of individual risk impacts; and assessment of risk impacts on the overall project scope, cost, and schedule. The review of base conditions is an important starting point. The base is the project stripped of all cost and schedule contingencies. In risk assessment, these are replaced with potential risk costs and risk schedule delays. An accurate base scope, cost, and schedule are critical. The review of base conditions should determine whether

- The scope is comprehensive and consistent with the proposed or approved environmental document, and encompasses all significant project components such as design, the environmental process, permitting, right-of-way, and construction;
- The cost and schedule are developed to an appropriate level of detail for the level of design, for example, ranging from several project elements during planning to tens or hundreds of elements during final design;
- Cost and schedule are based on an integrated cost and schedule model to determine critical path schedule and escalation.

The project scope should be checked for completeness, the schedule for logic, and the component costs and durations for reasonableness. If necessary to reduce the level of effort, only the critical elements would be checked in detail. Validation of the project cost and schedule estimate can be done separately from the risk assessment (beforehand) or as part of the risk assessment.

4.5.1 Identification and Quantification

Risks to the base scope and schedule can be identified through several methods. The base review will likely identify potential risk areas: design, cost, and schedule elements that are not certain or are possibly not reasonable or accurate. Other similar project experience is a good source of information on potential risks to a project. Brainstorming by a panel of experts, in a workshop setting perhaps, is another method for developing a comprehensive list of risks to a project. These efforts can be facilitated by using a risk checklist to ensure that risk identification has covered all relevant aspects of the project development process. All significant uncertainties in quantities, unit costs, cost markups (including allowances and soft costs), escalation rates, and durations or progress rates for each project component should be identified. All possible occurrence of major problems (or opportunities), including possible changes in scope, that would significantly impact the project cost or schedule should be considered.

Risks and risk impacts should be documented in a risk register. The most significant risks to a project should be screened, based upon some established threshold for minimum cost or schedule impact. Significant risks to the project are analyzed in detail to determine their individual and cumulative effects on the overall project cost and schedule (or to major component costs and durations).

Risk quantification, which involves estimating the cost and schedule impacts of identified risk events, can be similarly undertaken by referring to available objective data and by using an expert panel or workshop, among other methods. Risks are uncertain events, and therefore risk events are random variables. Risk impacts should be expressed quantitatively in terms of probability distributions, which express the relative likelihood of any possible value. Various convenient distributions can be used to reasonably and accurately characterize risk events in terms of likelihood of occurrence, probable cost, and probable duration. Significant correlations among parameters (e.g., costs of two different components) should be assessed, adequately justified, and implemented in the analysis.

4.5.2 Assessment

Various methods, such as analytical methods or Monte Carlo simulation, can be used to appropriately combine the risks to a project. Project cost and schedule effects can be determined as single-values (deterministic) or in terms of a range of possible values (probabilistic). Probabilistic values and probabilistic assessment of impacts allow the estimation of confidence levels for specific project cost or schedule values. Cost risk impacts and schedule risk impacts to a project (or major project component) can be analyzed separately or in an integrated approach. Integrated analysis of both cost and schedule impacts generally provides a more realistic and accurate picture of risks to a project. However, it requires more effort and skills than does the independent analysis of cost and schedule impacts. There are readily available simulation tools to assist with the integrated analysis of cost and schedule.

Fully integrated analysis is justified when cost and schedule risk impacts are complex and interrelated and when both are perceived to have potentially significant effects on project success. Under certain situations, however, integrated cost and schedule analysis may not offer sufficient benefit for the time, effort, and possibly expertise required. For projects where schedule issues are paramount, the assessment of impacts could be based on risks to the duration of project components. Similarly, for projects with major cost concerns, risk analysis focusing on risks posing primarily cost impacts could be sufficient in providing the information needed to implement corrective actions that ensure project success.

Benefits of performing risk assessment at a detailed level, for all major project components and including the individual risks that have been identified for each project component, are several. The additional information allows better risk prioritization and more cost-effective implementation of risk mitigation.

4.5.3 List of Products/Deliverables

Important products from the risk assessment portion of risk analysis include:

- Documentation on reasonableness and accuracy of project scope, cost, and schedule; estimated *base project component costs and durations* and *total project cost and duration*
- *Project component network*, which describes the major project activities and their relationships
- *Risk register*, a comprehensive list of risks and opportunities for all major project components
- *Assessment results*, including estimated risk impacts to total project cost and duration; list of *major and minor project risks*, ranked by each risk's contribution to changes in total project cost and duration; *probability density functions and cumulative distribution functions* of estimated base plus risk costs and base plus risk durations; *assessment of project contingency* required to attain desired levels of confidence of not overrunning the project budget.
- *Risk assessment report*, which documents the methods and results of the risk assessment process.

5. Risk Management

Main Points:

- *Risk management is contingent upon sound risk assessment.*
- *Risk management is the development of an action program and includes planning, implementation, and monitoring.*
- *Mitigate risks that will yield substantial payback (cost and time savings).*
- *Risk mitigation strategies are summarized in a risk mitigation register.*
- *Allocation of risks between project owner and contractors should be done in a fair and consistent manner.*
- *Monitor performance of risk mitigation measures and implement corrective actions to ensure measures are cost effective.*
- *Project owner has ultimate responsibility for establishing and monitoring performance of risk management plan.*

Risk management can only begin when risks have been properly identified and quantified. An effective risk management plan cannot be established independent of risk assessment. The assessment should identify individual risks and quantify their potential impacts. Without this detail, it is not possible to accurately determine which risks contribute to significant variance in total project cost and schedule and appropriately target risk mitigation measures.

A prioritized listing of risks, ranked by their relative contribution to project cost variance, is one of the important products of detailed, systematic risk assessment. It is the assumed starting point for the discussion of risk management in this section. However, it is recognized that such level of detail is not always possible or perhaps even the objective of project sponsors undertaking certain types of risk assessments. For projects early in the planning process, the identification of general issues—constraints and opportunities—influencing project development might be the primary objective.

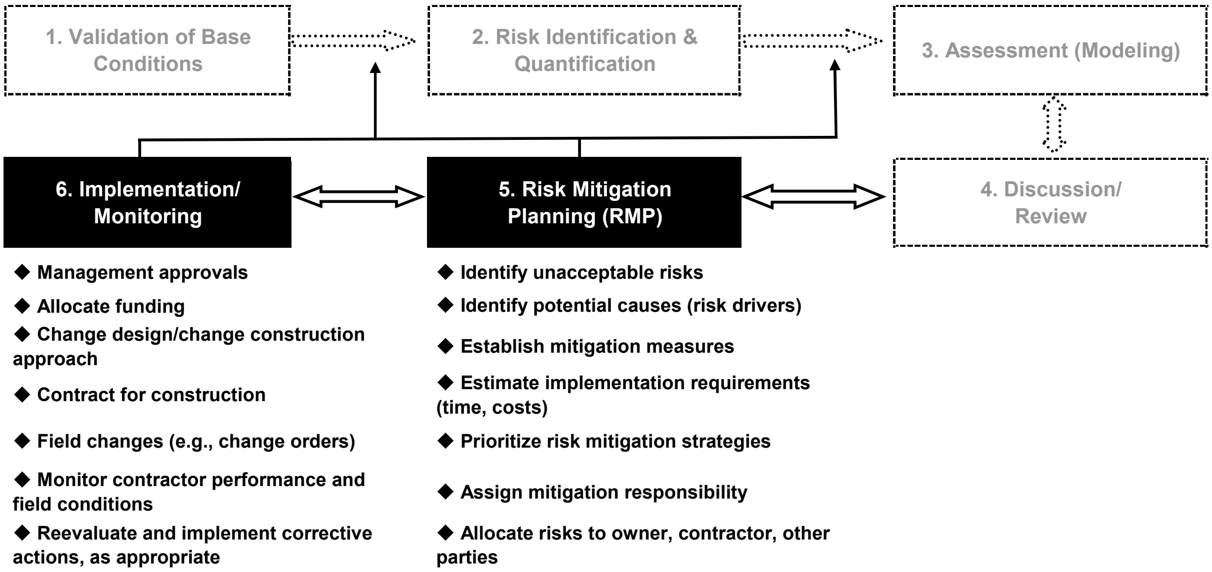
5.1 Identifying Critical Risks to a Project

In Figure 5-1, risk management tasks are highlighted. Risk management includes risk mitigation planning, implementation, and monitoring. Risk management must begin with a characterization and screening of risks to identify which warrant mitigation. Risk management does not end until construction is complete (and probably should continue into initial revenue operations as well, until the new system is proven).

5.1.1 Risk Prioritization

To mitigate risks cost-effectively, they need to be prioritized. Risks can be prioritized with respect to project cost separately from project schedule or they can be prioritized based upon the combined cost and schedule impacts. The relative importance of individual risks to a project's cost, for example, can be determined by estimating how individual risk impacts change the total project cost. The greater the change in project

Figure 5-1 Risk Management



cost the more significant the risk. Similarly, the relative importance of individual risks to a project's schedule can be determined by estimating how individual risk impacts extend the duration of the project's critical path. This is a straightforward exercise if risk impacts are assessed (using non-simulation or simulation methods) in an analytical model of the project. A risk event is added to (or subtracted from) the various risks being evaluated, and before-after model results compared.

Once risks have been prioritized based upon their effects on project cost and/or schedule, the project owner must determine which high-cost and significant schedule delaying risks to a project it can influence. This may involve both public policy and technical considerations. The same group of experts that participated in risk identification and quantification is well suited to helping the project owner determine which technical risks can be influenced within the scope of the design and construction program. It would be left to the owner's executive staff and policy boards to determine whether other political, legal, financial, and similar risks can be mitigated—or whether they would be classified as external risks. Even external risks ought to be evaluated and contingency plans prepared.

Of those risks under the influence of the project owner, two types are likely candidates for mitigation:

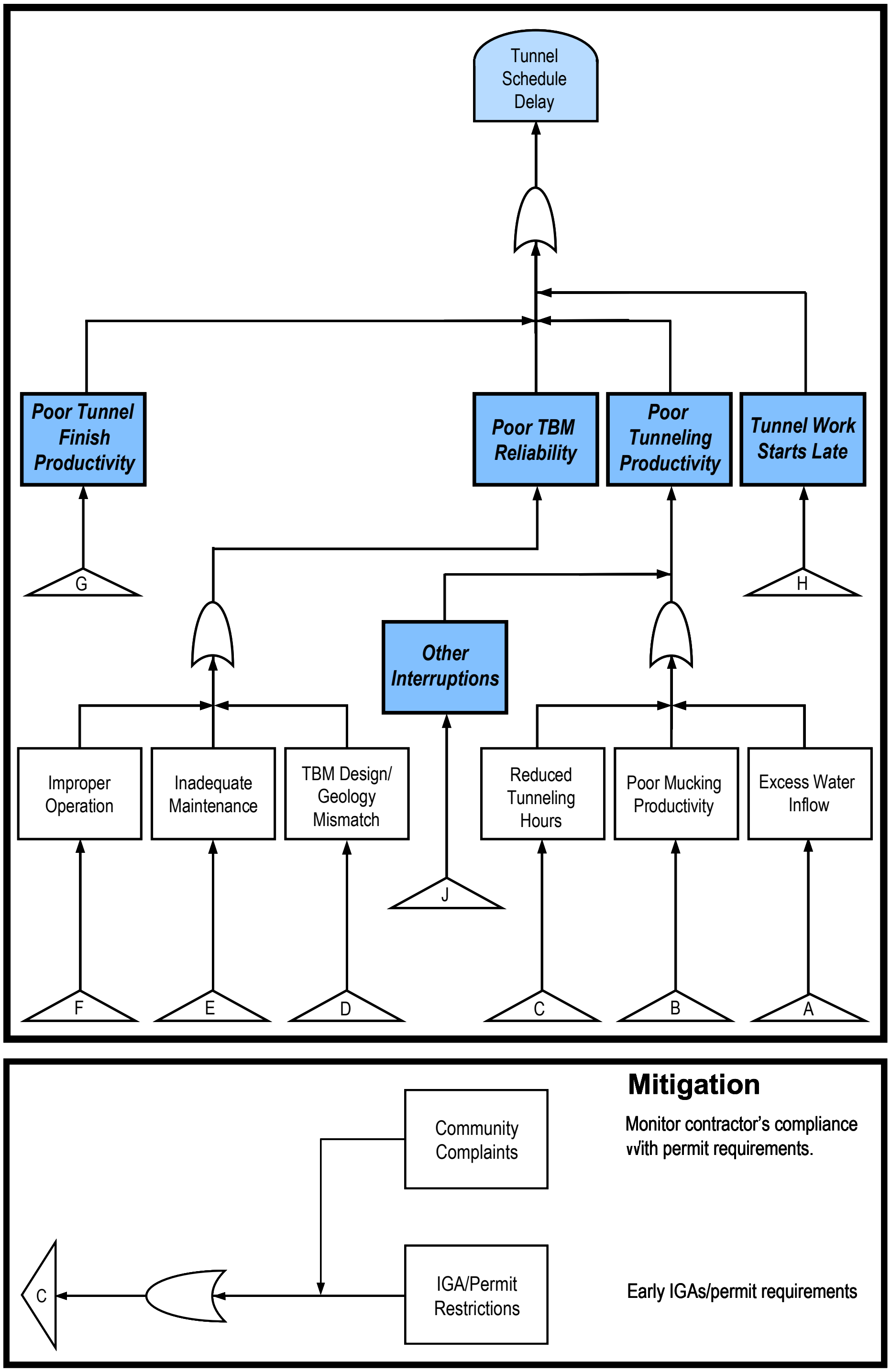
- Intolerable risks, such as events that could potentially stall a project or make it financially infeasible or unsafe.
- High cost, high likelihood risks.

5.1.2 Risk Causation

Risks identified in the assessment phase may or may not represent specific causal events. Risk events should have explicit causes and direct impacts, e.g., an earthquake is not a risk event (it does not have direct impacts) but is a possible cause of structural collapse (which does have direct impacts and is the proper characterization of the risk event). Often a risk event occurs when several underlying conditions are met or actions happen. It is helpful to understand the potential causes of a risk event to evaluate if it is feasible to mitigate the risk as well as how to mitigate it. Identifying root causes of risks can be part of risk assessment or risk management. For purposes of this report, evaluation of root causes is assumed to be part of risk management.

There are, for example, several possible causes of structural collapse, an earthquake being just one. A structure could be struck, perhaps by a truck or train and its cargo. Its foundations could fail. The design could be inadequate and the bearing capacity insufficient. Several methods are available for analyzing the underlying causes of or conditions contributing to a risk event. Fault tree (deductive logic), event tree (inductive logic), and cause-consequence (a blend of the two) analyses are structured analytical techniques for identifying the possible chains of actions that lead to an overall risk event. Figure 5-2 is an example of fault tree analysis used to determine why a tunneling project could fall behind schedule and go over budget.

Figure 5-2 Fault Tree Analysis of Tunneling Delay



The potential problem "dissected" in the figure is tunnel schedule delay. The significant risk events contributing to delay are the highlighted boxes. Causes of the risk events are traced backwards, with a more detailed example provided for the risk event carried back to cause "C" (community complaints → reduced tunneling hours → poor tunneling productivity). The level of detail in the breakdown of risk events is discretionary. Events ought to be described to the point where it is possible to understand what events contribute to the potential problem and their root, potentially mitigable, causes.

5.1.3 Risk Drivers

As project sponsors and the risk analysis team proceed through this process of evaluating risk events and their causes, it is important to look for common factors that contribute to the various risks included in the project risk register. For example, design errors or deficiencies were suggested as a potential cause of structural collapse. Design errors or deficiencies may be possible reasons for other risk events occurring on a project. Such common threads, or causes, are referred to as risk drivers.

Correctly identifying risk drivers will greatly assist in the establishment of risk mitigation strategies. It may be possible to eliminate or greatly reduce the potential severity of certain risks by focusing attention on key risk drivers. Suggested approaches for establishing risks drivers include fault tree analysis and regression analysis (both providing approaches for identifying the significant factors that contribute to risk events).

5.2 Establishing Risk Mitigations

Historically, in transit projects at least, project owners have attempted to mitigate risks through engineering decisions and to some extent through contracting arrangements. But, as has been discussed, many risks are not well understood or well quantified, and often risk mitigation has essentially amounted to a combination of general design allowances and contingency provisions. A systematic identification of risks and causes allows the project owner to develop more targeted and cost-effective risk mitigation strategies.

Several courses of action are available for addressing identified risks:[8]

1. Eliminating the risk, for example through design changes or policy actions or by prohibiting the "action, process or materials" causing the risk
2. Reducing the potential severity of the risk by similar actions
3. Transferring all or part of the risk to other parties
4. Accepting the risk, possibly without further action or perhaps with the purchase of insurance to offset the financial liability posed by the risk.

Just as there are various ways to perform risk assessment, there are various ways to establish risk mitigation strategies. For planning, design and construction risks that have

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[8] Adapted from R. Wideman, Project and Program Risk Management, Project Management Institute, Drexel Hill, PA, 1992, as referenced in *Risk Assessment in Fixed Guideway Transit System Construction*, U.S. Department of Transportation, Publication No. DOT-T-95-01, January 1994.

been determined to be within the influence of the project owner, the recommended approach is the same as for risk assessment: follow a collaborative process wherein the risk analysis team of experts, including the owner, identifies and quantifies appropriate risk mitigation measures. The workshop is an effective way to carry out (or at least review) the causes of risk events. What is clear in the facilitated workshop or any other approach used for risk mitigation planning is that the project owner must have the primary role in developing mitigation measures. It is the owner who must implement adopted measures.

The collaborative process may not be suited to establishing mitigation strategies for certain risks, in particular significant risks with public policy or legal ramifications. In the previous list of actions available to a project owner, items 3 (risk transfer) and 4 (risk acceptance) will often involve executive management decisions or the considerations of legal counsel. Policy actions to eliminate risks, included under item 1, also could require management decisions. The expert panel is probably not the proper entity to determine what policy actions should be taken or what financial or other liabilities should be assumed by the owner. These decisions are best left to executive management and policy boards. The expert panel can support the decision-making process by providing useful technical information.

5.2.1 Risk Mitigation Register

A reasonable approach for documenting risk mitigation strategies and their estimated impacts is to develop a risk mitigation register. The format is similar to the risk register described earlier in Section 4.3.2 and shown in Table 4-2. The mitigation register will only contain risks that can be mitigated. As explained earlier, first the risks are ranked in terms of their impact on the total project cost. The expert panel then should go through the ranked list of risks and try to formulate mitigation strategies.

Table 5-1 gives an example of the outcome of one such mitigation effort for the hypothetical eight-component light rail project of Table 4-2. Three risks that can be mitigated are listed in the order of their effect on project cost and schedule. For each risk, a number of procedures for mitigation are identified and listed along with an assessment of the magnitude of cost and duration savings if such approaches are successful. For each risk, the probability of success for the recommended measures has been estimated and reported.

As an example, consider Risk 4, Right-of-Way Cost and Availability. It is estimated that successful implementation of the proposed risk mitigations in column four would achieve an expected cost reduction of $6 million and an expected duration reduction of three months. The probability of successfully implementing the “mitigation plan” (estimated subjectively or based on historical data by the expert panel) for this risk item is estimated as 75 percent. So there is a 25 percent probability that none of these savings will materialize and the original estimates of cost and schedule impacts will hold. Further, it is understood that the estimates of cost and duration savings are uncertain. Because of this uncertainty, a range is provided for cost and duration savings as shown by the choice of a normal distribution. The expected value of cost savings is therefore 0.75 x $6 million = $4.5 million and the expected value of duration savings is 0.75 x 3 months = 2.3 months.

Table 5-1 Example of Risk Mitigation Evaluation Matrix (For Hypothetical Eight-Component Light Rail Project)

ID	Risk/Opportunity	Estimated Risk Impact (Expected Value)	Proposed Risk Mitigation	Mitigation Benefits				Expected Value of Mitigation		Cost to Implement
				Cost		Duration				
				Prob.[1]	Impact[2]	Prob.[1]	Impact[2]	Cost	Duration	
Risk 1.	**Permitting and Inter-agency Agreements (IAAs)** *(Unexpected Delays)*	Component A: $2.2 m; 7 mos. Component D: $21.6 m; 4 mos.	• Identify required IAAs early in final design; negotiate terms with affected agencies prior to 60% milestone' • Establish umbrella (i.e., program level) agreement that all agencies sign; prepare more detailed, agency-specific addenda to cover special details. • Establish one-stop permit process (e.g., with cities, county) and single points of contact. • Assign permit responsibility to contractor when practicable, making permits the contractor's rather than the grantee's schedule critical item.	95%	Discrete Component A: 75%, -$0.5 m 25%; -$1.0 m Component D: 50%, -$2.0 m 30%, -$3.0 m 20%, -$4.0 m	95%	Discrete Component A: 50%, -2 mos. 25%, -3 mos. 25%; -4 mos. Component D: 60%, -1 mos. 40%, -2 mos.	Component A: -$0.6 m Component D: -$2.6 m	Component A: -2.8 mos. Component D: -1.4 mos.	$0.1 m
Risk 4.	**Right-of-Way (ROW) Cost and Availability** *(Increased Costs; Acquisition Schedule Extended)*	Component D: $30.0 m; 6 mos.	• Update ROW costs early in final design; verify acquisitions list. • Draw upon experience and resources of other public agencies (e.g., DOTs) that frequently process property acquisitions; negotiate IAA for managerial/technical assistance. • Contract with property acquisition consultant to assist with appraisals and acquisitions. •Stage construction to allow adequate time to secure ROW; early construction where ROW is not required or easily secured; later construction where ROW is extensive.	90%	Lognormal	90%	Lognormal	-$5.0 m	-2.0 mos.	$0.5 m
Risk 8.	**Systems Equipment Integration** *(Installation and Test Problems; Delay to Revenue Operations Date)*	Component H: $10.0 m; 6 mos.	• Prepare systems integration plan early in design. • Designate key engineer with responsibility for ensuring systems requirements are incorporated in facilities designs. • Establish schedule for early award of critical path systems contracts; begin software and complex equipment development early; strengthen factory test requirements. • Establish coordination mechanism to ensure contractors developing new control systems work with equipment suppliers and with firms responsible for installation of existing systems that must be integrated into the project. • Schedule frequent vendor design and performance test reviews.	100%	Triangular	100%	Triangular	-$1.5 m	-4.0 mos.	$0.1 m

5.2.2 Technical Considerations and Objectives for Risk Mitigation

5.2.2.1 Mitigation Benefits versus Costs

The cost of mitigation is an important consideration. The project owner, with the assistance of the expert panel, must estimate the costs of implementing mitigation. In the last column of Table 5-1, these costs have been estimated for each of the three risk mitigation strategies. Mitigation of Risk 4, Right-of-Way Cost and Availability, for example, is estimated to cost $0.5 million in the form of consultant costs, other contracted assistance, and additional owner administrative expenses.

Benefits of mitigation are compared to the costs of mitigation in a benefit-cost ratio. The ratio must exceed 1.0 for the benefits of a mitigation measure to outweigh its costs. What is an acceptable benefit-cost ratio is largely a project management decision. For convenience, the comparison can be made using the expected value of mitigation benefits and the estimated mitigation costs. In the right-of-way example, the benefit-cost ratio is 9:1 for risk cost savings, or very favorable.

To determine the change in total project cost or total duration resulting from risk mitigation, the probabilistic cost and schedule model is rerun. The net change in probable project cost or duration can be compared to the cost of the mitigation.

On the cost side, this is a simple comparison of cost savings from mitigation to costs incurred in implementing the mitigation measures. With respect to schedule impacts, only duration savings on the critical path are going to affect the total project duration. Furthermore, the net change in project duration needs to be expressed in the same form as are the resources required to implement the mitigation. It is best to convert changes in the project schedule to costs. This can be done simply by looking at the change in escalated YOE costs that is produced by reducing the project's schedule risk. This generates the dollar value of changes in project duration, which can then be compared to the costs of implementing schedule risk mitigation measures.

5.2.2.2 Other Considerations

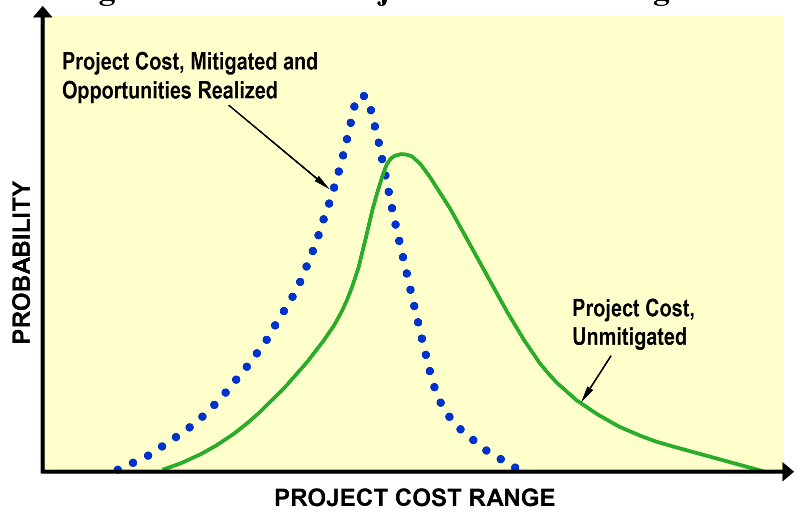
Other factors to consider in developing risk mitigation measures include.

- Implementation time and feasibility
- Implementation risks
- Responsible parties
- Capabilities of implementing parties
- Possible unintended consequences (e.g., additional costs such as claims, changes in project critical path, third party effects).

The time required to implement mitigation is also important. To delay a project in order to develop mitigation may indirectly generate costs and other complications that offset the expected direct benefits of mitigation.

Risk mitigation is intended to reduce the upside variation in project cost. Figure 5-3 shows the effect of mitigation on costs. The solid curve represents the probable range in total project costs absent any mitigation of risk. The dotted curve represents the effect of reducing the high-end impacts of major risks to the project. As argued, mitigation itself will likely have costs, and this could even result in a slightly higher most probable project cost (the cost with the highest probability) than in the unmitigated case. However, the project cost range associated with risks is reduced substantially. As a result, there is a high level of confidence the total project cost at completion will be lower than if no risk mitigation was implemented.

Figure 5-3 Total Project Cost with Mitigation



The preferred position for the project owner upon completing risk analysis is represented by the dotted curve. Comprehensive risk mitigation has both reduced the total cost variance and lowered the most probable project cost by eliminating certain risks perhaps, by more effective mitigation of risks, and by taking advantage of more opportunities to reduce project costs. Highest priority risk mitigation measures should therefore be those that (1) address unacceptable risks and (2) generate the greatest reduction in project risk costs, which lead to significantly lower total project costs relative to the cost of mitigation itself.

5.2.3 Parties Responsible for Mitigation Measures

High priority mitigation measures must be implementable. A major consideration for implementation is who is to be the responsible party. The project owner should identify which entities are to carry out mitigation measures as they are established. The responsible party might be the owner (e.g., for mitigation requiring administrative actions), the designer (e.g., for design changes), the contractor (who must follow contract specifications on materials, methods, quality control), or another entity. The ability of the responsible party to implement the recommended mitigation is an assessment to be made before assigning responsibility.

5.3 Risk Allocation

The assignment of responsibilities for risk mitigation implementation is part of the process of risk allocation. Risk allocation is simply that: allocating risks to the various parties involved in the development of a major project. The allocation may be based on who is responsible for creating the risk or who is deemed best able to manage the risk or some combination thereof. Risk allocation is almost always the prerogative of the project owner since ultimately the owner will bear the burden of risk consequences. In most circumstances, there is considerable benefit to the owner from allocating risks.

Considerable information about the principles and practice of risk allocation is available in published literature from academic researchers, the construction industry, and other organizations (see "Risk Assessment in Fixed Guideway Transit System Construction*,"* January 1994, for example). For this reason, the discussion here is limited. It is noteworthy that available information deals mainly with risk allocation between project owners and contractors. This is understandable since it is often construction risks that receive the most attention in traditional risk analysis. However, risk allocation during other phases of a project is also of interest.

The broad principles of risk allocation hold at all phases of project development. These include the following (paraphrased from "Risk Assessment in Fixed Guideway …," 1994):

- Allocate risk to the party in the best position to control it.
- Consider the consequences to the receiving party.
- Consider whether the cost incurred or charged by the receiving party is acceptable.
- Evaluate the potential for new risks being transferred back to the project owner.

As a project enters construction, the project procurement method, contract type, and construction documents are important mechanisms for allocating risk. Certain procurement methods, such as design-build, are explicitly designed to transfer additional risk, both design and construction, to the contractor. The CMGC procurement method assigns subcontracting and overall construction management responsibilities to the contractor. In the traditional design-bid-build approach, the project owner is responsible for completing the design and contract administration of possibly multiple contractors. The amount of risk the owner assumes during the construction period depends upon the structure of the contract documents. Just as with other procurement methods, the owner can attempt to have the contractor bear all or most construction risks. Risk allocation and risk management in contract relationships are discussed in the literature.

Important information to convey to contractors who are expected to assume major project risks includes the following (see "Guidelines for Tunneling Risk Management," International Tunnel Association Working Group No. 2, March 2003):

- Project owner risk management objectives, general and specific to the project
- General description of perceived project risks
- Project owner's strategy for risk management, including the owner's risk policy and risk acceptance criteria, and proposed risk management activities
- Project owner's role in risk management during construction and a process for dealing with risk issues.

Information provided by bidders in response to owner proposals for risk allocation can be used to evaluate bids and possibly as part of contract negotiations.

5.4 Implementation and Monitoring

When risk mitigations are established and assigned to responsible parties, project owner management must give final approval to implement the recommended measures and to fund any costs. The overall risk mitigation strategy may need final modifications but is then implemented through the variously cited mechanisms, such as design changes, construction contracting, and construction changes. Approvals and decisions on the implementation process should be initiated as early as possible to minimize the cost of implementation, which is likely to increase as the project advances.

The project owner should monitor the implementation process and the performance—the actual costs and consequences—of instituted mitigations. Reevaluation of risk mitigation strategies may be warranted or previously unanticipated risks may arise during construction. A process should be in place for reconvening the risk analysis process, on a limited scale perhaps, to systematically address these new conditions.

5.5 Risk Management Plan

A risk management plan pulls together information from the risk assessment and mitigation planning processes. It should include information from the risk register (the diagnosis of potential problems) and the risk mitigation register (the proposed remedies). It also identifies the risk implementation and risk allocation strategies. The plan would normally be completed in advance of obtaining final management approval of the risk mitigation program and the beginning of construction. The plan describes the program for which management approval is sought. At minimum the plan should include the following (see “Guidelines for Tunneling Risk Management”):

- Objectives of the risk management plan
- Prioritized listing and description of risks targeted for mitigation
- Technical and other requirements to mitigate risks (assessment of risk management competence)
- Risk mitigation measures, their costs and benefits
- Description of risk management responsibilities, project owner versus contractor versus others
- Description of actions to be implemented by each responsible party
- Monitoring program and process for follow-up or additional corrective actions. The program should also ensure information is obtained to evaluate the actual benefits of implemented mitigation.
- Implementation schedule; overall time and cost impact of the risk mitigation plan.

The risk management plan should be finalized upon management approval. It is recommended to become part of the project management plan, the guiding management document for project implementation. The risk management plan would also be part of risk analysis documentation for the project. FTA guidance calls for preparation of a report that describes the six steps of the risk analysis process, including findings and recommendations.

In the event of significant changes in risk circumstances as project implementation proceeds, including through the construction phase, the risk management plan should be updated to become an accurate, current record. Monitoring of performance of implemented risk mitigations is key to determining the ultimate benefits of risk analysis. This is the responsibility of the project owner. Mitigations may be incorporated into all phases of project development—planning, design, or construction. All relevant design submittals, for instance 30/60/90 percent drawings and construction bid documents, should be reviewed to ensure that proposed design mitigations become part of the basic project configuration. Mitigations that are to be implemented during construction can be monitored as part of an ongoing construction management program.

Incorporating lessons learned into the final risk management plan is useful. The plan will then become a valuable resource for the owner's next project.

5.6 Summary and Recommendations

Section 5 describes the risk management aspect of risk analysis. Risk management includes mitigation planning, implementation, and monitoring. Its success depends upon having completed a sound systematic risk assessment.

Whatever approach is used to carry out risk management, the project owner must be substantially involved. The product of risk management is a risk management plan, the implementation program for mitigating significant risks to successful project implementation. The plan is the project owner's document; the owner must fund and implement it. Ultimately, the owner bears most risks.

Risk management involves determining which risks are unacceptable or severe and can be mitigated cost-effectively. It includes allocating risks to responsible parties and implementing risk mitigation through various strategies, including procurement methods and contract documents. The process will be easier to carry out, and probably more successful, if the project owner has in place a risk policy, which sets out policies and objectives for risk management on construction projects. The policy should be supported by specific risk acceptance criteria. The criteria will assist owner staff and others involved in the risk mitigation planning in identifying what risks and what levels of risk are acceptable.

Monitoring of risk mitigation measures following their implementation is important. Successful mitigation reduces or eliminates risks at a reasonable cost.

5.7 List of Products/Deliverables

Important products from the risk management portion of risk analysis include the following:

- List of *significant risks subject to mitigation*, prioritized based upon contribution to changes in total project cost and/or duration; risk acceptance criteria.
- *Risk mitigation register*, identifying risk mitigation strategies for high priority risks, the estimated reductions in risk costs and/or durations if successfully implemented; the likelihood of success for the proposed mitigation measures; estimated implementation costs.
- *Benefit-cost assessment* of each mitigation strategy.
- *Risk management plan*, to be part of the project management plan and which summarizes findings from the risk assessment and risk mitigation tasks; risk allocation plans; mitigation monitoring program; responsible entities; and, at project completion, lessons learned.

6. Conclusions

Risk analysis is a valuable means of obtaining information that will help a project owner more effectively manage a project's scope, cost, and schedule as it advances through concept planning, design, and construction. Risk analysis involves the systematic evaluation of risks and opportunities facing a project—events that could adversely or beneficially affect a project's chances of success.

Risk analysis includes an assessment component and a management component. Assessment is critical to correctly identifying risks and quantifying their potential impacts on the scope and schedule. Management involves the planning and implementation of a program to mitigate significant adverse risks (and to realize promising opportunities). An effective risk management plan can only be established after all major risks and their potential impacts have been properly determined.

The critical steps of this process include

- *Comprehensive, objective review of the base project scope, cost, and schedule to validate their reasonableness.* An independent review is recommended for objectivity, but the project owner must still be an active participant in this and all other steps of risk analysis. The review should begin in advance of risk identification and quantification. It lays the necessary foundation; risk impacts are measured against and added to the base cost and schedule.
- *Detailed identification of all significant risks to a project and quantification of individual risks' events in terms of both potential cost and potential schedule impacts.* In addition to drawing on experience from other similar projects, a panel of industry experts is recommended as a means of developing information on risks.
- *Assessment of risk impacts on the project cost and schedule.* Various approaches are available for assessing impacts. Probabilistic methods are recommended for estimating both individual risk impacts and project impacts. They allow statistically valid characterization of costs and schedule impacts. Project sponsors can ascertain with greater confidence what cost and schedule allowances should be made to ensure that a project is completed within budget and on time. Risk quantification and assessment should be carried to as much detail as practicable. Without knowing the impacts of individual risks, it is not possible to prioritize risks for mitigation.
- *Preparation of a program to mitigate risks, which would include implementation and monitoring of mitigation measures and periodic reassessment of a project for new risks.* While other steps of risk mitigation can be carried out with the considerable assistance of others, risk management is primarily a project owner effort. The risk management plan, the ultimate objective of risk analysis, is the owner's action plan.

Risk analysis in public transit has been most often applied to projects well along in design. One purpose has been to assist funding agencies in determining whether the project has an adequate budget for construction. Risk analysis offers benefits if performed during other phases of project development, including during conceptual design or even construction should problems become apparent. The approach used to assess risk impacts and the level of analysis will likely differ depending on the objectives for risk analysis and information available. The basic steps of risk analysis will not change, however, with project size or phase. The process is recommended as an alternative to traditional methods of evaluating project feasibility with respect to scope, cost, and schedule. A major side benefit of risk analysis is its value as a communications tool that allows project sponsors to think about the ways the project could experience cost overruns or delays. Risk analysis encourages project sponsors to constantly identify preventive actions against potential risks and be proactive in realizing project opportunities.

REFERENCES AND RESOURCES ON RISK

The following list consists of resources for further reading in risk analysis and sources of transit cost data. More specific references are also provided in Appendix C as part of the examples of risk cost and schedule impact assessment.

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Appendix A

Glossary of Terms

GLOSSARY OF TERMS

Alternative analysis: one of the preliminary phases in project development where alternative solutions to the transit problem are evaluated and compared.

Budget allowances: budget allowance for items certain to be included in the project but not quantified at the time of the estimate; the allowance represents part of the base.

Base cost: the cost excluding add-on contingencies to cover unknowns (or risks).

Base Schedule: project schedule with all contingencies removed.

Baseline Cost Estimate (BCE): capital cost estimate organized into basic categories, such as proposed contract units (e.g., civil works, structures, vehicles, materials/supplies, systems equipment, etc.) and major project components (e.g., right-of-way, engineering, administration, finance costs, etc.); the BCE becomes part of the FFGA.

Conceptual planning: one of the early phases of project development.

Constructability: the concept of designing with the intention of facilitating the construction; design in such a way that the project is more efficient to build and maintain.

Construction manager/general contractor (CM/GC): similar to CM-at-risk, where the CM acts as GC and is responsible for budget and schedule.

Contingency budget: a reserve budget designated to cope with project cost or schedule uncertainties.

Continuous distribution: a statistical distribution for a random variable (*e.g.,* cost item or activity duration) represented with a continuous mathematical function.

Contract unit (CU): major transit projects usually consist of several contract units such as systems contract, facilities contract, *etc.*

Correlation: an indication of linear relationship between two random variables (*e.g.*, costs or durations) such that a change in one variable can give an indication of change in the correlated variable.

Critical path method (CPM): the network-based scheduling technique used for project scheduling, where the project is divided into several activities and precedence relationships between activities are portrayed.

Cumulative distribution function (CDF): a mathematical function that expresses the probability of a random variable being less than or equal to (i.e., not exceeding) any particular value, either continuous or discrete. This function is the cumulative curve for the *probability density function* or *probability mass function*.

GLOSSARY OF TERMS, CONTINUED

Design-build (DB): a project delivery system where a single party is responsible for both design and construction of the project.

Design-build-operate-maintain (DBOM): a project delivery system where a single party is responsible for designing, building, operating and maintaining a project for a specified duration.

Decomposed estimates: when project is broken down (decomposed) into several components and the cost of each component is separately estimated and summed up to arrive at the total cost estimate.

Deterministic estimate: estimate of project cost or schedule where uncertainties are not modeled as random variables; non-probabilistic estimate.

Discrete distribution: a statistical distribution for a random variable (*e.g.,* cost item or activity duration) represented with a discrete mathematical function.

Event tree: a graphical representation of probabilistic events.

Expected value: the average value of a random variable; the mean value of the variable.

External risks: risks not under direct control of the project owner, such as variations in exchange risk.

Fault tree: a graphical representation of causes of a failure (usually of a probabilistic nature); a reliability assessment tool.

Final design: also known as detailed design, the design phase usually following *preliminary engineering* and leading to a complete set of contract documents and specifications.

Full funding grant agreement (FFGA): the agreement that describes and sets the limit of the FTA's commitment to project funding.

Internal risks: risks that are largely under the control or influence of the project owner such as risks in the planning, engineering, construction, and management of projects.

Integrated cost and schedule estimates: an approach in project cost assessment where the effect of activity durations on cost (or *vice versa*) is considered explicitly.

Locally preferred alternative (LPA): the alternative chosen from among competing alternatives based on some kind of benefit/cost analysis.

Metropolitan planning organization (MPO): regional organization composed of local elected officials and state agency representatives to review and approve transportation investments in metropolitan areas. Concept created by federal law.

Mean: see *expected value.*

Median: the 50th percentile value. The value of random variable which can be exceeded with a probability of 50 percent.

Monte Carlo (MC) simulation methods: a probabilistic simulation approach where distributions of random variables are sampled several times using a computer. As the number of simulated samples increase, the result approaches theoretical distribution of the objective function (*e.g.* total project cost).

National Environmental Policy Act (NEPA): describes the requirements for assessing and reporting environmental impacts.

Project component unit (PCU): a subdivision of the *contract unit.* Breaking up each contract unit (CU) into a number of PCUs allows the risk assessment team to identify various risks and opportunities affecting CUs in a more accurate manner.

Probability density function (PDF): the PDF gives the range of possible values for a continuous random variable. It expresses the relative likelihood of any particular value of an infinite set of possible values being true.

Preliminary engineering (PE): a design phase, usually following the conceptual design, that brings the design effort (in transit projects) to about 30 percent level. At this level, some project owners opt to go with a design-build approach. The completion of this phase of design usually coincides with the conclusion of an environmental document.

Probability mass function (PMF): the PMF gives the range of possible values for a discrete random variable. It expresses the probability of any particular value of a finite set of possible values being true.

Project Management Plan (PMP): The guiding management document that describes how a project will be implemented by the owner.

Pareto's Law: the law of significant few; the realization that most of the project costs/risks can be explained with the variation of a relatively few significant items.

Project Evaluation and Review Technique (PERT): a network-based scheduling technique that models activity durations as random variables; a probabilistic scheduling technique where dependencies between activities are explicitly considered.

GLOSSARY OF TERMS, CONTINUED

Project network: the project schedule showing activities and their precedence relationships, usually in a CPM schedule.

Random variable: a random variable is obtained by assigning a numerical value to a probabilistic *event*. Any cost or schedule item that is modeled as a probabilistic function would be a random variable.

Risk allocation: the process of assigning project risks to various responsible parties, usually through contract documents.

Risk analysis: in the context of this report, the systematic evaluation of uncertainty about the scope, cost, and duration of a project.

Risk assessment: the process of *identifying* project risks and *quantifying* risk impacts.

Risk causation: identifying root causes of risks; for the purpose of this report, evaluation of root causes is assumed to be part of risk management.

Risk checklist: a listing of various risks that can potentially affect a project. The list can be used as a check in a risk assessment process to make sure no major *risk event* has been overlooked.

Risk event: a risk item that can potentially affect project cost or schedule. The term *event* carries a probabilistic connotation.

Risk Management Plan: one of the main outcomes of the risk management process that delineates actions to be taken for mitigating project risk impacts.

Risk mitigation or management: in the context of this report, these are interchangeable terms that describe the process of studying identified risks and trying to mitigate their negative effect on project budget and schedule.

Risk prioritization: the process of ranking project risks according to their effect on project budget and schedule, usually by considering each risk event's contribution to the total variance of risks.

Risk register: the listing of a specific project's risks identified during *risk assessment.*

Risk workshop: a one or two-day workshop for *assessment* or *mitigation* that studies project risks; an important step in the *risk analysis* process.

Single-value estimate: see *deterministic estimate.*

Year of expenditure (YOE) dollars: project cost expressed as the costs in the year(s) that expenditures are planned; explicit consideration of escalation.

Appendix B

Risk Checklist

RISK CHECKLIST

Project Feasibility
☐ Technical feasibility
☐ Long-term viability
☐ Political circumstances

Funding
☐ Sources of funding
☐ Inflation and growth rates
☐ Accuracy of cost and contingency analysis
☐ Cash flow
☐ Exchange rates
☐ Appropriation

Planning
☐ Scope
☐ Complexity of the project
☐ Technical Constraints
☐ Sole source material or service providers
☐ Constructability
☐ Milestones (schedule)
☐ Tune to complete (schedule)
☐ Synchronization of work and payment schedules

Engineering
☐ Design and performance Standards
☐ Unreliable data
☐ Complexity
☐ Completeness of design
☐ Accountability for design
☐ System integration

Type of Contract
☐ Lump sum
☐ Unit price
☐ Cost Plus
☐ Guaranteed Maximum

Contracting Arrangement
☐ Design-build
☐ Joint venture
☐ Single prime contractors
☐ Several prime contractors
☐ Innovative procurement methods
☐ Design-build-operate-transfer
☐ Design-build-operate-maintain
☐ Construction manager
☐ Owner-managed
☐ CM at-risk (CMGC)

Regional and Local Business Conditions
☐ Number of bidders
☐ Unemployment rate in construction trades
☐ Workload of regional contractors

Contractor Reliability
☐ Capability
☐ Capacity
☐ Credit Worthiness
☐ Personnel experience

RISK CHECKLIST, CONT.

Owner Involvement
- ☐ Management of project
- ☐ Supplying of material
- ☐ Testing and inspection
- ☐ Safety programs
- ☐ Communications and problem solving
- ☐ Partnering
- ☐ Start-up operations

Regulatory Conditions
- ☐ Licenses, permits, approvals
- ☐ Environmental regulations and requirements
- ☐ Patent infringement
- ☐ Taxes and duties

Acts of God
- ☐ Storm
- ☐ Earthquake
- ☐ Flood
- ☐ Fire
- ☐ Impact of site location on any of the above

Site
- ☐ Access/ egress
- ☐ Congestion
- ☐ Underground conditions
  - ☐ Soil Conditions (rock vs soil, etc.)
  - ☐ Water
  - ☐ Utilities (existing and new)
  - ☐ Archaeological finds
  - ☐ Hazardous wastes
- ☐ Noise, fume, dust
- ☐ Abutting structures/operations
- ☐ Security
- ☐ Disruption to public
- ☐ Hazards – safety and health
- ☐ Location and adequacy of construction support facilities
- ☐ Availability of utilities
- ☐ Topography / drainage / trafficability

Labor
- ☐ Productivity
- ☐ Strikes
- ☐ Minority representation
- ☐ Sabotage
- ☐ Availability
- ☐ Work Ethic / and productivity standards
- ☐ Wage scales
- ☐ Substance abuse
- ☐ Local rules
- ☐ Unions
- ☐ Material wastes
- ☐ Worker's compensation
- ☐ Skill levels
- ☐ Potential for adverse activity

RISK CHECKLIST, CONT.

Loss or Damages
☐ Owner’s responsibility
☐ Contractor’s responsibility
☐ Engineer’s responsibility
☐ Vandalism, sabotages
☐ Accidents
☐ Third Party Claims
☐ Owner Claims

Guarantees
☐ Schedule
☐ Performance
☐ Consequential losses
☐ Liquidated damages

Project Size
☐ Physical area
☐ Population – total and individual craft

Unfavorable Contract Clauses
☐ Differing site conditions
☐ Hold-harmless
☐ No damage for delay
☐ No relief for *force majeure* losses
☐ Not responsible for quantity variations

Area Factors
☐ Geography / geology / altitude
☐ Area economic conditions
☐ Government stability & sophistication
☐ Police, fire and medical support
☐ Local population attitude and stability
☐ Transportation network
☐ Communications
☐ Other support infrastructure (housing, etc.)

Weather
☐ Normal weather patterns
☐ Potential for extremes

Monetary
☐ Bidding cost vs. potential for award
☐ Escalation
☐ Exchange rates
☐ Area cost indices
☐ Payment floats
☐ Retention
☐ Unbudgeted premium time
☐ Overhead costs
☐ Regulatory penalties (OSHA, EPA, etc.)
☐ Bonuses & shared savings

RISK CHECKLIST, CONT.

Ability to Perform
☐ Familiarity with type work
☐ Availability and qualifications of key personnel
☐ Knowledge of area
☐ Completeness of design
☐ Quality of design
☐ Timeliness of design
☐ Complexity, constructability of design
☐ Requirements for new technology
☐ Competing activity on site
☐ Availability of access to work when required
☐ Need for work or fire permits

Time Factors
☐ Deadlines and milestones
☐ Available normal works days
☐ Potential for stoppages by other parties or situations

Owner Factors
☐ Financial stability
☐ Construction management sophistication
☐ Interferences
☐ Quality expectations
☐ Interpretation of contract
☐ Ability/willingness to meet obligations
☐ Change management policies

Contractor-Furnished Materials Factors
☐ Quantity variations
☐ Quality
☐ Price
☐ Availability
☐ Delivery uncertainties
☐ Contract-imposed procurement limitations
☐ Potential for waste in use
☐ Potential for loss (theft, vandalism, damage)

Construction Equipment Factors
☐ Availability
☐ Cost
☐ Loss or damage

Subcontractor/Vendor Factors
☐ Technical qualifications
☐ Financial stability
☐ Timeliness/reliability
☐ Bondability
☐ Minority, women, disadvantaged business and small business enterprise requirements

Care and Custody Exposure
☐ Constructed facilities
☐ Storage of materials/equipment furnished by others

Appendix C

Risk Assessment Examples

APPENDIX C1
NON-SIMULATION APPROACH FOR COST RISK ANALYSIS

INTRODUCTION

A non-computer approach is presented to compute the cumulative density function (CDF) of the total project cost. Generally, the Monte Carlo simulation is conducted to compute the CDF of the total cost. In the Monte Carlo approach, every cost item with a high potential for variability is modeled as a random variable. A computer program is used to generate random numbers according to specified statistical distributions, the generated random numbers and the fixed cost figures (those cost items believed to be estimated fairly accurately and not expected to show large variations) are added up, and a value for the total cost is computed. This procedure is computed many times and a cumulative distribution is obtained for the total project cost. This cumulative distribution is then used to compute the probability of completing the project at or below various costs and to estimate contingency sums. A slight modification of this approach is suggested by Curran (1989) and named "range estimating" where the user has to input the range of every random variable and then the computer performs a Monte Carlo simulation.

If the total project cost can be modeled as a summation of several cost components, then one can use the central limit theorem (CLT) to compute the total project cost probabilistically. According to CLT, the sum of n independent random variables is a random variable with a distribution that approaches a normal distribution as n becomes large. The mean of the sum will be the sum of the means of the independent random variables and the variance of the sum is the sum of the variances of the random variables. So the distribution of the sum can be completely specified even without having knowledge of the distributions of individual components. The PERT approach, a probabilistic scheduling approach developed in the late 1950s, uses CLT to develop the CDF of the total project duration (refer to Appendix C3).

RANGE ESTIMATES

We suggest that the method of three cost estimates, similar to the one suggested by PERT, be used for the proposed cost or risk factor. The user shall specify a lower bound (a), an upper bound (b), and a most likely value (m) for cost.

UNDERLYING STATISTICAL DISTRIBUTION

Some work has been done in the past to evaluate various statistical distributions for modeling construction costs (Spooner, 1974). Triangular, beta, normal, lognormal, and uniform distributions have been suggested by various authors.

Although there is no consensus on what type of distribution to use under various conditions, it appears that the cost distribution will most likely be a distribution with some skewness, the mean being larger than the mode. It obviously cannot take negative values and understandably should have confined tails. Because of the above concerns, we suggest using a triangular distribution for the risk factors (or the cost items depending on the method of analysis).

Much work has been done in PERT for defining the pessimistic and optimistic time estimates (Moder, et al, 1983; Moder and Rodgers, 1968). For this model, we propose to use 5 percent and 95 percent points for the definition of lower bound and upper bound of the costs. This means that the cost of the project may exceed the upper bound or may be smaller than the lower bound only one time in twenty if the project could be constructed repeatedly under similar conditions. This method is consistent with the method suggested by Moder, et al (1983) for conducting PERT analysis. Estimating 5 and 95 percentile values is always easier for the estimator because it is unlikely that the estimator has experienced an extreme value of the distribution. Use of other skewed distributions such as beta and lognormal could also be considered (Wiser, 1991; Touran and Wiser, 1991).

ESTIMATING DISTRIBUTION PARAMETERS

The next step in the model development process is to estimate parameters of the distribution, i.e., mean and variance, using lower and upper bounds and most likely value (mode) estimated by the cost analyst.

If the estimator can provide the values of *a, b*, and *m*, the mean and variance of the distribution for the cost component can be computed. These values in turn can be used in the application of the CLT in computing the mean and variance of the total project cost that will have an approximately normal distribution.

Mean and Variance for 0 and 100 Percent Estimates (*a* and *b*)

If the 0 and 100 percent points (*a* and *b* in the following equations) are estimated by the cost estimator, then the mean and variance of the cost (risk) factor can be calculated from Equations (1) and (2).

$$E(X) = \frac{a+m+b}{3} \qquad (1)$$

$$Var(X) = \frac{(a^2 + b^2 + m \quad - ab - bm - am)}{18} \qquad (2)$$

Mean and Variance for 5 and 95 Percent Estimates (a5 and b95)

If 5 percent and 95 percent points are estimated as discussed in the earlier section, then one can use Equation (1) for an estimate of mean (which is a good approximation if the distribution is not too skewed). The variance can be estimated from Equation (3)[1].

$$Var(X) = \left(\frac{b_{95} - a_5}{3.2} \right)^2 \qquad (3)$$

---

[1] Moder and Rogers (1968) show that the *$(b_{95}$-$a_5)$* difference varies from 3.1 to 3.3 (average of 3.2) standard deviations for triangular distribution (Moder *et al* 1983, p.283).

TOTAL PROJECT COST

According to CLT, the sum of *n* independent random variables (if *n* is *large;* in practice, *n* can be as small at 10) is a random variable that follows a normal distribution. The mean and variance of the sum can be calculated from Equations (5) and (6):

If $T = X_1 + X_2 + \ldots + X_n$ (4)
$E(T) = E(X_1) + E(X_2) + \ldots + E(X_n)$ (5) and,
$Var(T) = Var(X_1) + Var(X_2) + \ldots + Var(X_n)$ (6)

In the above equations, *T* is the total cost and X is a risk factor or cost item (an element that has been modeled as a random variable). E*(X)* is the mean and *Var(X)* is the variance of the indicated variable.

CORRELATION AMONG VARIABLES

When cost items or risk factors are not independent, then Equation (6) has to be adjusted according to Equation (7):

$$Var(T) = Var(X_1) + Var(X_2) + \ldots + Var(X_n) + 2\sum Cov(X_i, X_j) \quad (7)$$

In Equation (7), $Cov(X_i, X_j)$ is the covariance between X_i and X_j . This value can be calculated from Equation (8):

$$Cov(X_i, X_j) = \rho_{ij}\ \sigma_i\ \sigma_j \quad (8)$$

In Equation (8), ρ_{ij} is the correlation coefficient between X_i and X_j and σ is the standard deviation of the risk or cost factor.

It should be noted that while Equations (5) and (7) hold regardless of independence of risk factors, the assumption of normality under CLT is less accurate in case there are large correlations. Despite this limitation, the use of the method for obtaining insight into the range of cost possibilities is justifiable.

TYPICAL APPLICATION

Consider a hypothetical case where one is interested in the sum of six major cost items, A through F (see the following table). For each cost item, the three estimates are provided and the objective is to develop the range of possible values for the sum of these items. It will be assumed that these items are independent.

1 Cost Items	2 a_5	3 m	4 b_{95}	5 E(X)	6 Var(X)
A	1,000,000	2,000,000	4,000,000	2,333,333	$878.9\text{x}10^9$
B	520,000	780,000	1,200,000	833,333	$45.1\text{x}10^9$
C	1,580,000	2,100,000	2,460,000	2,046,667	$75.6\text{x}10^9$
D	58,000	100,000	150,000	102,667	$0.8\text{x}10^9$
E	8,120,000	8,870,000	9,999,000	8,996,333	$344.8\text{x}10^9$
F	4,100,000	5,200,000	6,800,000	5,366,667	$711.9\text{x}10^9$

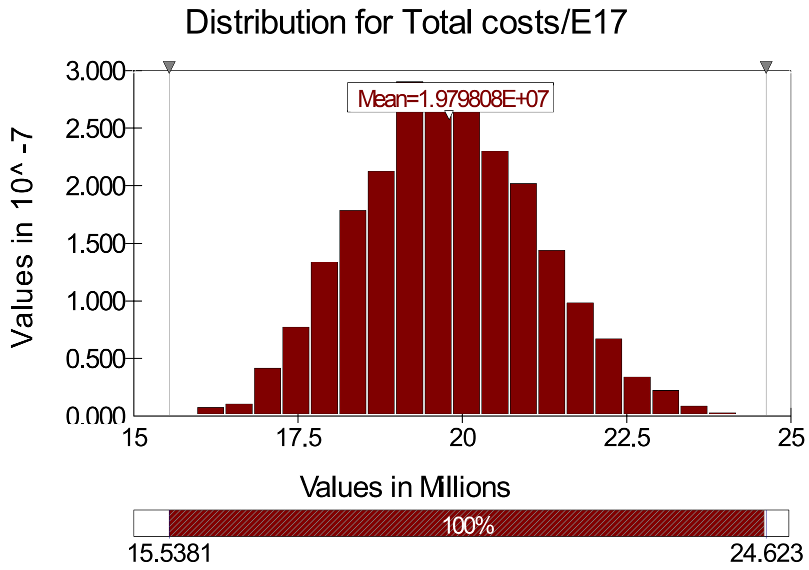
Values in columns 5 and 6 are calculated using Equations (1) and (3). The expected value of the total cost can be calculated from Equation (5) by summing up values in column 5. Variance of total can be calculated from Equation (6) by summing up values in column 6.

$E(T) = \$19{,}679{,}000$
$Var(T) = 2{,}057.1x10^9$

Although there are only six cost items in this example and cost items were clearly skewed (refer to three point estimates for various items), still we assume a normal distribution for the sum and verify this by simulating the whole process.

Simulation

At this point we model the cost items as triangular random variables with assigned 5 percent, mode, and 95 percent estimates and run a simulation experiment where the sum of these six variables is calculated 5,000 times. A histogram of these 5,000 values for the total cost is obtained as shown below. It is clearly very close to a normal distribution.

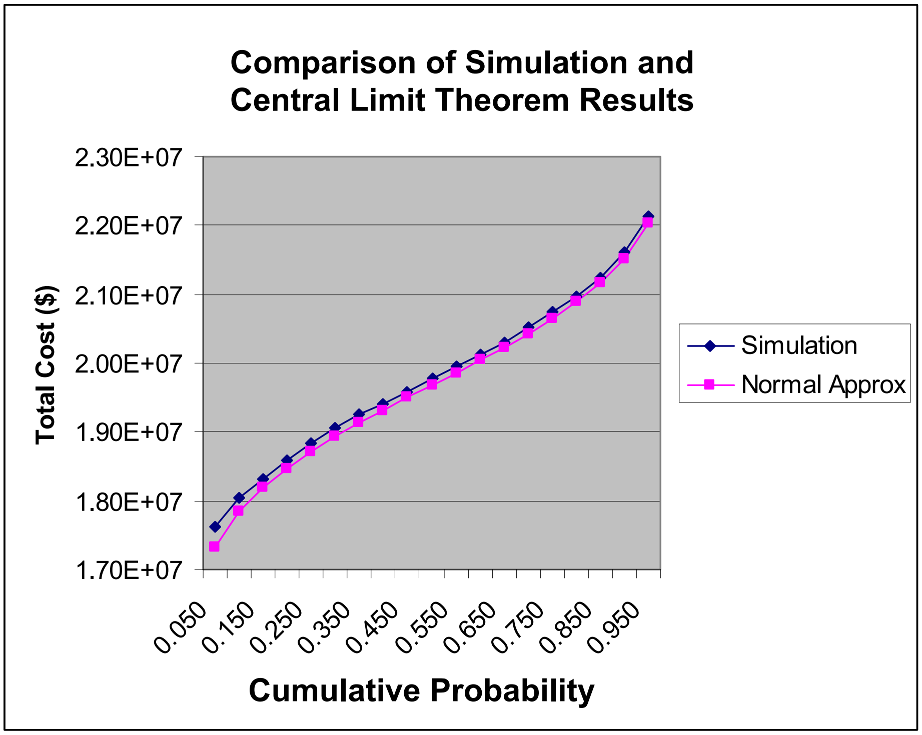


Simulation Results for the Total Cost

To compare the results of the non-simulation experiment with simulation results, we assume a normal distribution for the total costs (after CLT) and, using the normal probability values (either from a statistical table or using Excel spreadsheet), we obtain the coordinates for the CDF of the total cost (column 3 in the following table). We compare these values with values obtained from the simulation experiment (column 2 in the following table). The difference for almost all the points on the CDF is below 1 percent.

1 Cumulative Probability	2 Simulation	3 Normal Approx	4 Delta, %
0.05	1.76E+07	17319786.2	1.66
0.10	1.80E+07	17840869.7	1.06E-02
0.15	1.83E+07	18192443.18	7.28E-03
0.20	1.86E+07	18471862.71	6.61E-03
0.25	1.88E+07	18711579.49	6.32E-03
0.30	1.91E+07	18926852.28	6.77E-03
0.35	1.92E+07	19126334.55	6.29E-03
0.40	1.94E+07	19315623.98	4.15E-03
0.45	1.96E+07	19498764.04	3.94E-03
0.50	1.98E+07	19679000	4.57E-03
0.55	1.99E+07	19859235.96	4.08E-03
0.60	2.01E+07	20042376.02	4.30E-03
0.65	2.03E+07	20231665.45	3.30E-03
0.70	2.05E+07	20431147.72	4.07E-03
0.75	2.07E+07	20646420.51	4.42E-03
0.80	2.10E+07	20886137.29	3.69E-03
0.85	2.12E+07	21165556.82	3.88E-03
0.90	2.16E+07	21517130.3	4.05E-03
0.95	2.21E+07	22038213.8	4.09E-03

The difference between simulation results and results obtained from the proposed method is shown graphically in the figure below. Again, it is clear that the general shape of the two curves (theoretical normal and the simulated CDF) is very similar.



CONCLUSION

A mathematical model is presented to allow the risk analyst to develop a CDF for the total project cost without having to use a computer program or running a simulation model. The methodology proposed is modeled after the PERT method of probabilistic scheduling because of the industry's familiarity with it. This will make understanding of the proposed model more convenient. Cost components or risk factors of the project are assumed to be triangularly distributed because this distribution has several desirable characteristics for modeling cost and is easy to use and understand.

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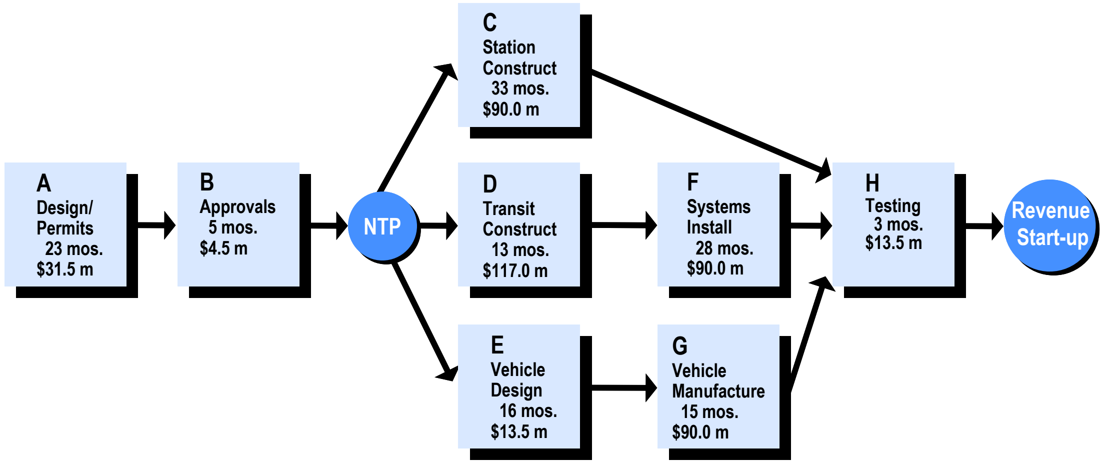
APPENDIX C2
COST RISK ASSESSMENT USING MONTE CARLO SIMULATION

In this Appendix C2, a simple example is presented to help explain the process of cost risk analysis in transit projects. While real-life applications in general are far more detailed, and risk assessment modeling can be done in different ways, this example explains what is involved in a typical cost risk assessment and modeling exercise. We have also a discussion comparing an integrated approach to risk assessment (the case where the effect of delay and cost risks are considered in risk modeling) and a cost only risk assessment. The integrated approach, using the same data, is explained in Appendix C5.

Assume that the schedule of a hypothetical transit project can be represented with a summary network as shown in Figure C2-1. In a real application, for appropriate resolution and efficiency, the network should have anywhere between 20 and 100 activities. In this case, we are using this summary network to show the application of Monte Carlo simulation approach for cost risk assessment. Let us assume that major cost components comprising the projects are the nodes shown in the network. The *base* cost of each component is given on each node. The base cost – that is the cost of component excluding any add-on contingencies –should represent an optimistic estimate of the cost assuming that unfavorable factors will not happen. However, even such an estimate is subject to some uncertainties. Many believe that the detailed project estimate prepared by a competent experienced estimator can be as much as 3 percent off the true cost.

Figure C2-1 Example Project Network: At-grade and Aerial Light Rail Transit
Base Cost [$450 M Current] and Schedule [72 Months]



Risk Factors

A *risk register* has been prepared for this project and is presented in Table 4-2 of the report (and in Table C5-2 of Appendix C5). The base estimate for the project is $450 million (see Figure C2-1). In many cases, some contingency items are built into cost components and the risk assessment team should strive to remove these elements from the base cost. In this example, because we are only concerned with cost risk factors, we have not considered Risk 9 and Risk 10 that depend on schedule delay. We can later estimate the effect of these risks in our comparison analysis.

MONTE CARLO SIMULATION

A Monte Carlo simulation analysis is performed on this project with a few simplifying assumptions. First, it was assumed that base costs are single-value estimates with no variability. We could have easily modeled these base components as random variables in the simulation approach. Second, only a linear model was assumed for calculation of total costs, *i.e.*, total cost is calculated as the sum of base total and the risk factors. In practice, any complex non-linear relationship can be simulated (such as the impact of cost escalation expressed as an exponential function). In this model, the total cost will have two components: a fixed-value component (which is equal to $450 million deterministic base cost) and a probabilistic risk cost (which is the sum of the risk factor cost impacts). The budget can then be compared against the sum of these risk factor costs to decide if there is sufficient contingency.

The simulation model was run for 1,000 iterations using *@Risk Professional*™ *Ver 4.5*. The simulation considered the effect of the first eight risk items in the risk register of Table C5-2. The simulation outcome is given in Figure C2-2. It shows that the mean value of the total cost is $499.6 million. From the table titled "Summary Statistics," one can see that, for example, if the owner or agency in charge desires an 80 percent confidence, then a budget of $533.1 million would be required.

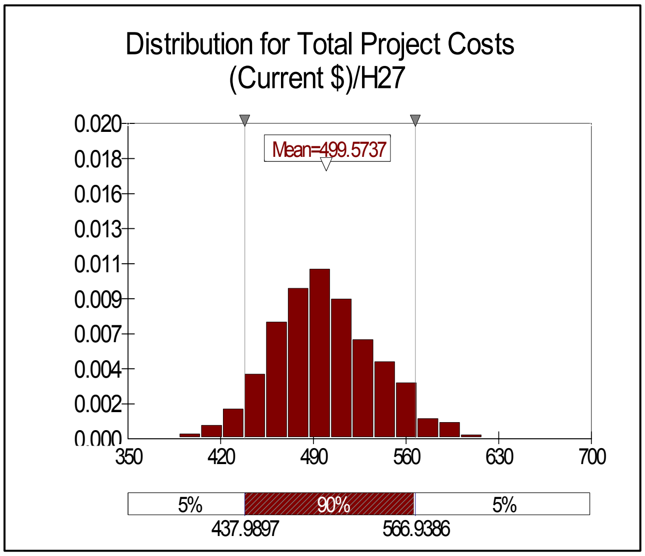
COMPARISON WITH INTEGRATED APPROACH

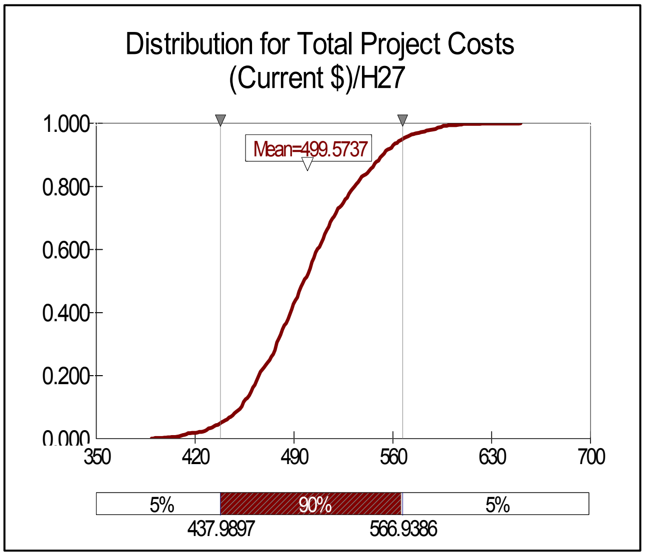
We can now compare the results of this analysis with the results of the integrated cost/schedule approach presented in Appendix C5. The results calculated here are based on *current dollars.* So we will compare the current dollar estimate of the two approaches. In the integrated analysis, the expected cost of the project was estimated as $509 million (Table C5-3). From the same table, one can see that the expected delay was 10 months and there was a 50 percent chance that the project could be delayed beyond 80 months. The expected 10-month delay will have an expected cost of 10 months x $0.5m = $5 million. The expected penalty for delaying beyond 80 months will be 50%x$10m = $5 million. The total delay impact is then $10 million that when added to the results of our analysis ($499.6+10=$509.6 m), shows two very close outcomes. In the cost only approach described in this Appendix C2, the analyst can add the effect of delay after calculating the cost distribution and arrive at a good estimate of the expected value of the total cost. What would be missing is a good estimate of the total variance in this case, so that by not considering the delays explicitly, an underestimation of variance of total cost may occur. The results of an integrated approach and a cost only (or schedule only) approach could also differ because in an integrated approach the analyst can model the correlation that may exist between risk cost and risk delay. For a more detailed discussion of when to use each approach, refer to Section 4 of the report.

Figure C2-2 Simulation Results for Total Project Costs (Current $) / H27

Summary Information	
Number of Simulations	1
Number of Iterations	1000
Number of Inputs	19
Number of Outputs	2
Sampling Type	Latin Hypercube
Simulation Start Time	4/15/2004 15:31
Simulation Stop Time	4/15/2004 15:31
Simulation Duration	00:00:01
Random Seed	32214762

Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	389.06451	5%	437.98972
Maximum	650.56354	10%	452.77863
Mean	499.57367	15%	459.73093
Std Dev	39.551546	20%	465.09479
Variance	1564.3248	25%	472.71896
Skewness	0.2440565	30%	477.55383
Kurtosis	3.0226493	35%	482.17474
Median	497.06882	40%	487.40784
Mode	501.82342	45%	492.47244
Left X	437.98972	50%	497.06882
Left P	5%	55%	501.98801
Right X	566.9386	60%	506.36017
Right P	95%	65%	512.05981
Diff X	128.94888	70%	517.86407
Diff P	90%	75%	525.22809
#Errors	0	80%	533.12024
Filter Min		85%	543.36725
Filter Max		90%	552.69128
#Filtered	0	95%	566.9386





APPENDIX C3
NON-SIMULATION APPROACH TO PROBABILISTIC SCHEDULING

Probably the earliest example of a probabilistic approach to scheduling was the introduction of *Program Evaluation and Review Technique (PERT)* in the late 1950s. PERT was developed to help manage the Polaris Missile System Project. It is based on a schedule network similar to a *critical path method (CPM)* network. The general premise of the approach is that activity durations are uncertain and hence can be properly modeled as random variables rather than deterministic values. So each activity in the network will be modeled with a duration that follows a probability distribution. The total duration is calculated along the critical path and is a random variable because it is the sum of activity durations (random variables) along the critical path. Because the total project duration is calculated as a random variable, then any duration associated with the project should be associated with a probability value. In other words, while in traditional CPM it is common to say that for example, the duration of a specific tunneling project is 730 days, in PERT, we can calculate that the probability of finishing this tunneling project in 730 days is 0.75, or the probability that the project duration is between 670 and 730 days is 0.67.

PERT has not seen widespread use in construction because of the extra effort involved in activity duration estimation and general lack of understanding and confidence in probabilistic approaches in the industry. Because we do not have many examples of PERT implementation, it would be hard to assess its effectiveness. However, it is a straightforward method for probabilistic scheduling with no need for simulation, and so we will briefly discuss the procedure here and point out its problems and strengths.

THREE TIME ESTIMATES

The main source of uncertainty in a schedule is activity duration. PERT models activity duration uncertainty by acknowledging that the duration can best be represented by a range rather than a single value. To achieve this, three time estimates are elicited from the scheduler in the following form:

a (pessimistic estimate): What is the shortest duration for this task, if everything goes well for your work?
m (most likely estimate): What is your best estimate for the duration of this task?
b (optimistic estimate): If all of your worries materialize, how long will the task take?

Mathematical definitions of *a, m,* and *b* are the 5 percent, most likely, and 95 percent values on the activity duration's cumulative distribution function (CDF)[1].

ACTIVITY DURATIONS

Developers of PERT noticed that the distribution used for modeling activity duration should preferably be skewed, uni-modal, and with confined ends (as the duration is

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[1] While original developers of PERT used 0 percent, most likely, and 100 percent points, we recommend using 5 percent and 95 percent points after Moder, *et al* (1983).

typically finite). They used a beta distribution because it possessed these characteristics, and because of its flexibility for assuming various shapes and forms. Because working with beta distribution is rather difficult, the PERT developers introduced simplifying equations for calculating mean and variance of each activity duration. Equations (1), (2), and (3) give the mean (t_e), standard deviation (σ_t), and variance ($var(t)$) of the PERT (similar to beta) distribution:

$$t_e = \frac{a + 4m + b}{6} \quad (1)$$

$$\sigma_t = \frac{b - a}{3.2} \quad (2)$$

$$Var(t) = \left(\frac{b - a}{3.2}\right)^2 \quad (3)$$

While each activity is modeled as a beta random variable and hence can take a skewed shape, the total project duration in the PERT approach is always normally distributed. This is because the project duration is calculated by adding activity durations along the critical path.

TOTAL PROJECT DURATION

If the number of activities on the critical path is larger than 10, then according to the *central limit theorem (CLT)*, the total duration is normally distributed. In practice, the assumption of normality has been used even when there were only four activities on the critical path (Moder, *et al* 1983). According to central limit theorem, the sum of *n* independent random variables (if *n* is *large;* in practice *n* can be as small at 10) is a random variable that follows a normal distribution.

In Equation (4), *T* is the total duration (which is a random variable following the normal curve) and t_i is a critical activity duration. The mean and variance of the sum can be calculated from Equations (5) and (6), where t_{ie} is the mean of the *ith* activity and $Var(t_i)$ is the variance of the *ith* activity duration.

$$T = t_1 + t_2 + \ldots + t_n \quad (4)$$

$$E(T) = t_{1e} + t_{2e} + \ldots + t_{ne} \quad (5) \quad \text{and,}$$

$$Var(T) = Var(t_1) + Var(t_2) + \ldots + Var(t_n) \quad (6)$$

Note that CLT works when random variables are independent. So in the PERT approach the assumption is that activity durations are independent of each other. This means that having information about an activity's duration should not change the scheduler's perception of any other activity duration (more specifically, no other critical activity) in the network. For example, the effect of inclement weather may cause durations of several activities to become longer. Assuming independence means that although we know of weather conditions, we sample various activity distributions independent of each other, although it is apparent that if one activity is delayed because of weather, some other activities could be affected also. If indeed there are correlations between activity durations, then the effect of using CLT is an underestimation of the variance of the total project duration.

EXAMPLE PROJECT

Consider the small CPM network shown in Figure C3-1. The critical path is shown with bold arrows. Critical activities are A, B, C, D, E, F, I, and J. Activity duration estimates (*a, m,* and *b*) are given in Table C3-1. For each activity, the expected value (mean) and variance have been calculated and are also shown in the table.

Figure C3-1 Example CPM Network

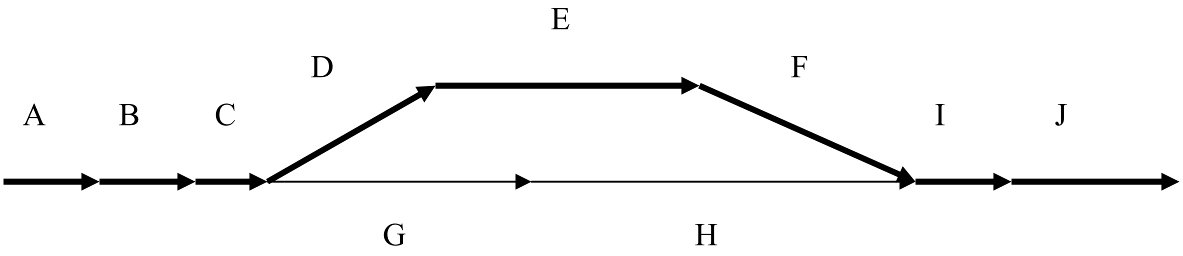


Table C3-1 Activity Durations for PERT Analysis

Activity	a	m	b	Mean	Std. Dev.	Variance
A	18	20	23	20.17	1.56	2.44
B	5	8	12	8.17	2.19	4.79
C	2	4	7	4.17	1.56	2.44
D	4	6	9	6.17	1.56	2.44
E	10	12	15	12.17	1.56	2.44
F	3	5	8	5.17	1.56	2.44
G	7	10	15	10.33	2.50	6.25
H	10	12	17	12.50	2.19	4.79
I	1	3	6	3.17	1.56	2.44
J	2	5	9	5.17	2.19	4.79

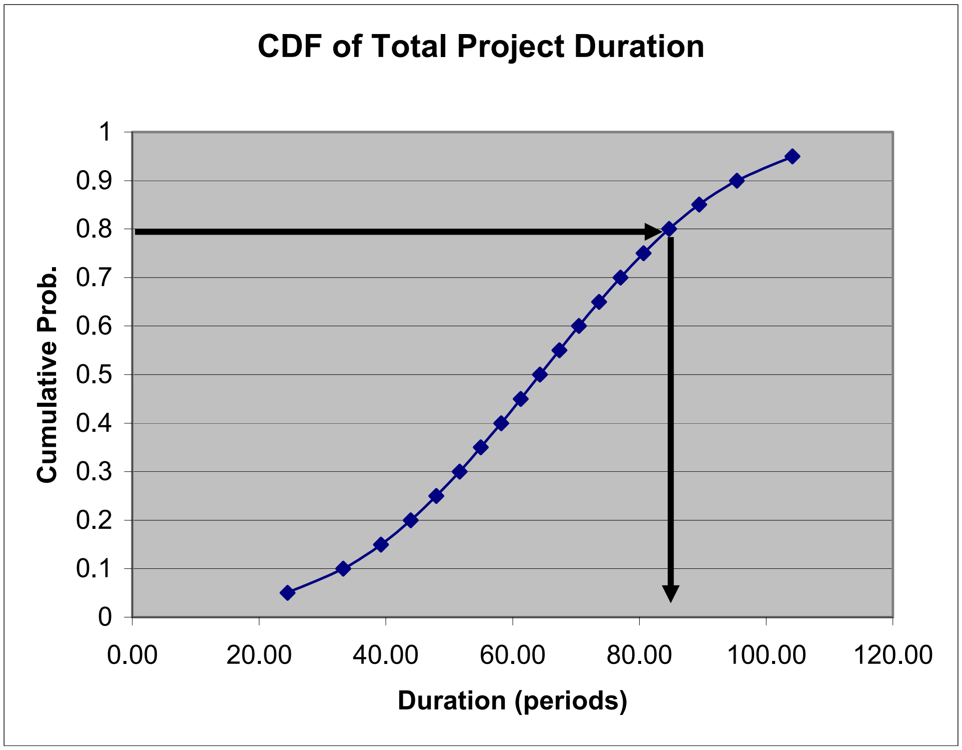
According to PERT procedure, a forward pass is performed along the longest path using activity expected values (means). Variances are summed up along that same path to calculate total project duration variance. Using Equations (5) and (6), we have:

$E(T) = 20.17+8.17+4.17+6.17+12.17+5.17+3.17+5.17= 64.36$ *periods*
$Var(T)=2.44+4.79+2.44+2.44+2.44+2.44+2.44+4.79=24.22$

This means that the total project duration follows a normal distribution with mean 64.36 and variance 24.22. So there is a 50 percent chance that the project can be completed in 64.36 periods.

Using normal probability table (or an electronic spreadsheet), one can calculate the CDF of the total project duration (see Figure C3-2) and then establish appropriate contingency values for the schedule. For example, assume that an 80 percent confidence is desired for project completion date. Using the CDF, one can see that a total duration of 85 periods is required to achieve that confidence level. So if the mean project duration is 64 periods, one needs a schedule contingency of 21 periods.

Figure C3-2 CDF of Total Project Duration



PERT APPLICATION AND SHORTCOMINGS

A relatively substantial upfront effort is required to conduct a PERT analysis. Each activity needs to be estimated with three values and later, a statistical analysis has to be carried out. From a practical point of view, however, a PERT analysis should be conducted at an aggregate network level where the whole schedule is divided into no more than 50 to 100 activities. Care should be taken that the activities are packaged in such a way that their independence can be assumed. Strength of PERT is in the planning phase when project managers are trying to establish project contingencies and potential schedule delays. For control purposes and project administration, much more detailed networks (such as traditional CPM where durations are fixed) consisting of several hundred activities are commonly used.

Another problem with PERT is the *merge event bias*. Consider the simple network in Figure 1. Activities F and H both merge at one point that designates the start of Activity I. The PERT procedure calls for calculation of variance along the longest path. As long as the longest path is *much* longer than parallel paths in the network, this works fine. However, sometimes the lengths of parallel paths are very close. As an example, in Figure 1, the length of A-B-C-D-E-F is 56.0 periods and the length of A-B-C-G-H is 55.0 periods[2]. Variances calculated along the first path up to the start of Activity I is

> $2.44+4.79+2.44+2.44+2.44+2.44=16.99$ for the longer path and
> $2.44+4.79+2.44+6.25+4.79=20.71$ for the shorter path.

This means that the shorter path has a good chance of becoming longer than the critical path due to its larger variance, a fact that the PERT procedure ignores. This problem can be overcome by using a Monte Carlo simulation approach in lieu of the PERT procedure. This procedure will be described later.

CONCLUSION

PERT is a probabilistic scheduling method that allows the user to encode activity duration uncertainty explicitly and to calculate its impact on the total project duration. The application is straight-forward and can always be used as a check for verifying the results of more sophisticated probabilistic scheduling approaches. It ignores potential correlations among activity durations and may provide biased results in case of networks with near critical parallel paths.

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[2] The length of each path is calculated by adding the mean of activities on each path.

APPENDIX C4
SIMULATION OF NETWORK SCHEDULES

The most common scheduling tools for large projects are schedule networks. Schedule networks (*e.g.*, CPM or PERT) consider activity precedences and provide a model for project duration. They identify the length of various sequences of activities required to accomplish the project. The length of the longest path usually defines total project duration and is called the *critical path.* In recent years, several software companies have marketed specialized software that allow the user to perform Monte Carlo simulation on a CPM network. Most of these software programs allow the user to define activity durations, costs, or resources (such as labor hour requirements, *etc.*) as random variables. Let us assume that the user has defined all activity durations as random variables by specifying a distribution type and also possible ranges or distribution parameters. The simulation software generates random numbers for activity durations according to specified distributions and calculates the forward and backward passes and identifies the network critical paths.

This process is repeated hundreds or thousands of times, each usually called an iteration. The number of iterations depends on the confidence intervals desired for the results. Each iteration produces a single value for total project duration. These values can then be organized in a histogram for total project duration. Using this histogram, a probability density function (PDF) and a cumulative distribution function (CDF) for total duration are compiled. These distributions can then be used to assess the probability of project delay beyond the project deadline. They can also be used to determine reasonable amounts of schedule contingency for the project. It should be emphasized that the user should only model those activities with high degree of uncertainty as random variables. If the duration of an activity can be estimated with reasonable accuracy and certainty, there would be no point in *ranging* that duration. The fewer the number of random variables, the easier it would be to verify the reasonableness of simulation results using manual methods after simulation is conducted. In each case, the simplest approach that makes sense provides the most effective mathematical model.

ADVANTAGES OF MONTE CARLO SIMULATION IN NETWORK RISK ANALYSIS

The Monte Carlo approach has several advantages over the non-simulation PERT approach. As described earlier, the PERT approach has the following shortcomings. In almost every case, a simulation approach can resolve these problems.

1) Activity durations are considered independent. This means that if we know the duration of one or several activities, this information will not affect our perception of the duration of other activities in the network. Most simulation software systems have the capability of modeling correlations between activities. Various softwares' approach in handling correlations is different, so users have to be aware of theoretical limitations and assumptions of the software with which they are working.

2) PERT calculates the critical path based on the length of the means (averages) of durations. In networks where there are several paths with almost equal mean lengths,

PERT ignores the possibility that any path other than the critical path could become critical. This approach is problematic; because of the random nature of durations, it is plausible that a non-critical path can become longer than the original critical path. This creates a bias in the results which is known as merge event bias1. Using a simulation approach, the user can avoid this bias. Every simulation iteration results in a project duration with a set of critical activities. Critical activities may change from iteration to iteration because the critical path may change due to duration variances. The software keeps track of the number of times that each activity becomes critical. For each activity, a criticality index is calculated by dividing the number of times the activity becomes critical by the total number of iterations. The criticality index is the likelihood of the activity becoming critical. This method is superior to the PERT approach which has a bias in selecting the path with the larger mean length.

3) While PERT is based on a beta distribution, in a Monte Carlo simulation approach the user can select any distribution type that seems appropriate. Consider a case where the scheduler has no preference for the value of duration other than a range. For example, the scheduler estimates that the duration of an activity is anywhere between three to four weeks. Using Monte Carlo simulation, she can specify a uniform distribution with a range of three to four weeks. Also, she can use various types of distributions in the same network.

4) The use of the central limit theorem in PERT implies that one needs several (say ten or more) activities along the critical path in order to be able to assume normality for the total duration. Simulation approach has no such limitation. Any number of activities can lie on the critical path and the approach does not make any assumptions regarding the shape of total duration distribution. It simply simulates the distributions and summarizes the results into a histogram. More importantly, simulation can be used to obtain distribution of duration between any two milestones in the network without concern for the small number of activities between the milestones.

5) Since the advent of PERT, a new genre of network-based scheduling techniques has been introduced. Precedence diagrams introduced in the early 1980s allow the scheduler to define relationships other than the traditional finish-to-start between activities. In fact, in most of the networks today, it is common to see activity relationships such as start-to-start or finish-to-finish. While the traditional PERT approach has no specific guidelines for modeling these kinds of relationships, simulation methods can be used effectively in all such cases. Every simulation iteration is a deterministic forward-backward pass and all kinds of lags and leads and relationship between activities can be conveniently simulated.

POTENTIAL PROBLEMS OF THE SIMULATION APPROACH

One of the most common pitfalls cited for simulation approach is that *simulation always works.* This means that no matter what the user inputs into the computer, the software

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[1] The reason for choosing this term is that in traditional arrow diagrams, the point of convergence of two or more paths (the merge event) was the point that the PERT approach would choose the longest average path, hence *merge event bias.*

generates a set of random numbers and produces results. The question is, “does the result make sense?” Another related issue raised with a simulation approach is that this is a *black box approach.* The user is not sure how the numbers are generated, what is the reliability of random number generator within the system, and how good are the results in general. This criticism can be leveled against almost any design package. For example, what is the reliability of a bridge design software system? How do we know that the stresses calculated by the software are accurate? Needless to say, a knowledgeable bridge engineer should be able to look at the output, do some checks and form an opinion on the reasonableness of the software output. In doing this, the bridge engineer may use an approximate analysis method, or check the results of a specific part of the design and use these as yardsticks to measure the validity of the detailed analysis output. The same can be said about a simulation experiment. Almost any complex system that is simulated can be simplified to a level where one can analytically estimate some key parameters of the results and use those to evaluate the reasonableness of the simulation results. For example, to check the validity of a schedule simulation analysis, one can resort to the classical PERT approach to evaluate the general validity of simulation results. It is also possible that simulation can verify the results of an analytical solution.

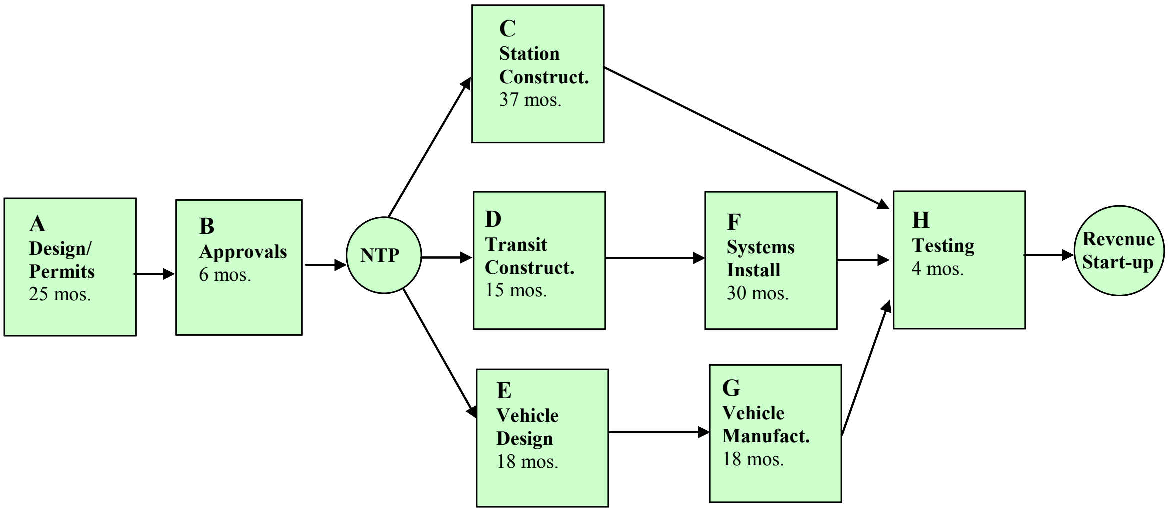
The other classical concern in simulation experiments is to decide on the number of iterations that are needed to obtain reliable results. In conducting a Monte Carlo simulation, the user is trying to obtain a full range of possibilities that can define a problem. If only a few simulation iterations are performed, it is possible that some less likely scenarios (that are still possible and can lead to major consequences for the project) are ignored, leading to erroneous results. To ensure that all possible combinations are tried a sufficient number of times, it is required that simulation be run many times, until the results *converge* to the true distribution of the outcome (for example, total project duration or total project cost). Just how many iterations are needed for this convergence to occur depends on many factors including the number of random variables, types of distributions used, complexity of the model, sensitivity of outcomes on the decisions, *etc.* Much work has been done on this topic. A lot of this research was motivated in the early days of simulation because of the cost of CPU time. Today, computer CPU time is inexpensive and software systems are extremely fast. For construction risk assessment applications, we are dealing with relatively simple equations. As an example, for simulating schedule networks, Moder *et al* (1983) suggest that sample sizes as small as 400 to 1,000 iterations could be sufficient. Using off-the-shelf software packages that run with commonly used scheduling systems, the user can run several thousand iterations in a matter of minutes. So, much of the concern about the convergence of the simulation results can be alleviated by running the simulation for several thousand times. In any case, the effect of number of simulations on the confidence interval of the parameters of the results (such as mean of duration) can directly be calculated. A procedure is described in Pritsker (1986) and many simulation textbooks. One can calculate the number of iterations needed in order to obtain a confidence interval with a certain width for the mean of project duration.

In conclusion, Monte Carlo simulation provides a legitimate and effective means for probabilistic analysis of project schedule. The outcome of the analysis is a distribution for project duration and criticality index values for all activities that were modeled as random variables (it should be noted that only activities with uncertain durations should be modeled as random variables). Using this information, the project management team can decide on the level of contingencies needed to assure project completion during a certain time frame. Also, they will be able to focus on activities that have the highest potential for affecting a schedule in a positive or negative way and think of mitigation measures accordingly.

EXAMPLE

Assume that the schedule of a hypothetical transit project can be represented with a summary schedule as shown in Figure C4-1. In a real application, the network should have anywhere between 20 and 100 activities. So the risk assessment is done at an aggregate level similar to the PERT procedure. Note that limiting the number of activities for the simulation is not because of software limitations, but ranging hundreds (or maybe thousands) of activity durations seems to be superfluous, requires a huge amount of time, and the accuracy of so many estimates would be hard to ascertain.

Figure C4-1 The Precedence Network (Schedule)
for Hypothetical Light Rail Transit Project



Please note that the network in Fig. C4-1 is very similar to the network used in Appendices C2 and C5, with the exception that here, there is a s*tart-to-start* link between D and F. Given that there is a *start-to start* link of six months between D and F, there are three parallel paths in this network with lengths as follows:

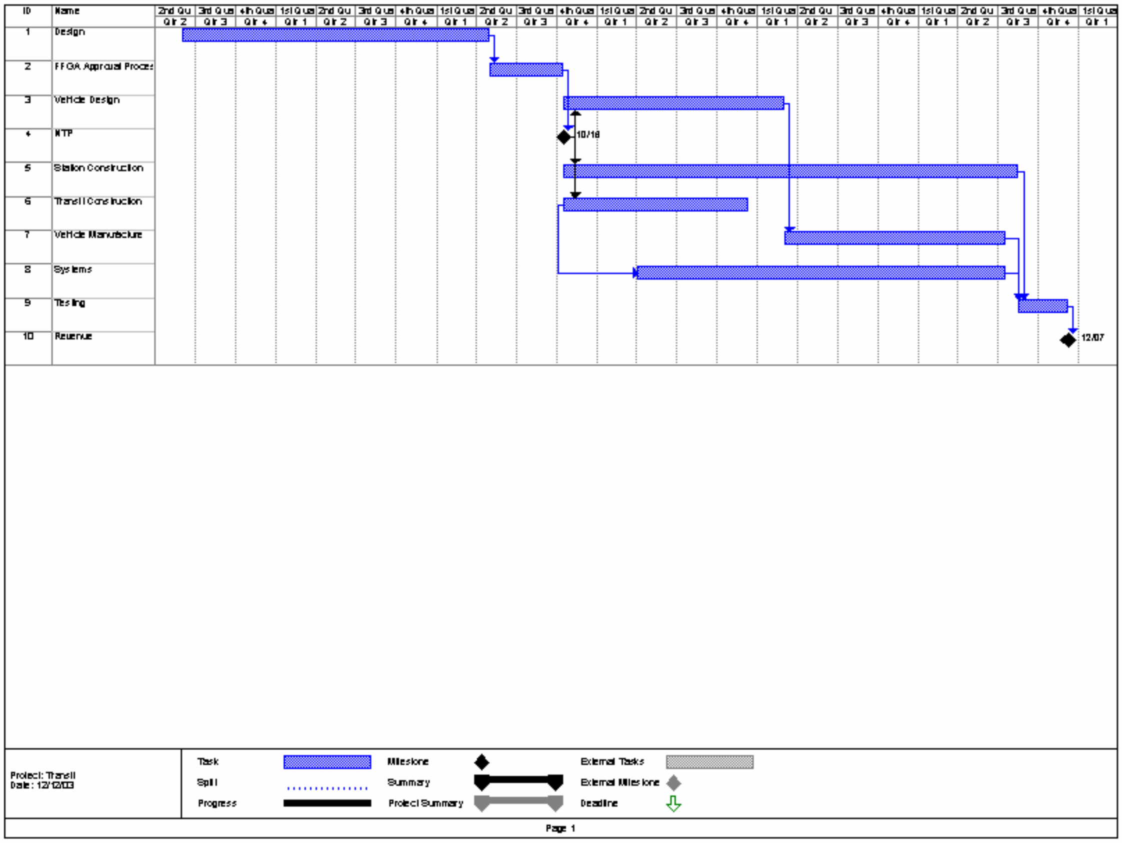
A→B→C→H	72 months
A→B→D→F→H	71 months
A→B→E→G→H	71 months

It is clear that while the critical path is A→B→C→H, due to uncertainty in activity durations, any of the two other paths can become critical as well. The mean value of activity durations is given on the network. Table C4-1 gives activity duration distributions and parameters. Some activities could not be estimated better than just providing a range. These were modeled as uniform distributions. For triangular distributions, optimistic and pessimistic estimates could be either 0 and 100 percent points (extreme values) or any other reasonable values such as 5 and 95 percent points (refer to the discussion in previous sections). Note that in this example, symmetrical triangular distributions are used to model activity durations. This does not need to be the case. The software can model skewed durations just as easily. A barchart of scheduled activities is shown in Figure C4-2. It shows that the project is planned to start in June 2004 and finish in May 2010.

Table C4-1 Activity Data

Activity	Distribution	Parameters
A	Triangular	22-25-28
B	Uniform	5-7
C	Triangular	32-37-42
D	Triangular	12-15-18
E	Uniform	15-21
F	Triangular	27-30-33
G	Uniform	15-21
H	Triangular	3-4-5

Figure C4-2 Barchart of the Project Schedule



MONTE CARLO SIMULATION

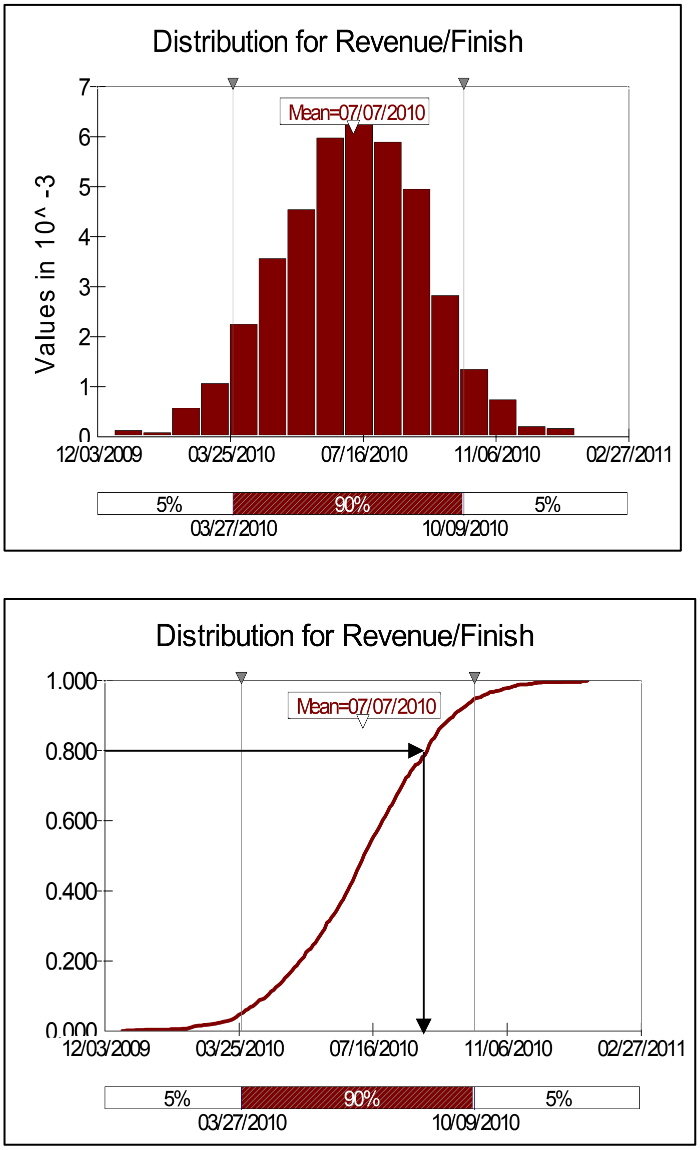
A Monte Carlo simulation analysis is conducted on this network using @Risk for Project^{TM} (2002). This software works with MS Project^{TM} (2002) scheduling software and allows the user to model various schedule elements such as durations and costs according to specified random variables. The simulation input consists of activity durations in the form of distributions presented in Table 1. The simulation output is the project finish time (revenue milestone). Because activity durations are probabilistic, the project finish time will have a range also.

The distribution for this finish time is given in Figure C4-3, a summary report prepared using the simulation software. It can be seen that finish time can happen any time between December 2009 and January 2011, however, the more likely finish time range is between May 15, 2010 (20 percentile value from the "Summary Statistics" table in Figure C4-3; this means that there is a 20 percent probability that the project can finish before this date) and August 31, 2010 (80 percentile value) (a 3.5 month period). The probability that the finish time falls within this range according to this simulation analysis would be 100%-20%-20%=60%. The probability for other date ranges can just as easily be calculated from the histogram and the S-shaped CDF. The expected completion date for the project is simulated as July 7, 2010.

The second chart (S-shaped curve) in Figure C4-3 is the cumulative distribution function (CDF) of the finish time. Using this curve, one can calculate the probability of project completion up to any given date. One enters the chart on the horizontal axis by specifying a date and read vertically to the curve and then horizontally to the cumulative probability value. An alternative method for using this curve would be to first assign a probability level against cost overrun. For example, let us assume that the owner is looking for a deadline where she is 80 percent sure that the project can be finished. Entering the chart on the vertical axis at 80 percent, she can read horizontally to the curve and then vertically to the date. For this example, the result can be obtained from the "Summary Statistics" table also. The date would be August 31, 2010. This method can be used to assign schedule contingency to the deterministic project schedule. By specifying the owner's required confidence level (probability of completion) and comparing the probabilistic duration with the one based on a more detailed deterministic analysis, a schedule contingency can be established. The advantage of such a contingency is that unlike traditional contingencies (5 percent or 10 percent of duration), the owner will have information about the level of confidence (probability of sufficiency of contingency) that such assigned contingency provides.

Simulation software also calculates a *criticality index* for each activity. As described before, the criticality index gives the likelihood of an activity being on the critical path. Criticality index is an effective measure for identification of important activities and alerting management against potential delays; it also helps in identifying mitigation techniques.

Figure C4-3 – Results of Simulation Analysis for the Schedule



Summary Information	
Project Name	Transit-test
Number of Simulations	1
Number of Iterations	1000
Number of Inputs	8
Number of Outputs	1
Sampling Type	Latin Hypercube
Simulation Start Time	01/12/2004 16:37
Simulation Stop Time	01/12/2004 16:38
Simulation Duration	00:00:50
Random Seed	1

Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	12/17/2009	5%	03/27/2010
Maximum	01/12/2011	10%	04/18/2010
Mean	07/07/2010	15%	05/03/2010
Std Dev	60.98491115	20%	05/15/2010
Variance	3719.159387	25%	05/28/2010
Skewness	-0.092723884	30%	06/07/2010
Kurtosis	2.954277091	35%	06/16/2010
Median	07/08/2010	40%	06/24/2010
Mode	04/10/2010	45%	07/01/2010
Left X	03/27/2010	50%	07/08/2010
Left P	5%	55%	07/16/2010
Right X	10/09/2010	60%	07/24/2010
Right P	95%	65%	08/02/2010
Diff X	195.96875	70%	08/09/2010
Diff P	90%	75%	08/19/2010
#Errors	0	80%	08/31/2010
Filter Min		85%	09/08/2010
Filter Max		90%	09/21/2010
#Filtered	0	95%	10/09/2010

Table C4-3 gives activity criticality indexes for the project as calculated and reported by simulation software. While the average critical path for the project remains A→B→C→H, it can be seen that critical activity C has only a 48.5 percent chance of being critical. Competing path E→G has a 29.8 percent and path D→F has a 21.7 percent chance of becoming critical also. These are completely ignored in a PERT approach because PERT only focuses on the mean critical path.

TABLE C4-3 – Criticality Indices of Network Activities

Activity	Criticality Index
A	100%
B	100%
C	48.5%
D	21.7%
E	29.8%
F	21.7%
G	29.8%
H	100%

Ignoring near critical paths usually results in an optimistic assessment of project finish time. In this example, the simulation results show a mean finish time of July 7, 2010. This is equivalent to an average total duration of 74 months. This is two months later than the May 31, 2010 calculated by adding 72 months to project start time (that can be obtained from deterministic and PERT analyses). The reason for this two months difference is that the simulation considers the possibility of other paths becoming critical due to the random nature of activity durations and the fact that three paths in the network have nearly equal lengths.

VERIFICATION OF RESULTS

We can now solve the same problem using a PERT approach and compare the results. The critical path consists of four activities A→B→C→H. We use the duration estimates from Table C4-1 with the exception that for Activity B we assume a most likely duration of 6 (as PERT needs three time estimates). By adding activity means we calculate the mean project duration (25 + 6 + 37 + 4 = 72 months). For each activity we estimate the standard deviation by finding the difference between the two extreme values and dividing this difference by 6[2]. The total variance along the critical path is calculated as 4. This is the sum of activity variances along critical path (Table C4-4). The standard deviation of total is the square root of the variance, *i.e.,* two months.

TABLE 4 – PERT Analysis of the Network

Activity	Std. Dev. (months)	Variance (months)
A	1	1
B	0.333	0.111
C	1.667	2.778
H	0.333	0.111

By reviewing Figure C4-3, one can see that the total project standard deviation was calculated as 60.98 days which is very close to the PERT result (i.e., two months). This shows close convergence between PERT and simulation results.

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[2] Note that in the PERT approach, the difference between pessimistic and optimistic durations should be divided by 6 if optimistic and pessimistic estimates are for 0 and 100 percentile points.

CONCLUSION

The use of Monte Carlo simulation for quantifying schedule uncertainty was described and its limitations and shortcomings were explained. Simulation provides a powerful tool for modeling duration uncertainty and for calculating the probability of finishing the project within a given period of time. The analysis can also be used for establishing schedule contingencies in a consistent manner.

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APPENDIX C5
INTEGRATED SCHEDULE AND COST EXAMPLE

In this example, an integrated cost/schedule risk model is developed for a hypothetical transit project. The project consists of combined at-grade and aerial LRT Line, 10 miles long with 10 stations, in semi-urban environment. This project was introduced earlier, in the main body of this report.

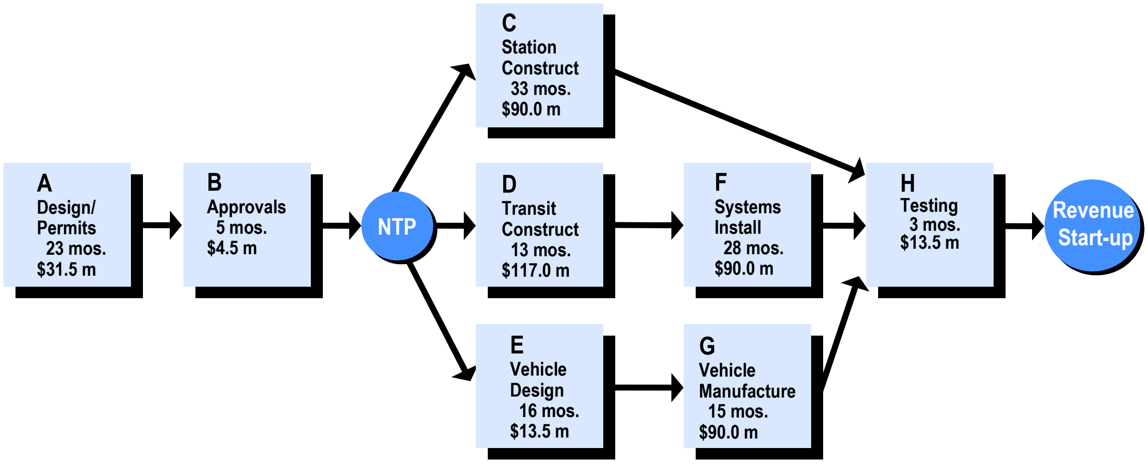
STRATEGY

Based on the current project delivery strategy, the project can be completely described as a network of eight major activities (which comprise a comprehensive and non-overlapping set), as shown in the project flow chart (Figure C5-1):

- Activity A – Design / permit
- Activity B – FFGA Approval
- Activity C – Station Construction
- Activity D – Transit Construction (including Real Estate)
- Activity E – Vehicle Design
- Activity F – Systems
- Activity G – Vehicle Manufacture
- Activity H – Testing

Figure C5-1 Example Project Network: At-grade and Aerial Light Rail Transit

Base Cost [$450 M Current] and Schedule [72 Months]



Note that each activity could be subdivided into sequences of additional, more detailed activities, e.g., Real Estate could be (and often is) a separate activity. Typically, several tens of activities are used to describe a project in adequate detail.

BASE FACTORS

Each major project component is divided into a base component and a number of potential risk factors. It is assumed that the current date is February 2004. This is the base for current costs, for project schedule, and for escalation.

The base factors include the "base" cost, "base" duration and "base" escalation rate of each activity in the project flow chart. They are estimated in an unbiased way (neither pessimistic nor optimistic), consistent with project assumptions – *i.e.,* no contingencies are included for potential problems. These are summarized in Table C5-1.

Table C5-1 Project Base Factors (Expected Values)

Activity (see Figure C5-1)	Base Cost (current $M)	Base Duration (mos)	Base Annual Escalation Rate	Base Start Date (mos)	Base End Date (mos)	Escalated Cost (YOE$M)
Activity A – Design / permit	31.5	23	3%	0	23	32.4
Activity B – FFGA Approval	4.5	5	3%	23	28	4.8
Activity C – Station Construction	90.0	33	3%	28	61	100.4
Activity D – Transit Construction (including Real Estate)	117.0	13	3%	28	41	127.4
Activity E – Vehicle Design	13.5	16	3%	28	44	14.8
Activity F – Systems	90.0	28	3%	41	69	103.1
Activity G – Vehicle Manufacture	90.0	15	3%	44	59	102.2
Activity H – Testing	13.5	3	3%	69	72	16.1
Total	450	72		28	72	501.0

There may be significant uncertainties in the base factors, e.g., due to uncertainties in the unit cost or in the quantities. In Table C5-1, only the "expected value" of each base factor is shown. Although the significant uncertainties in (and correlations among) the base factors could also be described in this table, they have instead been described under the risk items.

Referring to Table C5-1, one can see that the current base cost estimate for the project is $450 million (excluding contingencies). Using a 3 percent escalation factor and activity base durations, an escalated base cost of $501 million is calculated, using the mid-point of activity durations for cost escalation.

RISK FACTORS

"Risks" (potential problems) and "opportunities" (potential windfalls) are uncertain events that could result in changes in project cost or schedule, by affecting costs and/or durations of particular activities in the project flow chart.

A comprehensive and non-overlapping set of major risks/opportunities have been identified, as summarized in the first two columns of the "Risk Register" (Table C5-2) (Note: All costs are in current dollars):

- Risk 1. Permitting and Interagency Agreements: Permits required from approval agencies could be delayed; intergovernmental agreements between grantee and other agencies might not be concluded on schedule. In this example
    - Additional costs associated with redesign (activity A) are most likely $2 million, ranging from about $0.5 million (with 90 percent chance of exceedance) to about $4 million (with 10 percent chance of exceedance), asymmetrically. Hence, the cost (if it occurs) can be adequately described as a triangular distribution with a mode of $2 million, a 10 percentile of $0.5 million and a 90 percentile of $4 million.
    - Additional costs for transit construction (Activity D) associated with redesign are most likely about $15 million, ranging from about $5 million (with 90 percent chance of exceedance) to about $40 million (with 10 percent chance of exceedance), asymmetrically. Hence, the cost (if it occurs) can be adequately described as a triangular distribution with a mode of $15 million, a 10 percentile of $5 million and a 90 percentile of $40 million. This is relatively independent of the redesign cost.
    - Delays in permitting (Activity A) would have the following percentile values (asymmetrical):
        - 1 month minimum (100 percent chance of exceedance)
        - 3 months with 90 percent chance of exceedance
        - 5 months with 75 percent chance of exceedance
        - 6 months with 50 percent chance of exceedance
        - 8 months with 25 percent chance of exceedance
        - 12 months with 10 percent chance of exceedance
        - 18 months maximum (0 percent chance of exceedance)

      This delay would be positively correlated with additional costs in Activity A, i.e., longer delays would tend to occur with higher costs.

  - Delays in transit construction (Activity D) associated with redesign would have the following percentile values (asymmetrical):
    - 1 month minimum (100 percent chance of exceedance)
    - 2 months with 90 percent chance of exceedance
    - 3 months with 75 percent chance of exceedance
    - 4 months with 50 percent chance of exceedance
    - 5 months with 25 percent chance of exceedance
    - 6 months with 10 percent chance of exceedance
    - 8 months maximum (0 percent chance of exceedance)

    This delay would be positively correlated with additional costs in Activity D, i.e., longer delays would tend to occur with higher costs. In this example, a correlation coefficient of 0.50 is used to model all correlations, although the correlations for other projects may be different.

- The chance of such problems is only about 25 percent but would be systematic in affecting both Activities A and D. So the likelihood of occurrence of Risk 1 is estimated as 25 percent.

All other risk factors (risks 2 to 10) are quantified in similar manner and are reported in the Risk Register (Table C5-2). Also, note that each risk/opportunity could be subdivided into more detailed risks/opportunities. Typically, several tens of risks/opportunities are used to describe a project in adequate detail.

Table C5-2. Risk Register

Risk	Description	Cost Impacts if Occurs (current $M)	Schedule Impacts if Occurs (months)	Likelihood of Occurrence
Risk 1. Permitting and Interagency Agreements	Permits required from approval agencies could be delayed; intergovernmental agreements between grantee and other agencies might not be concluded on schedule.	Activity A: Tri1090* {0.5,2,4} Activity D: Tri1090{5,15,40}	Activity A: Cumulative{(1,3,5,6,8,12,18), (0,.1,.25,.5,.75,.9,1)}** +0.5 correlation coeff with Activity A cost impact Activity D: Cumulative{(1,2,3,4,5,6,8), (0,.1,.25,.5,.75,.9,1)} +0.5 correlation coeff with Activity D cost impact	25% systematic among activities, but independent of other risks
Risk 2. FFGA Approval	Grantee documentation of readiness to enter into full funding grant agreement negotiations with FTA might require further revisions, thereby delaying the anticipated FFGA approval date.	None	Activity B: 1 with 50% chance 2 with 30% chance 4 with 20% chance	10% independent of other risks
Risk 3. Station Design	Changes in stations features could occur late in final design and/or during early construction due to community concerns, requiring additional design effort and delaying start of certain construction activities.	Activity C: Exponentially distributred with a mean of 10	Activity C: LogNormal{5,2}*** +0.5 correlation coeff with cost impact	30% independent of other risks
Risk 4. Right-of-Way Cost and Availability	Property costs are uncertain and possibly higher than anticipated; the acquisition schedule, including obtaining of construction easements, could be extended. This includes demolition as well as cleanup of any	Activity D: LogNormal{30,15}	Activity D: LogNormal{6,2} +0.5 correlation coeff with cost impact	50% independent of other risks

Risk	Description	Cost Impacts if Occurs (current $M)	Schedule Impacts if Occurs (months)	Likelihood of Occurrence
	contamination.			
Risk 5. Utility Relocations	Locations of certain utilities are unknown and their relocation could be required. In this example, such relocations can only be done during a particular time frame.	Activity D: LogNormal{5,2}	Activity D: Uniformly distributed with a range of 0 to 12 independent of cost impact	20% independent of other risks
Risk 6. Changing Market Conditions	The construction market is changing, with bid prices on similar work components on other projects varying considerably. Procurement costs for major project components could be higher or lower than estimated.	Activities C-G: Normal{0.05,0.10}[#] x Activity Base Cost[##] +0.5 correlation coeff among activities	None	100% systematic among activities, but independent of other risks
Risk 7. Light Rail Vehicles Price	With vehicles likely to be supplied by firms based outside the U.S., prices could fluctuate significantly in response to changing dollar exchange rates.	Activity E: LogNormal{2,1} Activity G: LogNormal{20,5} independent between activities	Activity E: LogNormal{4,2} +0.5 correlation coeff with Activity E cost impact Activity G: LogNormal{4,2} +0.5 correlation coeff with Activity G cost impact	10% systematic among activities, but independent of other risks
Risk 8. Systems Equipment Integration	Problems in the installation and testing of complex systems equipment and controls (signals, communications, tractions power, fare collection, etc) could add to costs and delay the revenue operations date.	Activity F: LogNormal{5,2}	Activity F: LogNormal{6,2} +0.5 correlation coeff with Activity F cost impact	50% independent of other risks
Risk 9. Revenue Service Date	In this example, if revenue service does not start by a particular date (within 80 months from now, e.g., to coincide with a major	Activity H: 10	NA	Triggered if completion date is >80

Risk	Description	Cost Impacts if Occurs (current $M)	Schedule Impacts if Occurs (months)	Likelihood of Occurrence
	event like the Olympics), the grantee must pay a penalty.			(milestone)
Risk 10. Grantee Administrative Costs	Should project construction be extended, grantee administrative costs, including costs for construction management and design support during construction, will increase proportionately.	Activity H: 0.5 per month beyond base (72)	NA	Triggered if completion date is >72 (base)

Notes:

* Tri1090{10th percentile, most likely value, 90th percentile} represents a triangular distribution with three estimates as indicated.
** Cumulative{(set of values),(probability of non-exceedance for each value)} represents a cumulative distribution function with values defined by the user based on intuition, experience, or historical data.
*** LogNormal{mean, standard deviation} represents a lognormal distribution with indicated mean (expected value) and standard deviation. Lognormal is an assymetrical distribution that is commonly used to model costs.
# Normal{mean, standard deviation} represents a normal distribution with indicated mean and standard deviation.
In order to model the effect of Changing Market Conditions, each base estimate is multiplied by a normally distributed random variable with a mean of 5 percent. This means that on average the risk cost due to market conditions is 5 percent of the base cost.

MONTE CARLO SIMULATION

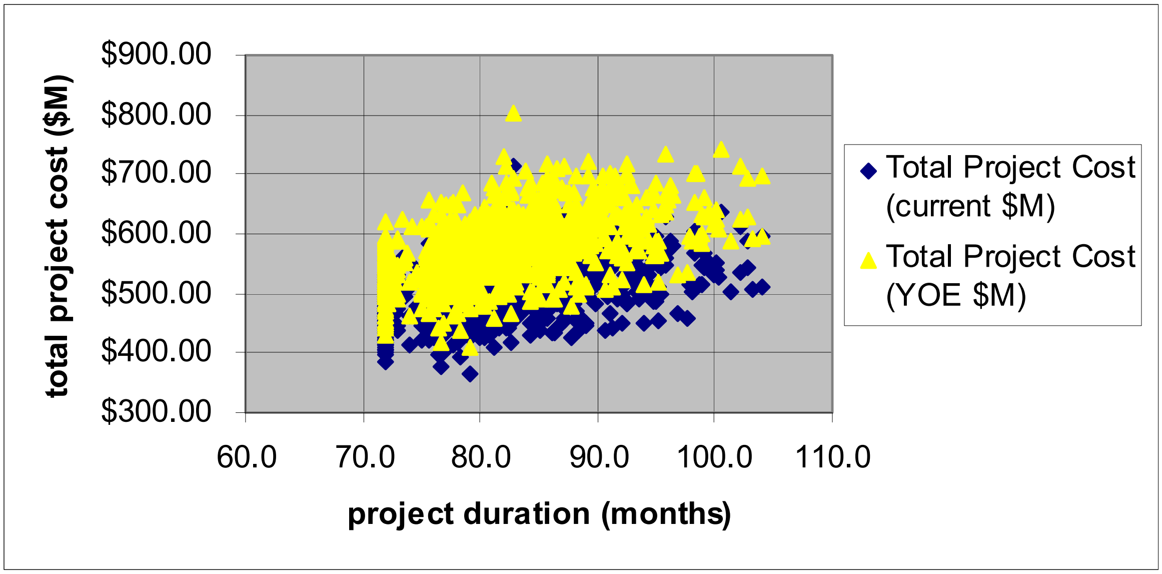
An integrated cost and schedule model was developed that represents the network (Figure C5-1) and the risk register (Table C5-2). The model was developed in EXCEL^{TM} spreadsheet. The simulation was performed using @RISK^{TM} software package. In each simulation iteration, random numbers were generated according to specified distributions. These random numbers were combined to arrive at total project cost and total project duration. For total duration, in each simulation iteration, the longest path in the flowchart was calculated. The simulation was run for 1,000 iterations.

The total cost (in current dollars) of each activity is simulated as the sum of the base cost (in current dollars) and all simulated risk costs (in current dollars) for that activity. The total escalated cost of each activity is simulated from the simulated total project cost (in current dollars) for each activity, the simulated schedule of each activity and the escalation rate for each activity. The total escalated project cost (in YOE dollars) is simulated as the sum of the simulated total escalated cost of each activity.

RESULTS

The integrated cost and schedule model was implemented with the assessed base factors and risk factors (Tables C5-1 and C5-2), generating 1000 equally likely "realizations". The raw results of all 1000 realizations are plotted in Figure C5-2, in terms of total project cost (both in current dollars and YOE dollars) versus total project duration for each realization. Note the positive correlation between total project cost (especially escalated) and total project duration, i.e., higher total project costs tend to be more likely with longer project durations.

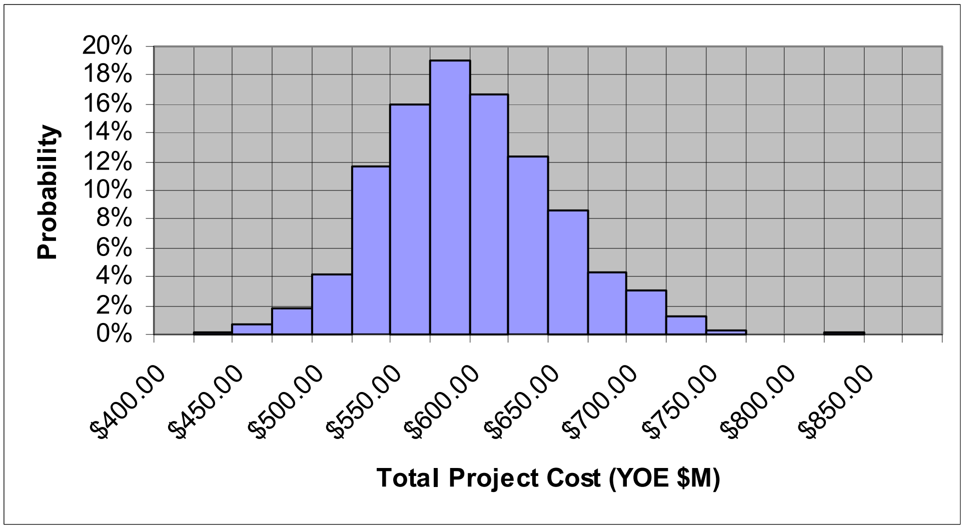
Figure C5-2 Scatter Plot of Total Project Cost and Schedule

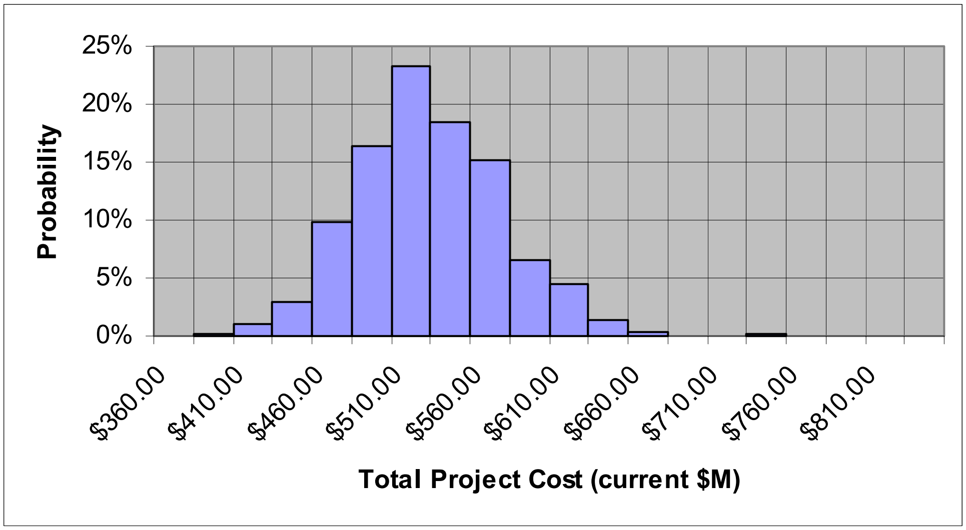


Discretized probability distributions of total project cost (in current dollars and in YOE dollars) and of total project schedule (in duration and in completion date) were derived from the 1000 realizations, as shown in Figures C5-3a-c.

Similarly, cumulative probability distributions and tables of probability distribution characteristics (i.e., mean, standard deviation, mode and percentiles) of project risk cost (in current dollars), total project cost (in current dollars and in YOE dollars), project risk delays, and total project schedule were derived from the 1000 realizations, as shown in Figures C5-4a-b and Table C5-3.

Figure C5-3a-c Discretized Probability Distributions for Total Project Cost and Schedule





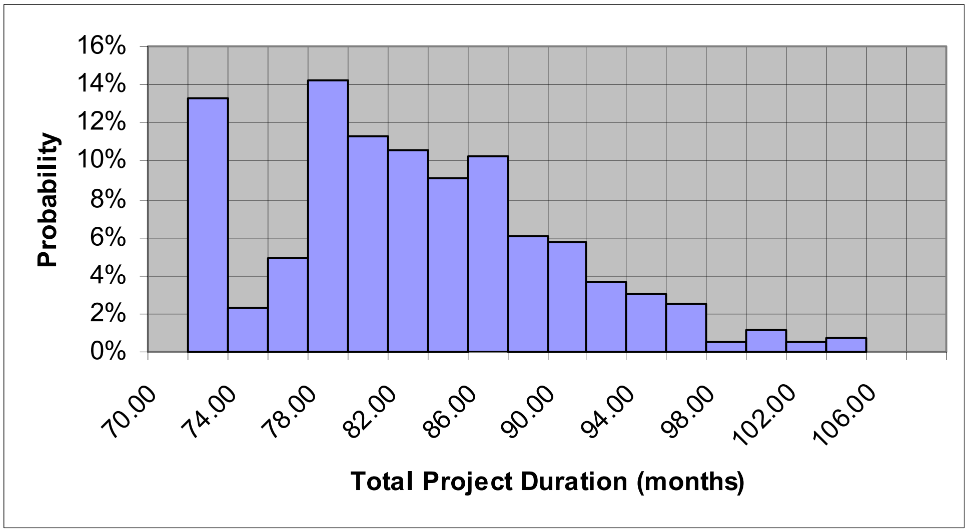


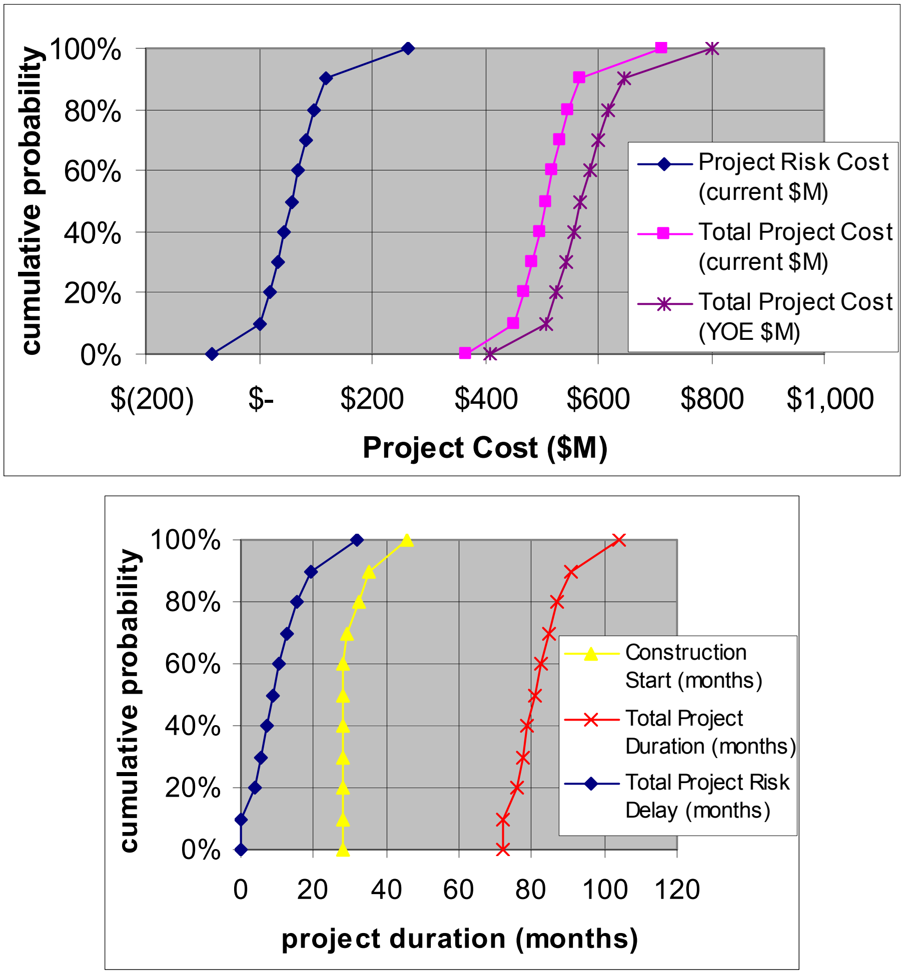
Table C5-3 Probabilistic Characteristics of Total Project Cost and Schedule

Statistics / Outcome	Project Risk Cost (current $M)	Total Project Cost (current $M)	Total Project Risk Delay (months)	Construction Start (months)	Total Project Duration (months)	Total Project Cost (YOE $M)
Mean	$ 59	$ 509	10	30	82	$ 574
Standard Deviation	$ 46	$ 46	7	4	7	$ 55
Mode	$ 53	$ 503	-	28	72	$ 593
0%	$ (84)	$ 366	-	28	72	$ 409
10%	$ 3	$ 453	-	28	72	$ 507
20%	$ 21	$ 471	4	28	76	$ 526
30%	$ 34	$ 484	5	28	77	$ 543
40%	$ 46	$ 496	7	28	79	$ 557
50%	$ 57	$ 507	9	28	81	$ 570
60%	$ 67	$ 517	11	28	83	$ 585
70%	$ 82	$ 532	13	29	85	$ 599
80%	$ 96	$ 546	15	32	87	$ 617
90%	$ 118	$ 568	19	35	91	$ 645
100%	$ 264	$ 714	32	46	104	$ 802

From the above, the following can be concluded:

- the escalated base cost (YOE, considering base schedule) is $501 million, compared to unescalated base cost (current) of $450 million, an increase of 11 percent (base escalation);
- the 80th percentile of unescalated total project cost (current) is $546 million, compared to unescalated base project cost (current) of $450 million, an increase of 21 percent (equivalent to cost contingency);
- the 80th percentile of total project duration is 87 months, compared to base project duration of 72 months, an increase of 21 percent (equivalent to schedule contingency);
- the 80th percentile of escalated total project cost (YOE) is $617 million, compared to escalated base project cost (YOE) of $501 million, an increase of 23 percent (equivalent to cost contingency, considering schedule contingency cost impacts); and
- the 80th percentile of escalated total project cost (YOE) is $617 million, compared to unescalated base project cost (current) of $450 million, an increase of 37 percent (equivalent to cost contingency plus escalation, considering schedule contingency cost impacts).

Figure C5-4 a-b Cumulative Probability Distributions for Total Project Cost and Schedule



RISK PRIORITIZATION

An important step in risk analysis is risk mitigation. In order to do risk mitigation, the team needs to concentrate on the most critical risk items. The relative significance of various risk items (for example, to guide risk management) is summarized in Table C5-4 in terms of their expected values of risk cost (in current dollars) and risk delay. Note, however, that:

- Although the primary indicator of risk significance is the expected value, which shifts the entire probability distribution, a secondary indicator of risk significance (not considered here) is the standard deviation, which narrows the probability distribution. Both affect higher percentile values (which can be analyzed), although the expected value generally has a larger impact.
- The expected value of risk delays is to particular activities, which may not be on the base critical path, and thus might not correspond to project delays. Hence, the expected delays are only an indication of the relative significance of each risk item with respect to schedule. Alternatively, the base float of

each activity could be determined and compared to the risk delays to determine approximate schedule impacts, which could be translated to increased escalation. However, this would be difficult where multiple risk delays affect one activity.

- Ideally, one could determine the effect of each risk on the 80th percentile of escalated total project cost, which would include both cost and schedule risk. However, the only conceivable way of doing this is to rerun the model for each risk item, assuming that that risk item has been completely mitigated (e.g., likelihood has been reduced to 0), and determining the difference in the 80th percentiles of escalated total project cost. This would not be practical for a large number of risk items.

Table C5-4 Relative Significance of Risks and Opportunities

	Cost (in current dollars)			Delays (in months)		
Risk	Expected Value	Risk Rank	Opp Rank	Expected Value	Risk Rank	Opp Rank
1. Permitting / IA Agreements	$ 6.23	3	NA	3.0	1	NA
2. FFGA Approval	$ -	10	1	0.1	7	NA
3. Station Design	$ 0.40	9	NA	2.2	4	NA
4. Right-of-Way Cost / Availability	$ 20.40	2	NA	2.3	2	NA
5. Utility Relocations	$ 1.10	8	NA	1.7	5	NA
6. Changing Market Conditions	$ 21.90	1	NA	0.0	8	1
7. Light Rail Vehicles Price	$ 2.96	7	NA	0.4	6	NA
8. Systems Equipment Integration	$ 3.17	6	NA	2.2	3	NA
9. Revenue Service Date	$ 5.40	4	NA	0.0	8	1
10. Grantee Administrative Costs	$ 5.34	5	NA	0.0	8	1

Note: “Opp Rank” means Opportunity Rank, where opportunity is negative risk.