ABSTRACT

Title of Document: A METHODOLOGY FOR PROJECT RISK ANALYSIS USING BAYESIAN BELIEF NETWORKS WITHIN A MONTE CARLO SIMULATION ENVIRONMENT

Javier F. Ordóñez Arízaga, Doctor of Philosophy, 2007

Directed By: Professor Gregory B. Baecher, Department of Civil and Environmental Engineering

Projects are commonly over budget and behind schedule, to some extent because uncertainties are not accounted for in cost and schedule estimates. Research and practice is now addressing this problem, often by using Monte Carlo methods to simulate the effect of variances in work package costs and durations on total cost and date of completion. However, many such project risk approaches ignore the large impact of probabilistic correlation on work package cost and duration predictions. This dissertation presents a risk analysis methodology that integrates schedule and cost uncertainties considering the effect of correlations. Current approaches deal with correlation typically by using a correlation matrix in input parameters. This is conceptually correct, but the number of correlation coefficients to be estimated grows combinatorially with the number of variables. Moreover, if historical data are unavailable, the analyst is forced to elicit values for both the variances and the correlations from expert opinion. Most experts are not trained in probability and have

difficulty quantifying correlations. An alternative is the integration of Bayesian belief networks (BBN’s) within an integrated cost-schedule Monte Carlo simulation (MCS) model. BBN’s can be used to implicitly generate dependency among risk factors and to examine non-additive impacts. The MCS is used to model independent events, which are propagated through BBN’s to assess dependent posterior probabilities of cost and time to completion. BBN’s can also include qualitative considerations and project characteristics when soft evidence is acquired.

The approach builds on emerging methods of systems reliability.

A METHODOLOGY FOR PROJECT RISK ANALYSIS USING BAYESIAN BELIEF NETWORKS WITHIN A MONTE CARLO SIMULATION ENVIRONMENT

By

Javier F. Ordóñez Arízaga

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2007

Advisory Committee:
Professor Gregory B. Baecher, Chair
Professor Miroslaw Skibniewski
Professor Ali Mosleh
Associate Professor Steven A. Gabriel
Adjunct Professor Kenneth O'Connell

Dedication

To my parents Fabián y Rosalía

and to my dearest Amelia

Acknowledgements

I would like to express my deepest gratitude and sincere appreciation to my advisor, Dr. Gregory Baecher. His advice and support were fundamental throughout the development of this research.

I also would like to thank the other members of the advisory committee, Dr. Steven Gabriel, Dr. Ali Mosleh, Dr. Kenneth O’Conell, and Dr. Miroslaw Skibniewski for their invaluable guidance and suggestions that contributed immensely to the direction of this dissertation.

My special appreciation and regards to other faculty, and staff of the Center for Advanced Transportation Technology at the University of Maryland, including Mr. John Cable, Mr. Phil Tarnoff, and Mrs. Jenny Prevots for their help and support.

Special thanks to my master’s advisor, Dr. Steven Gabriel, who has guided and encouraged me during my years at the University of Maryland.

Finally, I thank my family, my parents, brothers, and sister for their love and encouragement. And to my girlfriend, Amelia, my most sincere gratitude for her unconditional love and support all these years; without her this milestone would have never been accomplished.

Table of Contents

List of Tables

List of Figures

1. Introduction

Project management techniques are widely used to plan, execute, control, and deliver infrastructure projects. The goals of a successful project management endeavor are to finish on time, within budget and according to the specifications and quality standards. The ultimate benefit of implementing project management techniques is a satisfied customer.

With higher requirements of quality, increasing demand for shorter project completion times and more efficient use of available budgets, project management professionals are facing the necessity of using analytical and quantitative tools that are more sophisticated than traditional qualitative approaches.

It is not surprising that many projects are constantly over budget and behind schedule. Several reports, such as the ones presented in Section 2.2, are evidence of the small percentage of projects that meet their anticipated completion date and/or are within their estimated budget. When serious overruns occur on project cost and time estimates, the effects on the project can be damaging. In extreme cases, time and cost overruns can invalidate the economic case of a project, turning a potentially profitable investment into a loss.

Cost and time targets are sometimes missed because of unforeseen events that affect the project execution, however most often this happens because of events that could have been anticipated and taken into consideration during the planning phase. More difficult to assess is the likelihood and impact of these events on project performance; therefore it is necessary to explore a methodology that identifies risk sources and quantifies their effects on project targets.

This research intends to understand and analyze uncertainties that impact the schedule and cost of a project. Specifically, this research aims to develop a risk analysis methodology that integrates schedule and cost. The integration of schedule and cost will be helpful to identify work packages that could jeopardize the project's completion time and budget constraints as well as the expected return on investment.

This methodology allows us to develop a risk analysis model that can respond to questions such as, what is the probability of finishing a project by a certain date and within a certain cost. We will also be able detect in advance work packages that are prone to be affected by project risks and allocate contingencies that will safeguard the cost and time objectives. This type of analysis will help us obtain and distribute required contingencies in a more educated and justified way than the traditional approach of assigning a percentage of total cost.

One area we pay particular attention to is the affect of correlation on work packages' cost and duration estimates; if correlation is ignored there is a high risk of underestimating the variances of cost and time completion projections. The usual approach to deal with correlation is to set up a correlation matrix containing work packages that are affected by uncertainty and variability. Therefore, each work package cost and duration estimate is represented by a random variable. The problem with this approach is that the number of correlation coefficients to be estimated or assessed grows rapidly with the number of variables, which can be a cumbersome task. The required number of correlation coefficients for n variables is $\binom{n}{2}$; for example, to form a correlation matrix of a project that has 100 variables representing either cost or duration of work packages, we need to estimate 9450 correlation coefficients. Moreover, if no historical data are available for their estimation, the analyst will be forced to elicit these values from expert opinion. This elicitation faces one major challenge that is experts who are not trained in probability concepts will have difficulties not only understanding the correlation concept but also providing rational estimates.

As an alternative to this problem, this research proposes the use of Bayesian Belief Networks (BBN's) within a Monte Carlo Simulation (MCS) model.

Another area that the research addresses is the implications of a probabilistic schedule and cost baseline on project control and forecast.

Chapter 2 introduces background definitions related to project risk analysis and management. In that section concepts about uncertainty and risk set the stage for the proposed research. That chapter also presents a literature review of different techniques used in project risk analysis.

Chapter 3 presents the benefits of Bayesian belief networks for modeling project risks.

Chapter 4 presents a methodology for quantitative project risk analysis that describes the process for integrating BBN's within a MCS environment, followed by a case study in Chapter 5.

Chapter 6 explores the use of probabilistic baselines for project control and the use of conditional probabilities given actual performance observations for the prediction of total project cost and duration at completion.

Finally, Chapter 7 presents conclusions and summarizes findings of this research and provides recommendations for future research.

2. Literature Review

In this chapter, background, concepts and a comprehensive review of the literature related to project management and project risk analysis are presented.

2.1 Background

2.1.1 What is a Project?

The PMBOK, Project Management Body of Knowledge, (Project Management Institute 2004) defines a project as a temporary endeavor undertaken to create a unique product or service. It also states that projects are critical to the realization of the performing organization's business strategy because projects are means by which strategy is implemented.

"Projects are performed by people, constrained by limited resources and have to be planned, executed and controlled" (Gido and Clements 1999).

Most of the time projects have well-defined objectives, which are the expected results or products that should meet or exceed the customer's expectations. An objective is defined in terms of cost, time and scope.

Projects generally have a certain degree of uncertainty involved. Before a project is started a plan is established based on assumptions and estimations; however, these assumptions can turn out to be incorrect while the project is being executed, so it is very important to set up a methodology that takes into consideration these uncertainties, controls changes and updates the project assumptions.

2.1.2 The Project Management Cycle

The project management cycle has five phases: Initiation, Planning, Execution, Monitoring and Control, and Closeout. Each phase brings as a result the completion of one or more deliverables and it is necessary to review how well they were accomplished, so errors and corrective actions can be identified and implemented. The project cycle serves to define the beginning and the end of a project (Project Management Institute 2004).

The first phase, initiation, is where the needs, problems, and opportunities are identified. Projects are born when a need is identified and whoever is involved is willing to fund them in order to have that need satisfied. When a project is identified, it is often required to perform a feasibility study, so the organization would be able to decide if it is convenient to undertake such project.

In the planning phase the project management plan is developed and the project scope is defined. The project cost is determined and the activities that occur within the project are scheduled.

The execution phase is where the project management plan is executed to accomplish the project's requirements. This process includes the coordination of people and resources, the integration and execution of the activities of the project in accordance with the project management plan.

In the monitoring and control phase the project execution is observed so potential problems can be identified in a timely manner and a corrective action can be taken to control the execution of the project.

The close-out phase includes the processes used to formally terminate all activities of a project, hand-off the project to the owner or close a cancelled project.

This research focuses on the planning and monitoring and control phases of a project. Once the project scope is defined, the schedule and cost baseline can be analyzed in order to assess the risks that could affect the project performance so mitigating actions can be planned before the execution phase starts. Throughout the execution of the project, the project baseline is compared against the actual performance so any opportunities can be exploited or any corrective actions taken if necessary; this information can also provide useful forecast data of the project's expected final completion time and cost.

2.1.3 Variability and Uncertainty

Variability and uncertainty are inherent in a project. Variability is also called aleatory uncertainty or stochastic variability. Variability responds to the stochastic nature of a process where outcomes are random even though the process and its parameters are understood. Tossing a coin is a good example of the inherent randomness of a process. It is not reducible through either study or further measurement. Uncertainty, also called epistemic uncertainty or degree of belief, is defined as the lack of knowledge (level of ignorance) about the parameters that characterize the physical system. Uncertainty is by definition subjective since is a function of the assessor and it can sometimes be reduced by further measurement or study, or through consulting with more experts. Total uncertainty is the combination of variability and uncertainty. These two components act together to erode the ability to predict what the future holds (Vose 2000).

The degree of uncertainty is a measure of how much we believe something is true while probability is a numerical measurement of the likelihood of an outcome of some stochastic process.

The initial phases of the project life cycle are the ones that have the highest uncertainty since the relevant information is not always available nor stable (Laufer 1997). Consequently, consideration of variability and uncertainty is an important part of the project-planning endeavor.

2.1.4 Risk

Risk is defined as an exposure to the consequences of uncertainty. Risk is usually considered as an unwanted event that can be identified and quantified through its impact and probability of occurrence. The classical definition of risk states that *Risk = Probability of event x Magnitude of loss/gain*.

Risks are inevitable in projects and because of this, uncertainty influences project performance. Cooper (2005) defines risk in a project context as the chance of something happening that will have an impact upon project objectives. The PMBOK (Project Management Institute 2004) refers to project risk as an uncertain event or condition that, if it occurs, has a positive or a negative effect on a project objective. So we can state that risks involve threats and opportunities that can affect the achievement of project objectives.

2.1.5 Project Risk Management

Risk management is essentially removing or reducing the possibility of under-performance. The purpose of risk management is to improve project performance via systematic identification, appraisal and management of project-related risk (Chapman and Ward 2003). Risk management is a systematic process that identifies, analyzes, and responds to project risk. It includes maximizing the probability and consequences of positive events and minimizing the probability and consequences of adverse events to project objectives. Therefore, it is crucial to identify the sources of risk and its characteristics so a risk management plan can be developed, which will be the yardstick for controlling the project evolution and taking corrective measures if necessary. Risks can be assessed objectively and/or subjectively. When data are difficult to acquire, subjective judgment has to be used in order to evaluate likelihood and consequences of such risks.

The PMBOK (Project Management Institute 2004) defines the following project risk management processes:

- *Risk Management Planning - deciding how to approach, plan, and execute the risk management activities for a project.*
- *Risk Identification - determining which risks might affect the project and documenting their characteristics.*
- *Qualitative Risk Analysis – prioritizing risk for subsequent further analysis or action by assessing and combining their probability of occurrence and impact.*
- *Quantitative Risk Analysis – numerically analyzing the effect on overall project objectives of identified risks.*
- *Risk Response Planning – developing options and actions to enhance opportunities, and to reduce threats to project objectives.*
- *Risk Monitoring and Control – tracking identified risks, monitoring residual risks, identifying new risks, executing risk response plans, and evaluating their effectiveness throughout the project life cycle.*

This dissertation focuses on the risk identification process and in the quantitative risk analysis. It will also study the use of the results of the quantitative risk analysis in project control and forecasting methodologies.

2.2 Project Performance Record

The Chaos Report (Standish-Group 1995) claims that in the United States, each year more than US$250 billion are spent on IT applications development including approximately 175,000 projects. Project costs range from around two million dollars for large companies to approximately half a million dollars for small companies. This report indicates that 31% of the projects were cancelled before they get completed. It also indicates that 53% of the projects cost 189% of their original estimate and that one of the major causes of both cost and time overruns is restarts. For every 100 projects that start, there are 94 restarts. The average cost overrun is 178% for large companies, 182% for medium companies, and 214% for small companies. Over one-third of the projects experienced time overruns of 200 to 300%. The average overrun is 222% of the original time estimate. For large companies, the average is 230%; for medium companies, the average is 202%; and for small companies, the average is 239%. On the success side, the number of software projects that are completed on-time and on-budget averages only 16.2%.

For construction projects the record is significantly more promising, yet it is also observed that there is a consistent trend of cost overruns and time delays. For example, Figure 2-1 shows data for over 900 international projects financed by the World Bank and audited for actual against planned performance. On average, there was about a 30%

cost overrun and about a 60% delay in project completion time.

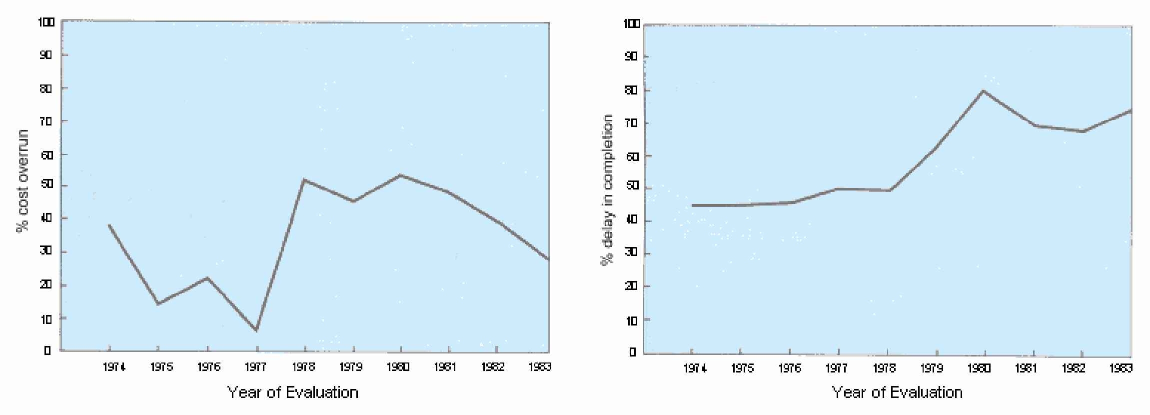


Figure 2-1: % Average Cost Overruns and Completion Delays (World-Bank 1984)

Al-Momani (2000) presents a quantitative analysis of 130 public projects in Jordan during the period 1990-97. These projects represent various construction categories that include housing, office and administrative buildings, school buildings, medical centers and communication facilities. He argues that the time to complete construction of public projects is frequently greater that the time specified in their respective contract: 106 of 130 were delayed.

Figure 2-2 shows a scatter plot of actual time versus planned time for public projects. The red line shows perfect correlation between (i.e. a 45° line), while the blue line is the best-fit linear regression. Al-Momani concludes that there is a consistent tendency to underestimate project duration; however, causes of delay are not studied. Although the article does not present information on project size and cost, it would be interesting to assess their respective effects on project delays.

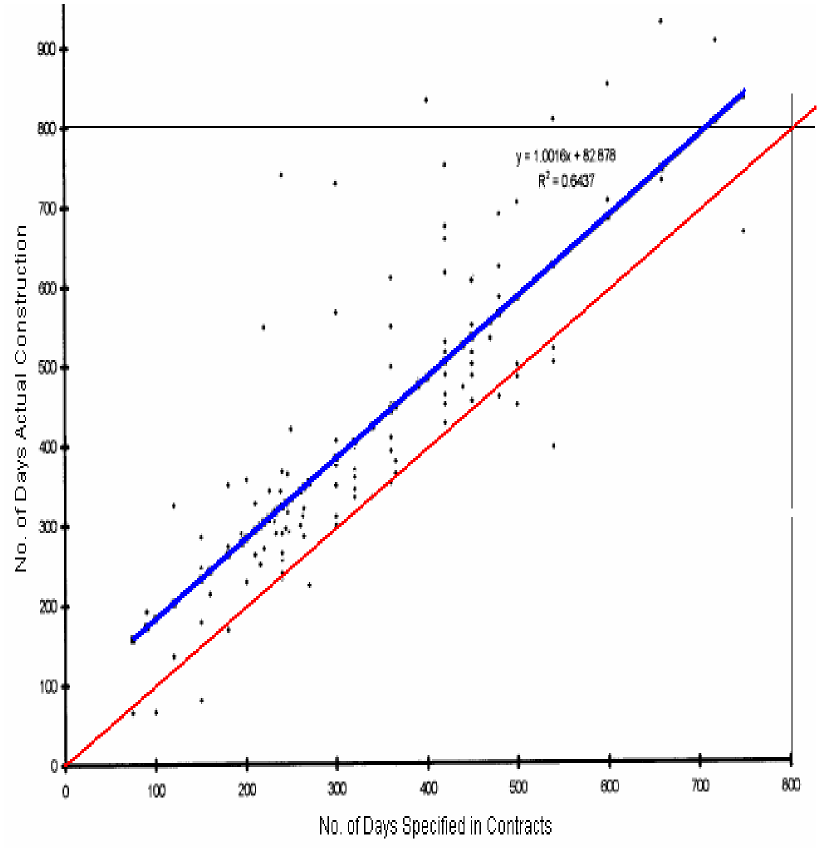


Figure 2-2: Scatter Plot of Actual Time Y versus Planned Time X for 130 Public Projects (Al-Momani 2000)

A more recent publication (Flyvbjerg et al. 2003) reports cost overruns in transport infrastructure projects on a sample of 258 project in 20 nations worth approximately US$90 billion (constant 1995 prices). This paper shows that transport infrastructure projects are consistently over budget. The average cost escalation is 45%, for fixed routes 34%, and for roads 20%. Figure 2-3 shows cost escalation of rail projects in Europe, the US and elsewhere; the cost escalation in Europe is 34.2% versus 40.8% in North America. For roads, the numbers are 22.4 versus 8.4%. This figure uses box plots where the 10th, 25th, 50th, 75th and 90th percentiles are reported as a way to show the cost escalation variability of each geographic category.

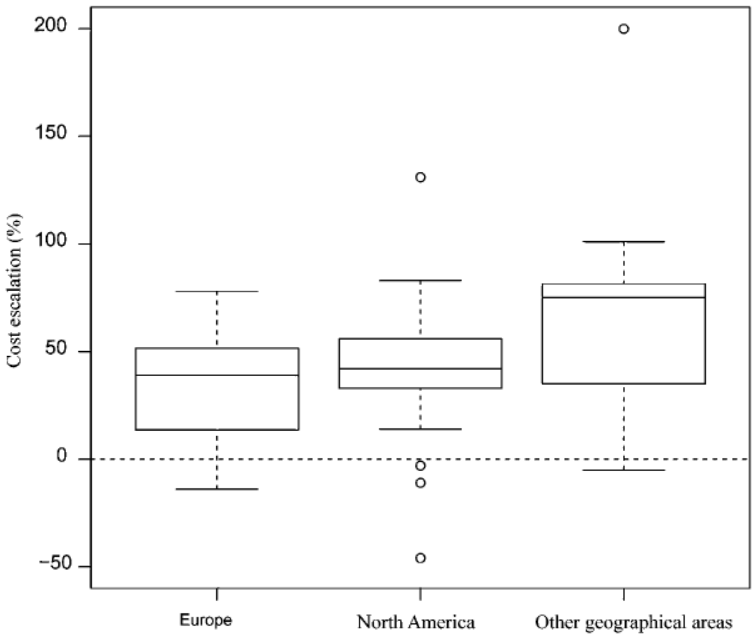


Figure 2-3: Box Plot of Cost Escalation for Rail According to Geographical Area (Flyvbjerg et al. 2003)

Flyvbjerg et al**.** (2003) also studied cost performance over time. Figure 2-4 shows cost escalation against year of decision to build on 111 projects. This diagram does not indicate a time trend, suggesting that cost performance is not improving.

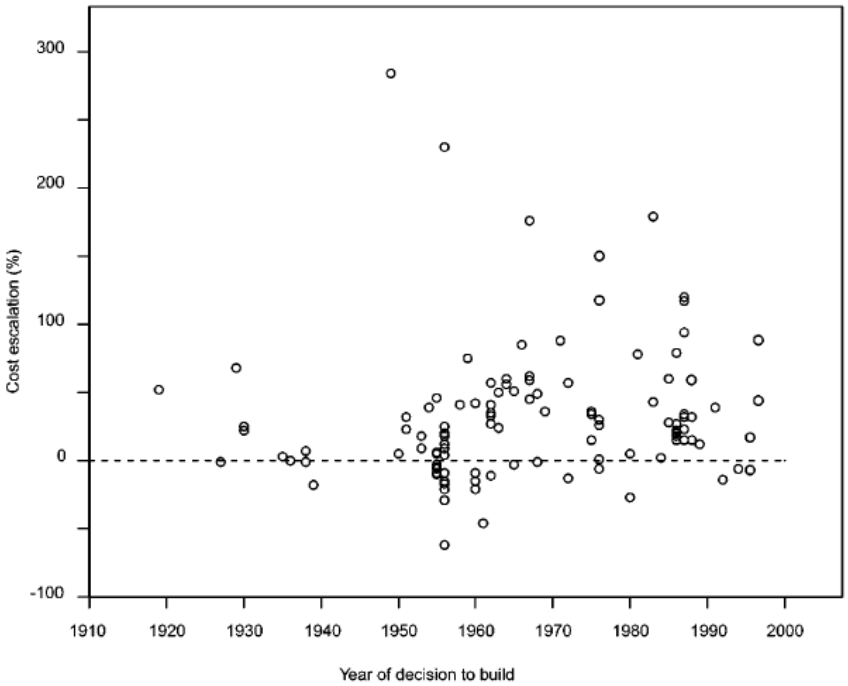


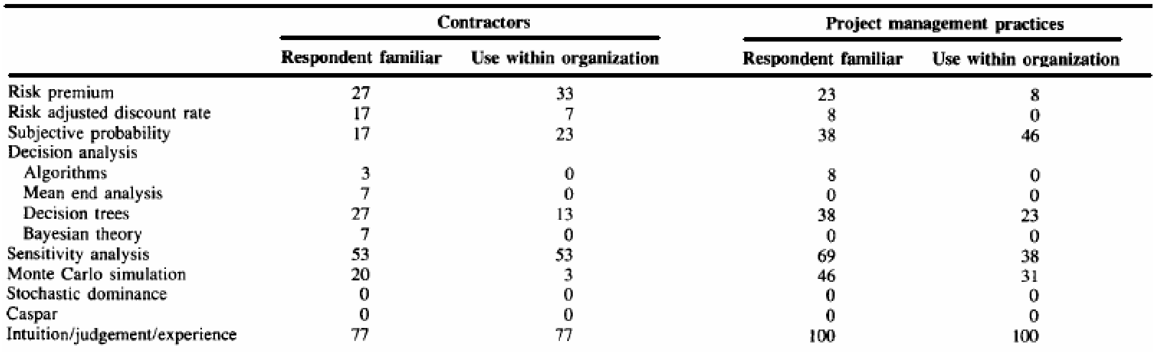
Figure 2-4: A Century of Cost Escalation (Constant Prices) (Flyvbjerg et al. 2003)

These reports are a few examples of the performance record of infrastructure projects; it seems that the use of unrealistic cost estimates and project schedules are common in the industry. It is necessary to understand the reasons of this systematic problem and more importantly to devise a risk analysis methodology to decrease the adverse consequences of cost overruns and delays, for example, the reduction of legal disputes and economic penalties.

2.3 Risk Analysis in Practice

There are several available techniques to perform project risk analysis, such as risk premium, risk adjusted discount rate, subjective probability, decision analysis, sensitivity analysis, Monte Carlo simulation, stochastic dominance, and intuition. In a research survey that involved contractors and project management practitioners of the top

100 firms in the UK Table 2-1, it is shown that the use of risk analysis for this industry is low with the exception the of intuition and judgment (Akintoye and MacLeod 1997).



	Contractors		Project management practices	
	Respondent familiar	Use within organization	Respondent familiar	Use within organization
Risk premium	27	33	23	8
Risk adjusted discount rate	17	7	8	0
Subjective probability	17	23	38	46
Decision analysis				
Algorithms	3	0	8	0
Mean end analysis	7	0	0	0
Decision trees	27	13	38	23
Bayesian theory	7	0	0	0
Sensitivity analysis	53	53	69	38
Monte Carlo simulation	20	3	46	31
Stochastic dominance	0	0	0	0
Caspar	0	0	0	0
Intuition/judgement/experience	77	77	100	100

Table 2-1: Techniques of Risk Management, % of Respondents (Akintoye and MacLeod 1997)

Table 2-1 shows that most respondents are familiar only with sensitivity analysis followed by decision trees, risk premium, Monte Carlo simulation (MCS) and subjective probability. It is also observed that almost all organizations depend on intuition and judgment. Some of the reasons that explain the lack of use of these techniques include:

- The degree of sophistication involved in techniques is unwarranted for project performance
- Risk analysis studies are seldom formally requested by clients
- Lack of expertise in the techniques
- The time needed plus lack of information and knowledge
- Difficulty to see the benefits

Another survey on risk management of software development and high-tech industrial projects (Raz and Michael 2001) claims that tools that are normally associated with risk management, such as decision trees, fault tree analysis and influence diagrams, were reported to be seldom used. This survey also recognizes that simulation is the tool that ranks the highest as a contributor to project risk analysis.

It is clear that there is a need to establish procedures and methodologies that are not only easy to implement in a project management but also provide clear results that show the benefits of their implementation. Due to the large quantity of work items and the characteristics of software that stores the project data, we anticipate the use of Monte Carlo simulation in our research.

2.4 Bias, Risk Attitude and Expert Opinion

In order to model the uncertainty that affects the model variables the analyst generally makes use of expert opinion. Risk analysis models almost invariably make use of subjective estimation. There are several reasons that make it almost impossible to obtain all the required data for determining the uncertainty of the variables; some of these reasons include (Vose 2000):

- The data have simply never been collected in the past
- The data are too expensive to obtain
- Past data are not longer relevant
- The data are sparse, requiring expert opinion to fill the gaps
- The area being modeled is new

For these reasons it is important to understand the nature of human decision-making and most importantly consider what influences the capacity of making sound decision.

2.4.1 The nature of human judgment: bias and risk attitude

Judgments and decisions are made based on information that has been processed by the individual in charge of these endeavors; however several studies have shown that people are inconsistent and biased in the process of interpreting information (Cooke 1991; Kahneman et al. 1982; Raiffa 1993; Terrell 1998).

In (Birnie and Yates 1991) it is stated that in the construction industry the following biases are likely to be present:

- Representativeness: People attach much more significance to certain cues than to others. Estimators may see a similarity to an item of construction in a previous contract and the extent of this similarity becomes the dominant factor in the probability assessment of duration and cost; however it does not consider differences in quantity, physical location, or market conditions.
- Availability: Because of limited memory, people depend on associations which are not reliable. For example, a previous experience of material shortage or delays caused by inclement weather will influence estimations and decisions; this happens because these actions will be based on pieces of information rather than an objective consideration of all available data.
- Adjustment and anchoring: When using a previous piece of information as an anchor point and then adjusting it to take account of any special features, this type of bias affects estimation accuracy. The estimation could result in a biased prediction because of an unsuitable anchor point or insufficient adjustment of anchor point. The authors also point out that this

bias can also lead to the incorrect evaluation of compound events.

In (Mak and Raftery 1992; Raftery 1994), the authors investigate the presence of systematic bias and the effects of risk attitude in estimation and forecasting in construction projects. According to the authors there are two groups of reasons that introduce biases into estimates:

- The first one stems from common rules of thumb (or heuristics) and biases in the cognitive processes of human beings making judgments and forecasts
- The second source of error and bias comes from the tendency to make unrealistic simplifying assumptions. This tendency to assume away real world uncertainty and to assume that estimates and forecasts are deterministic numbers.

In this research, the authors formulated a questionnaire related to cost estimation of construction projects; the questionnaire was designed to test representativeness, availability and anchoring and adjustment on 62 final year undergraduate quantity surveying students. The results of the study demonstrate that the subjects tended to be less prone to making judgments than might been expected from the literature on bias; the statistical analysis results were not conclusive in whether the subjects adopted the heuristics or not. It is noticeable that general methodological problems are present since the subjects have some expertise in the domain, therefore they are likely to notice if information, although available, is incorrect. This observation made the authors argue that domain-specific experts should not demonstrate a generalized tendency to adopt the availability bias. The authors also recognized that optimistic and pessimistic project cost estimates are a function of the risk attitude of the forecaster; they also argue that it is more likely that the decision maker attitude will be different than the forecaster's. This may lead to biased decisions even though if the decision adjusts for the bias of the forecaster; this happens because of the nature of the adjustment, which is likely to be quite arbitrary and thus may also result in bias.

Figure 2-5 shows the potential disagreement when the people adopt conservative forecasting as a method of coping with certain types of managerial control of professional work. In this figure, the estimator does not report his/her most likely cost estimate from his/her cost distribution; instead he/she reports an extremely conservative cost estimate "X" evidencing his/her tendency to be markedly risk averse. The manager on the other hand receives that number ("X") assuming that it is the most likely value of the estimator's distribution. The manager in order to mark-up the cost will calculate the associated risks to secure work at favorable rates for the firm causing the bias.

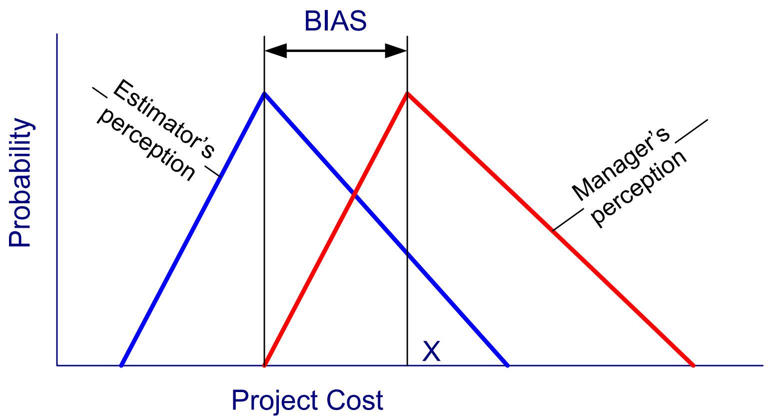


Figure 2-5: Forecasting Bias. Adapted from (Mak and Raftery 1992; Raftery 1994)

As it has been constantly acknowledged throughout this dissertation, risk analysis and management in infrastructure projects depend heavily on intuition, judgment and experience; therefore special attention should be given to the calibration and assessment of estimates given by experts. The following section will deal with this topic.

2.4.2 Experts

Experts’ judgment provides valuable information for risk analysis especially when hard data are not available or are too costly to acquire. Risk analysis studies use probabilistic distributions to represent uncertainty; therefore when expert opinion is needed in this area, it should be expressed in terms of probability estimates or distributions.

When expert opinion is in a quantitative form it can be considered as data. When eliciting this data we should keep in mind that the elicitation process used has a great impact on the quality of it. Clemen and Winkler (1999) recommend that the elicitation process should be designed and conducted not only by a team of individuals that are knowledgeable in the substantive issues of interest but also knowledgeable about probability.

Cooke (1991) emphasizes that the fundamental goal of science is to build consensus and therefore the following five principles should be considered when collecting expert assessments:

- *Reproducibility*: All results must be reproducible, with calculation models and data being clearly specified and made available.

- *Accountability*: The source of data (name and institution) must be identified, and data must correspond to the exact source from which the data are elicited.
- *Empirical Control*: Experts’ assessments must be, in principle, physically observable.
- *Neutrality*: The elicitation process must ensure that the actual beliefs of experts be collected (e.g., no punishment or rewards through a self-rating system).
- *Fairness*: All experts must be regarded equally before the aggregation process.

When eliciting expert opinion, we usually ask for the uncertainties over a number of calibration variables. Each expert gives percentile information for the uncertainty distributions for each of his/her calibration variables. For example, this elicitation can be performed using four intervals 0% to 5%, 5% to 50%, 50% to 95%, and 95% to 100%.

If an expert is “well calibrated”, 5% of the realizations of his/her calibration variables should fall in his/her corresponding 0% to 5% interval, 45% of the realizations should fall in his/her corresponding 5% to 50% intervals, etc. In other words, a well-calibrated expert is someone that when he or she states a probability p over the set of variables, a proportion of events p actually occurs. Following this concept the quality of the information can be measured by comparing the empirical distribution given by the calibration variables against the distribution given by the expert.

Vick (2002) explains calibration as one measure of overconfidence bias in the relationship of subjectivity assigned probabilities to measured long-run frequencies of the same occurrence, and overconfidence as the tendency for people to be more sure about uncertain occurrences than they should be. In terms of assigning subjective probabilities for single event occurrences, the overconfidence bias is manifested as assigning values too extreme at either end of the probability scale [0 or 1]. For continuous variables, overconfidence promotes probability distributions that are too narrow with insufficient dispersion about the mean. Vick considers that overconfidence bias as the most persistent and tenacious form of bias in subjective probability estimation. Lichtenstein et al. (1982) states that overconfidence exists when *“the proportions correct [in a set of assessments] are less than the assessed probabilities”*.

Fischoff (Vick 2002) reported one experiment in which three groups of subjects were asked to answer different kinds of questions and to provide their subjective probabilities that each answer was correct. The first set of questions involved the judgment of which two lethal events occurred more frequently (i.e., drowning or bee stings) and were given to two groups. The third group received general knowledge questions (i.e. whether potatoes are native to South America or Europe). Each group consisted of 40 to 60 graduate students and 13,000 answers in total and subjective probabilities were collected. Figure 2-6 shows the corresponding subjective probabilities of error against actual error frequencies. The observed results provide insight into several aspects. First, the type of question seemed to make little difference, and the three groups’ responses were fairly tightly bounded. The respondents were well calibrated only within a rather small probability range from 0.2 to 0.5. Below this range, overconfidence bias was demonstrated by the actual error frequencies that were higher than estimated error probabilities.

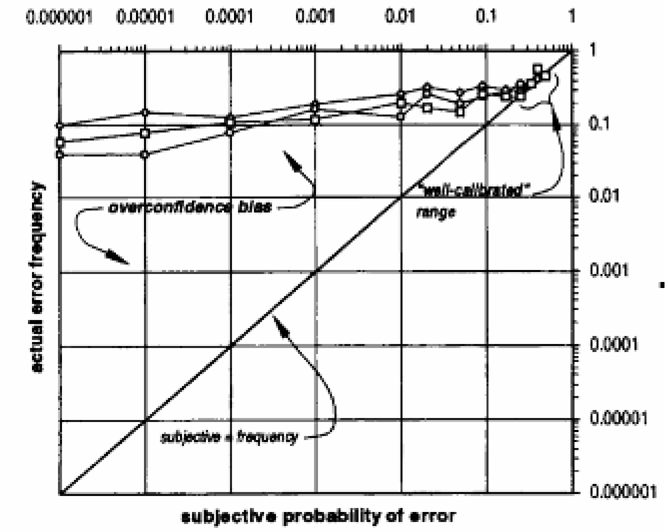


Figure 2-6: Overconfidence Bias and Calibration

Source: Experimental Data from Fischhoff (Vick 2002)

2.4.3 Calibration and aggregation of expert opinion

Several researchers have developed mathematical models not only to calibrate the estimates given by experts but also to combine them. Calibration models can be found in (Bedford and Cooke 2001; Bhola and Cooke 1992; Cooke 1991; Lichtenstein et al. 1982; Mendel and Sheridan 1989; Meyer and Booker 2001; Wiper et al. 1994)

In most of the cases, by having a variety of data sources or available experts, it is expected that these different sources would disagree when trying to give a probability assessment on a variable of interest. The disagreement comes from a variety of reasons that include different analytical methods, different information sets, or different philosophical approaches. In the other extreme, if experts do not disagree there would be no point in consulting more than one. Clemen and Winkler (1999) claim that the fundamental principle that underlies the use of multiple experts is that they can provide more information that a single expert.

The aggregation of expert opinion is classified in two groups: mathematical and behavioral combination methods. In the mathematical approach, expert opinions are expressed in terms of subjective probability in order to produce a single combined probability distribution. On the other hand, the behavioral approach tries to generate a group consensus among the participants through interaction. Examples of expert opinion aggregation models can be found in (Bier 2004; Clemen 1987; Clemen and Winkler 1999; DeGroot and Mortera 1991; French 1981; Genest and Zidek 1986; Goossens et al. 1998; Jouini and Clemen 1996; Kahn 2004; Kallen and Cooke 2002; Linstone and Turoff 1975; Morris 1974; Morris 1977; Morris 1983; Mosleh and Apostolakis 1986; Mosleh et al. 1988; Ouchi and World Bank. 2004; Pulkkinen 1993; Pulkkinen 1994; Winkler 1968; Winkler 1981; Worsham 1980).

In the construction industry it is an accepted practice to provide three point estimates for cost and time of work packages; these points represent the optimistic, the most likely and pessimistic estimates. These data allow the analyst to define a probabilistic distribution that can be used in the schedule and cost risk analysis of the project.

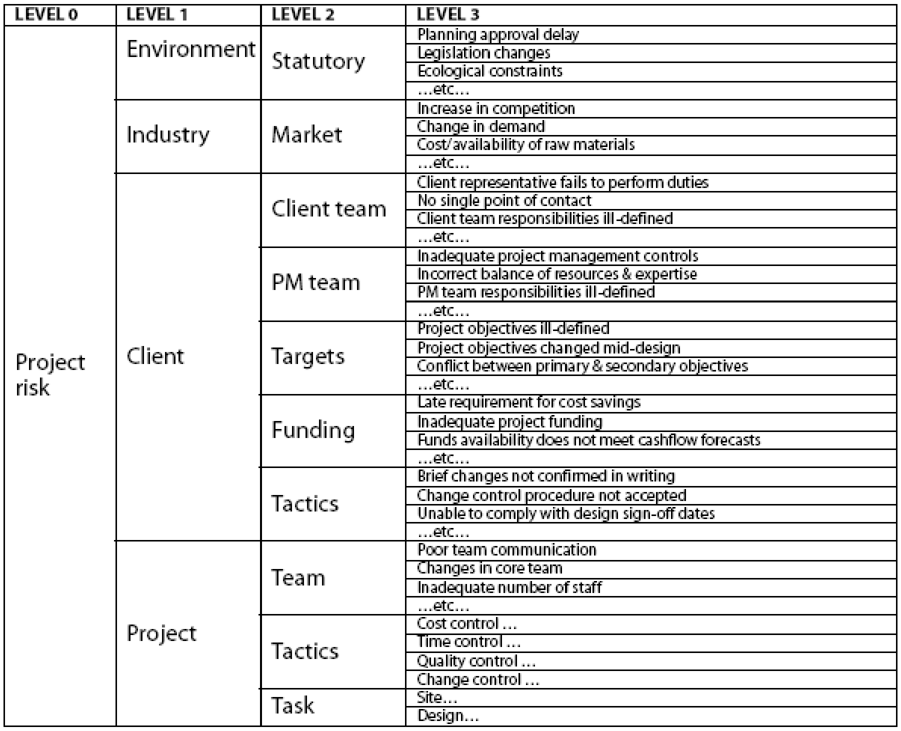
Although the elicitation of cost and time estimates in construction is familiar to many practitioners, no evidence of attempts to assess and score the quality of these estimates has been found in literature related to project risk analysis. It is expected that by using calibration and aggregation methodologies that fit with organizational operations, more reliable data can be used in risk analysis studies.

2.5 Project Risks

It is recognized that construction industry operations are plagued by risk (Flanagan and Norman 1993), however often risk has not been dealt adequately, resulting in poor performance with increased costs and time delays.

An important step in managing risk is the risk assessment process, where risks that affect the project are identified and then categorized. According to the PMBOK (Project Management Institute 2004) risk categories provide a structure that ensures a comprehensive process of systematically identifying risk to a consistent level of detail and contributes to the effectiveness and quality to the risk identification process. This publication recommends the use of a risk breakdown structure (RBS), where risks are classified under the following groups: Technical, External, Organizational, and Project Management. Examples of RBS's for different types of projects are described in more detail in (Hillson 2002). Hillson author states that a RBS is a powerful aid to risk identification, assessment, and reporting; the ability to roll-up or drill-down to the appropriate level provides new insights into overall risk exposure on the project.

The following table, for example, classifies project risks for the construction design industry.



LEVEL 0	LEVEL 1	LEVEL 2	LEVEL 3
Project risk	Environment	Statutory	Planning approval delay
			Legislation changes
			Ecological constraints
			…etc…
	Industry	Market	Increase in competition
			Change in demand
			Cost/availability of raw materials
			…etc…
	Client	Client team	Client representative fails to perform duties
			No single point of contact
			Client team responsibilities ill-defined
			…etc…
		PM team	Inadequate project management controls
			Incorrect balance of resources & expertise
			PM team responsibilities ill-defined
			…etc…
		Targets	Project objectives ill-defined
			Project objectives changed mid-design
			Conflict between primary & secondary objectives
			…etc…
		Funding	Late requirement for cost savings
			Inadequate project funding
			Funds availability does not meet cashflow forecasts
			…etc…
		Tactics	Brief changes not confirmed in writing
			Change control procedure not accepted
			Unable to comply with design sign-off dates
			…etc…
	Project	Team	Poor team communication
			Changes in core team
			Inadequate number of staff
			…etc…
		Tactics	Cost control …
			Time control …
			Quality control …
			Change control …
		Task	Site…
			Design…

Table 2-2: RBS for Construction Design (Chapman 2001)

Tah et al. (2001) present another example of classification of risks in construction projects using a hierarchical risk-breakdown structure (HRBS). The HRBS allows risk to be separated into those that are related to the management of internal resources and those that are prevalent in the external environment; moreover, the use of this hierarchical basis enables risk grouping for better cause-effect determination. Authors assert that external risks are relatively uncontrollable while internal factors are more controllable and vary between projects. Some of the internal factors are local to individual work packages within a project, whereas others are global to an individual project and cannot be associated with any particular work package. The figure below depicts a HRBS for a construction project.

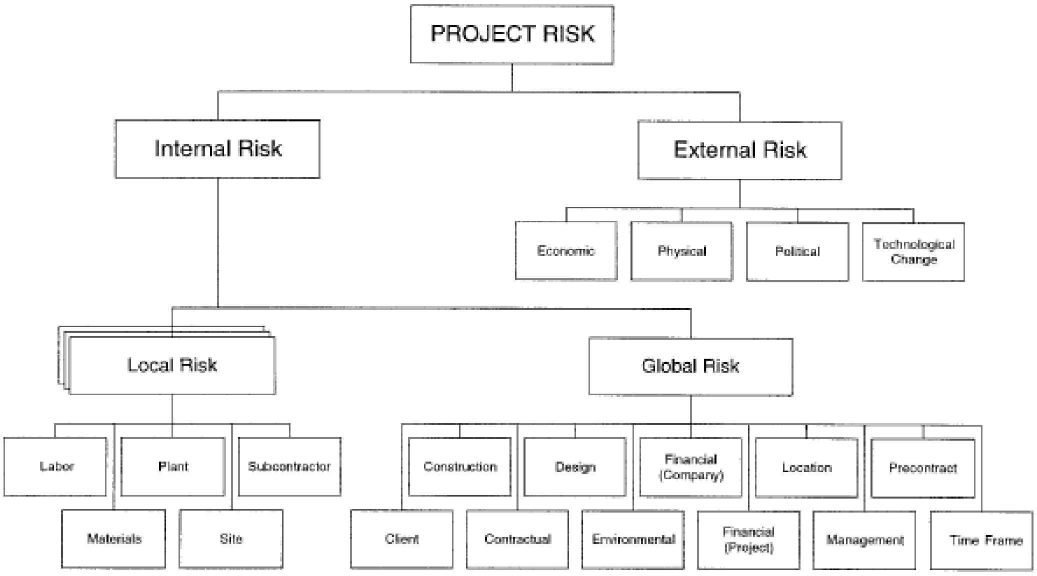
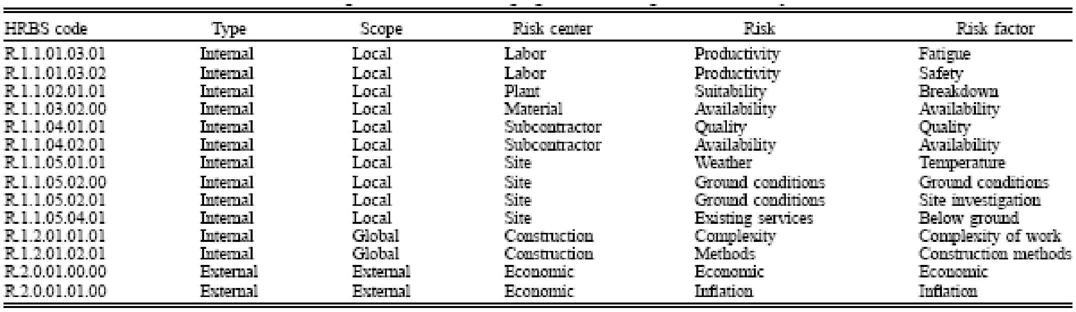


Figure 2-7: HRBS of a Construction Project (Tah and Carr 2001)

Another important definition presented by the previous authors is that risk factors do not affect project activities directly, but do so through risks. The distinction made between risk and risk factors allows one to make assumptions that risks are triggered by risk factors.

Risk factors are more concrete abstractions of the risk and define situations that can be individually assessed with a limited amount of information. HRBS makes use of a risk catalogue; where the collection of risks has been define using a common language and a hierarchical structure. As an example, Table 2-3 shows a part of a construction project risk catalog example.



HRBS code	Type	Scope	Risk center	Risk	Risk factor
R.1.1.01.03.01	Internal	Local	Labor	Productivity	Fatigue
R.1.1.01.03.02	Internal	Local	Labor	Productivity	Safety
R.1.1.02.01.01	Internal	Local	Plant	Suitability	Breakdown
R.1.1.03.02.00	Internal	Local	Material	Availability	Availability
R.1.1.04.01.01	Internal	Local	Subcontractor	Quality	Quality
R.1.1.04.02.01	Internal	Local	Subcontractor	Availability	Availability
R.1.1.05.01.01	Internal	Local	Site	Weather	Temperature
R.1.1.05.02.00	Internal	Local	Site	Ground conditions	Ground conditions
R.1.1.05.02.01	Internal	Local	Site	Ground conditions	Site investigation
R.1.1.05.04.01	Internal	Local	Site	Existing services	Below ground
R.1.2.01.01.01	Internal	Global	Construction	Complexity	Complexity of work
R.1.2.01.02.01	Internal	Global	Construction	Methods	Construction methods
R.2.0.01.00.00	External	External	Economic	Economic	Economic
R.2.0.01.01.00	External	External	Economic	Inflation	Inflation

Table 2-3: Fragment of Common Language for Describing Construction Project Risks (Tah and Carr 2001)

Diekmann and Featherman (1998) argue that internal uncertainty and external uncertainty have different impacts on project cost. Internal uncertainty is caused by incompletely defined estimating parameters and it is associated with items listed in the cost breakdown structure. Examples of this type of uncertainty are subsurface conditions, incomplete knowledge of pricing or market conditions, etc.

External uncertainty, on the other hand, arises from risks that are beyond the project scope; examples are regulatory or macro-economic changes in governmental policies. Internal uncertainty is best characterized by specifying a feasible range of values and probability distributions, while external uncertainty is more appropriate modeled by assessing the likelihood of that event happening or not.

Beeston (1986) presents a different approach to classify project risks. He classifies them as fixed risks and variable risks. According to his interpretation these two types of risks have to be treated differently in terms of the allowance that is allocated to each type. A risk allowance is a sum of money that is allocated to work packages that are likely affected by risks.

A fix allowance is a sum of money which will either be incurred as a whole, with an estimated probability, or not at all. A variable risk allowance can occur to varying degrees so no fixed sum of money can be allocated to it.

In Akintoye's research survey (1997), the construction practitioners consider financial and contractual risks as the most important ones. The risk consequences or implications of contractual risk include claims and disputes, disruption of work, stoppages of work, lack of coordination, delays, and inflated cost.

Financial risk to the contractor includes whether the project owner has enough money to complete the project, financial failures of the client or subcontractors, availability of money, etc. Financial risk influences the cash flow of construction contractors. Examples of construction risks are, for example, availability and productivity of labor, soil and site conditions, material shortages and quality, site safety, etc.

The different risk classification approaches are helpful when analyzing and assessing the effects of risk on project performance. We anticipate that in the development of our risk analysis model, it will be necessary to use a combination of these methodologies to account for all significant and appropriate risks affecting the project.

2.6 Modeling Uncertainty

The most common way to model uncertainty it the use of probability density distributions (PDFs) that can be incorporated in risk analysis models. For example, a Monte Carlo simulation model makes use of probability distributions for cost and/or duration of work packages; the model then defines a PDF for the total cost and/or duration of the project where the probability of meeting certain targets can be evaluated.

If data are available, PDFs can be approximated using general techniques such as the method of moments (NRC U.S. Nuclear Regulatory Commission, 1989), maximum likelihood estimators (MLE), and ordinary least squares (OLS) methods. On the other hand, data are not always available, so subjective estimates of PDFs can be considered for risk analysis models. It is necessarily important to acknowledge the importance of subjectivity; even if objective data form the basis of a forecast, judgments are exercised in the various adjustments that are made to produce the estimate for the project being considered (Fellows 1996).

It is important to mention though, the great impact of input probability distributions on the quality of the output of a risk assessment model, so careful attention should be give to the selection of PDFs to be used and most importantly to their parameters. The coherence of subjective probabilities is ensured by converting subjective estimates to moments and shape characteristics of the input variable.

In the construction industry several PDFs are considered adequate for modeling activities duration and construction operations, as well as cost of work packages. Probability distributions for activity durations include Beta, Triangular, Normal, and Uniform distributions; for cost Lognormal, Triangular, Pearson-type and Beta distributions are the preferred.

Although several studies have compared the use of different distributions in risk assessment models, results present mixed opinions. For example, Fente et al.(2000) claims that most of the construction data sets lay in the beta region, therefore he presents a methodology for the estimation of the beta parameters. Conversely, Wilson et al. (1982) studied the use of beta vs. triangular distributions on ground operations concluding that there were not significant differences in the simulation outputs. More details on the determination of beta parameters for construction operations can be found in (Schexnayder et al. 2005).

Another example presented in (Touran 1997), where results of sensitivity studies of the use of normal and lognormal PDFs on tunneling operations, did not show any statistically significant difference in the predicted mean completion time. Maio et al. (2000) studied the effects on simulation results of different PDFs for construction simulation models. That study uses beta PDFs to define probabilistic duration of construction activities.

Back et al. (2000) studied the determination of triangular distributions from historical cost data. The authors claim that beta and triangular distributions are the most suitable, however, due to the more complicated process of the calculation of the beta parameters and its variety of shapes, the triangular distribution is preferred.

Referring to subjective probability estimation, Chau (1995b) studied the validity of the triangular distribution assumption in simulation of construction costs. His investigation concluded that the practice of assigning subjective values as parameters of this type of distribution causes an upward bias in the cost estimate. The error caused by the use of this probability distribution creates a systematic upward bias of approximately 20%. In another study by the same author (Chau 1995a), it is proposed the use of a log-triangular distribution as a way to reduce the bias introduced by the typical triangular distribution. This distribution is an exponential transformation of the triangular distribution and is still determined by the three-point estimate.

Examples of procedures for elicitation of subjective probabilities for project risk analysis can be found in (Abourizk and Sawhney 1993; Lau and Somarajan 1995; Ranasinghe and Russell 1993).

2.7 Qualitative Project Risk Analysis

Qualitative approaches in project risk analysis are very popular among project management practitioners due to their easy implementation and communication of results to other project participants. After the identification of potential risks a "risk register" is created. The general procedure first assesses qualitatively the probability of occurrence of each risk and then its consequences on project performance. For example, the following table assigns a score to the qualitative probability of risk occurrence.

Likelihood	Score
Not Likely	1
Low Likelihood	2
Likely	3
High Likely	4
Near Certainty	5

Table 2-4: Qualitative Risk Likelihood Assessment

In a similar way the consequence of certain risk on project schedule, cost and technical performance can be also evaluated as follows:

Schedule	Cost	Technical	Score
Minimal or no impact	Minimal or no impact	Minimal or no impact	1
Additional activities required; able to meet key dates	Budget increase <1%	Minor performance shortfall, same approach retained	2
Minor schedule slip; will miss need date	Budget increase <5%	Moderate performance shortfall, but workarounds available	3
Project critical path affected	Budget increase <10%	Unacceptable, but workaround available	4
Cannot achieve key project milestone	Budget increase >10%	Unacceptable, no alternatives exist	5

Table 2-5: Qualitative Risk Consequence Assessment

Once the occurrence probability and consequences of each risk are scored they can be mapped into a matrix where the importance of each one can be evaluated. An example of that is depicted in the figure below.

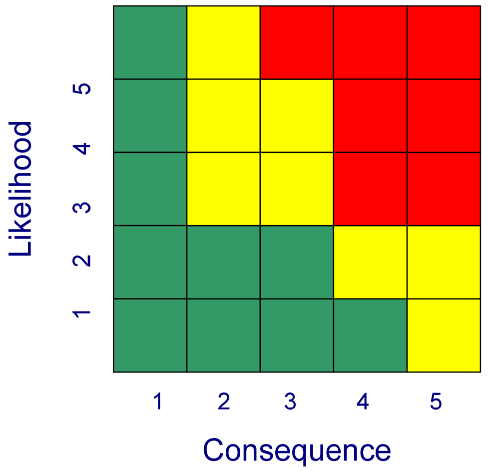


Figure 2-8: Importance Matrix for Qualitative Risk Analysis

Figure 2-8 provides a way to rank the importance of each risk affecting the project. For example, risks that fall in the upper right area of the matrix are the ones to be considered critical and need to be investigated in order to avoid undesirable results on project performance targets; conversely, risks mapped in the lower left area of the matrix are less critical. The benefits of this methodology are visible for risk prioritization and communication; however, it is limited when assessing and planning for consequences in terms of money and time. A qualitative analysis is an important input for quantitative risk analysis, which is discussed in the following section.

Examples of qualitative risk analysis methodologies can be found in (Cooper and Broadleaf Capital International. 2005; Project Management Institute 2004; Smith and Merritt 2002).

2.8 Quantitative Project Risk Analysis

Traditional methods of cost estimating and project scheduling are often oriented towards a deterministic approach and fail to address the inherent variability of the real world, for which a probabilistic methodology is better suited. With the current market conditions, it is not enough to have a good project plan, or even a proper monitoring and controlling system; organizations need to be prepared for project risks and be ready to do something about them (Raz et al. 2002).

Quantitative risk analysis uses probability distributions to represent the uncertainty in such measures of the project as the cost of a line-item in the cost breakdown structure or the duration of an activity in the project schedule. Since the inputs are uncertain, so are the outputs such as total project cost or completion date, that are also best represented as probability distributions. Quantitative risk analysis usually occurs after risk identification and qualitative risk analysis (risk prioritization after identification of risks). One reason for this phasing is that it is important to include all main project risks in the model of the project's cost and schedule (Hulett 2004).

Quantitative risk analysis is always recommended for large, complex or visible projects and may be tailored to smaller projects as necessary. Quantitative risk analysis is typically performed to examine the viability of the project cost or time objectives.

A project risk analysis will be able to respond to questions such as what the probability of finishing a project by a certain date or within a certain cost. It will also help to detect in advance the activities that are likely to be affected by project risks and more importantly allocate contingencies that will safeguard the cost and time objectives. This type of analysis will help us to obtain and distribute the required contingencies in a more educated and justified way than the traditional approach of assigning a percentage of the total cost. Moreover, a risk analysis model can give us important information about where in the project is the most risk, so special attention can be given to the critical areas of the project in order to maximize the opportunities for success.

Monte Carlo Simulation (MCS) is probably the most widely used method for this type of analysis. MCS generates a random sample of values to represent the derived variable whose uncertainty has to be quantified. From this random sample one can plot a cumulative distribution function (CDF) and estimate statistics such as the expected value, variance and higher moments. In a project management context this CDF could represent total cost or project duration.

In a simplistic cost risk analysis model, every cost component with a potential for variability is modeled as a random variable. The generated values and the constant cost figures (cost components that are considered to have no variability) are added up and a value for the total cost is computed. This procedure is repeated thousands of times so a cumulative distribution can be obtained. Although the procedure is simple, special attention should be given to the cost components that are correlated.

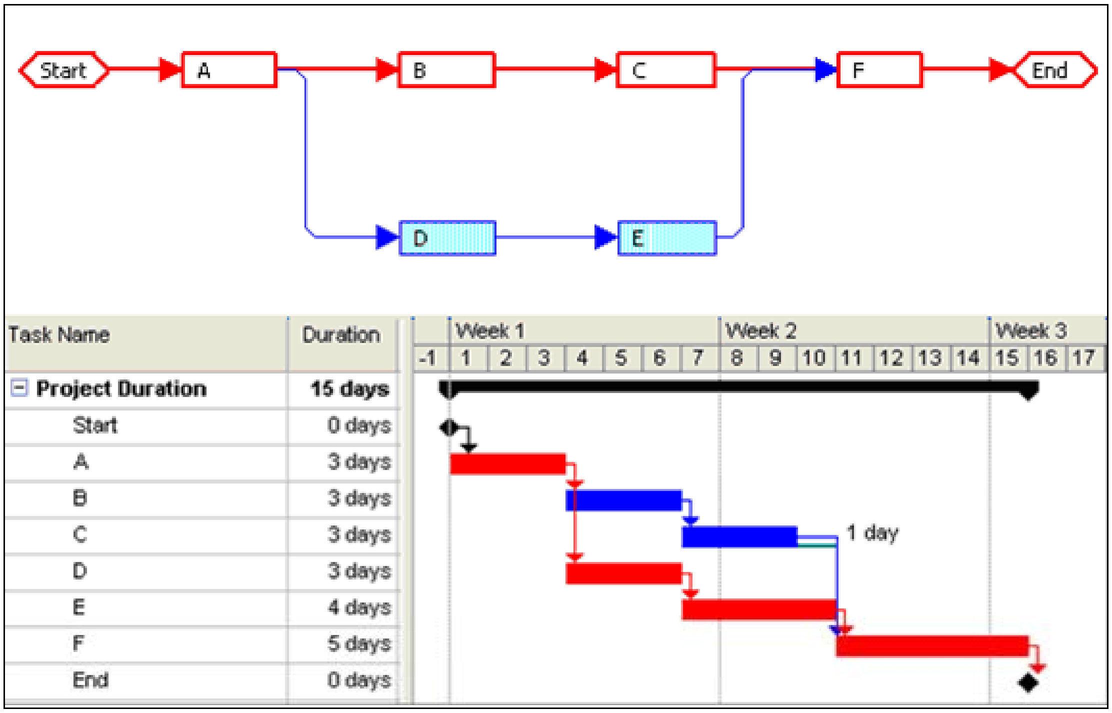
Analyzing schedule risk is somehow a little more complicated. This happens because of the precedence relationships among activities and constraints that are imposed by construction operations or availability of resources. We will refer to this in more detail in the following sections.

2.8.1 Schedule Risk Analysis

Project schedules can be displayed in a variety of ways such as Gantt charts, bar charts, and network diagrams. The later is considered as the most adequate in the construction industry since it shows the project activities and their precedence relationships and any constraints that affect their start and finish times.

The determination of the project duration is subjected to the individual activity durations and the network structure. The Critical Path Method (CPM), developed in the late 1950s by DuPont Inc., is largely used for determining the minimum completion time for a project as well as the start and finish times of each activity (Moder et al. 1983). The critical path represents the sequence or path of activities that take the longest to complete, and all activities along this path are termed critical activities. The length of the critical represents the minimum project duration. CPM however, conveys a sense of certainty in the estimation of activity and project duration.

CPM assumes that the duration of activities are deterministic, therefore the estimated project duration is deterministic. This assumption implies that activity durations can be estimated with certainty, which is not realistic as we have discussed in previous sections. The following figure presents an example of a small project network where activity durations and precedence relationships are shown. This example will be used to explain the rationale of schedule risk analysis throughout this section.



Task Name	Duration
⊟ **Project Duration**	**15 days**
Start	0 days
A	3 days
B	3 days
C	3 days
D	3 days
E	4 days
F	5 days
End	0 days

Figure 2-9: CPM Project Network

Figure 2-9 shows a project duration of 15 days with a critical path that includes activities A-D-E-F; this duration was calculated using the CPM.

As an improvement to quantify the uncertainty in activity durations and the project network, the Program Evaluation and Review Technique (PERT) was developed by the U.S. Navy in cooperation with Booz-Allen Hamilton and the Lockheed Corporation for the Polaris missile/submarine project in 1958 (Malcolm et al. 1959).

PERT estimates the expected value and variance of activity duration using an approximation of the beta distribution using a three point estimate *a*, *m*, and *b* for the calculation of the expected duration (T_i) and the variance, such as:

$$E\left(T_i\right) = \frac{a + 4m + b}{6} \tag{1.1}$$

$$Var\left(T_i\right) = \frac{\left(b - a\right)^2}{36} \tag{1.2}$$

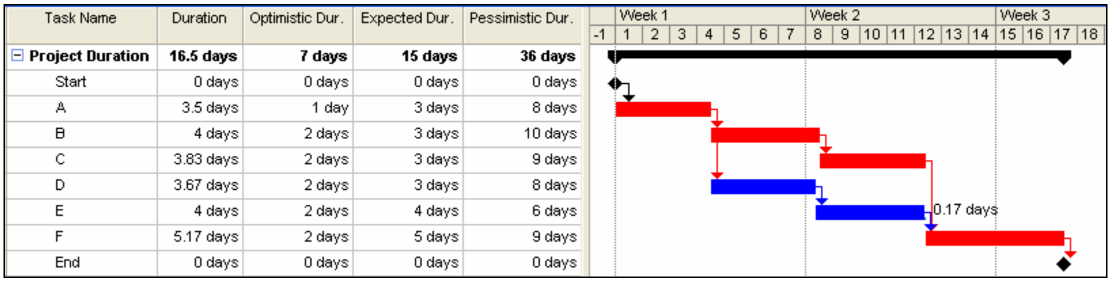
where, T_i is a random variable that represents the duration of activity *i*, *a* is the most optimistic time estimate (min), *m* the most likely, *b* the most pessimistic time estimate (max).

For illustrative purposes and in order to apply PERT, instead of using a single most likely estimate of the activity duration, the data shown in Figure 2-9 were modified so that for each activity an optimistic, most likely and pessimistic duration were assigned. It is assumed that these three point estimates capture the estimator's uncertainty of activity duration. The table below shows the calculated expected time and variance for each activity.

Activity	a	m	b	$E(T_i)$	$Var\ (T_i)$
A	1	3	8	3.50	1.36
B	2	3	10	4.00	1.78
C	2	3	9	3.83	1.36
D	2	3	8	3.67	1.00
E	2	4	6	4.00	0.44
F	2	5	9	5.17	1.36

Table 2-6: PERT Calculation of Project Network Example

Figure 2-10 shows the project network that results from the PERT calculation. It is noticeable that the expected project duration is now 16.5 days and that the critical path has changed; the new critical path includes activities A, B, C and F with a total variance of the 5.86 (assuming that activity durations are statistically independent). Path A-D-E-F has an expected duration of 16.3 days and a variance of 4.17. Assuming that activity durations are statistically independent from each other and applying the central limit theorem we can asses the probability of finishing the project within certain duration. For example, if we want to now what is the probability of finishing the project within 15 days (project duration calculated using CPM), we determine that there is only a 40% change of finishing the project within this time. With these results, we can observe that taking into consideration uncertainty in activity durations can dramatically change the results that are obtained in the CPM. For this example, it is important to note that using a normal distribution might not be accurate for such a small number of random variables.



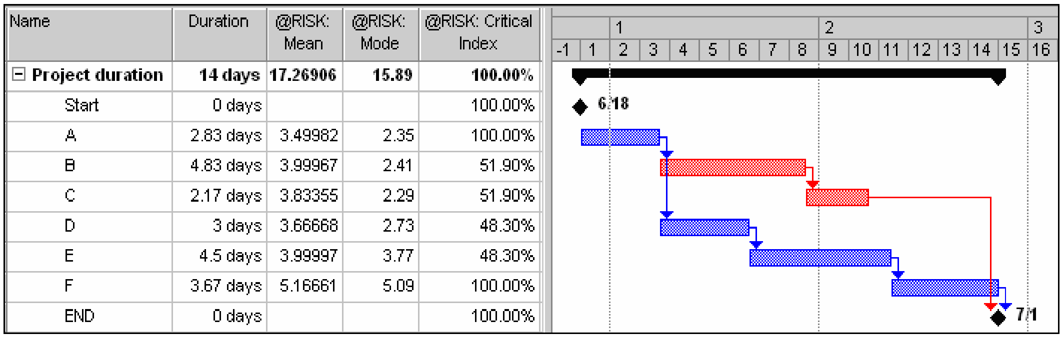
Task Name	Duration	Optimistic Dur.	Expected Dur.	Pessimistic Dur.
⊟ **Project Duration**	**16.5 days**	**7 days**	**15 days**	**36 days**
Start	0 days	0 days	0 days	0 days
A	3.5 days	1 day	3 days	8 days
B	4 days	2 days	3 days	10 days
C	3.83 days	2 days	3 days	9 days
D	3.67 days	2 days	3 days	8 days
E	4 days	2 days	4 days	6 days
F	5.17 days	2 days	5 days	9 days
End	0 days	0 days	0 days	0 days

Figure 2-10: Project Network Using PERT

Even though PERT represents an improvement over CPM, PERT presents some shortcomings. These shortcomings related to the estimation of activity durations are the simplifying assumptions in the approximation for expected value, which restrict the shape of the probability distribution to only one of three types, namely those of skewness

$\pm 1/\sqrt{2}$ or 0 (Ranasinghe 1994b). The drawback in the time estimation is the assumption that the project duration and its uncertainty can be determined by the longest path, this implies that the maximum expected value is assigned as the project duration disregarding paths that could have higher variances. Another limitation is that PERT assumes that activity durations are independent from each other, which it is not always true, for example when various activities are influenced by the same factor, their durations may be correlated.

More recent studies apply Monte Carlo Simulation (MCS) to overcome the limitations of deterministic methods (Elkjaer 2000; Lee 2005; Ranasinghe and Russell 1992a). Using randomly generated numbers to determine activity durations, a scenario that involves a random set of durations is recorded. Each scenario produces a deterministic CPM schedule. After several hundreds of iterations, the procedure produces a CDP of the project duration that provides information about its range of variability. Also, each scenario can save information on critical activities. Therefore, at the end of the simulation we can have an idea of how critical an activity is by using a metric called the Critical Index, which the percentage of time that an activity is critical in a MCS. Figure 2-11 shows results from our sample project network. Results were obtained by assigning PERT distributions for activity durations and applying MCS. Among the results, we can see that the Critical Index shows that there is almost an equal chance that both paths (A-B-C-E and A-D-E-F) are critical. This information is vital for the project manager; with this type of analysis he/she can be aware of this matter before project execution starts.



Name	Duration	@RISK: Mean	@RISK: Mode	@RISK: Critical Index
⊟ Project duration	**14 days**	**17.26906**	**15.89**	**100.00%**
Start	0 days			100.00%
A	2.83 days	3.49982	2.35	100.00%
B	4.83 days	3.99967	2.41	51.90%
C	2.17 days	3.83355	2.29	51.90%
D	3 days	3.66668	2.73	48.30%
E	4.5 days	3.99997	3.77	48.30%
F	3.67 days	5.16661	5.09	100.00%
END	0 days			100.00%

Figure 2-11: Monte Carlo Simulation Results for Project Network

The CDF of the project duration is depicted in Figure 2-12. If we assess the probability of finishing the project within 15 days (as given by CPM; see Figure 2-9), we determine that there is only a 17.6% chance of this happening.

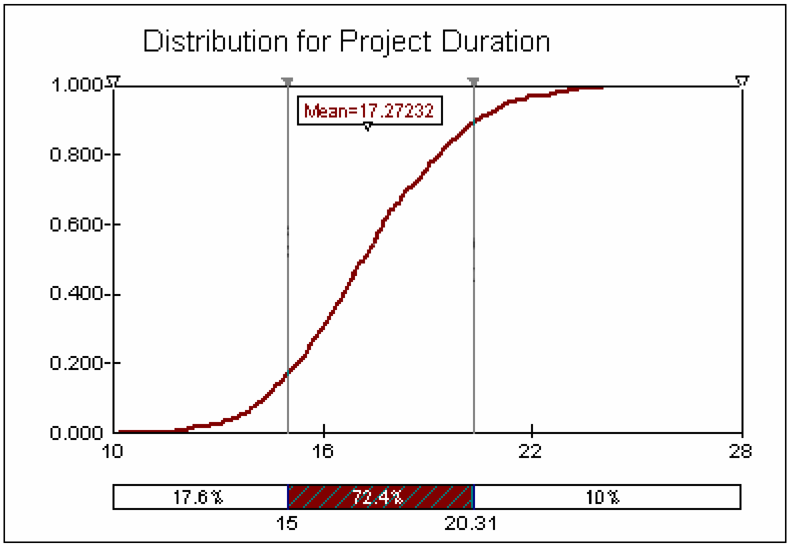


Figure 2-12: CFD Resulting from a MCS of the Project Network

Another advantage of using MCS is that the impact of possible changes in the topology of the project network can be assessed by implementing probabilistic and conditional branching. Examples of this type of analysis can be found in (Hulett 1996; Pollack-Johnson and Liberatore 2005; Pontrandolfo 2000). Probabilistic branching allows the project to branch from one task to any number of other tasks during the simulation; each of the task groups that could be branched has a probability value. Conditional branching (if/then type of conditions), on the other hand, allows for checking if certain conditions are true during a simulation, and if they are, to change values in the activities that are affected. As an example, if a certain activity takes longer than expected, we could make decisions such as increasing the resources in the other activities to avoid project delay.

In our example we have added an extra activity “X”, which has a 20% probability of being part of the project network; see Figure 2-13. A practical example of the application of probabilistic branching would be an activity that did not pass a quality test and has to be redone, therefore extending the project duration. The results obtained after performing MCS are shown in Figure 2-14; here the resulting bimodal PDF shows the importance of this analysis for planning and management purposes. The mean of the distribution is 21 days; however, the probability of finishing between 20 and 24 days is less than 10%.

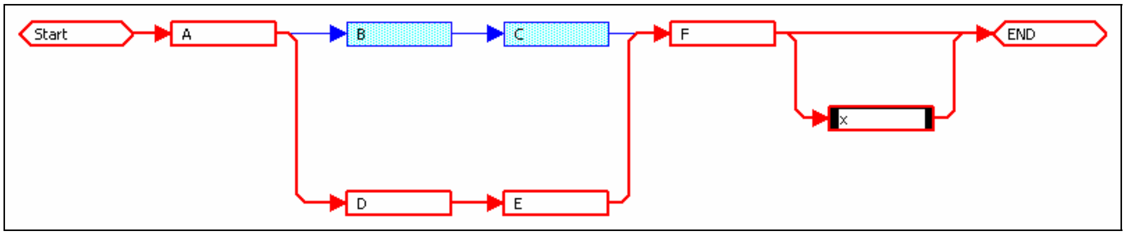


Figure 2-13: Project Network with Probability Branching

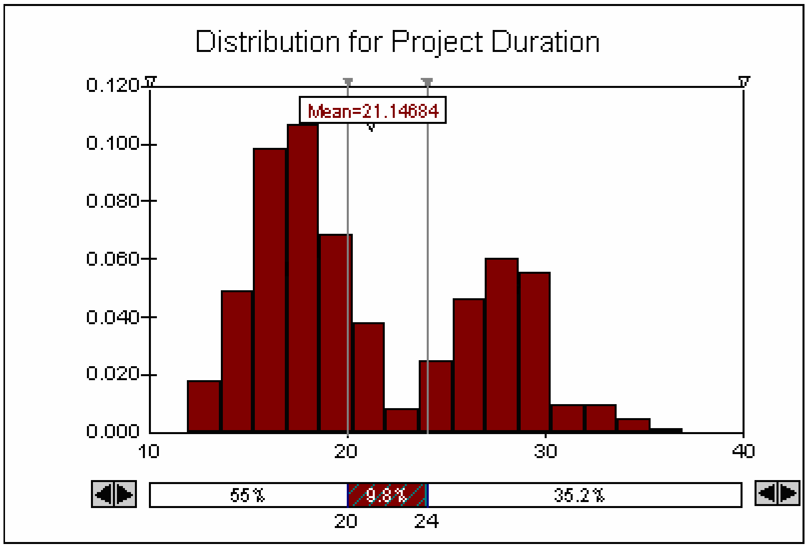
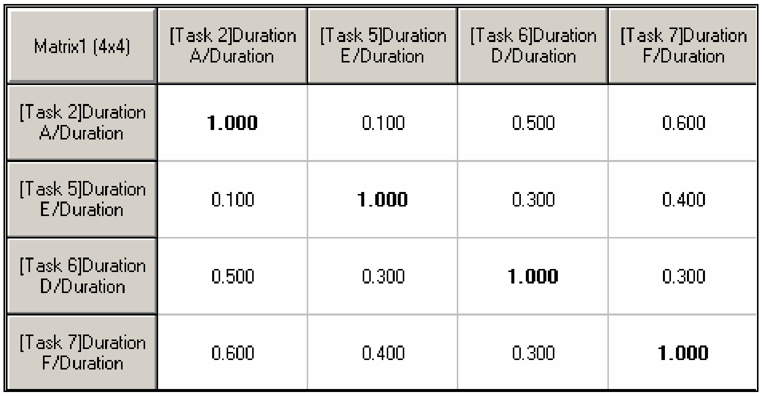


Figure 2-14: Project Duration PDF for Probabilistic Branching Example

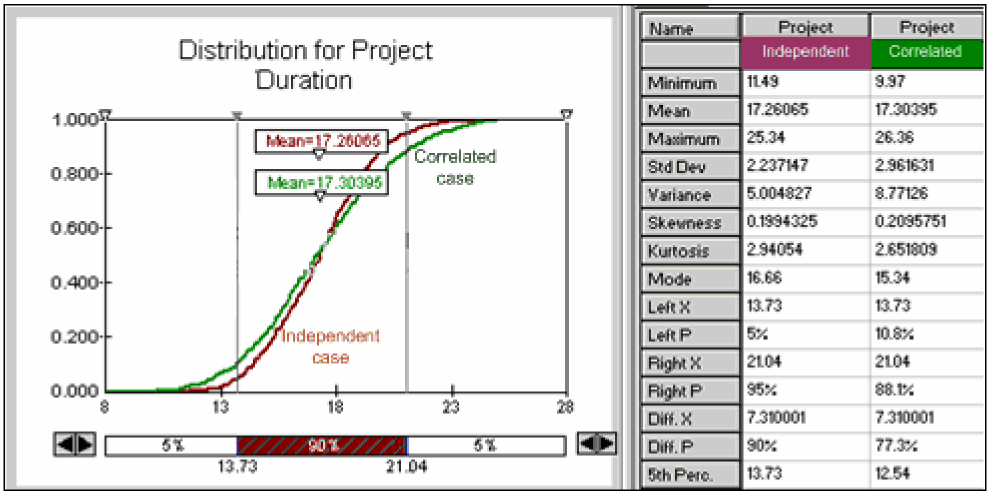
In construction projects, activities are often influenced by common factors such as weather, labor and site conditions, so their durations may be correlated (Wang and Demsetz 2000a; Wang and Demsetz 2000b). As an example, we have incorporated correlation among four activities in our project network: A, E, D and F. The following table shows the correlation coefficients used.



Matrix1 (4x4)	[Task 2]Duration A/Duration	[Task 5]Duration E/Duration	[Task 6]Duration D/Duration	[Task 7]Duration F/Duration
[Task 2]Duration A/Duration	**1.000**	0.100	0.500	0.600
[Task 5]Duration E/Duration	0.100	**1.000**	0.300	0.400
[Task 6]Duration D/Duration	0.500	0.300	**1.000**	0.300
[Task 7]Duration F/Duration	0.600	0.400	0.300	**1.000**

Table 2-7: Correlation Coefficients of Activities in Project Network

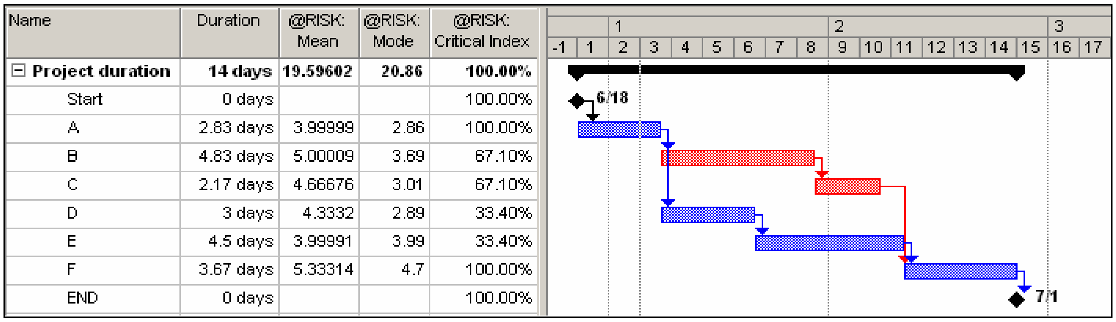
The impact of correlation can be observed in Figure 2-15. Failing to account for correlations among activities not only underestimates the variance of the project duration, but also can affect the parameters such as the mean and mode. For example, for the original project (no correlation considerations), the probability that the duration will be less or equal than 21 days is 95%, while for the correlated case this probability is only 88%. The treatment of correlations will be examined in more detail in the next section.



Name	Project	Project
	Independent	Correlated
Minimum	11.49	9.97
Mean	17.26065	17.30395
Maximum	25.34	26.36
Std Dev	2.237147	2.961631
Variance	5.004827	8.77126
Skewness	0.1994325	0.2095751
Kurtosis	2.94054	2.651809
Mode	16.66	15.34
Left X	13.73	13.73
Left P	5%	10.8%
Right X	21.04	21.04
Right P	95%	88.1%
Diff. X	7.310001	7.310001
Diff. P	90%	77.3%
5th Perc.	13.73	12.54

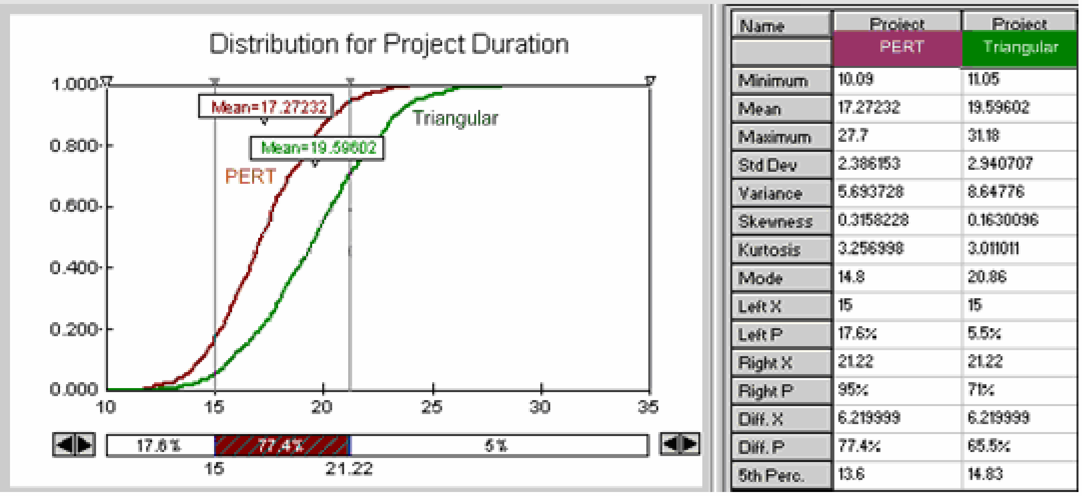
Figure 2-15: Project Duration’s CDFs Showing Effects of Correlation among Activity Durations.

As a final illustrative exercise, we have performed a sensitivity analysis in which we assessed the impact of using a different probability distribution to model uncertainty in project activity durations. Using triangular distributions with the same parameters (a, m and b) as the PERT distribution previously used, we obtained the following results:



Name	Duration	@RISK: Mean	@RISK: Mode	@RISK: Critical Index
⊟ **Project duration**	**14 days**	**19.59602**	**20.86**	**100.00%**
Start	0 days			100.00%
A	2.83 days	3.99999	2.86	100.00%
B	4.83 days	5.00009	3.69	67.10%
C	2.17 days	4.66676	3.01	67.10%
D	3 days	4.3332	2.89	33.40%
E	4.5 days	3.99991	3.99	33.40%
F	3.67 days	5.33314	4.7	100.00%
END	0 days			100.00%

Figure 2-16: Project Network Results Using Triangular Distributions to Model Activity Uncertainty



Name	Project PERT	Project Triangular
Minimum	10.09	11.05
Mean	17.27232	19.59602
Maximum	27.7	31.18
Std Dev	2.386153	2.940707
Variance	5.693728	8.64776
Skewness	0.3158228	0.1630096
Kurtosis	3.256998	3.011011
Mode	14.8	20.86
Left X	15	15
Left P	17.6%	5.5%
Right X	21.22	21.22
Right P	95%	71%
Diff. X	6.219999	6.219999
Diff. P	77.4%	65.5%
5th Perc.	13.6	14.83

Figure 2-17: CDFs of Project Duration for PERT and Triangular Distributions

The results from the figures above show the impact of the distribution chosen to model subjective estimates of activity durations. As we can see from Figure 2-17, there is a significant difference between the results obtained by the two models. We considered that picking the right probability distribution is subject of further study; however, it is not part of the scope of this dissertation.

Diaz and Hadipriono (1993) conclude that PERT is the simplest method and yields the most optimistic results, while MCS produce more conservative results. Other studies that are related to this subject include (Kamburowski 1997; Lau and Somarajan 1995; Nasir et al. 2003; Ranasinghe 1994b; Touran 1997).

2.8.2 Cost Risk Analysis

As mentioned before, traditional methods of cost estimating are often oriented towards a deterministic approach and fail to address the inherent variability of the real world. Quantitative cost risk analysis uses probability distributions to represent the uncertainty in components that are included in the cost breakdown structure. In a simplistic cost risk analysis model, every cost component with a potential for variability is modeled as a random variable. Individual cost components are added up through a MCS, so the total project cost, determined as a probability distribution, can be obtained.

In order to generate satisfactory results for the MCS cost model, there are two important aspects that have to be considered. The first is the choice of which distributions to use to represent input variables and second to include the dependency relationship among these variables.

Literature on the subject of cost risk analysis argues that probability distributions of cost components are unimodal and right-skewed and that the range of cost values must be positive. If costs are skewed to the right, it is implied that the most likely estimate is closer to the minimum estimate that to the maximum estimate. The reason for this is that there is a theoretical lower bound for the component's cost, which is determined by the minimum amount of resources required to construct the system. However, there is not a theoretical upper limit whose probability of occurrence is minimal.

It is also noticeable that in the construction industry the use of the three point estimates is common and well accepted when historical data are not available. Although there is not common agreement on which distribution is the best to model project costs, the distributions that are most often recommended are the triangular, beta and lognormal for both subjective estimation and historical data fits (Back et al. 2000; Chau 1995a; Chau 1995b; Touran and Suphot 1997; Wall 1997; Yang 2005).

When dependence exists, the estimated PDFs of the cost components variables are the marginal PDFs of the joint PDF of the component variables. The PDFs alone are not sufficient for estimating the PDF of total project cost. When positive dependence exists, the effect of assuming independence is underestimation of the variance of the system variables.

Chau (1995a) asserts that under the independence assumption, the single figure estimate of the system variable is almost guaranteed to be exceeded if the summation of the estimates is a large number of small subsystem variables. He also notes that this seems to contradict the conventional wisdom that subdivision of construction projects into smaller work packages facilitates cost estimation and improves accuracy.

In construction cost estimating the assumption of independence is usually adopted due to the difficulty of modeling dependence. The extent and nature of interdependence does not depend only on the specific project characteristics but also on the number of cost components and the way they are defined. In general, the larger the number of components, the higher the chance that dependence exists (Chau 1995a). The author notes that the bias resulting from the assumption of independence when dependence actually exists is a function of the nature and extent of dependence. One way to avoid correlation is to divide the system into fewer subsystems or by grouping correlated or independent subsystems into a single subsystem; however this strategy might complicate the estimation of subsystems if they are too large or complex.

There are various measures of dependence; among them, we can name the Pearson correlation coefficient and the non-parametric rank correlation coefficient (Spearman's correlation coefficient); the later being the most commonly used. The correlation represents the co-movement of two cost components; when one is more expensive, the other tends to cost more (or less for a negative correlation). Both correlation measures range from a value of -1 to 1. The value of 1 indicates perfect correlation while -1 indicates conversely perfect negative dependence. A value of 0 means no correlation.

There is a common agreement that the rank correlation coefficient is a better measure of dependence for construction costs since these costs are frequently not normally distributed; in addition the dependence between two components may be monotonic but not linear in which case the Pearson correlation is not a suitable measure. This issue is examined in more detail in (Chau 1995a; Ranasinghe 2000; Touran and Suphot 1997; Touran and Wiser 1992; Yang 2005)

Correlation data may be obtained by statistical analysis on historical data or by subjective judgment. Several studies on construction data show empirical results that clearly suggest the presence of cost correlation (Newton 1992; Touran and Suphot 1997; Wall 1997). When historical data are not available, subjective judgment is needed for the estimation of correlation coefficients. For example Chau (1995a) categorizes dependency in: negative strong, negative medium, negative weak, independent, positive weak, positive medium, positive strong with coefficients of -0.85, -0.55, -0.25, 0, 0.25, 0.55, and 0.85 respectively. Touran (1993) gives values of 0.15, 0.45, and 0.8 for weak, moderate and strong correlation correspondingly. Another applicable methodology to elicit subjective correlations based on conditional expected value is presented in (Bury 1975); this methodology is also used in (Ranasinghe 2000; Ranasinghe and Russell 1992b).

An important requirement for including the correlation information in the MCS model is to assure that the coefficients in the correlation matrix are theoretically consistent with a functional relationship, so the variance of the variable derived by the MCS is nonnegative. By definition, the variance is the second moment about the expected value of the derived variable; therefore, it has to be nonnegative. Another way to see this is that if the consistency condition is ignored the determinant of the correlation matrix could be negative and this will lead the decision variable to have a negative variance. A quick way to check for consistency is to test that the Eigen values of the correlation matrix are nonnegative. In (Ranasinghe 2000; Ranasinghe and Russell 1992b; Yang 2005), the authors present algorithms that in case the correlation matrix is not consistent by iteratively applying small deductions to the correlation coefficients the condition of consistency is satisfied.

Generally speaking the impact of internal uncertainties on estimated cost can be calculated using MCS models, but we have to recognize that MCS models cannot readily deal with the conditional characterization of risk required by risk factors. Diekmann and Featherman (1998) presented a hybrid technique that uses influence diagramming to model the external uncertainties in conjunction with MCS to model. In the next chapter we present a methodology that takes into consideration the effects of risk factors not only on the cost estimate but also on the project schedule.

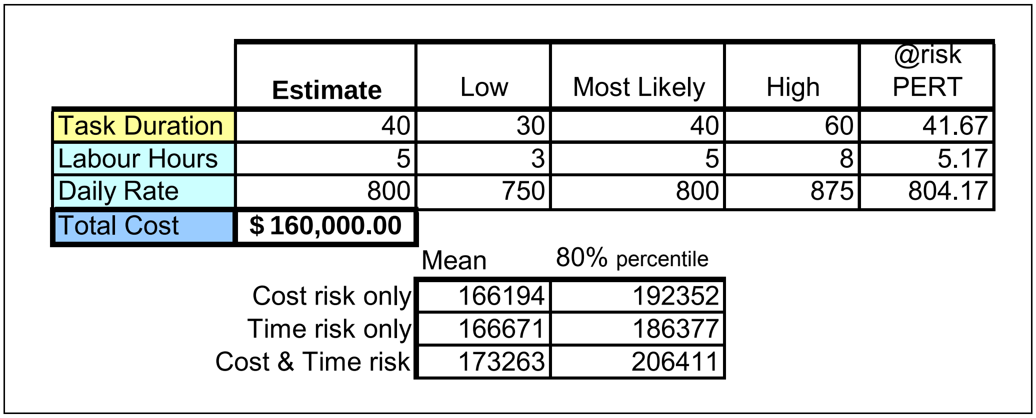
2.8.3 Integrated Schedule-Cost Risk Analysis

Schedule-cost integration refers to the simultaneous consideration of probabilistic schedule and cost risk analysis as an effort to understand the risk involved in a project. This analysis provides a more reliable cost and schedule baseline that can be used for planning purposes or for measuring the performance of the project throughout execution.

Due to the inherent uncertainty and several risks that affect infrastructure projects, it is important to analyze their combined effects. The literature review reflects, however, that most methods focus on either cost or schedule risk only. The literature on the subject also reveals that MCS is the risk analysis technique that is used for this type of analysis since it offers a viable alternative when analytical models are mathematically intractable or must be oversimplified.

The fact that lengthy schedule delays can cause project cost overruns requires a simultaneous analysis of cost and schedule risk; therefore, it is incorrect to assume that cost is independent of schedule. This correlation between cost and schedule is ignored if cost and schedule risk are analyzed separately.

In order to illustrate this problem, a simplistic example adapted from (Hullet 2002) integrates the duration and cost of an activity is shown below. The data include duration, labor hours and labor compensation from which the total cost is calculated. The second column shows a deterministic approach that uses the most likely estimates for the input variables. The following three columns show three point estimates for the activity variables that represent the uncertainty around the variables; these variables are assumed to follow a PERT distribution. The last column is the mean of PERT distributions. The results of the MCS model are shown considering three cases: uncertainty for cost only, uncertainty in activity duration and the combination of both.



	Estimate	Low	Most Likely	High	@risk PERT
Task Duration	40	30	40	60	41.67
Labour Hours	5	3	5	8	5.17
Daily Rate	800	750	800	875	804.17
Total Cost	**$ 160,000.00**				

	Mean	80% percentile
Cost risk only	166194	192352
Time risk only	166671	186377
Cost & Time risk	173263	206411

Figure 2-18: Cost Model

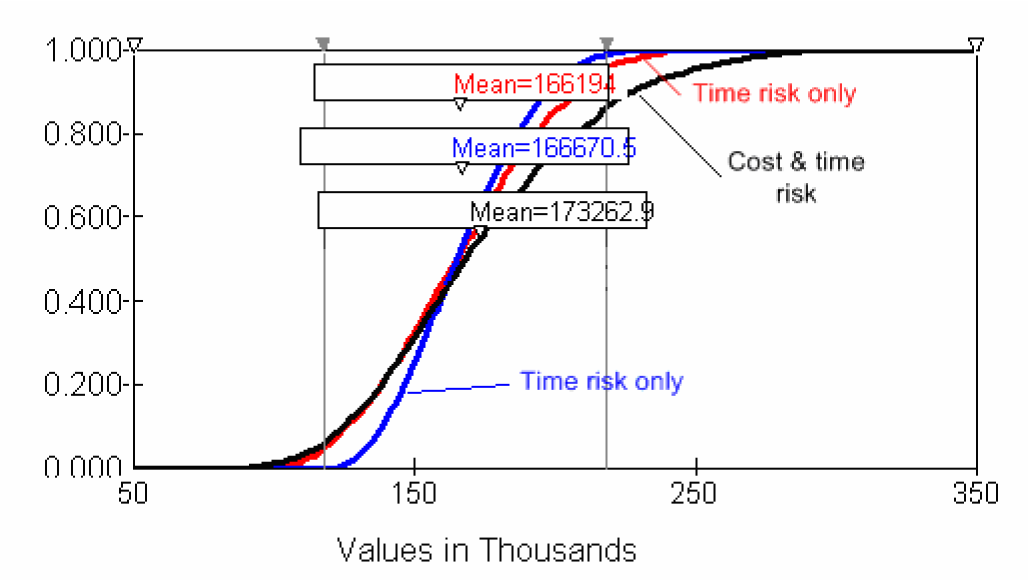


Figure 2-19: CDFs Generated for the Cost Model by a MCS

It is observed from Figure 2-18 and Figure 2-19 that if cost and time are considered independent, the estimation is too optimistic. The integrated model shows that the total cost uncertainty is greater when cost and time are dependent.

An integrated simulation approach that analyses the combined effect of cost and schedule uncertainty requires a simultaneous examination of all correlated variables. Correlation measures are needed for modeling dependencies between cost variables, schedule variables and cost and schedule variables. Several studies on the topic present simulation methodologies for the development of cost-schedule integration models; however most of them fail to address correlation issues among activities and how to deal with different cost and schedule structures (Rao and Grobler 1995; Sha'ath and Singh 1994).

Often, the schedule is related to work breakdown structure while the cost estimate is not (See Figure 2-20). Hullet (2002) recommends that it is easier to take the cost values in the cost estimate and apportion them into the schedule summary tasks. A more comprehensive approach to deal with the cost and schedule data is presented by Isidore et al. (2002; 2001). Figure 2-21 shows an approach that permits having a common basis for analysis so the cost and schedule data can be related allowing the construction of a simulation model that integrates uncertainties in the project cost estimate and schedule.

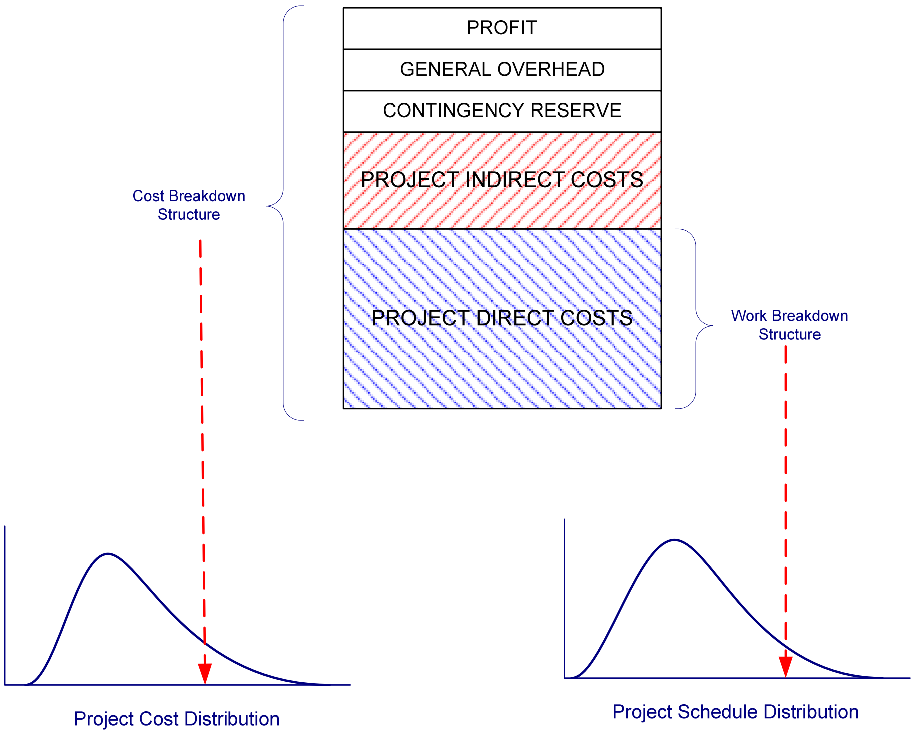


Figure 2-20: Data Generation Approach for Traditional Non-Integrated Range Estimating and Probabilistic Scheduling, Adapted from (Isidore et al. 2001)

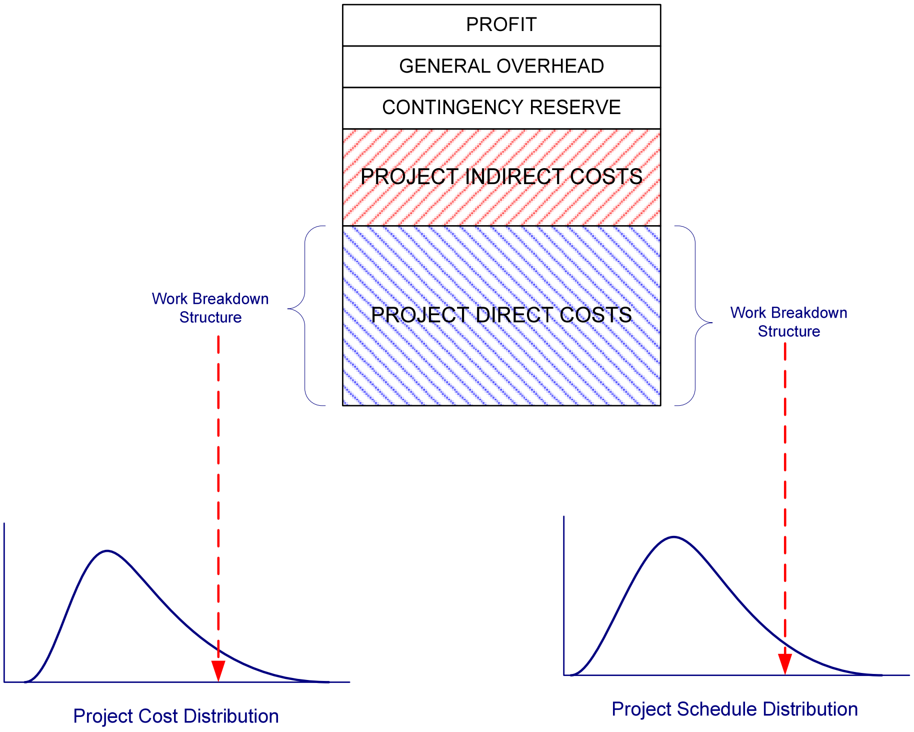


Figure 2-21: Data Generation Approach for Integrated Range Estimating and Probabilistic Scheduling, Adapted from (Isidore and Back 2002)

The idea behind a common basis such as the use of the project WBS is that cost and time models can use the same work packages, so an integrated analysis can be performed.

In (Isidore and Back 2002; Isidore et al. 2001) two methods are presented that permit the integrated analysis: an activity based costing event simulation and a multiple event simulation analysis for determining cost and schedule baselines. These methods seem to generate adequate results; however they only consider internal uncertainty within work packages. An extension on the application of these approaches is contemplated in order to incorporate external uncertainties and risk factors.

2.8.4 Contingency Calculation

In the construction industry, risk manifests itself in unforeseen expenditures that were not envisioned at the planning stage. If risk can be assessed, it can be reflected by the inclusion of a contingency sum.

In many sectors of the construction industry it is a common practice to use single point estimates of percentage of total cost as contingencies that are then added to account for risk and uncertainties related to the project. The intention is that the project budget becomes a more realistic representation of the investment that is needed (Mak and Picken 2000).

Probabilistic risk analysis directly helps the process of contingency determination and allocation. The use of the results generated by the risk analysis (i.e., CDF of project cost), allows management to analyze probabilities of exceeding certain targets. By determining the level of risk acceptance, the amount of contingency and tender price can be determined. Studies on this topic include (Ranasinghe 1994a; Ranasinghe 1994b; Touran 2003a; Touran 2003b; Wang 2002)

In (Beeston 1986), the author asserts that difficulty arises when it is necessary to consolidate the risk allowances to produce an aggregated risk allowance which can be added to the basic estimate. If we total the maximum values which the allowances can have for the work packages, the result is too pessimistic because the chance of all the risks occurring at this level is usually negligible. However, it is important to take into consideration the dependence among risks, for example with some risks, if one occurs other are very likely to also occur, or perhaps all arise from the same cause. If risks' dependencies are ignored the answer can be grossly optimistic.

3. Bayesian Belief Networks for Project Risk Analysis

The project risk analysis literature claims that the effects of correlation among work packages' cost and duration estimates cannot be ignored; however a practical methodology to account for correlation has yet to be developed. Although, there is evidence that positive dependence exists between durations and costs of project activities (Touran and Suphot 1997; Touran and Wiser 1992; van Dorp and Duffey 1999), most project risk methodologies in use today assume independence, where only the marginal distribution of variables considered for the model are used to describe the multivariate distribution of the total cost or duration of the project. The drawback of this common assumption is that if correlation among work packages is ignored, there is a high risk of underestimating the variance of total cost and time completion projections.

The usual approach to deal with correlation in project risk analysis is to set up a correlation matrix for the cost or duration of work packages that are considered as random variables in the model. The problem with this approach is that the number of correlation coefficients to be estimated or assessed grows rapidly with the number of variables involved. The required number of correlation coefficients for n variables is $\binom{n}{2}$. Moreover, if no historical data are available for the correlation coefficients estimation, the analyst will be forced to elicit these values using expert opinion. This elicitation faces a major challenge, which is that most experts are not trained in probability.

Another approach to deal with correlation effects is the use of risk factors that affect a group of activities within a project (Elkjaer 2000; van Dorp 2004; van Dorp and Duffey 1999). The concept of risk factors is similar to the "common cause" events that are widely used in fault tree analysis in other engineering applications (Zhang 1989). This approach is described in detail in Chapter 4.

Another problem with current project risk analysis methodologies is that impacts of concurrent risks are assumed to be additive. In reality, risks are very often interdependent and their impact varies simultaneously with a compounding effect.

An additional challenge to be solved is how to use qualitative considerations such as organizational, environmental and regulatory aspects within a quantitative analysis.

These problems motivate the development of a methodology that can handle qualitative and hard evidence and at the same time considers dependency effects. One tool that allows us to deal with these requirements is Bayesian belief networks (BBN's). The use of BBN's as an alternative to face these challenges is presented in this chapter.

3.1 Bayesian Belief Networks

Bayesian belief networks, also called Bayesian networks, are graphical tools used to represent a high-dimensional probability distribution. They are convenient for making inferences about uncertain states when limited information is available (Bedford and Cooke 2001). Bayesian networks have been used for making diagnosis in medical and engineering applications and are common in artificial intelligence (Cowell 1999; Jensen 2001; Pearl 1988; Russell and Norvig 2003).

Figure 3-1 is an example of a Bayesian network with four variables: X_1, X_2, X_3, and X_4. Nodes in this graph represent variables, and links represent dependencies or causal influences. The links permit us to express the dependence relationships between variables; the strength of these relationships is expressed by forward conditional probabilities, for example, the conditional probability of event X_3 given that X_1 and X_2 occurred is $P\left(X_3 \middle| X_1, X_2\right)$.

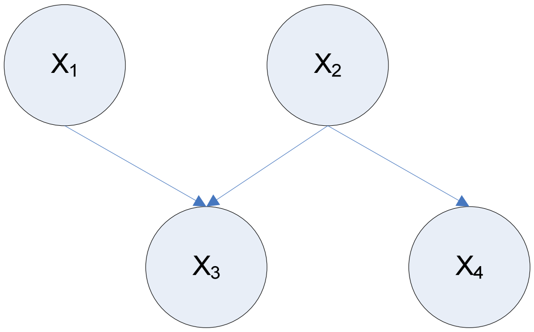


Figure 3-1: Bayesian Network Example

The traditional notion of independence uses equality of numerical quantities, as in $P\left(X_1, X_2\right) = P\left(X_1\right) \cdot P\left(X_2\right)$, suggesting that one must test that the joint distribution of X_1 and X_2 is equal to the product of their marginal probabilities in order to determine whether X_1 and X_2 are independent. However, people can easily and confidently detect dependencies, even though they may not be able to provide precise numerical estimates of probabilities.

Therefore, the advantage of a network representation is that it allows people to directly express the fundamental qualitative relationship of “direct dependency”. The network displays a consistent set of additional direct and indirect dependencies and preserves it as a stable part of the model, independent of the numerical estimates (Pearl 1988).

3.2 *Bayesian Belief Networks in Project Management Literature*

The use of BBN's in project management is somewhat limited. In this section we summarize the most representative findings.

In Fan and Yu (2004) BBN's are incorporated in a risk management decision support system based on the assumption that if more resources are added to project activities the cost of these activities will increase while the risk may be lower. The BBN'Ss come into play within a feedback loop that accommodates resources to control risks after evidence is observed and updated in the network.

In McCabe et al.(1998) belief networks and event simulation are used as a diagnostic tool for construction operations as a way to improve performance. Evidence brought to the belief network evaluates the cause of the operational problem as a way to take corrective actions.

Nasir et al. (2003) present a comprehensive list of risk variables that affect project schedules. The authors constructed a belief network using schedule risks as input variables and construction activities type as output variables. When evidence of project conditions is acquired, the states of input variables are updated; output nodes that represent percentage of increase or reduction of activity durations are then inferred. The model provides lower and upper distribution limits as a percent of the most likely duration.

McCabe and Ford (2001) note that the advantages of using belief networks to model risk are the following:

- BBN's are excellent modeling environments for situations where there are conditional or influential relationships

- BNN can integrate data and expert opinion seamlessly
- The structure of a network is very intuitive, and domain experts do not need to understand the background technology to be able to participate in knowledge elicitation
- Models are asymmetric in that evidence can be entered at any node, and all remaining nodes are recalculated. There is no direction constraint on the logic once it has been developed

According to Attoh-Okine (2002) and McCabe and Ford (2001) the most significant barriers for the use of belief networks include the following:

- Producing the right graph, one that resembles a model of the type of reasoning being applied, and
- It is often difficult to collect data and/or expert knowledge in a consistent and unbiased manner
- Eliciting conditional probability values from the domain expert

3.3 Construction of Bayesian Belief Networks

Belief networks can be constructed using expert elicitation or historical data if available. This information permits the determination of the representative variables, their possible states and probability estimates for the construction of the network.

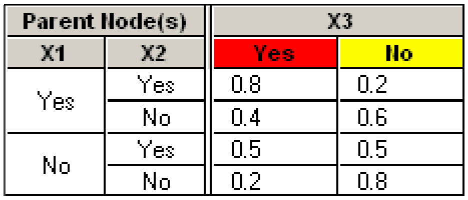
The general process to construct a BBN is as follows:

a. Define the relevant variables and order them. For example, we can assume they are called $X_1 \ldots X_m$; where X_1 is the first in the ordering, X_2 is the second, etc. It is recommended that dependent variables are considered first in the order, so when they are graphed the construction of dependency relationships is easier.

b. Define the relationship among variables. For each variable, set $Parents(X_i)$ to be a subset of $\{X_1 \ldots X_{i-1}\}$ such that we have conditional independence of X_i and all other members of $\{X_1 \ldots X_{i-1}\}$ given $Parents(X_i)$

c. Define the states of the variables. This research uses only variables with a limited number of conditions, so these variables are limited to the discrete case. Each set of possible conditions of a discrete variable is called a state. As an alternative for the use of a continuous variable, its range can be discretized and states defined.

d. Estimate conditional probabilities of the relationships in a probability table of $P\left(X_i = k\ Assignments\ of\ \ Parents(X_i)\right)$. For example, a table for node X_3 from Figure 3-1 must list the values of $P(X_3 \mid X_1, X_2)$ for each possible combination of parent values. Assuming that X_1, X_2, and X_3 are binary variables with states “Yes” and “No” the probability table for X_3 using equally likely outcomes is:



Parent Node(s)		X3	
X1	X2	Yes	No
Yes	Yes	0.8	0.2
	No	0.4	0.6
No	Yes	0.5	0.5
	No	0.2	0.8

Table 3-1: Probability Table for Variable X_3 using BBN from Figure 3-1

3.4 How Bayesian Belief Networks Work

BBN's provide a model representation of the joint distribution of a set of variables in terms of conditional and prior probabilities.

In order for a Bayesian network to model a probability distribution, the following must be true: Each variable is conditionally independent on all non-parents nodes in the graph and the probability of each of its states depends only on the value of all its parents' states. This implies that the probability of the network given its dependency structure is:

$$P(X_1 \dots X_n) = \prod_{i=1}^{n} P(X_i \mid parents(X_i))$$

For example, the Bayesian network in Figure 3-1 shows that X_3 depends on X_1 and X_2, and X_4 depends only on X_2. Then the joint probability of variables X_1, X_2, X_3, and X_4 can be computed using conditional probabilities based on these dependencies such as $P\left(X_1, X_2, X_3, X_4\right) = P\left(X_1\right) \cdot P\left(X_2\right) \cdot P\left(X_3 \middle| X_1, X_2\right) \cdot P\left(X_4 \middle| X_2\right)$.

The assumption that BBN's are acyclic networks where any two variables are conditionally independent of each other if they are not connected by an arrow defines the called d-separation principle; this simplification allows capturing the induced dependency relationship among variables. In other words, dependency is mediated by nodes that lie on the paths connecting them. This assumption makes that two nodes are conditionally independent of each other if there are intermediate nodes on the path between them.

The inference of a BBN involves the calculation of marginal probabilities conditional on the observed data or added evidence using Bayes Theorem. Bayes Theorem states that:

$$P\left(A \middle| B\right) P\left(B\right) = P\left(A, B\right) \tag{3.1}$$

where, $P(A,B)$ is the probability of the joint event $A \wedge B$. Since $P(A|B)P(B) = P(B|A)P(A)$; this yields Bayes Theorem in the form of:

$$P(B|A) = \frac{P(A|B)P(B)}{P(A)} \tag{3.2}$$

If $P(A)$ and $P(B)$ are conditional on *C*, (3.1) reads:

$$P(A|B,C)P(B|C) = P(A,B|C) \tag{3.3}$$

Then Bayes' Theorem conditioned on *C* is:

$$P(B|A,C) = \frac{P(A|B,C)P(B|C)}{P(A|C)} \tag{3.4}$$

By the total probability Theorem, (3.2) and (3.4) can be expressed as:

$$P(B_i|A) = \frac{P(A|B_i)P(B_i)}{\sum_{j=1}^{n} P(A|B_j)P(B_j)} \tag{3.5}$$

$$P(B_i|A,C) = \frac{P(A|B_i,C)P(B_i|C)}{\sum_{j=1}^{n} P(A|B_j,C)P(B_i|C)} \tag{3.6}$$

In order to do inference in a BBN we need to know the conditional probabilities formed by the dependency relationships among variables. For this purpose we can use the chain rule of probability that allows decomposing a joint distribution of *n* variables into conditional probabilities such as:

$$P(X_1,....,X_n) = P(X_1)\prod_{i=2}^{n} P(X_i|X_1,...,X_{i-1}) \tag{3.7}$$

McCabe et al.(1998) argue that belief networks provide great flexibility for accepting input and providing output. Because of the symmetry of Bayes Theorem, BBN's can provide information about the causes of certain effect without redeveloping the network. In other words, BBN's have the inherent ability to reverse its logic. BBN's are also capable of updating beliefs with the entry of additional evidence, which is called intercausal inference. New evidence is entered at any point in the network and the likelihood of remaining values are evaluated and compared against their previously believed values.

Enumerating all appropriate conditional probabilities for the evaluation of the joint distribution of interest is computationally expensive. For example if we have binary-state variables in the Bayesian network the process is exponential in the number of variables.

There are some modeling tricks however, that help to reduce the number of conditional probabilities required in the relationship quantification stage and the number of calculations required. For example, one technique is called "divorcing". This technique involves the introduction of "intermediate" variables in order to reduce the exponential effect of having a large number of parents.

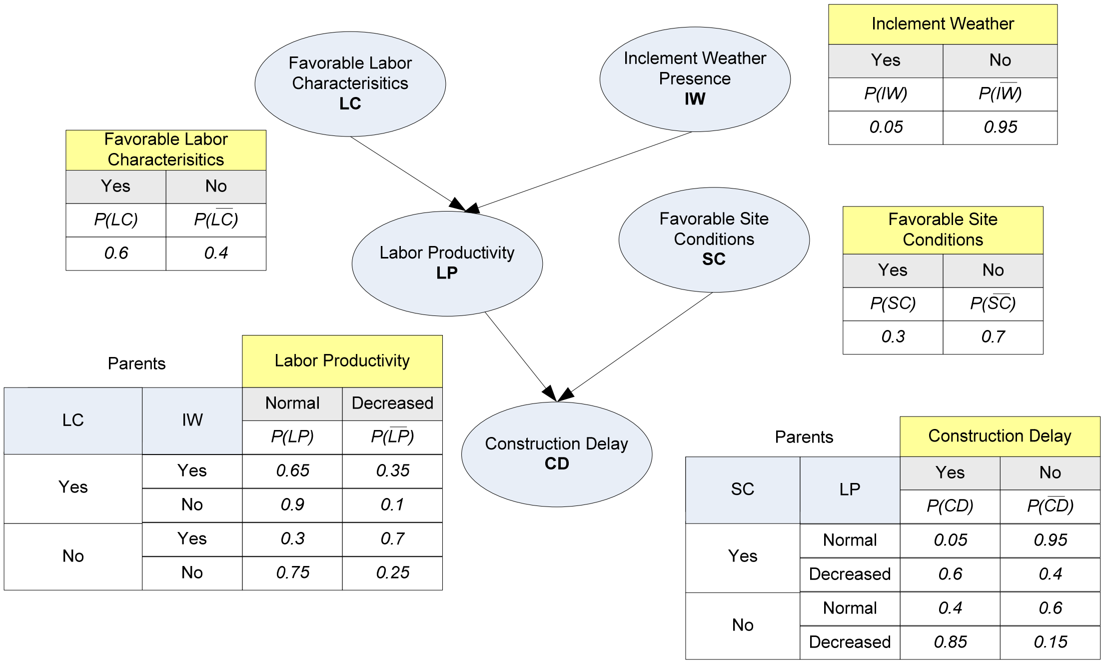
Another approach uses the causal independence (CI) method to define a discrete distribution that can dramatically reduce the number of prior probabilities necessary to define a distribution. A parent variable can influence its child in a way that is either dependent or independent on the value of other parents. In a non-causal independent case all parents of a node may interact, and every nuance of the combination space can be separately weighted. On the other hand, causal independence nodes represent the independent case where all parents are completely separate; therefore reducing dramatically the number of conditional probabilities to be assessed. A CI distribution reduces the number of assessments from $2^{(N+M)}$ to $M*(N+1)$, where N is the sum of the number of states of the parent nodes and M the number of states of the child node. Details and examples of the implementation of these and other modeling tricks can be found in (Eyers 2001; Jensen 2001).

For networks that are single-connected (only one path between any two nodes) an exact solution can be found by applying the Bayes Theorem. If more than one path connects any two nodes in a network, this network is called multiple-connected. In general, querying multiply connected networks is non-deterministic polynomial (NP) complete. This means that a non-deterministic polynomial time algorithm to solve the networks does not exist (Charniak 1991). NP complete problems are the hardest NP problems and are known to be intractable. Consequently, there are several heuristic algorithms that have been developed for the evaluation of BBN's, such as: The junction tree method, stochastic simulation and likelihood weighting. The scope of this research does not include details on these algorithms; however, more information can be found in (Jensen 2001; Pearl 1988).

For a better understanding on how BBN's work, the following section presents an example of the evaluation of a small single-connected network.

3.4.1 Evaluation Example

Figure 3-2 presents an example of a small single-connected BBN for the evaluation of construction delays. This example is presented as way to demonstrate how the Bayes Theorem is used for probability inference and propagation. This example comes from the construction industry where the execution of a project is affected by external risk events and/or inherent characteristics of the project and its resources. This Bayesian network models the probability of construction delay due to the presence of inclement weather and unfavorable site conditions; it also qualitatively takes into consideration the characteristics of labor. The model has five binary-state variables, of which three of them are independent: "Inclement Weather Presence" (IW), "Favorable Site Conditions" (SC) and "Favorable Labor Characteristics" (LC). The fourth variable is "Labor Productivity" (LP) which is dependent on LC and IW. "Construction Delay" (CD) is the last variable and is dependent on LP and SC.



Inclement Weather	
Yes	No
$P(IW)$	$P(\overline{IW})$
0.05	0.95

Favorable Labor Characterisitics	
Yes	No
$P(LC)$	$P(\overline{LC})$
0.6	0.4

Favorable Site Conditions	
Yes	No
$P(SC)$	$P(\overline{SC})$
0.3	0.7

Parents		Labor Productivity	
LC	IW	Normal	Decreased
		$P(LP)$	$P(\overline{LP})$
Yes	Yes	0.65	0.35
	No	0.9	0.1
No	Yes	0.3	0.7
	No	0.75	0.25

Parents		Construction Delay	
SC	LP	Yes	No
		$P(CD)$	$P(\overline{CD})$
Yes	Normal	0.05	0.95
	Decreased	0.6	0.4
No	Normal	0.4	0.6
	Decreased	0.85	0.15

Figure 3-2: Small Example of a Bayesian Network for the Evaluation of Construction Delay

From the figure above we see that each variable has its own probability table. For example, the IW variable has two states: "Yes" and "No" with probabilities of

$P(IW) = 0.05$ and $P(\overline{IW}) = 0.95$, respectively. This means that there is a 5% probability that inclement weather that will affect the project.

In the case of LP, the variable has two states “Normal Labor Productivity” and “Decreased Labor Productivity”. This node however has two binary-state parents, which increases the number of entries in its probability table; this happens because of the possible combinations of parent states. The first entry in the probability table, for example, corresponds to $P(LP \mid IW{=}\text{Yes}, LC{=}\text{Yes}) = 0.65$. This means that there is a 65% chance that labor productivity will be normal given that inclement weather is present and the characteristics of the labor are favorable.

As an exercise we can infer, for example, the probability of a construction delay given unfavorable site conditions, no inclement weather and unfavorable labor characteristics. This is translated in mathematical notation to:

$$P\left(CD \middle| \overline{SC}, \overline{IW}, \overline{LC}\right) \tag{3.8}$$

The information provided in Figure 3-2 shows only conditional probabilities based on each node’s parents. In order to evaluate a network we need to know the probability values conditioned on child variables; therefore (3.8) has to be manipulated in a way that the conditional probabilities can be read directly from the original Bayesian network.

We can start by calculating the marginal probabilities of the Labor Productivity (LP) and Construction Delay (CD) nodes.

$$\begin{aligned} P(LP) = {} & P(LP \mid IW, LC)P(IW)P(LC) + P\left(LP \middle| \overline{IW}, SC\right)P\left(\overline{IW}\right)P(LC) \\ & + P\left(LP \middle| IW, \overline{LC}\right)P(IW)P\left(\overline{LC}\right) + P\left(LP \middle| \overline{IW}, \overline{LC}\right)P\left(\overline{IW}\right)P\left(\overline{LC}\right) \end{aligned} \tag{3.9}$$

$$\begin{aligned}P(CD) &= P(CD|LP,SC)P(LP)P(SC)+P(CD|\overline{LP},SC)P(\overline{LP})P(SC)\\ &+P(CD|LP,\overline{SC})P(LP)P(\overline{SC})+P(CD|\overline{LP},\overline{SC})P(\overline{LP})P(\overline{SC})\end{aligned} \tag{3.10}$$

The values needed for the calculation in (3.9) and (3.10) can be read directly from their respective probability tables. The calculated marginal probabilities correspond to $P(LP)=0.82$ and $P(CD)=0.38$ respectively. We know therefore, that the probability of normal labor productivity is 82% and 38% for the chance of construction delay.

Going back to our joint probability of interest, we can apply Bayes Theorem to rearrange the expression, such as:

$$P(CD|\overline{SC},\overline{IW},\overline{LC})=\frac{P(\overline{SC},\overline{IW},\overline{LC}|CD)\cdot P(CD)}{P(\overline{SC},\overline{IW},\overline{LC})} \tag{3.11}$$

From Figure 3-2 we can observe that variables SC, IW and LC are independent of each other; therefore (3.11) can be written as:

$$P(CD|\overline{SC},\overline{IW},\overline{LC})=\frac{P(\overline{SC}|CD)\cdot P(\overline{IW}|CD)\cdot P(\overline{LC}|CD)\cdot P(CD)}{P(\overline{SC})\cdot P(\overline{IW})\cdot P(\overline{LC})} \tag{3.12}$$

In (3.12), denominator terms can be read directly from the probability tables in Figure 3-2; the numerator terms require further analysis however.

Applying Bayes Theorem to the numerator terms $P(\overline{SC}|CD)$, $P(\overline{IW}|CD)$ and $P(\overline{LC}|CD)$ individually, we have the following:

$$P(\overline{SC}|CD)=\frac{P(CD|\overline{SC})}{P(CD)}P(\overline{SC}) \tag{3.13}$$

$$P\left(\overline{IW}\middle|CD\right)=\frac{P\left(CD\middle|\overline{IW}\right)}{P\left(CD\right)}\cdot P\left(\overline{IW}\right) \tag{3.14}$$

$$P\left(\overline{LC}\middle|CD\right)=\frac{P\left(CD\middle|\overline{LC}\right)}{P\left(CD\right)}\cdot P\left(\overline{LC}\right) \tag{3.15}$$

To evaluate the posterior probabilities in (3.13), (3.14) and (3.15) we must consider the conditional structure from the network to include all parents of each node. Using the chain rule and the total probability Theorem we have that:

$$P\left(\overline{SC}\middle|CD\right)=\frac{P\left(CD\middle|\overline{SC},LP\right)P\left(LP\right)+P\left(CD\middle|\overline{SC},\overline{LP}\right)P\left(\overline{LP}\right)}{P\left(CD\right)}P\left(\overline{SC}\right) \tag{3.16}$$

$$P\left(\overline{IW}\middle|CD\right)=\frac{P\left(CD\middle|\overline{IW},LP\right)P\left(LP\middle|\overline{IW}\right)+P\left(CD\middle|\overline{IW},\overline{LP}\right)P\left(\overline{LP}\middle|\overline{IW}\right)}{P\left(CD\right)}P\left(\overline{IW}\right) \tag{3.17}$$

$$P\left(\overline{LC}\middle|CD\right)=\frac{P\left(CD\middle|\overline{LC},LP\right)P\left(LP\middle|\overline{LC}\right)+P\left(CD\middle|\overline{LC},\overline{LP}\right)P\left(\overline{LP}\middle|\overline{LC}\right)}{P\left(CD\right)}P\left(\overline{LC}\right) \tag{3.18}$$

(3.16) can now be evaluated by using the probability tables information from Figure 3-2, then $P\left(\overline{SC}\middle|CD\right)=0.88$.

Since CD is d-separated from IW and LC, (3.17) and (3.18) can be rewritten as:

$$P\left(\overline{IW}\middle|CD\right)=\frac{P\left(CD\middle|LP\right)\cdot P\left(LP\middle|\overline{IW}\right)+P\left(CD\middle|\overline{LP}\right)\cdot P\left(\overline{LP}\middle|\overline{IW}\right)}{P\left(CD\right)}\cdot P\left(\overline{IW}\right) \tag{3.19}$$

$$P\left(\overline{LC}\middle|CD\right)=\frac{P\left(CD\middle|LP\right)\cdot P\left(LP\middle|\overline{LC}\right)+P\left(CD\middle|\overline{LP}\right)\cdot P\left(\overline{LP}\middle|\overline{LC}\right)}{P\left(CD\right)}\cdot P\left(\overline{LC}\right) \tag{3.20}$$

What we have left is the evaluation of the conditional probabilities of the enumerator of the two equations above. Applying the total probability law we have that:

For (3.19)

$$P\left(CD \middle| LP\right) = P\left(CD \middle| LP, SC\right) \cdot P\left(SC\right) + P\left(CD \middle| LP, \overline{SC}\right) \cdot P\left(\overline{SC}\right) \tag{3.21}$$

$$P\left(LP \middle| \overline{IW}\right) = P\left(LP \middle| \overline{IW}, LC\right) \cdot P\left(LC\right) + P\left(LP \middle| \overline{IW}, \overline{LC}\right) \cdot P\left(\overline{LC}\right) \tag{3.22}$$

$$P\left(CD \middle| \overline{LP}\right) = P\left(CD \middle| \overline{LP}, SC\right) \cdot P\left(SC\right) + P\left(CD \middle| \overline{LP}, \overline{SC}\right) \cdot P\left(\overline{SC}\right) \tag{3.23}$$

$$P\left(\overline{LP} \middle| \overline{IW}\right) = P\left(\overline{LP} \middle| \overline{IW}, LC\right) \cdot P\left(LC\right) + P\left(\overline{LP} \middle| \overline{IW}, \overline{LC}\right) \cdot P\left(\overline{LC}\right) \tag{3.24}$$

and, for (3.20)

$$P\left(CD \middle| LP\right) = P\left(CD \middle| LP, SC\right) \cdot P\left(SC\right) + P\left(CD \middle| LP, \overline{SC}\right) \cdot P\left(\overline{SC}\right) \tag{3.25}$$

$$P\left(LP \middle| \overline{LC}\right) = P\left(LP \middle| \overline{LC}, IW\right) \cdot P\left(IW\right) + P\left(LP \middle| \overline{LC}, \overline{IW}\right) \cdot P\left(\overline{IW}\right) \tag{3.26}$$

$$P\left(CD \middle| \overline{LP}\right) = P\left(CD \middle| \overline{LP}, SC\right) \cdot P\left(SC\right) + P\left(CD \middle| \overline{LP}, \overline{SC}\right) \cdot P\left(\overline{SC}\right) \tag{3.27}$$

$$P\left(\overline{LP} \middle| \overline{LC}\right) = P\left(\overline{LP} \middle| \overline{LC}, IW\right) \cdot P\left(IW\right) + P\left(\overline{LP} \middle| \overline{LC}, \overline{IW}\right) \cdot P\left(\overline{IW}\right) \tag{3.28}$$

At this point, the information for evaluating our network can be obtained directly from the original probability tables, so we know that $P\left(\overline{IW} \middle| CD\right) = 0.93$ and $P\left(\overline{LC} \middle| CD\right) =$ 0.45.

Finally replacing all these values in (3.12), we can calculate the probability of our joint distribution such as $P\left(CD \middle| \overline{SC}, \overline{IW}, \overline{LC}\right) = 0.52$

Now, to demonstrate how new evidence can update the probability estimates in the Bayesian network consider the following scenario. For example, assume that we are interested in finding out the probability of experiencing construction delays given that we have observed unfavorable site conditions and unfavorable labor characteristics. We are also curious to know how the construction delay probability changes if inclement weather is present or not. Since we have already constructed all the necessary relationships to propagate evidence among the variables of the model, we can simply update the probability entries of the risk event with 1 or 0 values that represent the certainty of that an event has occurred or not.

For illustrative purposes, the following table shows the effects of adding evidence on the probability of construction delay; evidences are be added to the model one at the time.

Added Evidence	Construction Delay Probability
None	$P(CD) = 0.38$
Unfavorable Labor Characteristics	$P(CD \mid LC=0) = 0.42$
Unfavorable Site Conditions	$P(CD \mid LC=0, SC=0) = 0.52$
No Inclement Weather	$P(CD \mid LC=0, SC=0, IW=0) = 0.51$
Inclement Weather	$P(CD \mid LC=0, SC=0, IW=1) = 0.72$

Table 3-2: Impacts of Adding Evidence to BBN Example

3.5 Using Bayesian Belief Networks to Account for Risk Dependencies, Qualitative Aspects of the Project, and non-Additive Risk Impacts

As mentioned before one of the main challenges that project risk analysts face is the lack of a methodology that correctly models dependency between project activities. Not considering correlation effects among project’s work packages can dangerously underestimate the variance of the estimated distribution for total cost and project duration.

A risk factor approach would allow the use of causal relationships to relate the occurrence of a risk event with its consequences on performance of a specific project activity or groups of them. If a group of activities are affected by a common risk factor the realization of the risk event will have cost and time consequences on them; this will indirectly induce correlation in those activities.

The use of risk factors is an adequate alternative to the classical approach that uses a correlation matrix within a simulation model; however, currently risk factors affecting project performance have been modeled assuming that they are mutually independent and their impact analyzed separately. In reality, risk factors act interpedently; there are situations when the occurrence of certain risk event can increase the likelihood or even trigger the occurrence of some others.

For example, the figure below presents a BBN that models the interaction of different construction risks and labor characteristics for the evaluation of the probability of construction delay. Figure 3-3 presents several relationships of interdependency among risk factors and respective possible states of each variable; for example, the risk of construction delay is affected by reduced productivity of labor and the presence of independent risk factors like inclement weather and unfavorable site conditions. On the other hand, labor productivity can be influenced by the presence of inclement weather and also by the characteristics of the labor.

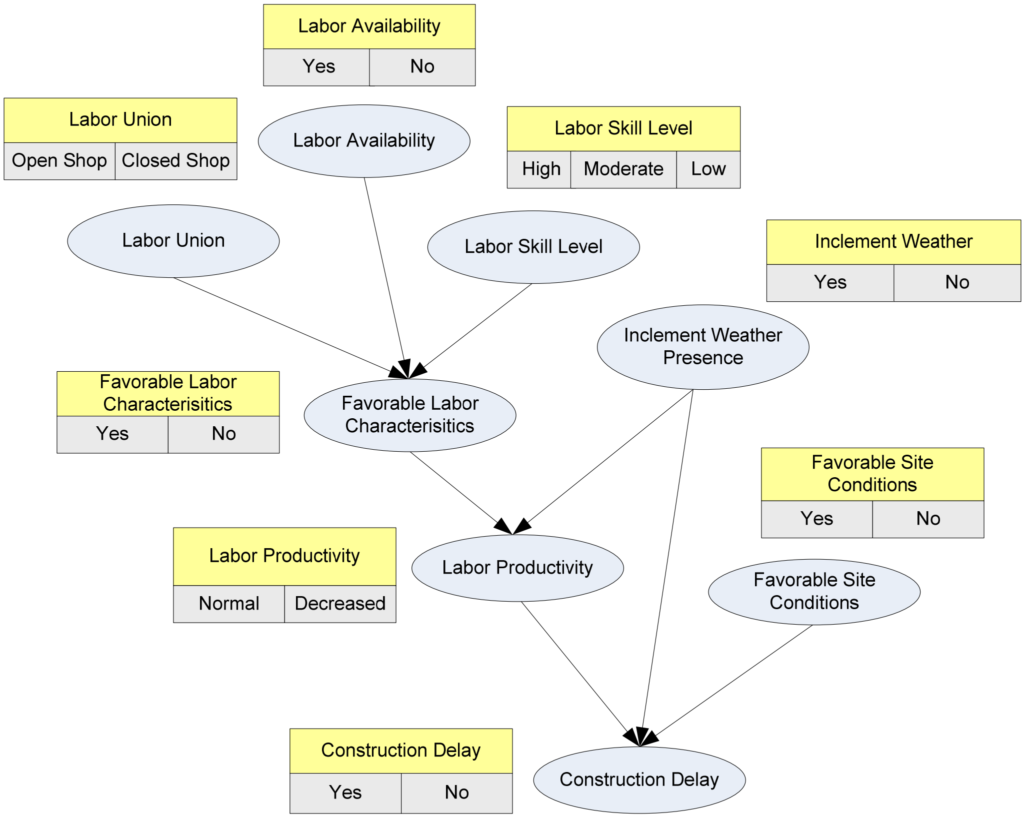


Figure 3-3: BBN for Integration of Risk Dependencies and Qualitative Characteristics

While a qualitative risk analysis is able to account for qualitative information about the project, such as quality of the resources, completeness of design, experience of management, etc, integrating this information within a quantitative model has not been applied yet in quantitative project management applications. A BBN is a tool that allows the analyst to incorporate qualitative information and interrelate it with other probabilistic variables. For example in Figure 3-3, the Labor Characteristics node has two states: favorable or unfavorable. The most probable state of this node is determined by assessing qualitatively labor conditions that include skill level, availability and how labor is organized.

Another example where qualitative information is included within a BBN is shown in Figure 3-4; in this model, project characteristics and design quality are used for the inference of the magnitude of change orders.

BBN’s are also able to integrate into their analysis impacts due to the occurrence of risk events and qualitative evidence. It is reasonable to think that when several risk events occur simultaneously, the total impact is not necessarily the summation of their individual impacts; however, research in non-additive impacts is very limited and suitable methodologies for this purpose are non-existent. In (Cooper and PA Consulting Group 2004), the authors assert that compounding impacts can occur when multiple changed conditions on a project combine to produce a total cost impact greater than the sum of the individual changes’ impacts. We believe that the use of BBN’s and the recognition of risk factors can help us to understand and reconcile non-additive risk impacts. For example, in the figure below, the Change Order Magnitude node has four states. Observations on project characteristics and quality design and evidence of occurrence of risk events can be propagated through the BBN to infer the most probable state for the magnitude of the change orders.

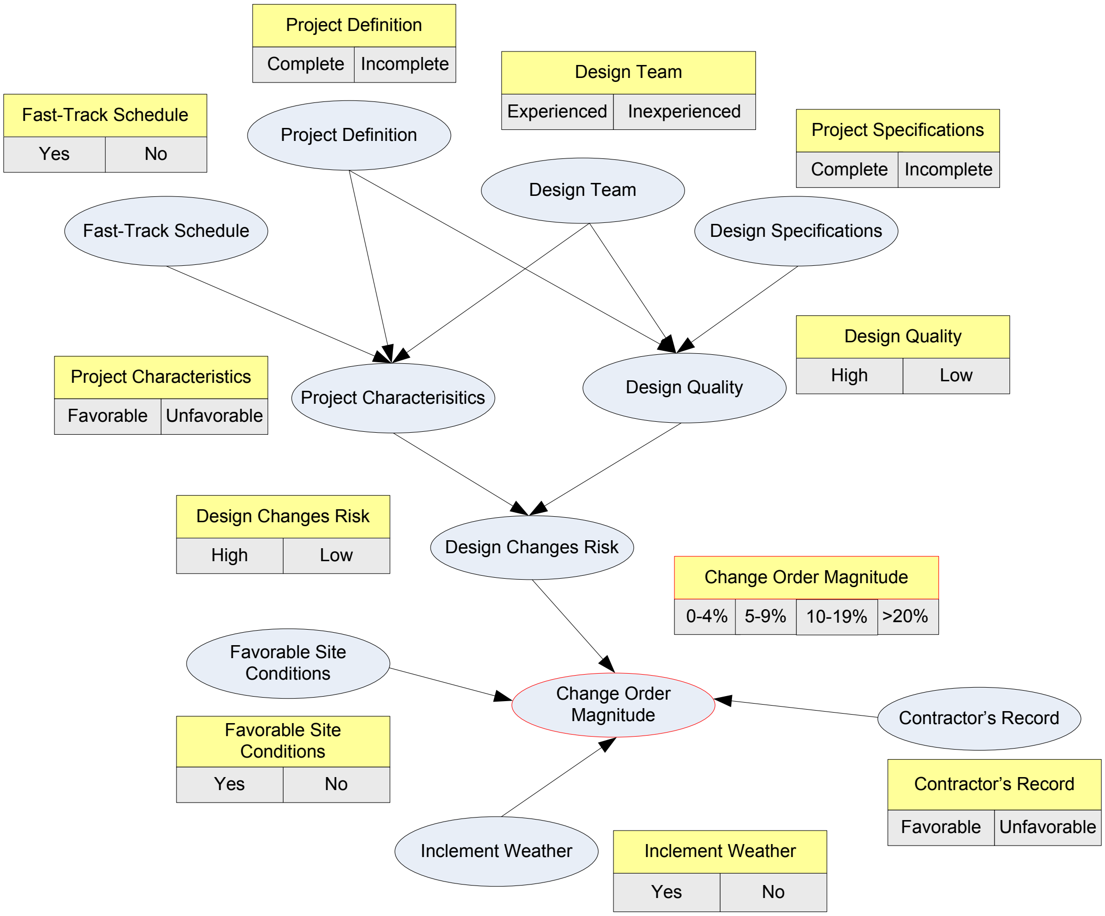


Figure 3-4: BBN for Change Order Magnitude Prediction

The examples presented in this chapter do not pretend to be an exhaustive nor complete representation of all factors that contribute to the realization of certain risk and/or its consequences, but a simplistic representation for a clearer explanation of the proposed use of BBN's for project risk analysis.

3.6 Summary

BBN’s are a suitable tool for project risk analysis. The use of them can alleviate some of the deficiencies of current methodologies. Specifically, BBN’s provide a way for modeling interdependencies among risk events; they are also able to consider into the analysis, qualitative characteristics such as contractual, organizational, environmental, economic and regulatory aspects that can affect the performance of a project. Furthermore, BBN’s can help to model non-additive impacts due to the simultaneous realization of risk events.

This research proposes the integration of BBN’s and risk factors within a Monte Carlo simulation model. The following chapter discusses this approach in detail.

4. A Methodology for Project Risk Analysis Using Bayesian Belief Networks within a Monte Carlo Simulation Environment

Bayesian Belief Networks (BBN's) can be used in project risk analysis to consider qualitative characteristics, dependency among risk factors and to examine non-additive impacts due to concurrent risk occurrences.

This chapter presents a methodology for the integration of BBN's within an integrated cost-schedule Monte Carlo simulation (MCS) model. The simulation program models the occurrence of independent risk events that will be propagated through BBN's to assess the posterior probabilities of dependent risks and their respective cost and time impacts. BBN's will also include qualitative considerations that can be propagated when soft evidence is acquired.

4.1 *Project Uncertainty and Risk*

The PMBOK (Project Management Institute 2004) refers to project risk as an uncertain event or condition that, if it occurs, has a positive or a negative effect on a project objective. Risks are inevitable in projects and because of this, uncertainty influences project performance. For the application of the proposed methodology, a project risk is defined as the possibility that the outcome of an uncertain event affects negatively or positively the cost and time performance of project activities and/or their planned execution. Uncertainty is defined as the lack of knowledge about the parameters that characterize the physical system. In our methodology we can consider two types of uncertainty: internal and external. Internal uncertainty is the uncertainty associated with the items listed in a cost estimate or activity durations; this uncertainty is caused by incompletely defined estimation parameters or incomplete knowledge. External uncertainty arises from risks that are beyond the immediate scope for the project (Attoh-Okine 2002). We propose that internal uncertainties should be considered at a work package level only; for this purpose we can use probability distributions to model uncertainty in duration estimates and non-time dependent costs as described in Section 2.6. Time dependent costs are directly related to the length of the project or specific groups of activities. This consideration, covered in later sections, permits the integration of project schedule and cost using a MCS model. Our approach is coherent with the one presented in (Diekmann and Featherman 1998), where the authors claim that internal uncertainty is best characterized by specifying a feasible range of values and probability distributions, while external uncertainty is more appropriately modeled by assessing the likelihood of that risk event happening or not.

For classifying risks we need to know first if they are external or internal to the project. Authors assert that external risks are relatively uncontrollable while internal factors are more controllable and vary between projects (Tah and Carr 2001). Risks can also be either local or global. Local risks affect a single or a group of work packages within a project, whereas global risks cannot be associated with any particular work package and affect the project as a whole. Using this classification and the nature of risks, they can be grouped for better cause-effect determination that is essential when using BBN's and for risk management purposes. It important to consider how these risks could impact the project. The consequence of the realization of a risk event can be classified in fixed or variable which can have impact on time and/or cost performance. These two types of risk consequences are treated differently regarding the allowance that is allocated to each type. A fix risk consequence occurs when the cost or time impact incurs as a whole, with an estimated probability, or not at all. A variable risk consequence can occur to varying degrees so no fixed monetary sum or time impact can be allocated to it. The figure below can be used as an aid for classifying risks and their respective impacts.

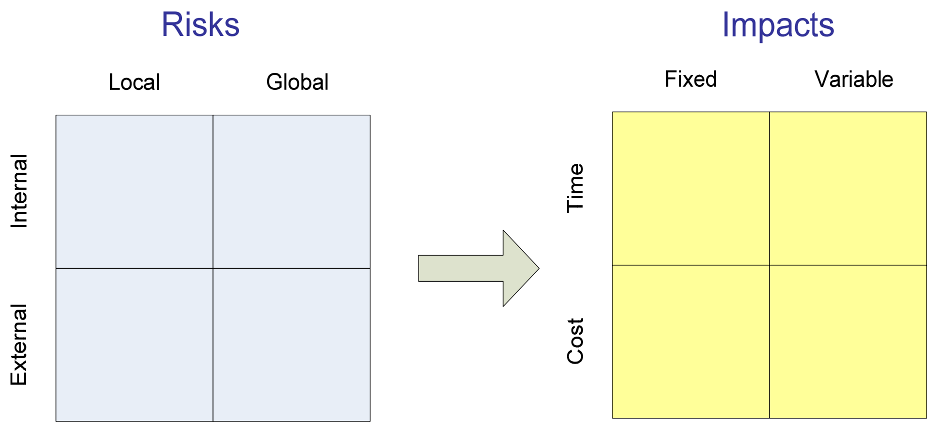


Figure 4-1: Risk and Consequences Classification

Risks affecting a project depend on characteristics of the industry in which the project is conceptualized as well as on uniqueness of it. For example the following table presents several risk variables that affect projects related to the construction industry. It compiles a list of risks, project conditions and environment characteristics that could impact the execution of this type of project. More details about definitions and states of the risk variables can be found in (Eyers 2001; Nasir et al. 2003)

Environmental	**Owner**
Natural disasters	Owner type: private/public/non-profit
Seasons	Owner financial stability
Extreme Weather	Funding source
Precipitation	Budget revisions
Humidity	Decision making efficiency
Geotechnical	Progress payment
Archeological remains presence	**Design**
Unexpected subsurface conditions	Fast track schedule
Availability/experience of geotechnical consultant	Design team experience
Local geotechnical history	Design team coordination
Labor	Multifunctional building
Labor union characteristics	Project definition completeness
Labor dispute/strike	Complexity/constructability of design
Labor availability	Design specification completeness
Labor wage scales	Design quality
Labor skill level	Design changes risk
Potential for adverse activities	Scope creep
Labor injuries	Work quantity deviations
Labor productivity	**Material**
Contractual/Legal	Reliance on JIT material delivery
Construction claims	Secure material yards
Construction clauses	Material theft/fire
Contractor payment type	Material procurement
Contractor non-labor resources	Material delivery
Vendor bondability	Material shortage
Critical items import	Material waste
Equipment quality	**Political**
Theft of equipment and tools	Community attitude
Damage to equipment	Strong dissenting group
Equipment failure	Relevant public inquiries
Equipment shortage	Potential of delay by external parties
Economic Risk	Project stopped/abandoned
Contractor / subcontractor failure	Permits required
Supplier failure	Regulatory penalties
International market prices	**Management**
Construction market escalation	Project management capabilities
Inflation	Trade coordination
Tax rates	Cooperative environment
Exchange rates	Cost control and accounting
Area condition	Long-work stoppages
Construction area location	**Contractor**
Reconstruction project	Contractor prequalification
External site activity	Contractor ability and experience
Traffic conditions	New technology
On-site congestion	Defective work
Traffic permits and approvals	Rework
Competing activity on site	Short breaks
Site security	
Intense security needed	
Working hours restriction	

Table 4-1: Risks Affecting Construction Projects, Adapted from (Eyers 2001; Nasir et al. 2003)

For the implementation of our risk analysis methodology we make use of risk factors. Definition and benefits of using this approach are described next.

4.1.1 Using a Risk Factor Approach to Model Project Risks

Risk factors are more concrete abstractions of risk and define situations that can be individually assessed with a limited amount of information.

Risk factors affect a project through the occurrence of events that disrupt the development of an activity or a group of activities causing variations from the expected duration and cost estimates. This means that risk factors do not affect project activities directly, but do so through conditional consequences given that a risk event has occurred as shown in the figure below.

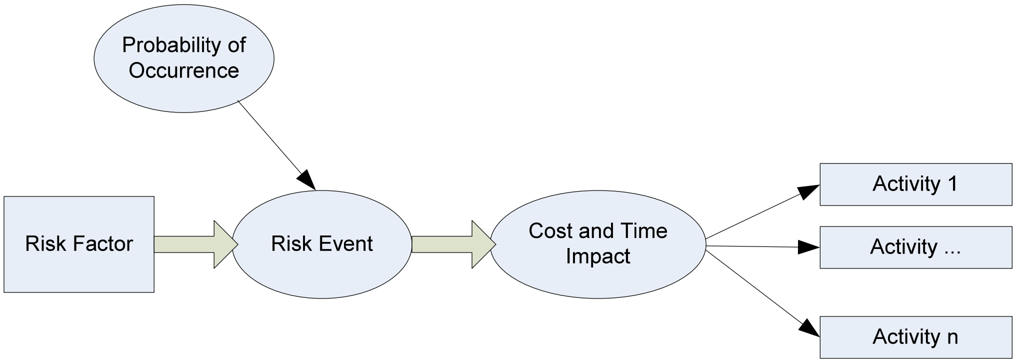


Figure 4-2: Risk Factor Model

The concept of risk factors is similar to one of common causes that is widely used in fault tree analysis in other engineering applications (Zhang 1989). The fact that a group of activities is affected by a common risk factor will indirectly induce correlation when consequences of that risk materialize. The rationale and motivation for the use of risk factors as an alternative to deal with correlation between project activities is presented in detail in several studies such as (Elkjaer 2000; van Dorp 2004; van Dorp and Duffey 1999).

The main advantage of using risk factors is that we can make use of causal relationships to relate the occurrence of a certain risk event with its consequences on project activities. One example of the application of a risk factor for a construction project is the risk of inclement weather; if inclement weather occurs, it delays not only the execution of open-sky activities that are scheduled at that time but also could affect the productivity of labor and machinery incurring in increased costs.

The figure below presents a model for the use of risk factors affecting activities within a project. Activities are organized using a Work Breakdown Structure (WBS), which is a fundamental planning tool that establishes the structure for managing the work to its completion in a project management system. A WBS divides a complicated task into smaller tasks using a hierarchical structure where tasks and subtasks are organized into work packages or activities. In here a work item is one small piece of the project and a work package is the lowest-level item. A WBS is formally defined as a deliverable-oriented grouping of project elements that organizes and defines the total work scope of the project (Project Management Institute 2004).

A work package is the lowest level of the WBS and establishes the baseline for project scheduling, tracking, and cost control. Work packages describe in detail the work required to meet project needs and to match the project manager’s initial work plan. Each work packages contains the following information: scope, budget and schedule; it relates the work to be performed to time, cost, and people.

The accumulation of the budgets of all work packages provides an estimate cost for the total project. The work packages are then integrated in a schedule using the logical relationships and constraints to define work sequence (Oberlender 2000).

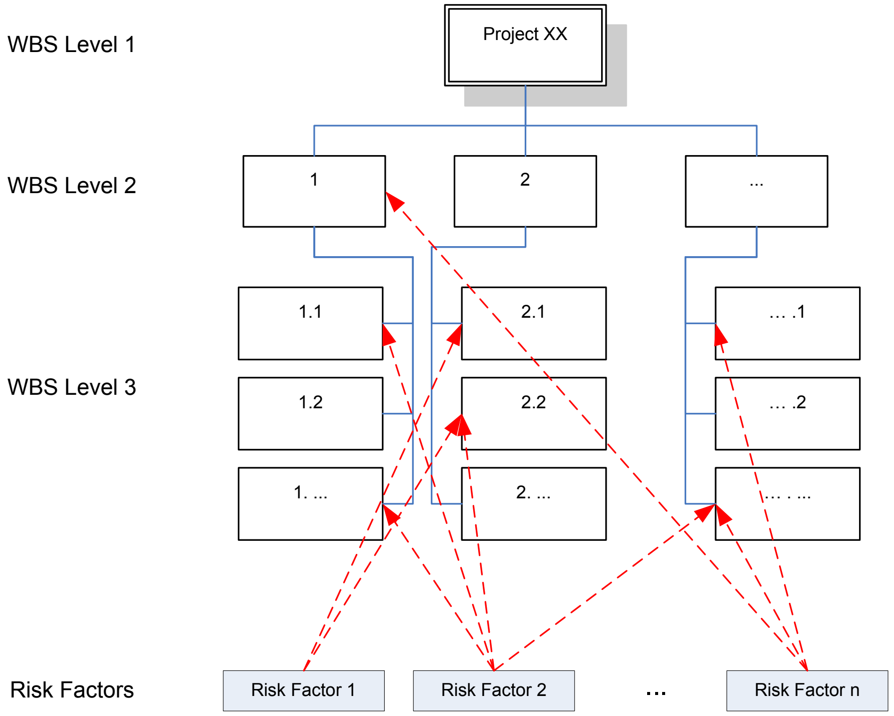


Figure 4-3: Mapping Risk Factors to Project Work Breakdown Structure

In the figure above we can observe that a risk factor can affect one work package or several of them at the same time; for example work package 2.1 is affected only by risk factor 1 while all activities that belong to the work group 1 (work packages 1.1, 1.2, …, 1. ...) are affected by risk factor *n*. We can also think that one activity can be affected by more than one risk factor such as work package 2.2 which is affected by risk factors 1 and 2.

One of the main problems with current risk factor models used in project risk analysis is that risks affecting project performance are considered mutually independent;

moreover it examines risk impact of each risk factor separately. In reality, risk factors are very often interdependent and their impact varies simultaneously with a compounding effect. As presented in Chapter 3, the use of BBN's provides a way for modeling interdependencies among risks and non-additive impacts due to their simultaneous realization; BBN's are also able to consider into the analysis qualitative information such as contractual, organizational, environmental, economic and regulatory aspects that can affect the performance of a project.

4.2 Cost-Schedule Integration

A more realistic project risk analysis involves the simultaneous consideration of cost and schedule risk. Schedule delays can cause serious project cost overruns; examples of increased project costs due to schedule delays include additional overhead and administrative expenses, contractual penalties for late deliveries, additional resources needed for accelerating progress, loss of revenue for late start of operations and collection of revenues, etc.

This implicit correlation between the duration of the project and its total cost brings the necessity for integrating schedule and cost risks. An integrated simulation approach is not an easy task since it has to consider the combined effects of cost and schedule uncertainties by simultaneously examining all correlated variables. Typical methodologies that use a correlation matrix in input parameters require evaluation of correlation coefficients for modeling dependencies between cost variables, schedule variables and cost and schedule variables. As discussed in the literature review most of the current approaches fail to address these correlation issues and do not provide a method for dealing with different cost and schedule structures (Rao and Grobler 1995;

Sha'ath and Singh 1994). Often, the schedules are related to Work Breakdown Structures while the cost estimates are related to Cost Breakdown Structures (CBS). A CBS is a hierarchical structure that rolls budgeted resources into elements of costs, typically labor, materials and other direct costs.

There are a couple ways to relate a WBS with a CBS for a risk analysis model where special attention should be given to time-dependent costs. The first one is to determine the cost value of a work package from the project cost estimate and assign it to the belonging schedule summary task and using a common time unit a total figure can be derived after the duration uncertainty is evaluated (Hullet 2002). The second approach is to adopt the WBS as a common basis for the analysis to relate the cost and schedule data of work packages as depicted in Figure 2-21. Using the project WBS implies that besides durations estimates, only direct costs can be assigned to each work package. This allows the consideration of internal uncertainties related to time and direct cost of individual work packages. This is the approach adopted in the proposed methodology.

Direct costs are the cost attributed to the production activities of the project; examples of direct costs for a construction project include labor, equipment, crews, materials and sub-contractors. It is important to notice however, that in certain cases the value of some direct costs can be also dependent on the productivity of the resources needed; therefore, these costs are also dependent on the duration of the work package, in which case this duration will determine a portion of the value of the total direct cost of such work package.

The total direct cost of a project is the summation of all project work packages' fixed and time-dependent direct cost such as:

$$Total\ Direct\ Costs = \sum_{WorkPackage(i)=1}^{n} \left[Fixed\ Direct\ Costs_{(i)} + Time\text{-}Dependent\ Direct\ Costs_{(i)} \right] \quad (3.29)$$

Indirect costs are also an important part of a project total cost. Indirect costs consist of two components: project overhead and general overhead.

Project overhead costs are field-related cost that are incurred in achieving contract completion, but which do not apply directly to any specific work item. Within the project overhead cost, indirect costs can be either fixed or variable. Examples of fixed indirect cost are: project office expenses, site installations and operations of site installations, etc. Variable indirect costs, on the other hand, are dependent on project duration. Examples of variable indirect cost include wages and salaries of supervisors, medical and safety personnel, etc.

General overhead costs are fixed indirect costs unrelated to a specific contract, rather to the operation of the contractor’s home office. The general overhead charged to a project can be calculated as a proportion of the project direct cost times the total home-office overhead in a year divided by the expected sum of direct costs of all projects during the year (Hegazy 2002). This project cost structure can be better represented in the figure below.

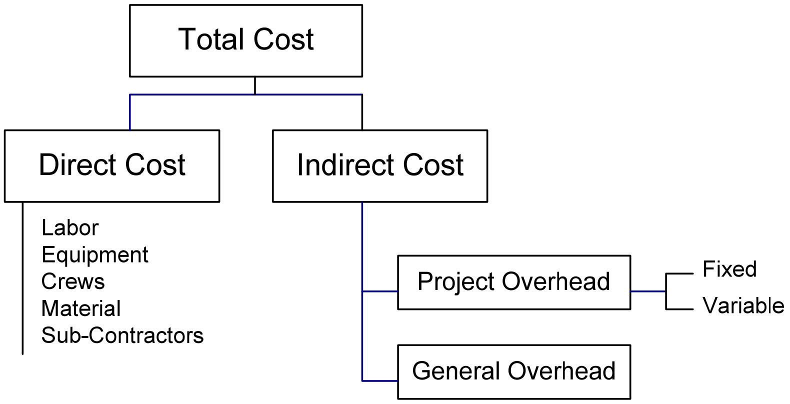


Figure 4-4: Cost Structure of a Construction Project

Hegacy (2002) presents a comprehensive list of project overhead costs for the construction industry, which is shown in the following table:

Variable Cost ($/day):	**Fixed Cost:**	**Fixed Cost:**	**Fixed Cost:**
WAGES & SALARIES	**A. OFFICE EXPENSES**	**B. SITE INSTALLATIONS**	**C. OPERATION OF SITE INSTALLATIONS**
SUPERVISION	**OFFICE EQUIPMENT AND SUPPLIES**	**EQUIP. ERECTION**	**ROAD & YARD MAINTENANCE**
PROJECT MANAGER	-FURNATURE & FURNASHINGS	**NON-PAY ROADS & YARDS**	-COST OF SURFACE MAINTENANCE
PROJ. SUPERINT.	-EQUIPMENT(e.g. COMPUTERS)	-CONSTRUCTION OF SITE HAUL	DUST CONTROL, SNOW REMOVAL,
GEN. SUPERINT.	-SUPPLIES & STATIONARY	-PREPARATION OF CAMP SITES,	DRAINAGE MAINTENANCE
ASS. SUPERINT.	-POSTAGE, POSTAGE MACHINES	YARD AREAS, & STORAGE SITES	**PROJECT OPERATION & MAINT.**
TRADE SUPOERINT.	-BADGES, TENCILS	-CONSTRUC. OF DOCKS, PIERS	-TRAILOR LOT RENTALS
MASTER MECHANIC	-PAYROLL & ACC. COMPUTER	LOADING PLATFORMS, etc.	-BUILDING REPAIRES & MAINT.
ASSIST. MECHANIC	**ENGIN. EQUIPMENT AND SUPPLIES**	-CONSTRUCTION OF FENCES	-BUILDING INTERNAL SERVICES
ENGINEERING	-SURVEYING EQUP. & SUPPLIES	**BUILDING ERECTION & DISMANTLE**	-JANITORIAL SERVICES
PROJECT ENGINEER	-REPRODUCTION EQUP. & SUPPL.	-OFFICE, WAREHOUSE, etc.	-GARBAGE PICK-UP
OFFICE ENGINEER	-DRAFTING EQUP. & SUPPLIES	-CAMP AND HOUSE TRAILERS	-FUEL SUPPLY
COST ENGINEER	-COMPUTER EXPENSES	-WORKSHOPS	**SERVICES, OPERATION & MAINT.**
SCHEDULE ENGR.	-PHOTOGRAPHIC EQUP. & SUPPL.	-EXPLOSIVES MAGAZINES	-WATER SYSTEM
DESIGN ENGINEER	-CONSULTING, TESTING & INSP.	-WORK PLATFORMS	-SEWAGE SYSTEM
FIELD ENGINEER	**LEGAL & PUBLIC RELATIONS**	-MATERIAL WEIGH SCALES	-DRAINAGE SYSTEM
ENGR. TECHNICIAN	-LEGAL/AUDIT FEES	**SERVICES INSTALL. & REMOVAL**	-AIR SUPPLY AND DISTRIBUTION
OFFICE & CLERICAL	-DONATIONS / PR	-WATER SYSTEM	-HEATING AND DISTRIB. SYSTEM
PERSONNEL MANGER	**MEDICAL & SAFETY SUPPLIES**	-SEWAGE SYSTEM	-STANDBY GENERATORS
PURCHASING AGENT	-MEDICAL EXAMINATIONS	-DRAINAGE SYSTEM	-POWERLINES,LIGHTING SYSTEM
ACCOUNTANTS	-MEDICAL SUPPLIES	-AIR SUPPLY AND DISTRIBUTION	-ELECTRICAL HOOK UPS
PAYMASTER	-SAFETY & WEATHER WEAR	-HEATING AND DISTRIB. SYSTEM	-COMMUNICATIONS INSTALLATION
WAREHOUSE CHIEF	-SIGNS & BARRICADES	-STANDBY GENERATORS	**INDIRECT TRANSPORTATION**
GENERAL HELP	-FIRE PROTECTION SUPPLIES	-POWERLINES,LIGHTING SYSTEM	-PICKUPS, CREW-CABS, CREW-
EQUIPMENT CLERK	**EMPLYEE MOVE IN, MOVE OUT**	-ELECTRICAL HOOK UPS	TRANSPORT, CREW BUSES, etc.
MEDICAL & SAFETY	-HOURLY EMPLOYEES	-COMMUNICATIONS INSTALLATION	**WAREHOUSE OPERATIONS**
SAFETY SUPERVIS.	-SLARIED EMPLYEES	**SHOP EQUIP. & SHOP TOOLS**	-VEHICLE AND DRIVER
FIRST AID MEN	-HEAD OFFICE VISITS\	-PURCHASE / INSTALL. OF HOISTS,	-PICK UP SERVICES
NURSES	-EXECUTIVES	SMALL TOOLS, WINCHES, JACKS, etc.	-YARD EQUIPMENT
SECURITY MEN	-FAMILY MOVE IN/OUT	**FINAL CLEAN UP**	**SERVICE & MAINT. EQUIPMENT**
EMPLOYEE BENEFITS	**CATERING COST**	-COST OF LABOUR, EQUIP.,OR MATERIAL	-SHOP SUPPLIES (e.g. BOLTS)
-WORKMEN'S COMPENS.	-ROOM AND BOARD ALLOWANCE	TO CLEAN UP THE SITE AT COMPLETION	-WELDING SUPPLIES
-SOCIAL SEC. & PEN. PLAN	-LIVING EXPENSES ALLOWANCE		-GENERAL SHOP LABOUR
-UNEMPLOYMENT INS.	**NON-RECOVERABLE INS. COSTS**		**EXPENDABLES**
-HEALTH, WELFARE, GROUP INS.	-INSURANCE CLAIMS (e.g. AUTO)		-COST OF MACHINE ATTACHEMENTS
-VACATION AND HOLIDAY PAY	**INSURANCE, TAXES & BONDS**		THAT UNDERGO WEAR (e.g. BITS)
TRAVEL TIME PAY	-INSURANCE		**ELECTRICAL POWER CHARGES**
TRAVELLING EMPLOYEES	-TAXES (PROPERTY, BUISENESS)		**PROJECT SMALL TOOLS**
LABOR ADJUSTMENTS	-BONDS (PERFORMANCE)	**Fixed Costs: D. OTHERS**	
-SHIFT PREMIUMS	-EQUIPMENT TAXES		
-HIGHT PREMIUMS	-EQUIP. & VEHICLE LICENCE	**FINANCING**	
-UNDERGROUND PREMIUMS	**COMMUNICATION EXPENSES**	-COST OF FINANCING THE JOB	**ESCALATION**
-COMPRESSED AIR PREMIUMS	-LONG DISTANCE CHARGES	CALCULATED AT CURENT RATE	
-PRODUCTION BONUS	-TELEX, FAX LINE CHARGES		**CONTINGENCIES**
-EQUIPMENT PREMIUM	**FRIGHT EXPENSES**	**HEAD OFFICE SUPPORT**	-ESTIMATED COST OF INTERFER-
	-FRIGHT AND EXPRESS COST	-MONTHLY OR % CONTRIBUTION	ENCES INCLUDING; FLOODS, STRIKES,
	-HANDLING, PACKING	TO MAINTENANCE OF HEAD	TAX INCREASE, EARTHQUAKES
	MISCELLANEOUS	OFFICE FACILITIES & STAFF	
	-PARTIES / ENTERTAINMENT		**BONUS OR PENALTY**
	-DUES, LICENCES, PERMITS		
	-YARD, OFFICE RENTALS		

Table 4-2: List of Project Overhead Costs (Hegazy 2002)

A detailed list of project overhead costs is of great help for the calculation of the total indirect cost of the project such as:

$$Total\ Indirect\ Cost = Fixed\ Indirects + \left[Variable\ Indirects(\$/day) \times Project\ Duration\right] \tag{3.30}$$

Then the total project cost is:

$$Total\ Cost = Total\ Direct\ Costs + Total\ Indirect\ Costs \tag{3.31}$$

Using the WBS as a common basis for organizing the schedule and cost data and including costs that are time-dependent in the analysis allows the project schedule to interact directly with the calculation of the total project cost. The simulation model that is later described uses this framework to integrate time and cost through a cost schedule-driven model.

4.3 Using Bayesian Belief Networks within Monte Carlo Simulation Environment

4.3.1 Monte Carlo Simulation

The principal application of Monte Carlo Simulation is to study the behavior of stochastic processes. These are problems in which the input is stochastic. MCS is particularly effective when the process is nonlinear or involves many uncertain inputs, which my be distributed differently from each other (Hartford and Baecher 2004).

MCS generates a large number of sets of randomly generated values for the uncertain parameters and numerically computes the performance function of each set. From this random sample one can plot a cumulative distribution function (CDF) and estimate statistics such as the expected value, variance and higher moments. Regardless the number of stochastic inputs, each run gives one observation of the process; therefore, increasing the number of stochastic input variables does not increase the number of runs for a given level of accuracy that can be established by applying methods of statistical inference.

The number of iterations required in a simulation varies depending on the size and complexity of the model. One way to determine an adequate number of iterations is to keep track the stability of output distributions being generated in the simulation. As more and more iterations are executed during a simulation, the output distributions become more “stable”. This happens because the statistics that describe those distributions change less and less as additional samples are obtained. The simulation can be stopped when these statistics change less that certain percentage of convergence (e.g., 1%). The statistics that are considered for this test are the mean, standard deviation, and percentiles (5% to 95% in 5% increments) of each output. Monitoring convergence is done by calculating these statistics on the generated data of the model outputs at regular intervals throughout the simulation.

The literature review in Chapter 2 shows that MCS is the preferred method for project risk analysis. MCS offers a viable alternative when analytical models are mathematically intractable or must be oversimplified. This is actually the case for multi-process scheduling, precedence constrained scheduling, scheduling with individual deadlines and scheduling with probabilistic and/or conditional branching; Garey and Johnson (Garey and Johnson 1979) classify these problems as NP complete because of their intractability.

More details on MCS theory and implementation can be found in most risk analysis text books; useful references are (Bedford and Cooke 2001; Clemen et al. 2001; Hartford and Baecher 2004; Raftery 1994; Ross 2002; Vose 2000)

4.3.2 A Model for Project Risk Analysis Using Bayesian Belief Networks within a Monte Carlo Simulation Environment

Project risk analysis benefits greatly from the integration of BBN’s and MCS. On one hand, BBN’s present an adequate alternative for modeling interdependencies among risk events; BBN’s are also capable of considering qualitative characteristics of a project into a risk analysis model as well as incorporating non-additive impacts due to the simultaneous realization of risk events. On the other hand, MCS models for project risk analysis offer several other advantages. First, project schedules with probabilistic and/or conditional branching characteristics can be easily implemented generating useful results such as criticality of activities and consistency of critical paths. Secondly, probability distributions can be used for modeling internal uncertainties related to productivity, duration and cost of project activities and their effects on the project objectives studied. Finally, external uncertainties and risk events can also be incorporated into the model by using probability distributions to represent their occurrence. The following figure depicts the process of how BBN’s and MCS interact together as the basis for the proposed methodology.

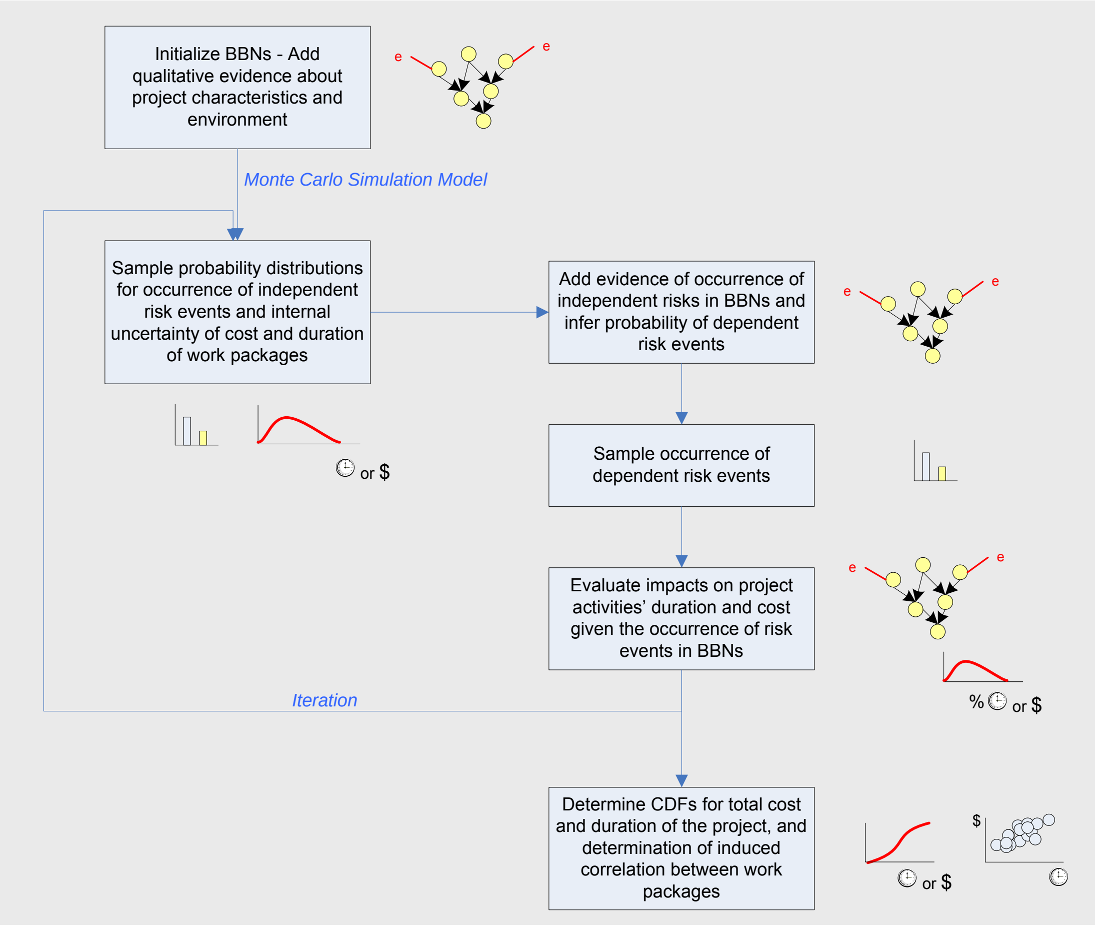


Figure 4-5: Integration of Bayesian Belief Networks within a Monte Carlo Simulation Environment

The first step in Figure 4-5 is the initialization of BBN's that contain in their structure characteristics of the project and the environment that surrounds it. This information is qualitative in nature and describes, for example, organizational structure, management support, quality of design documents, availability of resources, etc. This information is added as evidence in the corresponding BBN's so changes on probabilities of occurrence of dependent risks or states of dependent nodes can be evaluated.

After the initialization of BBN's is done the process goes into a MCS model where the following steps are iterated several hundreds of times as directed by the analyst:

The MCS program first samples values from probability distributions that represent the internal uncertainty of cost, productivity or duration of project activities. The occurrence of independent risk events is also sampled from their respective probability distributions.

Once that the occurrence of independent risk events is evaluated, this information is considered as new evidence in the BBN that are part of. This evidence is then propagated through the BBN to assess the posterior probabilities of dependent risks to sample their occurrence.

Each of the iterations of the MCS model generates information on the values that were sampled from probability distributions that represent activities' internal uncertainty as well as the realization of independent and dependent risk events. Given the realization of a risk event, time and cost consequences are then evaluated and assigned to the affected project activities. If more than one risk event is present and the combined effect of their presence is non-additive, their realization can also be considered as evidence in a specific BBN that assesses the compounding effects of risks happening simultaneously.

Figure 4-6 presents how the BBN-MCS model interacts with a project network. A project network is a graphical representation of the activities that were identified in the project WBS and in which the logical relationships among them are shown.

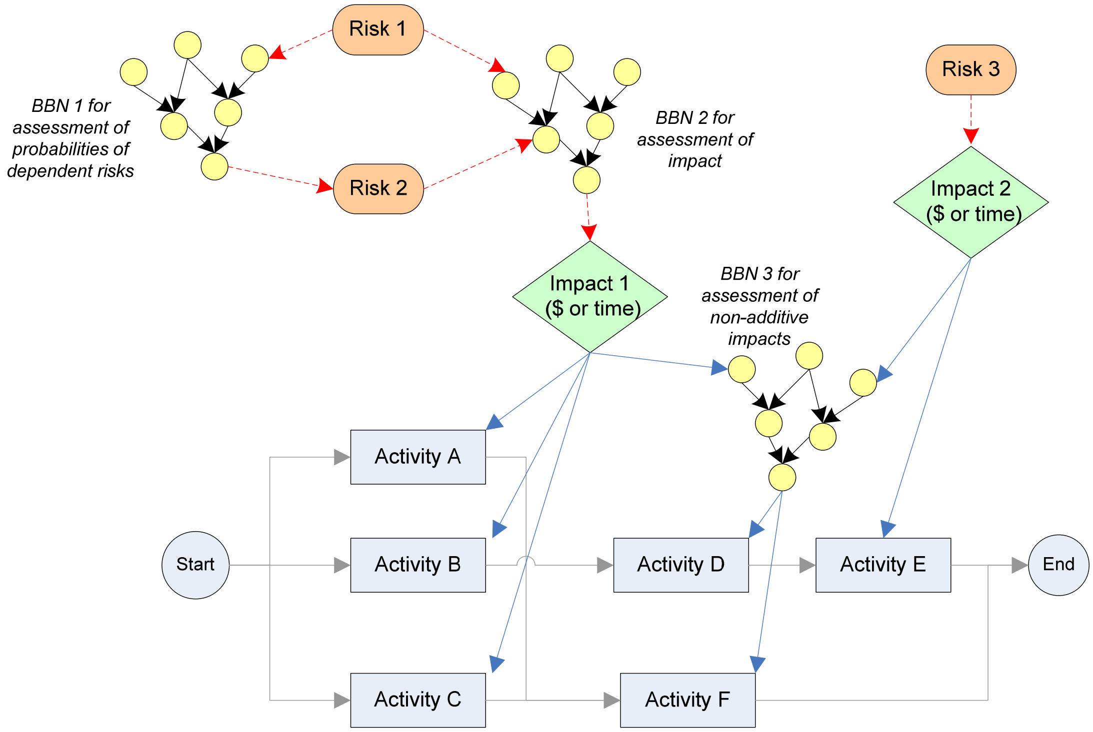


Figure 4-6: Interaction of a BBN-MCS Model with a Project Networks

In this example there are three Bayesian networks, BBN 1, BBN 2 and BBN 3 and two independent risks, Risk 1 and Risk 3. Risk 2 is considered dependent and its probability of occurrence is conditional on the realization of Risk 1 as well as on any other qualitative information or evidence contained in BBN 1. BNN 1 acts as a tool for assessing probabilities of dependent risks.

BBN 2, on the other hand, evaluates the magnitude of consequences conditional on the realization of the risks 1 and 2; these consequences are transmitted to project activities through a time and/or cost impact. In this example, the extent of Impact 1 is dependent on the presence of Risk 1 and Risk 2 and affects activities A, B and C.

If Risk 3, occurs it creates an Impact 2 that affects activity E directly. That is not the case for activities D and F which can be affected by impacts 1 and 2. However, if these impacts act at the same time the total impact is not necessarily the addition of both. BBN 3 provides the means to evaluate compounding effects of several impacts.

4.4 Methodology

In this section we present the necessary steps for the application of the BBN-MCS model as a methodology for project risk analysis. These steps are:

a) The first thing to do is to review the project scope, the project plan and any assumptions that were made during in the initiation and planning phases. The completeness of the work to be performed as well as the methods for its execution should be analyzed in detail so any problems can be identified and solved in this stage.

b) Large projects tend to have hundreds and sometimes even thousands of activities in their project schedules; if this is the case, project activities can be grouped into work packages. Each work package should be identified so a sequence logic can be established using a project network that is coherent to the project WBS. If the original project schedule has a reasonable number of project activities (e.g., less than 150 activities) it can be used directly for the model.

c) For each activity or work package a direct cost and duration should be estimated. This information is considered as the base values and corresponds to their most likely estimates, which are thought to be the duration and/or cost of the work package under normal circumstances and without the occurrence of major problems. If these estimated values are uncertain, probability distributions should be used to account for that fact; at this stage only the internal uncertainty of the element is considered. The following table provides a guide format for compiling work packages' information.

Activity Number	Project Activity	Base Cost	Base Duration

Table 4-3: Work Package Base Information

d) Determine the indirect cost per unit of time as suggested in Section 4.2 for purposes of integrating project schedule and total cost.

e) Identify risks and opportunities that could lead to changes in cost and/or duration of work packages. This process is typically performed through workshops where the project team and the risk analysts participate. The outcome of this step defines a risk registry, which is a list of risk events that impact negatively or positively project activities. It is important to also identify the possible causes or other risk than can be triggered by such events; this information is useful for the later construction of BBN's for the evaluation of the dependency effects among risk events.

If the risk assessment on the project cash flow is required in the analysis, it is recommendable to include escalation rates as a variable in the model.

The following table provides a format that facilitates the construction of the risk registry.

Item	Risk or Opportunity	Classification	Probability of Occurrence	Activities Affected	Impacts	
					Cost (Fixed or Variable)	Time (Fixed or Variable)
		☐ Internal ☐ External ☐ Local ☐ Global				
		☐ Internal ☐ External ☐ Local ☐ Global				

Table 4-4: Risk Registry

Cost and time impacts can be expressed as a percentage increase or decrease of the base cost and duration values of the affected activities. Impacts can also be expressed as a fixed number or using a probability distribution. These values are obtained from available information and/or expert opinion.

f) Investigate characteristics of executing and owner organizations, the project itself and the surrounding environment that influence the project performance. This information should be properly recorded for its use in later steps.

g) Construct BBN's to model risk events dependencies, to account for influences of qualitative project characteristics on risks occurrence and on the magnitude of their impacts, and to reflect non-additive impacts of simultaneous occurrences. Construction of BBN's is covered in Section 3.3

h) Add acquired information as evidence to BBN's that include qualitative project information.

i) Implement the BBN-MCS model presented in Section 4.3.2. This model uses the project schedule, the risk registry, and BBN's developed to evaluate the risk and uncertainty in total project cost and schedule.

j) Evaluate risk impacts, uncertainty and sensitivity in project cost and schedule.

k) Identify and rank the most significant risks and explore possible ways to reduce their occurrence and impacts associated with those risks problems. Also this step should include the identification of opportunities and the alternatives to maximize their benefits. Risk and uncertainties can be prioritized in terms of relative contribution to the risk cost and schedule. This information is an important input for project risk management, mitigation and control process; although, these processes are beyond the scope of this dissertation, useful references in the topic are (Chapman and Ward 2003; Cooper and Broadleaf Capital International. 2005; Flanagan and Norman 1993; Raz et al. 2002).

l) Evaluate risk management strategies for critical risks and uncertainties. Evaluate the cost and duration to implement risk management alternatives and the benefits of their implementation. The following tables present a format for reporting purposes.

Rank	Risk	Cost / Schedule Relative Impact	Management Action

Table 4-5: Prioritization of Project Risks

Rank	Opportunity	Cost / Schedule Relative Impact	Management Action

Table 4-6: Prioritization of Project Opportunities

m) Report results, which include:

- CDF of project total cost and duration

- Correlation matrix generated by the BBN-MCS model
- Probability of meeting milestones and budget constraints
- Critical index of work packages or activities and potential critical paths if more than one
- Project work packages or activities that are most prone to be affected by risks and uncertainty
- Prioritized project risks and opportunities
- Risk management strategies and actions

It is important to note that when the project progresses new information is acquired and the model can be updated and the analysis repeated as a way to revise results and forecast cost ant duration at completion. The process described above can be repeated several times to include different scenarios.

4.5 Summary

This chapter presented a methodology for the integration of Bayesian belief networks (BBN's) within an integrated cost-schedule Monte Carlo simulation (MCS) model.

The necessary steps for the implementation of this methodology have been outlined. This chapter also introduced a way to classify project risks and brought the necessity to consider the correlation of project cost and its duration. A method to integrate cost and schedule was presented.

The following chapter presents a case study of a transportation infrastructure project for demonstrating the implementation and benefits of the methodology proposed here.

5. Case Study

In this chapter the BBN-MCS model is used to perform a risk analysis of a real infrastructure project. Here the benefits of using the developed methodology and the improvements in the analysis are revealed. Specifically, the use of BBN's allow for the incorporation of qualitative evidence about the project characteristics and its surrounding environment; this capability of the model also permits the creation of different scenarios of analysis, so assumptions and constraints can be probabilistically tested on project objectives through the risk model.

BBN's are also used to incorporate dependency and causality relationships among risk factors and variables that capture uncertainty. Moreover, BBN's are used to incorporate non-linear consequences when risks occur simultaneously.

The following sections will show how such considerations where modeled.

5.1 Background

The case study used in this chapter refers to a transportation infrastructure project owned by the Washington State Department of Transportation (WSDOT). For proprietary reasons, as requested by WSDOT, the name of the project and its location cannot be disclosed, as well as any details about the existing infrastructure involved. In order to honor this confidentiality agreement, actual names of related infrastructure were changed.

An aerial photo of the area of influence of the project is presented in Figure 5-1 where the new structures are highlighted. This project consists of:

- Replacement of a major signalized intersection that involves state highway US-XX and state road SR-YY with a full interchange; the SR-YY will be realigned and go over the highway. See Figure 5-2.
- Removing a signalized intersection at US-XX and H Road where the later will be realigned over the US-XX and connected to J Road, which is extended to connect to SR-YY and the new interchange as shown in Figure 5-3.

The design and construction of this interchange aims to improve safety, reduce the risk of collisions, decrease congestion, and enhance economic vitality for the area.

Project construction is scheduled to begin in 2010 and has an estimated cost of $25.7 million ($M) in 2006 dollars.

Figure 5-1: Aerial View of the Project Area of Influence

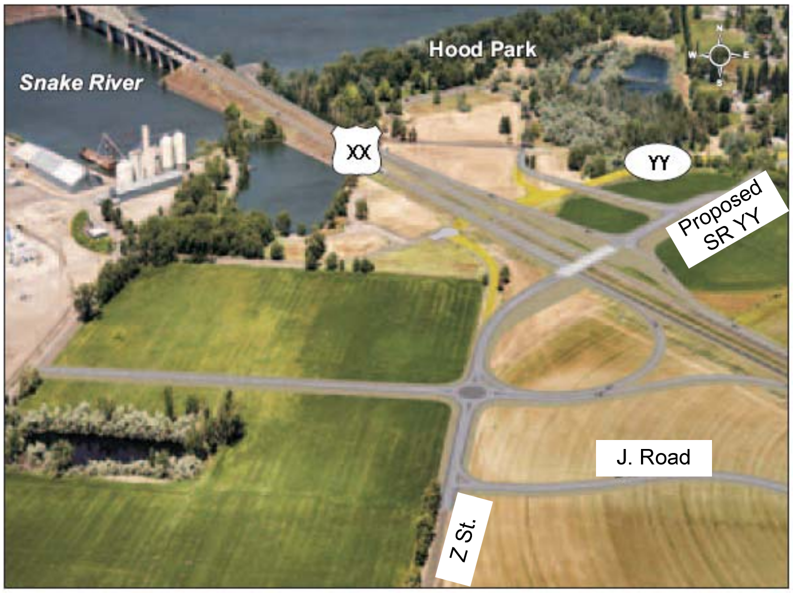


Figure 5-2: Proposed Interchange at US-XX and SR-YY

Figure 5-3: Bridge at H Road over US-XX

5.2 Project Data

The data provided by WSDOT corresponds to a Cost Risk Assessment (CRA) conducted in July 2006 to evaluate and quantify the cost and schedule uncertainty associated with the project. This CRA report was developed using a Cost Estimate Validation Process (CEVP) developed by WSDOT; details about this process can be found in Roberds and McGrath (2006) and WSDOT (2005).

The CRA report includes a summary of project cost, a project flow chart, uncertainties in project activities, and a risk register that are fundamental for the application of the methodology proposed in this dissertation. A single scope and delivery alternative was analyzed for this project.

5.2.1 Summary of Project Activities Base Cost and Durations

Base cost and duration values were prepared by the Project Team and validated by subject matter experts (SMEs) through a workshop that was part of the CEVP and CRA conducted for this project. These base values correspond to the planned costs and durations without considering contingencies or major risk issues. The table below presents the project activities as well as their base costs and duration values.

Activity Number	Project Activity	Base Cost (2006 $M)	Base Duration (months)
0	Previous Costs (Costs to Date)	0.25	1
1	Preliminary Design (<30%)	0.1	3
2	Environmental Documentation	0.48	18
3	DCE / DNS		0
4	Final Design (30% - 100%)	0.41	12
5	ROW Plan / Access Hearing	0.2	6
6	ROW Acquisition (excluding Reserve land swap)	2.7	18
7a	Reserve land swap - ID candidate sites + prelim approval		2
7b	Reserve land swap - Legislative action		12
7c	Reserve land swap - Negotiate	0.13	8
7d	Reserve land swap - NEPA	0.16	12
7e	Reserve land swap - Purchase / swap	0.4	3
8	Permitting and Mitigation Planning	0.16	12
9	PS&E (including DDP approval)	0.21	6
10	ROW Certification		0
11	Ad / bid / award / negotiate		3
12	Pre-construction PM		41
13	NTP		0
14	Early Utility Relocations	0.07	3
15	Stage 1 - Build SR-YY IC (excl ramps)	8.7	8
16	Off-site mitigation		3
17	Close SR-YY IS & Detour to H Road		0
18	Stage 2 - Finish SR-YY IC ramps & Hood Park Entrance	1.84	2
19	Reopen SR-YY IC / Close H Road IS / Detour to SR-YY		0
20	Stage 3- Build H Road Bridge	7.38	8
21	Complete		0
22	Contruction PM	2.51	21

Table 5-1: Base Activity Costs and Durations

The total base cost of the project is $25.7M and includes previous costs to date of $0.25M in 2006 dollars.

A more detailed summary of the base costs can be found in Appendix A, where the most significant drivers are structures, earthwork and right of way that represent approximately the 45% of the total project cost.

When the CRA report was developed, detailed engineering had not begun; however, this report claims that the estimate, methodology and detail were appropriate for the level of design that had taken place.

5.2.2 Project Master Schedule

The figure below shows the project master schedule that represents the precedence relationships among project activities; the project network is used by the risk analysis model as the basis for the integrated cost and schedule model.

This type of schedule models can be easily constructed using software packages such as Microsoft Project (Microsoft Corporation 2003) or Primavera Project Management (Primavera Systems 2005); although these applications allow for the quick construction of project schedules, they are restrictive in the creation of calculation formulas that a user might need because the information is stored in a data base. For this reason, the project network was constructed in Microsoft Excel (Microsoft Corporation 2003) where cost and duration data can be manipulated and connected to the MCS and BBN applications; details on the construction and calculations required for such project networks can be found in (Roberds and McGrath 2006).

The figure below presents the project master schedule.

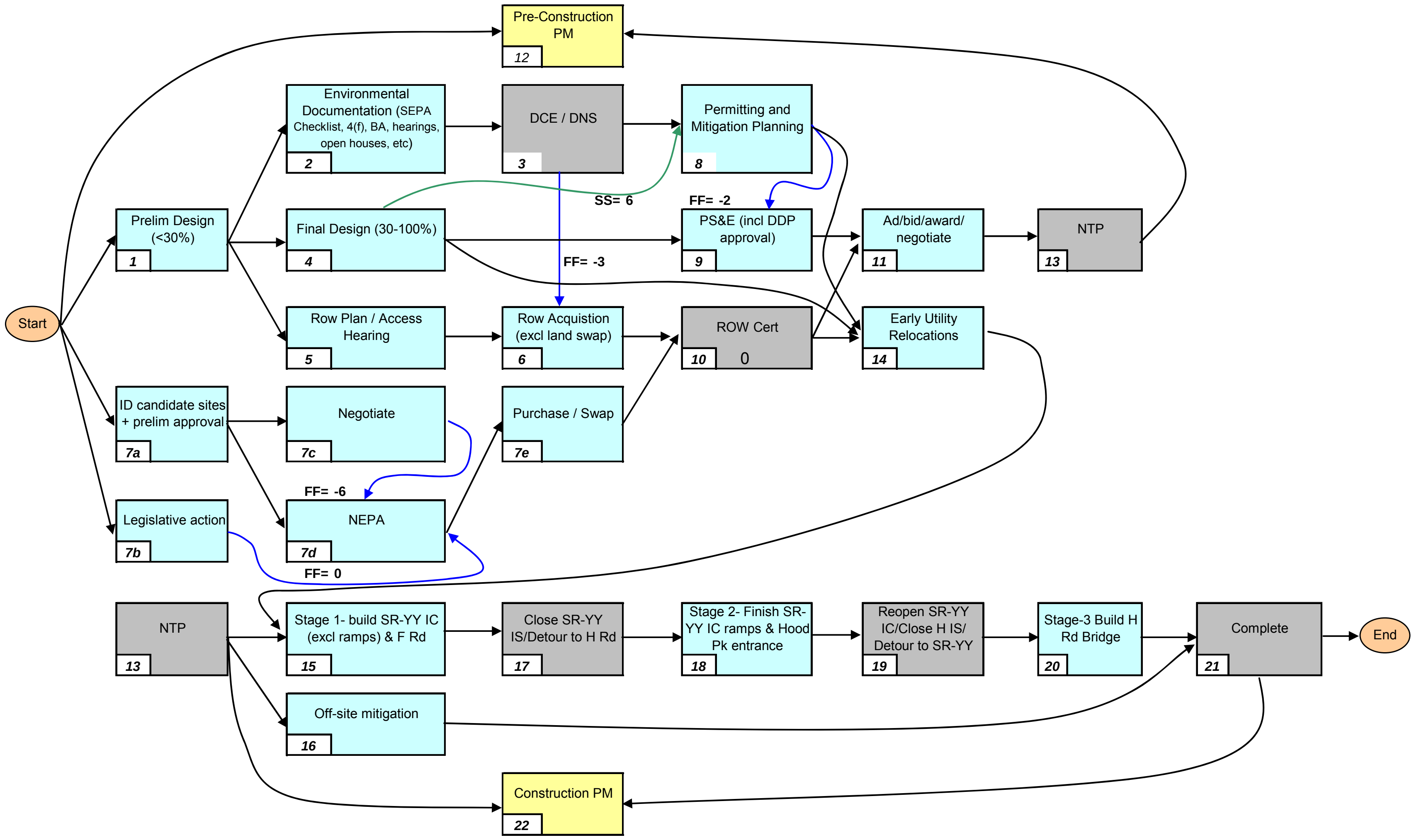


Figure 5-4: Project Network

Figure 5-4 presents the project network, where the precedence relationships among activities from Table 5-1 are denoted by the arrows. Most activities have a “Start-Finish” relationship with their predecessors; when other relationships such as “Start-Start + lag” or “Finish-Finish + lag” were needed, their arrows were labeled as “SS = lag” and “FF= lag”, respectively. Activities 12 and 22 are summary activities, so their duration is dependent on the duration and logic of contained activities; this is beneficial to model time-dependent costs (e.g., pre-construction and construction project management costs).

The project has a start date of August 8, 2006[1]. Using CPM calculations in the network above the base project duration is 62 months with a completion date of October 2011. The project has two main phases, pre-construction and construction. They have base durations of 41 and 21 months, respectively. An important milestone of the project is activity 13, which represents the Notice to Proceed (NTP) event and the start of the construction phase. The construction phase is divided in three stages represented in activities 15, 18 and 20.

The schedule model should accommodate the following constraints:

- Activity 11 that represents the “Advertisement/Bid/Award/Negotiate” process cannot fall between May 1st and October 1st of any year; if this happens the start date of this activity should be delayed until October 1st. This constraint is required to avoid a summer advertisement date. The base Ad date is October 2009.
- Construction activities have to be shutdown during winter, specifically during December and January.

---

[1] Year 2006 is considered as the year of study and used as the year for current dollars in cost results.

5.2.3 Project Assumptions and Exclusions

The following assumptions were documented in the CRA report:

No funding constraints apply
The project is at about 10% design, with a preferred alternative. The preferred alternative has already been subjected to a Value Engineering study Single Design/Bid/Build construction contract
Negotiation and legislation for land swap can be completed in reasonable time
Land swap includes wetland mitigation
Port provides land for J Road, and maintains ownership after construction until turn-over to county
Wetlands are Class III, with 1 acre of impact that must be mitigated at about 4:1 (including buffers)
Utilities (electric, cable, etc.) are on franchise and must relocate at no cost to project
No compensation to gas stations for loss of business due to losing access to US-XX at H Road – if inverse condemnation upheld, costs will come from elsewhere (not to project)
Do not need access to US-XX at H Road for emergency vehicles
Land from USACE in reasonable time (and reasonable cost)
Keep surplus property (proceeds do not go to project anyway)
No extension of realigned H Road past S.L. Road
Detour onto S.L. Road approved
Full take of main commercial property for sale at H Road
Runoff to shoulder and direct infiltration is approved for new impervious surface
No additional scope
Documented Categorical Exclusion (DCE) with Determination of Non Significance (DNS) is the appropriate environmental documentation
No noise walls are required
No retaining walls will be used (fill slopes/embankments will be used)

Table 5-2: Project Assumptions

The following exclusion is also stated:

The project team chose to exclude any “project stopping” risks, such as insurmountable public, private, or political opposition, and other potentially significant risks such as reduced funding or delays in securing additional funding if required. The results presented in the CRA and in this case study are conditional on the assumption that these risks do not occur.

5.2.4 Base Uncertainty and Risk Register

The CRA report contained two basic components needed for the risk analysis of this project; the first one is the identification of uncertainties affecting the base cost estimate presented in Appendix A. These uncertainties affect unit prices or quantities in the cost estimate that is used for allocating cost to the project activities as shown in Table 5-1.

The second component is the Risk Register which describes and categorizes risks and opportunities that impact the duration and/or cost of project activities.

The uncertainty analysis and the Risk Register were developed through a workshop that included the project team members and SMEs.

The table below presents a summary of the uncertainties affecting the base cost estimate. The values presented in this table represent the combined unit price and quantity uncertainty, in 2006 dollars and unless noted, they are exclusive of risks and opportunities of the Risk Register.

Item	Unit	Deterministic Base	Low (10th percentile)	High (90th percentile)
ROW – H Road ($2.0M) and SR-YY IC ($0.7M)	LS	$2.7M	$1.8M (-35%)	$3.3M (+25%)
ROW – Land Swap (base = 40 ac @ $10,000/acre)	LS	$0.4M	$0.2M	$0.5M
ROW Admin – H Road and SR-YY IC	LS	$0.2M	minor	minor
ROW Admin – Land swap	LS	$0.1M	minor	minor
Wetland mitigation (note: range includes opportunity to reduce impacts from embankment by using retaining walls) base = 2 acres impacts @ 3:1 mitigation ratio (incl buffers) @ $200,000/acre for wetland construction (excl ROW)	LS	$1.2M	$0.5M	$1.5M
Bridge structures (range excludes mobilization and uncertainty in configuration (see risk), but includes uncertainty in Type, Size, and Location (TS&L) for bridge and foundation)	SF	$160/sf	$150/sf (-16.7%)	$200/sf (+11%)
Utility Relocation	LS	$0.07M	minor	minor
Earthwork		$4.34M (incl mob, sales tax, CE)	-20%	20%
Pavement		$2.17M (incl mob, sales tax, CE)	-20%	20%
Retaining walls – all types. None in base			N/A	N/A
Drainage (including conveyance, retention/detention/water quality) (base = $80k for two structures, $0 for 27ksf new impervious surface)	LS	$0.07M	minor	minor
TESC		2% ($0.35M incl mob, sales tax, CE)	2% (+0%)	3% (+50%)
Noise walls			minor	minor
Other traffic items				
ITS (conduit, cameras, …, VMS)				
Temporary Traffic Control		10% ($2.12M incl mob, sales, tax, CE)	6% (-40%)	11% (+10%)
Allowance for Minor Items		15% ($1.62M incl mob, sales, tax, CE)	-10%	10%
Mobilization		8% ($1.2M incl mob, sales tax, CE)	6% (-25%)	10% (+25%)
Sales Tax		8%	-insig	+insig
Preliminary Engineering (excludes ROW negotiation)		13% ($1.72M)	10% (-23%)	15% (+15%)
Program Management			minor	minor
Construction Engineering (incl cultural monitoring, etc.)		14% ($2.49M)	12% (-14%)	16% (+14%)

Table 5-3: Summary of Base Uncertainty

Values shown in the table above represent the base value and the reasonable bounds of the distribution that models uncertainty expressed as the 10th and the 90th percentile. These values reported by the CRA were assessed from historical cost data and/or elicited from experts in a workshop.

Some other costs such as Preliminary Engineering and Construction Engineering are linked directly through the simulated model outcomes as a function of an increase in project duration.

In the same table the term “Minor” indicates that either the range of uncertainty is less than +/- 5% or the total dollar amount of the line item is not significant.

The following table shows the Risk Register summary where identified risks and opportunities affecting the project have been classified and categorized in six groups:

- Construction (C)
- Design, Environmental, Permitting (E)
- Right-of-Way (R)
- Scope Changes (S)
- Utilities (U)
- Minor and Unidentified Risks and Opportunities

Item	**Risk or Opportunity**	**Classification**	
	Construction		
C1	Market Conditions – Uncertain Competition in Contracting Market	☐ Internal ☒ External	☐ Local ☒Global
-	Market Conditions – Uncertainty in Cost Inflation of Labor, Equipment, and Materials	☐ Internal ☒ External	☒ Local ☐Global
Minor	Delays in bid process	☐ Internal ☒ External	☐ Local ☒Global
C2	Construction Change Orders	☒ Internal ☐ External	☒ Local ☐Global
-	Extended Overheads	☒ Internal ☐ External	☒ Local ☐Global
C3	Uncertain construction staging / phasing	☒ Internal ☐ External	☐ Local ☒Global
Minor	Other construction duration uncertainty	☒ Internal ☐ External	☒ Local ☐Global

Item	Risk or Opportunity	Classification	
Minor	Work-window restrictions: ESA for migratory birds	☐ Internal ☒ External	☒ Local ☐Global
	Design, Environmental, Permitting		
E1	Uncertain configuration of SR-YY Interchange	☒ Internal ☐ External	☒ Local ☐Global
E2	Uncertain TS&L for H Road overcrossing	☒ Internal ☐ External	☒ Local ☐Global
Minor	Uncertainty in retaining walls	☒ Internal ☐ External	☒ Local ☐Global
E3	Uncertainty in earthwork	☒ Internal ☐ External	☒ Local ☐Global
Minor	Uncertainty in pavement	☒ Internal ☐ External	☒ Local ☐Global
E4	Uncertainty in drainage / storm water management	☒ Internal ☐ External	☒ Local ☐Global
Minor	Uncertainty in allowance for miscellaneous items	☒ Internal ☐ External	☒ Local ☐Global
Minor	Other design un certainty	☒ Internal ☐ External	☒ Local ☐Global
Minor	Uncertain soft costs	☒ Internal ☐ External	☒ Local ☐Global
E5	Change in Seismic Design Standards	☒ Internal ☐ External	☒ Local ☐Global
E6	Uncertain wetland mitigation	☐ Internal ☒ External	☒ Local ☐Global
Minor	Uncertain noise walls	☒ Internal ☐ External	☒ Local ☐Global
Minor	Well-protection issues	☐ Internal ☒ External	☒ Local ☐Global
E7	Issues completing environmental documentation	☐ Internal ☒ External	☒ Local ☐Global
Minor	Delays getting design completed and/or approved	☐ Internal ☒ External	☒ Local ☐Global
E8	Access Issues	☐ Internal ☒ External	☒ Local ☐Global
E9	Permitting issues	☐ Internal ☒ External	☒ Local ☐Global
Minor	4(f) issues	☐ Internal ☒ External	☒ Local ☐Global
E10	Encounter unanticipated archaeological / cultural / historical site	☐ Internal ☒ External	☒ Local ☐Global
Minor	Encounter unanticipated contamination	☐ Internal ☒ External	☒ Local ☐Global
	Political and Other External Influences		
-	Uncertainty in funding (amount and/or timing)	☐ Internal ☒ External	☐ Local ☒Global
-	Issues involving Tribes (other than included elsewhere, such as in environmental documentation risk)	☐ Internal ☒ External	☐ Local ☒Global
Minor	Issues related to detour	☒ Internal ☐ External	☒ Local ☐Global
Minor	Other issues (e.g., USFW, USACE)	☒ Internal ☐ External	☒ Local ☐Global

	Right-of-Way		
-	Uncertain cost escalation rate for ROW	☐ Internal ☒ External	☒ Local ☐Global
R1	Land swap with Wildlife Reserve	☐ Internal ☒ External	☒ Local ☐Global
Minor	ROW from Port (south of US-XX for SR-YY IC and for J Road extension)	☐ Internal ☒ External	☒ Local ☐Global
N/A	Potential reverse condemnation for two gas stations at H Road	☐ Internal ☒ External	☒ Local ☐Global
-	Uncertainty in main H Road ROW (T-shaped parcel)	☒ Internal ☐ External	☒ Local ☐Global
R2	Opportunity to swap land with USACE at Hood Park (base = $100k)	☒ Internal ☐ External	☒ Local ☐Global
N/A	Opportunity to sell surplus land	☐ Internal ☒ External	☐ Local ☒Global
Minor	Other ROW uncertainty	☐ Internal ☒ External	☒ Local ☐Global
	Scope Changes (not captured separately)		
S1	Gateway enhancement at SR-YY and other aesthetic treatments	☒ Internal ☐ External	☒ Local ☐Global
S2	Pedestrian path improvements	☒ Internal ☐ External	☒ Local ☐Global
Minor	Additional ramp length	☒ Internal ☐ External	☒ Local ☐Global
	Utilities		
-	Relocation of High-Power Lines at H Road	☐ Internal ☒ External	☒ Local ☐Global
U1	Encounter unknown utilities and/or damage existing utilities during construction, or have to pay for utility relocation	☒ Internal ☐ External	☒ Local ☐Global
U2	Planned utility relocations not completed on time	☒ Internal ☐ External	☒ Local ☐Global
	Minor and Unidentified Risks and Opportunities		
	Aggregate Minor Risks	☒ Internal ☐ External	☐ Local ☒Global
	Aggregate Minor Opportunities	☒ Internal ☐ External	☐ Local ☒Global
	Unidentified Risks	☒ Internal ☐ External	☐ Local ☒Global
	Unidentified Opportunities	☒ Internal ☐ External	☐ Local ☒Global

Table 5-4: Risk Register Summary

The complete version of the Risk Register is presented in Appendix B. The information presented there includes a detailed description of each risk event and opportunity as well as its probability of occurrence along with the time and cost impacts on specific project activities.

5.2.5 Cost Escalation

Cost escalation is recognized as a significant issue of concern in multi-year infrastructure projects. Cost escalation impacts the year-of-expenditure (YOE) cost statistics but not the current dollar cost statistics.

This cost escalation is composed of two main factors: Inflation and Real Escalation. The first component reflects national economic conditions while the later represent short-term fluctuations in commodities (e.g., steel, crude oil).

WSDOT has an official Construction Cost Index (CCI) data set that indicates that the escalation rate can vary significantly from year to year, so it is important to incorporate this uncertainty in the calculation of future cost values for planning and budgeting purposes at an agency level.

This dissertation has not studied cost escalation factors; however, it uses the suggested approach from the CRA report where the following probability distributions are used to model the escalation factor:

Year	Annual Escalation Rates for Particular Year			
	Lower 10%	Mode	Upper 10%	Distribution
2006	2.80%	5.20%	8.50%	Triangular(10th, mode, 90th)
2007	0.80%	4.30%	9.30%	Triangular(10th, mode, 90th)
2008	-1.10%	3.30%	10.20%	Triangular(10th, mode, 90th)
2009	-3.10%	2.40%	11%	Lognormal(0.158, 0.0582) shift =-0.124
2010-2026	-3.10%	2.40%	11%	Lognormal(0.158, 0.0582) shift =-0.124

Table 5-5: Annual Escalation Rates

Cost escalation will affect construction and design activities in the network model. By using cost escalation rates and the project schedule, the escalated cost of each activity can be calculated. For every iteration of the MCS model, costs are escalated to the midpoint of scheduled activities and distributed evenly over the activity's duration, so the project cash flow can be assessed as well as its cumulative profile.

The CRA report uses for the cost escalation rate of ROW activities a Triangular distribution with 10th percentile of 4%, a mode of 6%, and a 90th of 10% to represent uncertainty around its base value. The MCS model samples one value of the distribution and apply this rate to all other years.

5.3 *Risk Analysis Model*

The model was constructed using three commercially available software packages. The main platform was Microsoft Excel (Microsoft Corporation 2003); this software stored the data and permitted the construction of the cost estimate and the project network so the integrated schedule-driven cost model could be used with the MCS engine and the BBN application.

@RISK (Palisade Corporation 2004) is an add-in to Microsoft Excel (Microsoft Corporation 2003) used to perform the simulation process.

Bayesian networks are handled by MSBNX (Microsoft Corporation 2001), which is a Bayesian network editor that communicates with the other two applications through Visual Basic (Microsoft Corporation 2003) code.

As explained in Section 4.3.2, uncertainties and independent risk events are modeled using probability distributions; these probability distributions are sampled using MCS with @RISK. Bayesian networks are updated with any acquired qualitative evidence, as well as the occurrence of independent risks, so the probability of occurrence of dependent risk can be assessed and sampled and their results combined to account for cost and time consequences in the base model. BBN’s are also used to account for any compounded effect of concurrent occurrences of risk events.

The risk model assigns probability distributions to represent uncertainties that affect the base cost estimate as shown in Table 5-3. Normal probability distributions were used when there was an indication that unit prices are build-ups or sums of independent items, so the Central Limit Theorem applies. Lognormal distributions were used to reflect values that are a result of the product of uncertain but independent unit price and quantity, and PERT distributions were used for asymmetric variables.

The CRA report assumes that base uncertainties of construction items in Table 5-3 are to be moderately positively correlated with a rank correlation coefficient of 0.5; other uncertainties are assumed to be independent from each other. The simulation model incorporates this information using a correlation matrix. Correlations coefficient values are checked later as part of the sensitivity analysis.

The base cost estimate from Appendix A and the uncertainty data from Table 5-3 are used to allocate cost to project activities.

The occurrence of risk events and opportunities are typically modeled using Binomial distributions or discrete distributions when their occurrence is defined within the different scenarios (e.g., Risk event E7). Impacts on project activities are either fixed or variable; when impacts are variable the consequence is modeled using a probability distribution. Given the occurrence of a certain risk event or opportunity, the time and/or cost impact is sampled and added to the correspondent activity as described in the Risk Register.

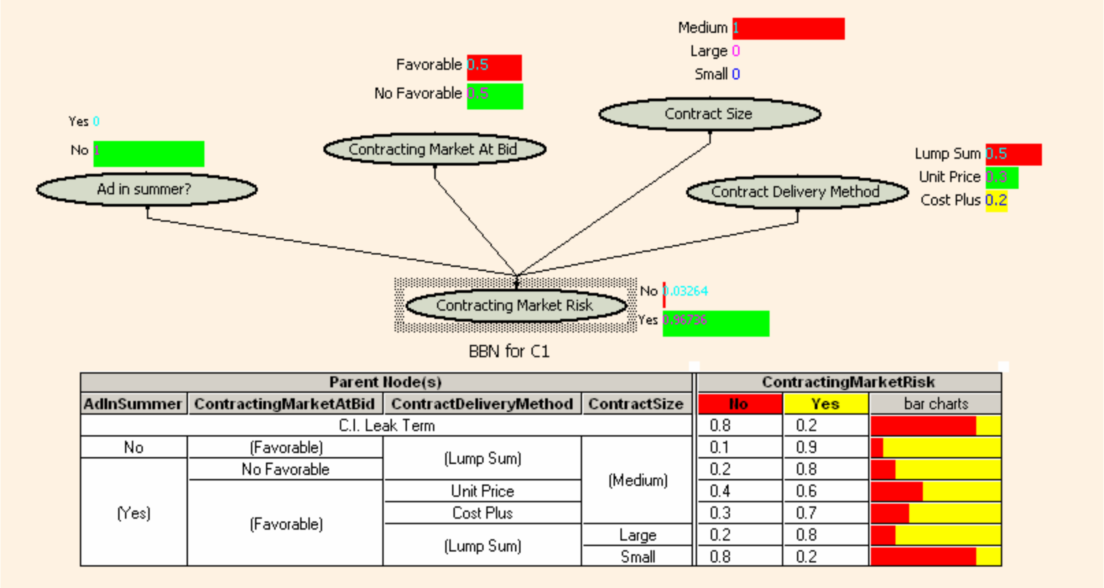
When risk events are dependent on the occurrence of others or their likelihood of occurrence is influenced by certain scenarios described in qualitative terms, BBN's are used to propagate such information as evidence. BBN's are also used for assessing non-additive impacts from concurrent risks' occurrences

5.3.1 Bayesian Belief Networks Used for the Case of Study

Risks such as C1: "Uncertain competition in contracting market", C2: "Construction change orders" and C3: "Uncertain construction staging / phasing" are highly dependent on external conditions of the project that influence their probability of occurrence.

According to the Risk Register (Appendix A), C1 is dependent on the contracting market condition at the time of bid, the contract delivery method and the size of the contract; C1 is also influenced by the constraint that the project is not advertised in the summer which might result in poor bids, therefore increasing the occurrence of this risk. The figure below presents the BBN where such qualitative conditions are considered for the evaluation of the occurrence of C1. Here, actual information has been added as evidence to the network and the probability of C1 is inferred; as seen in this figure, information about the size of the project and the Ad date constraint were updated as evidence.

The calculation of risk C1 was performed assuming causal independence (CI) among the parent variables of this risk; this concept is explained in detail in Section 3.4. The first row in the probability table is the "C.I. Leak Term" that specifies how likely it is that C1 will not occur, even when all parent nodes are in their normal state. Each of the remaining rows shows the consequences of having a parent node in a non-normal state. To help distinguish between a normal state and one or more abnormal states, names of normal states are in parenthesis.



Parent Node(s)				ContractingMarketRisk		
AdInSummer	ContractingMarketAtBid	ContractDeliveryMethod	ContractSize	No	Yes	bar charts
C.I. Leak Term				0.8	0.2	🟥🟨
No	(Favorable)	(Lump Sum)	(Medium)	0.1	0.9	🟥🟨
(Yes)	No Favorable			0.2	0.8	🟥🟨
	(Favorable)	Unit Price		0.4	0.6	🟥🟨
		Cost Plus		0.3	0.7	🟥🟨
		(Lump Sum)	Large	0.2	0.8	🟥🟨
			Small	0.8	0.2	🟥🟨

Figure 5-5: Bayesian Network for the Evaluation of C1

According to the CRA report, change orders represent a historical average of a 3%-4% cost increase. C2 is the risk of changes made by contractors due to design errors and omissions and changed conditions. This risk is also impacted by the amount of structures involved in the project since it typically generates more change conditions. So in this case, not only the occurrence of the risk can be influenced but also the cost impact. For example, if there is evidence of poor quality in the design documents and incomplete specifications, the likelihood of having change orders should be increased as well as the magnitude of the cost impact; if such design deficiencies are observed, it is natural to think that this impact should be higher. The BBN in Figure 5-6 models these qualitative factors affecting the likelihood of C3 occurring and two possible states for the cost impact: Average and High. If evidence on such adverse conditions is observed, the probability of high cost impact will be updated, so the simulation model can use the most probable state to define which consequence distribution to sample from.

On the other hand, C3 is affected by contractor's efficiency, quality of design, and labor availability. The figure below presents the BBN that incorporates that information to evaluate the probability of occurrence of C3.

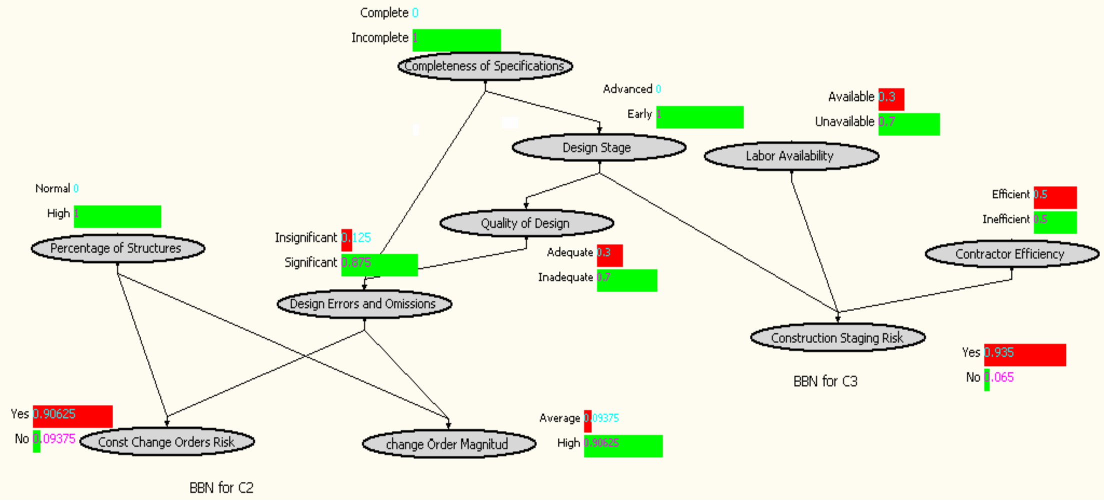


Figure 5-6: Bayesian Network for the Evaluation C2 and C3

Another application of BBN's is when modeling conditional probabilities of events. This occurs in the case of risk E2: "Uncertain Type, Size and Location (TS&L) for H Road overcrossing". According to Appendix A, Issue 2 of E2 has five possible mutually exclusive scenarios that could occur given the realization of certain conditions that precede them. These conditions are the type of alignment of the road, the full or partial take of a parcel of land, and the possibility of change in use of the surrounding land. This logic can be easily modeled using a decision tree to account for the conditional probability of each state; however, using BBN's would first let us analyze the impact of each possible condition in the risk adjusted project cost and duration and also update information when observed or decisions are made. Such a model is shown in upper left part of the BBN shown in the figure below.

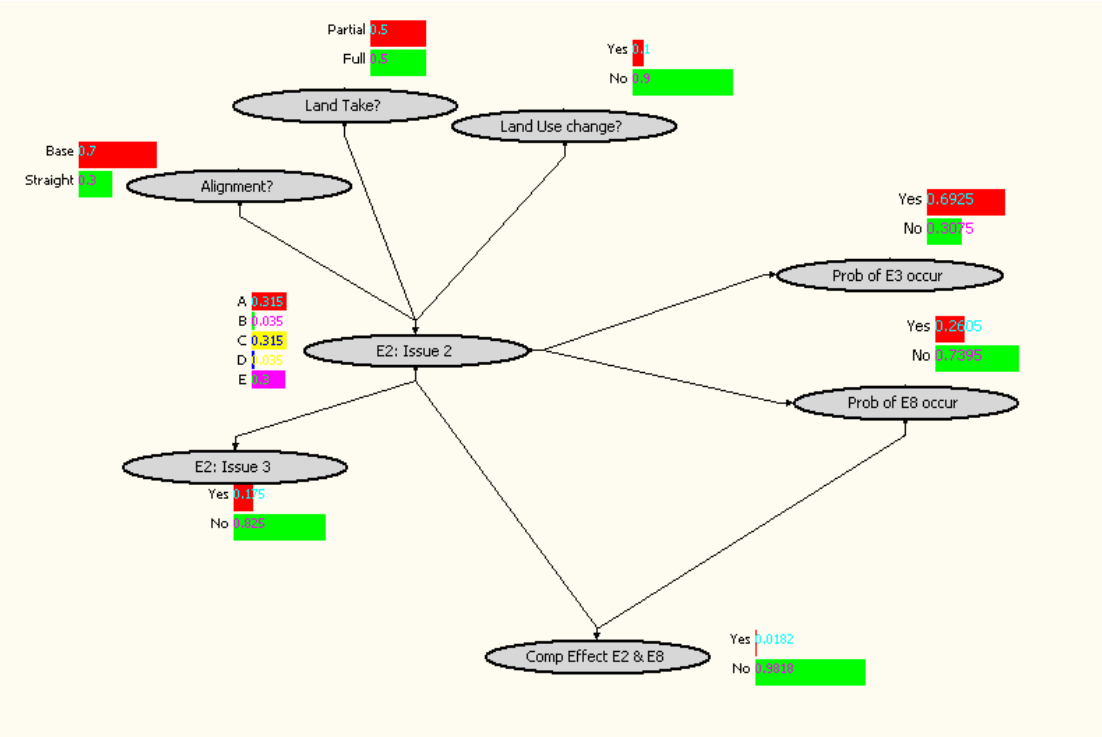


Figure 5-7: Bayesian Network for the Evaluation of E2, E3 and E8

The occurrence of Issue 3 from E2 is also dependant on the realization of Issue 2; if outcome E from Issue 2 occurs, Issue 3 cannot take place. This type of conditional logic can also be implemented in a BBN. When the MCS samples the occurrence of the different scenarios of Issue 2, the probability of occurrence of Issue will be modified accordingly before that risk is sampled.

In Figure 5-7, we can also see that the occurrence of risks E3: “Uncertainty in earthwork” and E8: “Access issues” are also dependent on which scenario from E2 is realized; in this way, dependency among risks can be also modeled using BBN’s. Another example is shown in Figure 5-8, where a BBN models how the probability of occurrence of risk S1: “Gateway enhancement at SRYY” increases if risk E1 is realized.

BBN’s can also be used to model the effect of the combined effect of concurrent risks affecting the same group of activities. If two or more risks occur at the same time, the total cost impact might not be the summation of individual impacts; BBN’s in Figure 5-7 and Figure 5-8 check for the occurrence of risks and define whether a concurrent cost impact is likely to occur so this information can be communicated to the MCS model.

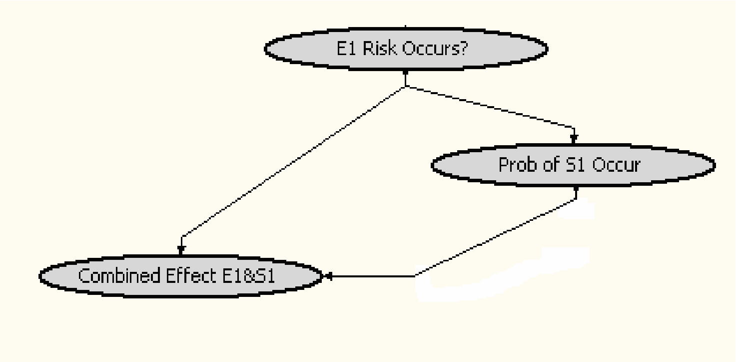


Figure 5-8: Bayesian Network for the Evaluation of S1

As mentioned before, BBN’s can be used to model decision trees to account for dependencies of possible states of a variable; this type of analysis uses an asymmetric probability assessment of parent variables affecting the variable of interest. Each branch of the tree represents a logical grouping of states with similar prior probabilities. These grouped states can be further subdivided as necessary to represent the complete distribution; details on this type of assessment can be found in (Microsoft Corporation 2001). This type of application was used for modeling risk E7: “Issues completing environmental documentation” as shown below.

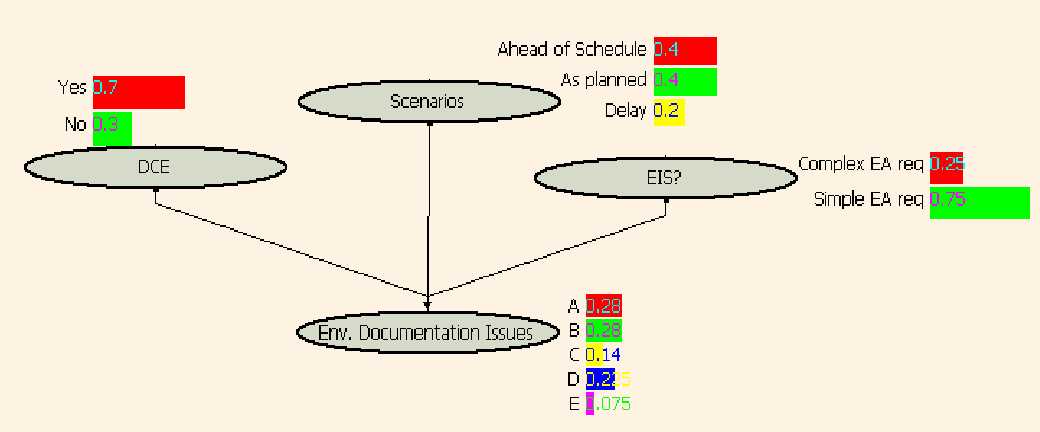
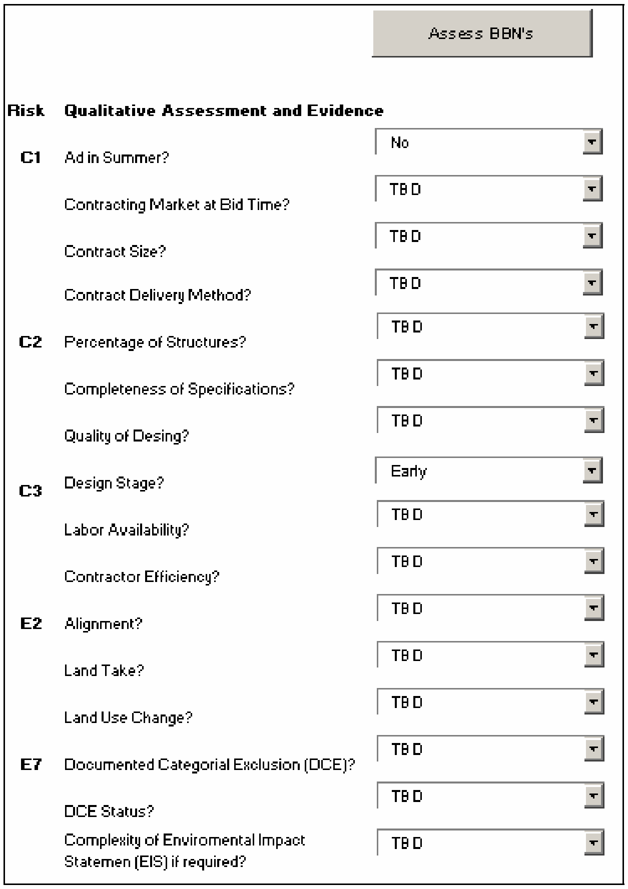


Figure 5-9: Bayesian Network for the Evaluation of E7

5.3.2 Risk Model Interface

Once the required BBN’s are constructed, text files that describe the network structure and the probability values assigned to each node are created and stored, so they can used by a third party application. In our case, Microsoft Excel is used as the main interface where any acquired evidence can be updated and transmitted to the respective BBN’s using an inference engine provided by MSBNX (Microsoft Corporation 2001). An example of this functionality is shown in the following figure, which is a capture of the model interface. The qualitative characteristics that have been added for the base case of the model are the constraint of not allowing the project advertisement date happening in summer, and that design is in the early stage.

All other states of the qualitative variables are to be determined (TBD) when evidence is acquired or decisions made.



Risk	Qualitative Assessment and Evidence	
C1	Ad in Summer?	No
	Contracting Market at Bid Time?	TBD
	Contract Size?	TBD
	Contract Delivery Method?	TBD
C2	Percentage of Structures?	TBD
	Completeness of Specifications?	TBD
	Quality of Desing?	TBD
C3	Design Stage?	Early
	Labor Availability?	TBD
	Contractor Efficiency?	TBD
E2	Alignment?	TBD
	Land Take?	TBD
	Land Use Change?	TBD
E7	Documented Categorial Exclusion (DCE)?	TBD
	DCE Status?	TBD
	Complexity of Enviromental Impact Statemen (EIS) if required?	TBD

Figure 5-10: Interface to Add Qualitative Evidence to Bayesian Networks Used for the Base Case

The risk analyst can use the interface above to assign any observations acquired as well as to create different scenarios before running the MCS on the integrated cost schedule model.

Captions of a portion of the network model as well as the risk register model are presented below.

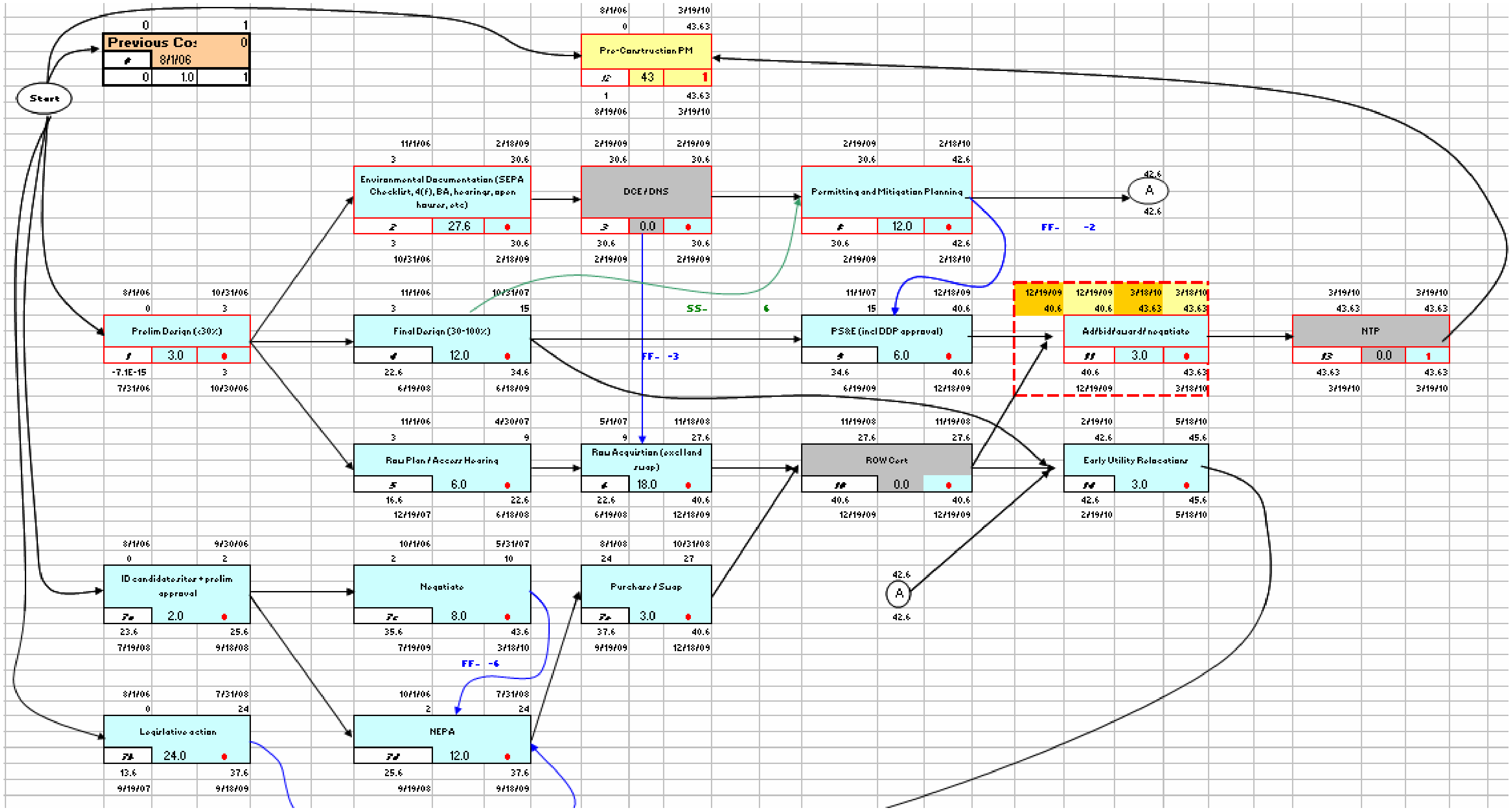
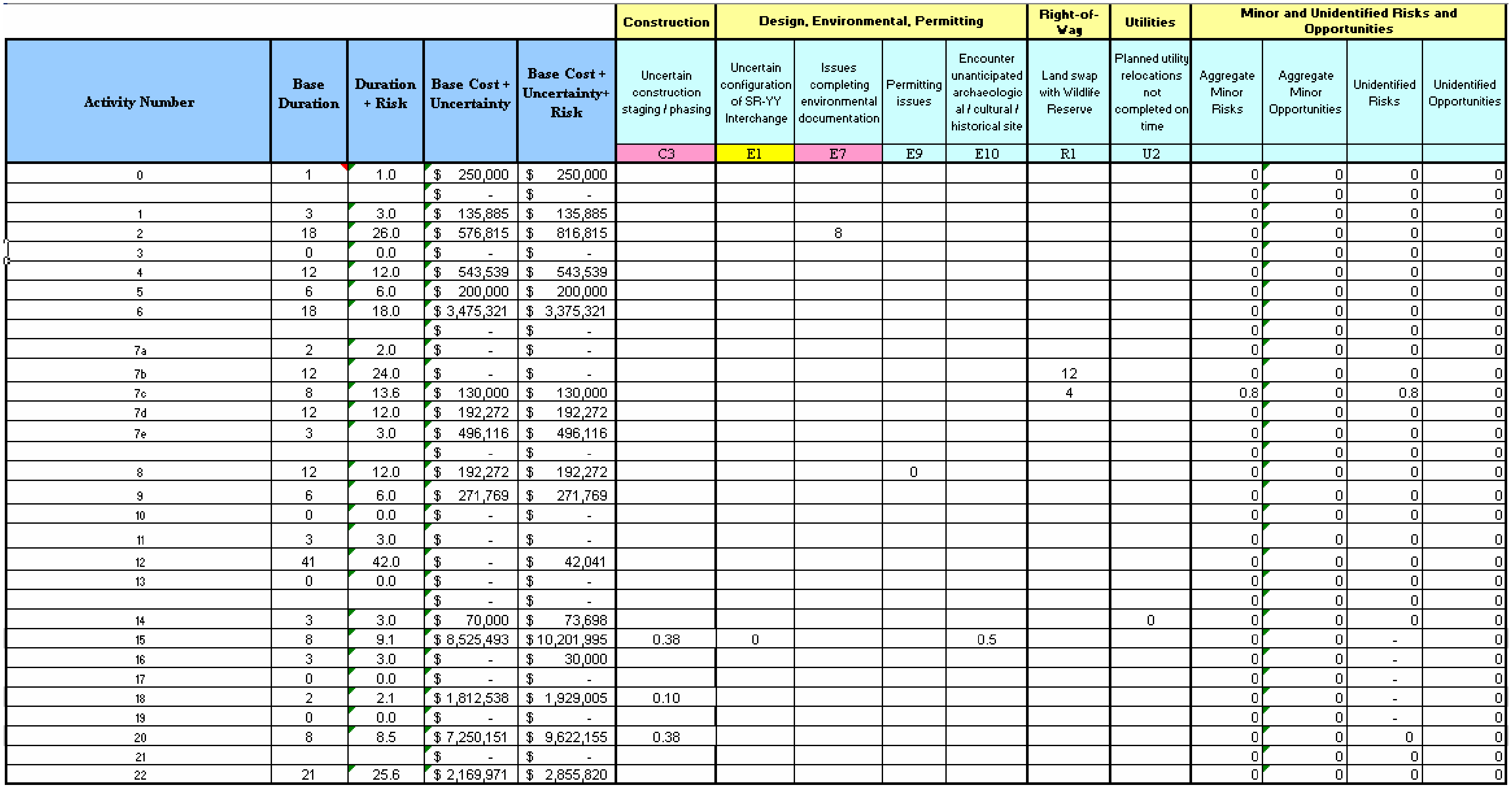


Figure 5-11: Portion of the Project Network Model



					Construction	Design, Environmental, Permitting				Right-of-Way	Utilities	Minor and Unidentified Risks and Opportunities			
Activity Number	Base Duration	Duration + Risk	Base Cost + Uncertainty	Base Cost + Uncertainty+ Risk	Uncertain construction staging / phasing	Uncertain configuration of SR-YY Interchange	Issues completing environmental documentation	Permitting issues	Encounter unanticipated archaeological / cultural / historical site	Land swap with Wildlife Reserve	Planned utility relocations not completed on time	Aggregate Minor Risks	Aggregate Minor Opportunities	Unidentified Risks	Unidentified Opportunities
					C3	E1	E7	E9	E10	R1	U2				
0	1	1.0	$ 250,000	$ 250,000								0	0	0	0
			$ -	$ -								0	0	0	0
1	3	3.0	$ 135,885	$ 135,885								0	0	0	0
2	18	26.0	$ 576,815	$ 816,815			8					0	0	0	0
3	0	0.0	$ -	$ -								0	0	0	0
4	12	12.0	$ 543,539	$ 543,539								0	0	0	0
5	6	6.0	$ 200,000	$ 200,000								0	0	0	0
6	18	18.0	$ 3,475,321	$ 3,375,321								0	0	0	0
			$ -	$ -								0	0	0	0
7a	2	2.0	$ -	$ -								0	0	0	0
7b	12	24.0	$ -	$ -						12		0	0	0	0
7c	8	13.6	$ 130,000	$ 130,000						4		0.8	0	0.8	0
7d	12	12.0	$ 192,272	$ 192,272								0	0	0	0
7e	3	3.0	$ 496,116	$ 496,116								0	0	0	0
			$ -	$ -								0	0	0	0
8	12	12.0	$ 192,272	$ 192,272				0				0	0	0	0
9	6	6.0	$ 271,769	$ 271,769								0	0	0	0
10	0	0.0	$ -	$ -								0	0	0	0
11	3	3.0	$ -	$ -								0	0	0	0
12	41	42.0	$ -	$ 42,041								0	0	0	0
13	0	0.0	$ -	$ -								0	0	0	0
			$ -	$ -								0	0	0	0
14	3	3.0	$ 70,000	$ 73,698							0	0	0	0	0
15	8	9.1	$ 8,525,493	$ 10,201,995	0.38	0			0.5			0	0	-	0
16	3	3.0	$ -	$ 30,000								0	0	-	0
17	0	0.0	$ -	$ -								0	0	-	0
18	2	2.1	$ 1,812,538	$ 1,929,005	0.10							0	0	-	0
19	0	0.0	$ -	$ -								0	0	-	0
20	8	8.5	$ 7,250,151	$ 9,622,155	0.38							0	0	0	0
21			$ -	$ -								0	0	0	0
22	21	25.6	$ 2,169,971	$ 2,855,820								0	0	0	0

Figure 5-12: Portion of the Risk Register Model

5.4 *Model Results*

5.4.1 Base Case

Using the qualitative information of the base case described earlier (see Figure 5-10) and after running the integrated risk analysis model, probability distributions were generated for the project's total cost, and its end date and total duration; the characteristics of such distributions are shown in the table below.

	Output Statistics				
	Total Base Cost + Base Uncertainty (Current $M)	**Risk Adjusted Total Cost** (Current $M)	**End Date**	**Total Duration (months)**	**Risk Adjusted Total Cost** (YOE $M)
Minimum	$ 19.89	$ 19.84	Aug-09	36.3	$ 20.68
Maximum	$ 34.96	$ 38.25	Nov-14	99.3	$ 61.76
Mean	$ 26.23	$ 28.23	Mar-12	67.3	$ 35.01
Standard Deviation	$ 1.79	$ 2.49		10.7	$ 4.60
Mode	$ 26.35	$ 28.44	Oct-11	62.0	$ 33.45
Percentile					
5.0%	$ 23.38	$ 24.25	Oct-10	50.9	$ 28.17
10.0%	$ 23.94	$ 25.02	Mar-11	55.1	$ 29.50
15.0%	$ 24.33	$ 25.64	Apr-11	56.9	$ 30.35
20.0%	$ 24.70	$ 26.08	Jun-11	58.7	$ 31.14
25.0%	$ 24.97	$ 26.49	Aug-11	60.2	$ 31.77
30.0%	$ 25.26	$ 26.86	Sep-11	61.3	$ 32.40
35.0%	$ 25.48	$ 27.24	Oct-11	62.1	$ 32.94
40.0%	$ 25.72	$ 27.53	Oct-11	62.9	$ 33.49
45.0%	$ 25.95	$ 27.86	Nov-11	63.7	$ 34.09
50.0%	$ 26.20	$ 28.20	Feb-12	66.4	$ 34.59
55.0%	$ 26.43	$ 28.52	Mar-12	67.4	$ 35.18
60.0%	$ 26.65	$ 28.83	Apr-12	68.3	$ 35.74
65.0%	$ 26.92	$ 29.16	May-12	69.5	$ 36.35
70.0%	$ 27.17	$ 29.49	Jul-12	71.1	$ 37.01
75.0%	$ 27.44	$ 29.89	Sep-12	73.1	$ 37.81
80.0%	$ 27.75	$ 30.29	Nov-12	75.1	$ 38.65
85.0%	$ 28.09	$ 30.80	Mar-13	79.7	$ 39.69
90.0%	$ 28.54	$ 31.43	Aug-13	84.7	$ 40.85
95.0%	$ 29.22	$ 32.48	Nov-13	87.5	$ 43.24

Table 5-6: Characteristics of Probability Distributions for Total Project Cost and Duration

The number of iterations used for this MCS-BBN model was 5000. This number of iterations is sufficient to guarantee that all output distributions are stable within a 1% convergence rate; this means that the simulation was stopped when changes in the statistics of those variables (mean, standard deviation and percentiles in 5% increments) were less than that 1% threshold.

The first distribution in Table 5-6 represents the total cost of project affected by the uncertainties surrounding the base estimate. The risk adjusted total cost column describes the distribution of the total cost of the project considering the impact of risks and opportunities from the Risk Register in Appendix B. The two following columns represent the end date and project duration uncertainty. The last column corresponds to the "year of expenditure" (YOE) cost using escalation rates from Table 5-5 and the schedule model. Monetary values are expressed in millions of US dollars ($M) and duration in months.

Table 5-6 is useful in determining a confidence level of a project budget or duration; for example, if one would like to determine the project cost that corresponds to an 85% confidence level, the necessary budget is 30.8 $M.

We can also use this table to evaluate the probability of finishing the project within certain duration and cost. The deterministic estimate of the project duration is 62 months with a total cost of 25.71 $M; the probability of meeting these targets is 33.3% and 15.81% respectively.

Cumulative probability distributions (CDFs) for the project's total cost including base uncertainties, risks and opportunities and escalated values are shown in Figure 5-13 and Figure 5-14, respectively.

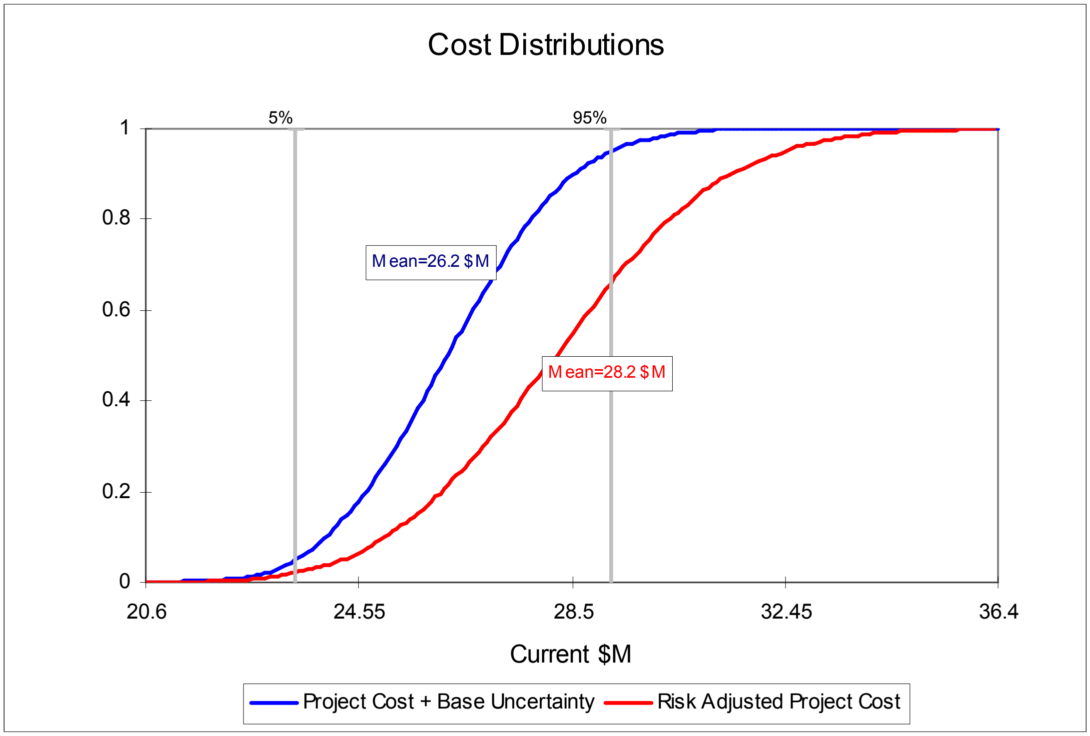


Figure 5-13: Probability Distributions for Total Project Cost Including Base Uncertainties and for Risk Adjusted Project Cost Including Impacts of Risks and Opportunities from the Risk Register

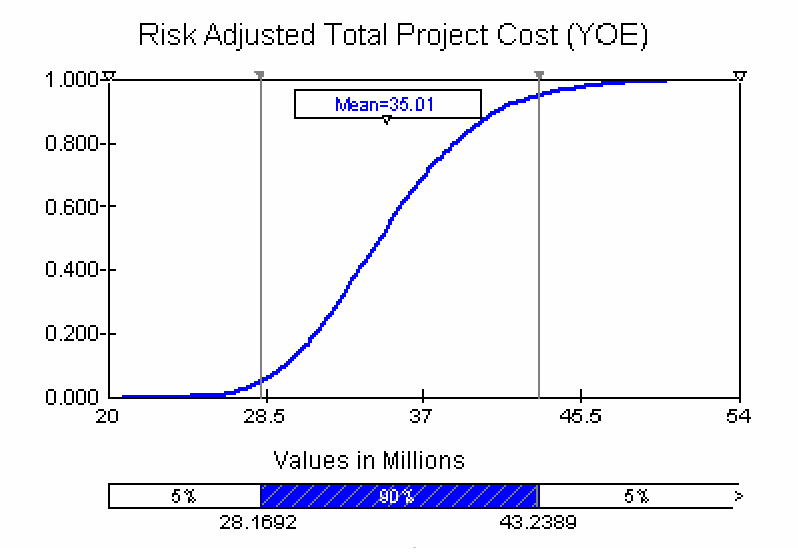


Figure 5-14: Probability Distribution for Total Project Cost (YOE $M)

Project duration is presented in terms of its probability distribution function (PDF) in the figure below. What is interesting is that this distribution is actually bi-modal; the second mode corresponds to the adverse situation when risk events C3 and R1 occur; this is confirmed though a sensitivity analysis on the total duration variable shown later.

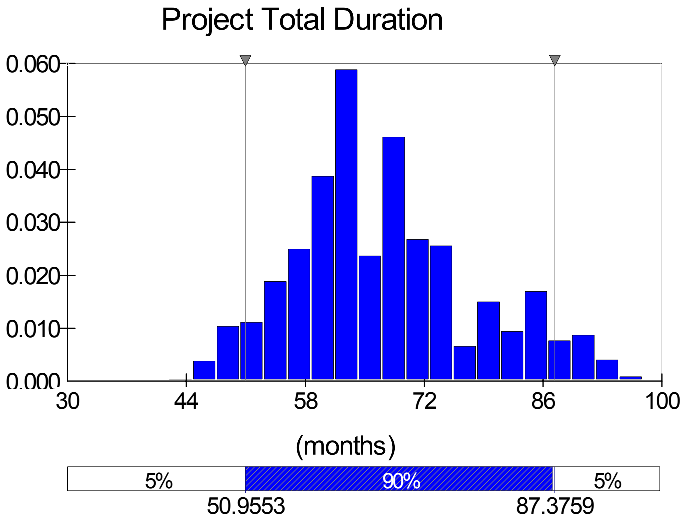


Figure 5-15: Probability Distribution for Project Duration

Another key result is the integrated analysis of duration and total costs of the project; Figure 5-16 presents the simulated non-escalated cost and duration combinations for the project[2]. In this figure, the project total cost is affected by the base uncertainties and by risks and opportunities from the Risk Register.

---

[2] Note: The simulation model was performed using a personal computer (PC) with a Centrino-Duo processor of 1.66 Ghz and 1 GB of RAM. The simulation used 5000 iterations with a fixed seed of 1,

Using the sample data set, one can assess the joint probability of finishing by a certain date and within a certain cost; for example, the probability that the project will finish on or before October 2011 and with a cost less than or equal to 25.71 $M is only 8.4%.

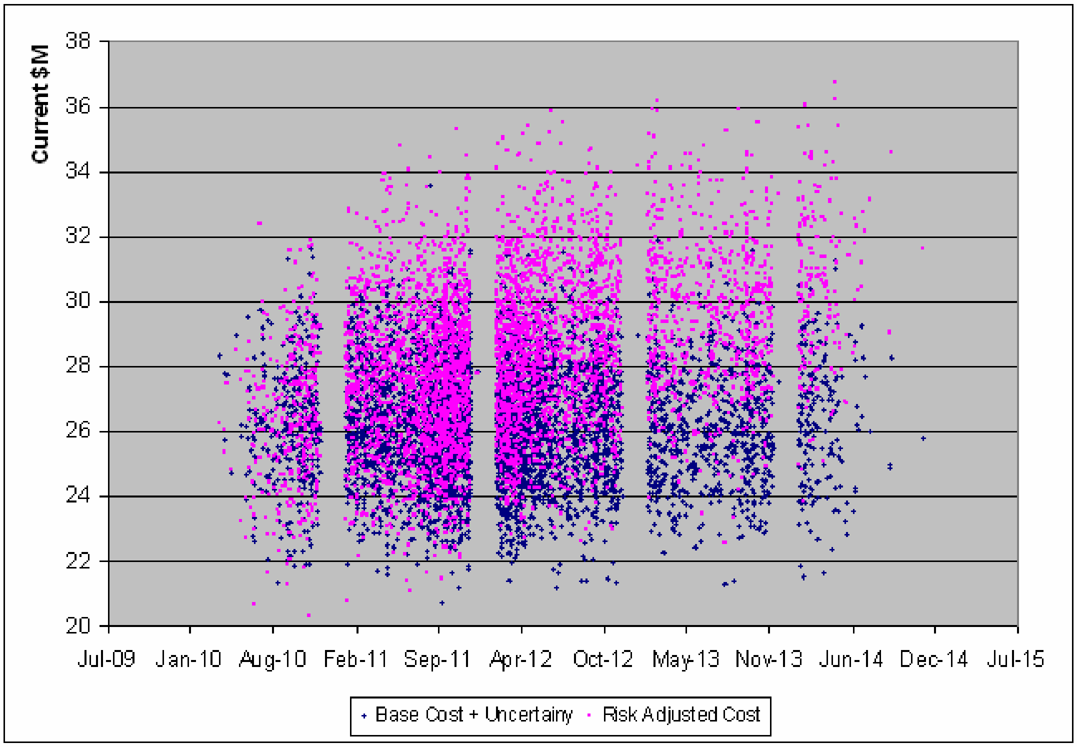


Figure 5-16: Simulation Results for Total Cost vs Completion Date

Figure 5-17 compares the non-escalated total cost (current $) to the escalated case (YOE $).

---

so results of different scenarios can be compared. The simulation time was 6 minutes 34 seconds and used Latin Hypercube sampling. The number of inputs and outputs were 314 and 29 respectively.

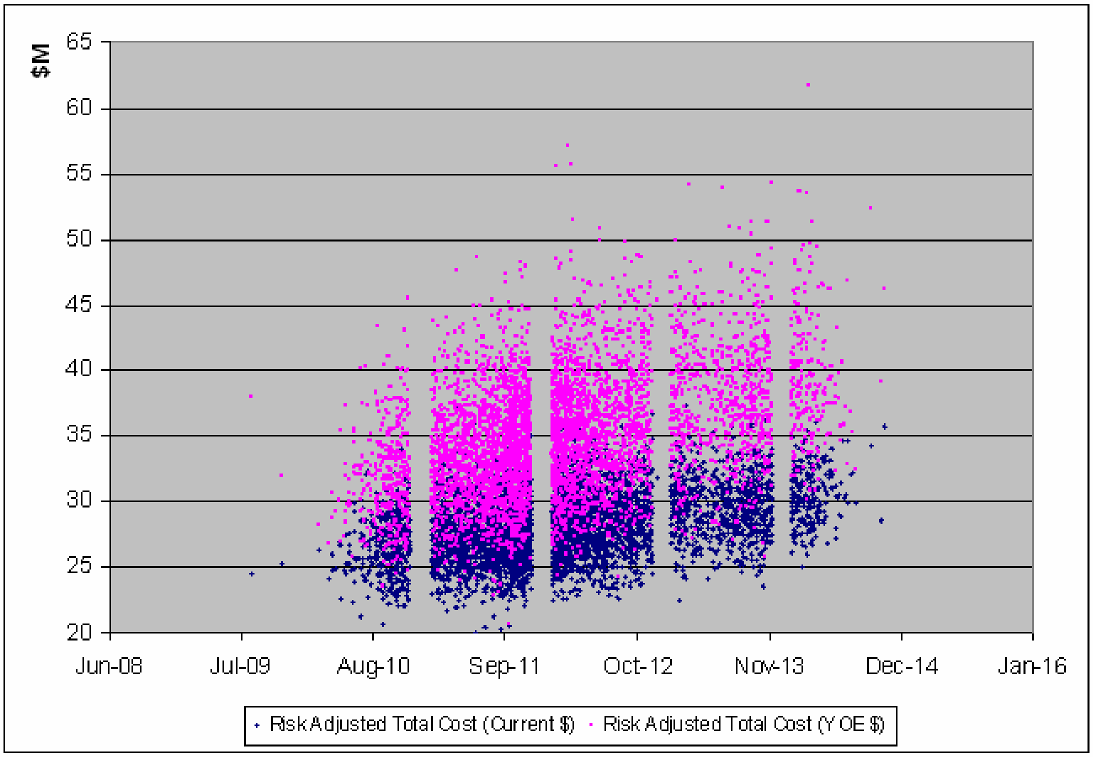


Figure 5-17: Simulation Results for Risk Adjusted Total Cost (Current $ and YOE$) vs Completion Date

As observed in the two figures above, there are discontinuities in the date range of the plotted data; this happens because one of the activities that is a predecessor of the completion milestone is construction related (see Figure 5-4), and as mentioned earlier construction activities must be stopped during December through January.

Table 5-7 and Table 5-8 present the ranked list of cost risk and cost opportunities on an expected mean basis, where the risks are as defined in the Risk Register (Appendix B). This is useful for risk management purposes since the management team has now a better idea of most critical risks and can proceed into a risk mitigation phase.

Rank	Item	Description	Contribution to Expected Cost Risk	
			%	Current $M
1	-	Extended Overheads	16.58%	0.54
2	E5	Change in Seismic Design Standards	15.69%	0.51
3	C2	Construction Change Orders	14.17%	0.46
4	E2	Uncertain TS&L for H Road overcrossing	11.40%	0.37
5		Unidentified Risks	8%	0.27
6		Aggregate Minor Risks	8%	0.27
7	E1	Uncertain configuration of SR-YY Interchange	6.21%	0.20
8	S1	Gateway enhancement at SR-YY and other aesthetic treatments	4.87%	0.16
9	C1	Market Conditions – Uncertain Competition in	3.96%	0.13
10	E4	Uncertainty in drainage/ stormwater management	3.69%	0.12
11	E7	Issues completing environmental documentation	2.54%	0.08
12	S2	Pedestrian path improvements	2%	0.05
13	U1	Encounter unknown utilities and/or damage existing utilities during construction, or have to pay for utility relocation	1%	0.04
14	E8	Access Issues	0.80%	0.03
15	E6	Uncertain wetland mitigation	0.49%	0.02
16	E10	Encounter unanticipated archaeological / cultural / historical site	0.15%	0.01

Table 5-7: Ranked List of Expected Cost Risks

Rank	Item	Description	Contribution to Expected Cost Opportunity	
			%	Current $M
1	E3	Uncertainty in earthwork	20.8%	0.26
2	E2	Uncertain TS&L for H Road overcrossing	18.5%	0.23
3	-	Extended Overheads	15.0%	0.19
4	E6	Uncertain wetland mitigation	13.0%	0.16
5	C1	Market Conditions – Uncertain Competition in	10.3%	0.13
6		Unidentified Opportunities	8.3%	0.10
7		Aggregate Minor Opportunities	8.2%	0.10

Table 5-8: Ranked List of Expected Cost Opportunities

As mentioned in the CRA report, it is important to note that a number of uncertainties in the Risk Register were symmetric with respect to the base; therefore, those uncertainties might not show up in the expected-value contribution list. However, they contribute to the overall uncertainty in project cost. To reflect this, a sensitivity analysis that looks at the correlation between input variables and an output variable can be performed. Using the correlation coefficient of each variable and the output variable, the impact on the uncertainty of each input can be ranked. This is presented in Figure 5-18 and Figure 5-19, where total cost and duration are analyzed; the larger the correlation coefficient, the more sensitive the output variable is to change in the input variable.

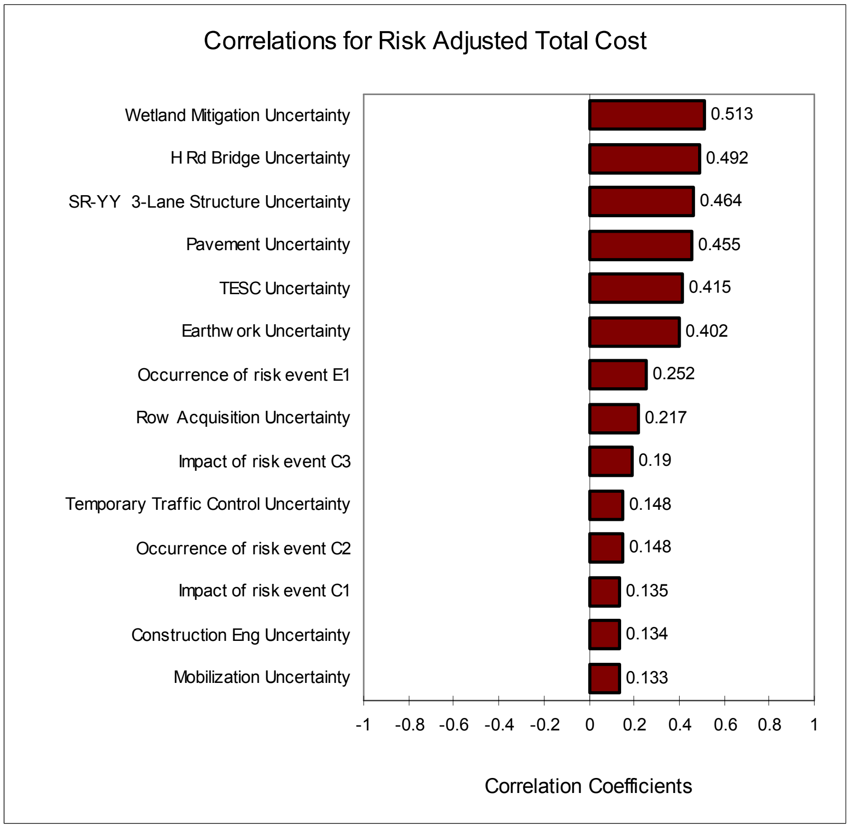


Figure 5-18: Sensitivity Analysis of Risk Adjusted Total Cost (Current $)

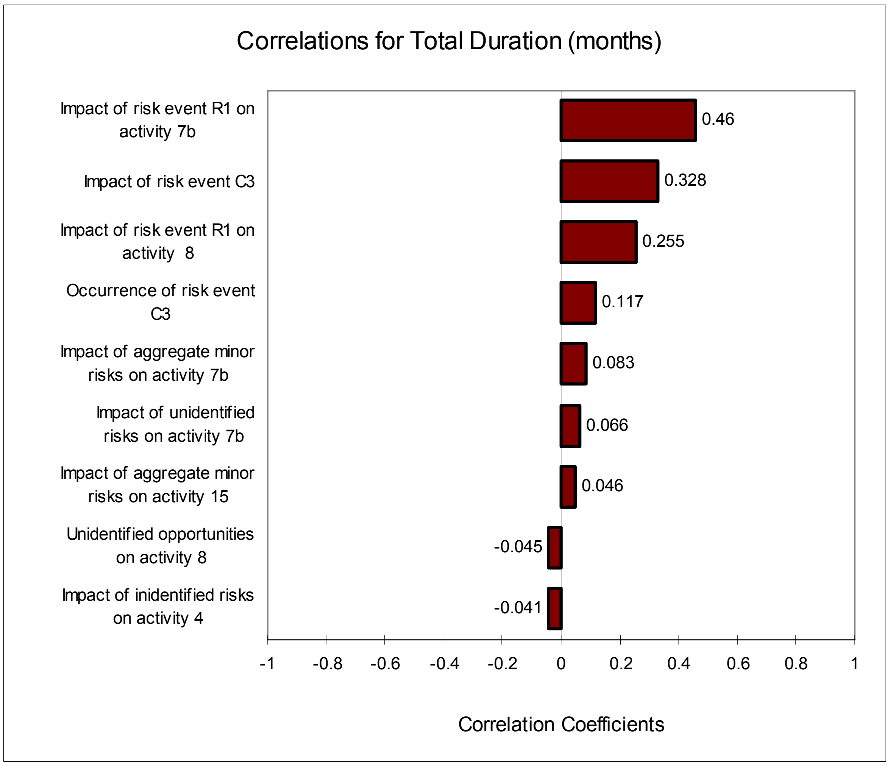


Figure 5-19: Sensitivity Analysis of Project Duration

Other results are the project cash flow and the project cumulative expenditure profile (S-Curve) that is generated using the escalated cost and the simulated network. This information is beneficial for planning purposes since the management team can evaluate the funds that the project requires at each period of time (e.g., years, months). Also, this information is useful to establish a performance measurement baseline that guarantees a certain confidence level and that can be used for control purposes; this will be discussed in Chapter 6.

Figure 5-20 and Figure 5-21 show the probabilistic project cash flow and the probabilistic S-Curve respectively. These figures represent the mean cost value at the end of each year as well as the characteristics of the yearly cost distribution (+/- 1 standard deviation away from mean, and the 5th and 90th percentiles).

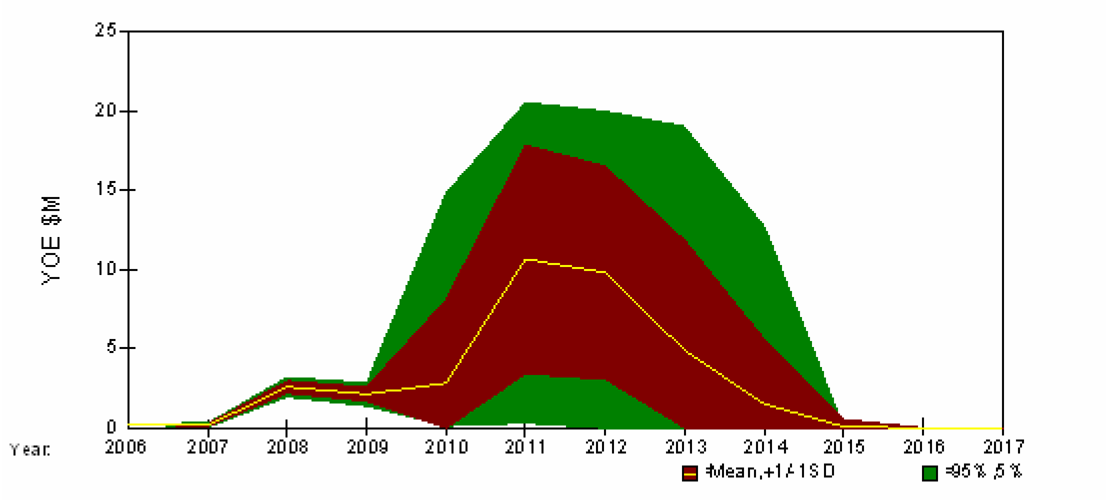


Figure 5-20: Probabilistic Project Cash Flow (YOE $M)

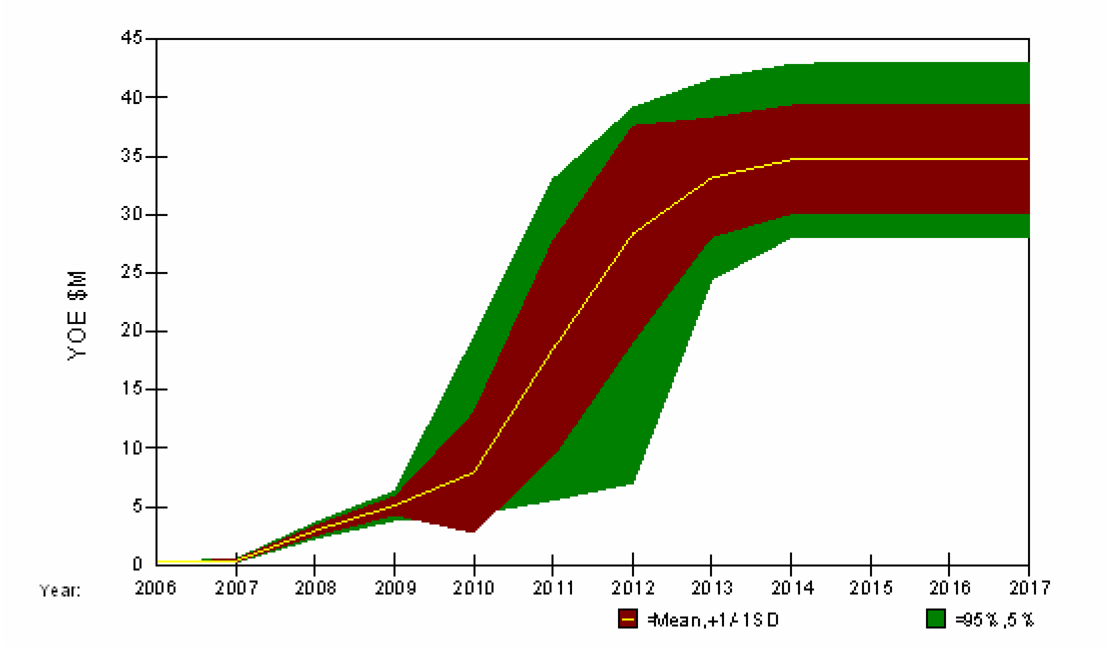


Figure 5-21: Probabilistic Project Expenditure (S-Curve)

Finally, Figure 5-22 shows how sensitive the total cost probability distribution is to different correlation coefficients among the construction items from the base uncertainty in Table 5-3. The base case assumes that there is a moderate correlation among construction uncertainty items and uses a correlation coefficient of 0.5. Multiple simulations were used to incorporate correlation coefficients that ranged from 0.25 to 0.75. As observed in the figure below, the effect is not significant. Table 5-9 shows the characteristics of each PDF.

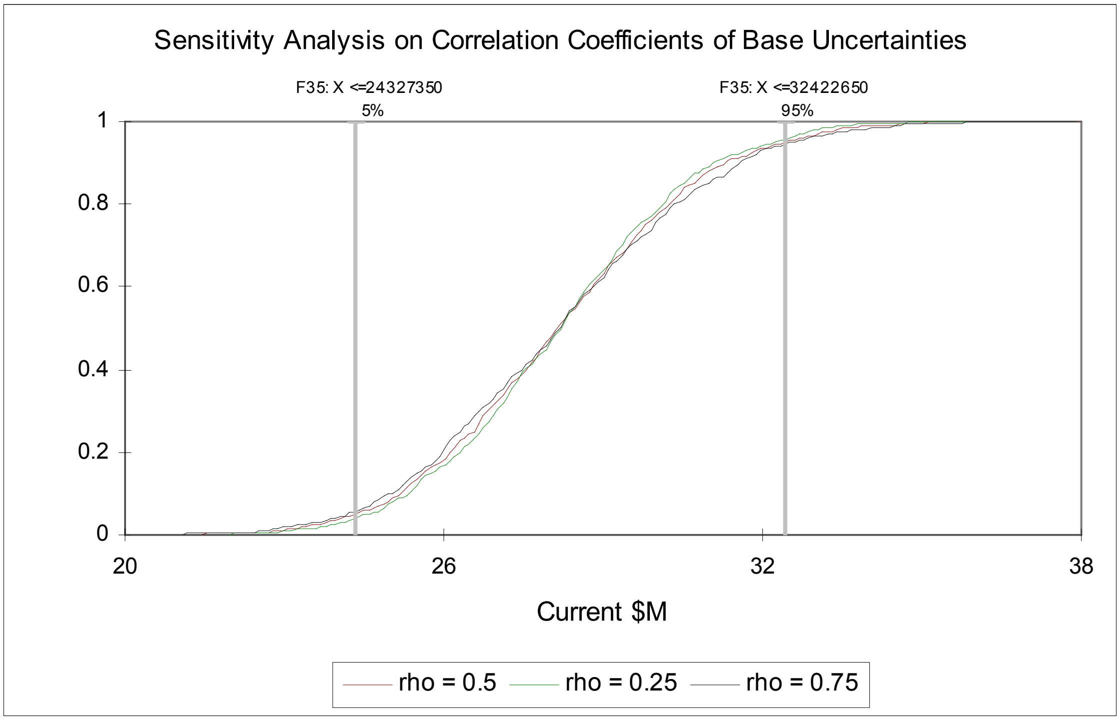


Figure 5-22: Sensitivity of Project Total Cost to Correlation Coefficients Used for Base Uncertainties

	Risk Adjusted Total Cost Current $M		
	rho=0.5	rho=0.25	rho=0.75
Minimum	20.08	20.59	20.18
Mean	28.21	28.21	28.22
Maximum	36.82	35.30	37.17
Std Dev	2.43	2.27	2.59
Variance	5.93	5.17	6.72
Mode	27.77	29.42	29.94

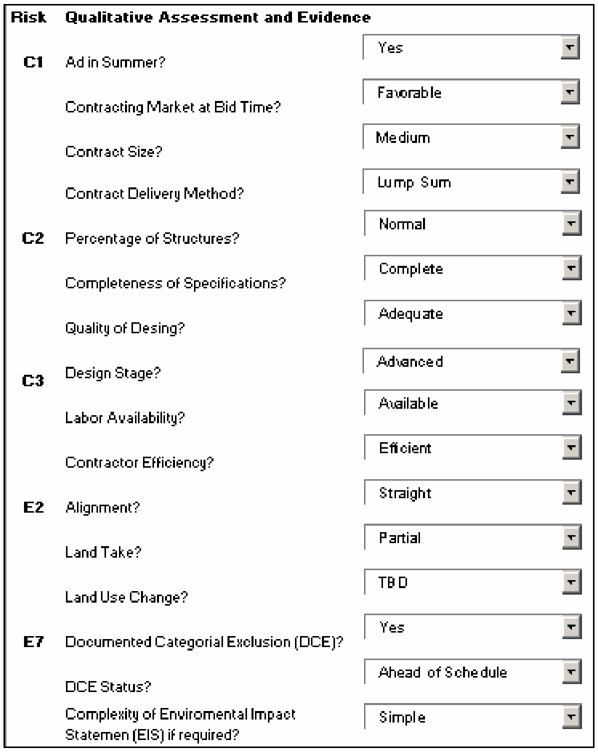
Table 5-9: Effects of Different Correlation Coefficients used for Base Uncertainties on the Project Total Cost Probability Distribution

5.4.2 Incorporating More Information through Bayesian Networks

As stated earlier, BBN's allow for the incorporation of qualitative observations about the project as well as any evidence or decisions that would affect its execution. In this section, we have created two possible scenarios to reflect the impact of such observations in the project's total cost and duration.

The first scenario allows the project advertisement date to happen in summer; other observations and decisions are assumed to be true and added to the qualitative assessment data as shown in Figure 5-23.

Figure 5-24 and Table 5-10 show the impact of such added evidence on the risk adjusted total cost probability distribution.



Risk	Qualitative Assessment and Evidence	
C1	Ad in Summer?	Yes
	Contracting Market at Bid Time?	Favorable
	Contract Size?	Medium
	Contract Delivery Method?	Lump Sum
C2	Percentage of Structures?	Normal
	Completeness of Specifications?	Complete
	Quality of Desing?	Adequate
C3	Design Stage?	Advanced
	Labor Availability?	Available
	Contractor Efficiency?	Efficient
E2	Alignment?	Straight
	Land Take?	Partial
	Land Use Change?	TBD
E7	Documented Categorial Exclusion (DCE)?	Yes
	DCE Status?	Ahead of Schedule
	Complexity of Enviromental Impact Statemen (EIS) if required?	Simple

Figure 5-23: Qualitative Evidence for Scenario 1

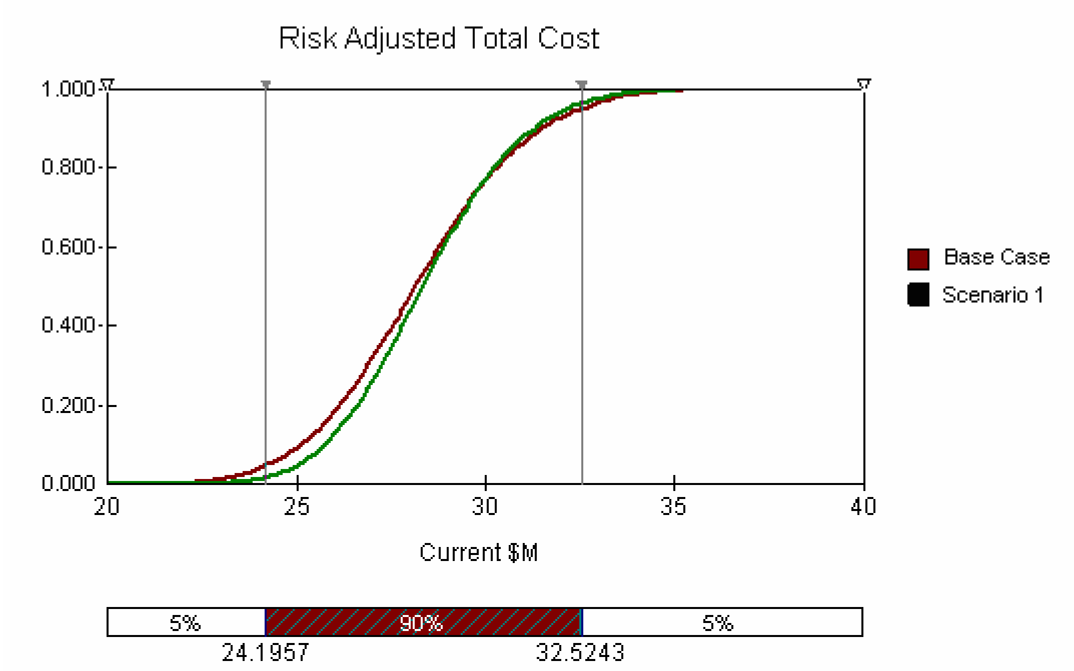


Figure 5-24: Probability Distributions for Project Total Cost – Base Case vs. Scenario 1

	Risk Adjusted Total Cost (Current $M)	
	Base Case	Scenario 1
Mean	28.22	28.43
Minimum	20.07	21.96
Maximum	39.71	36.67
Std Dev	2.48	2.15
Variance	6.13	4.63
Mode	27.75	28.15
5th Perc.	24.20	25.05
95th Perc.	32.52	32.08

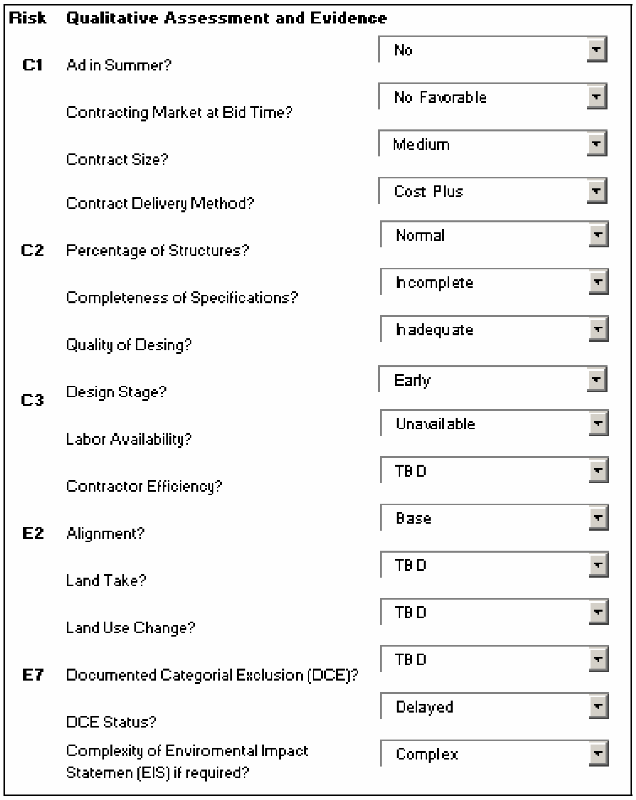
Table 5-10: Probability Distribution Characteristics for Project Total Cost

Base Case vs. Scenario 1

In Table 5-10 we can see that CDF of the total cost of Scenario 1 has a higher mean and mode than the CDF of the base case; however, the variance of it is smaller.

A second scenario incorporates more information about a variable of interest. The following figure shows added evidence that represents an unfavorable situation with respect to the quality of the design and specifications, along with factors that affect the occurrence and the impact magnitude of several risks.

Figure 5-26 and Table 5-11 compare the probability distribution of the project duration for the base case and the two scenarios.



Risk	Qualitative Assessment and Evidence	
C1	Ad in Summer?	No
	Contracting Market at Bid Time?	No Favorable
	Contract Size?	Medium
	Contract Delivery Method?	Cost Plus
C2	Percentage of Structures?	Normal
	Completeness of Specifications?	Incomplete
	Quality of Desing?	Inadequate
C3	Design Stage?	Early
	Labor Availability?	Unavailable
	Contractor Efficiency?	TBD
E2	Alignment?	Base
	Land Take?	TBD
	Land Use Change?	TBD
E7	Documented Categorial Exclusion (DCE)?	TBD
	DCE Status?	Delayed
	Complexity of Enviromental Impact Statemen (EIS) if required?	Complex

Figure 5-25: Qualitative Evidence for Scenario 2

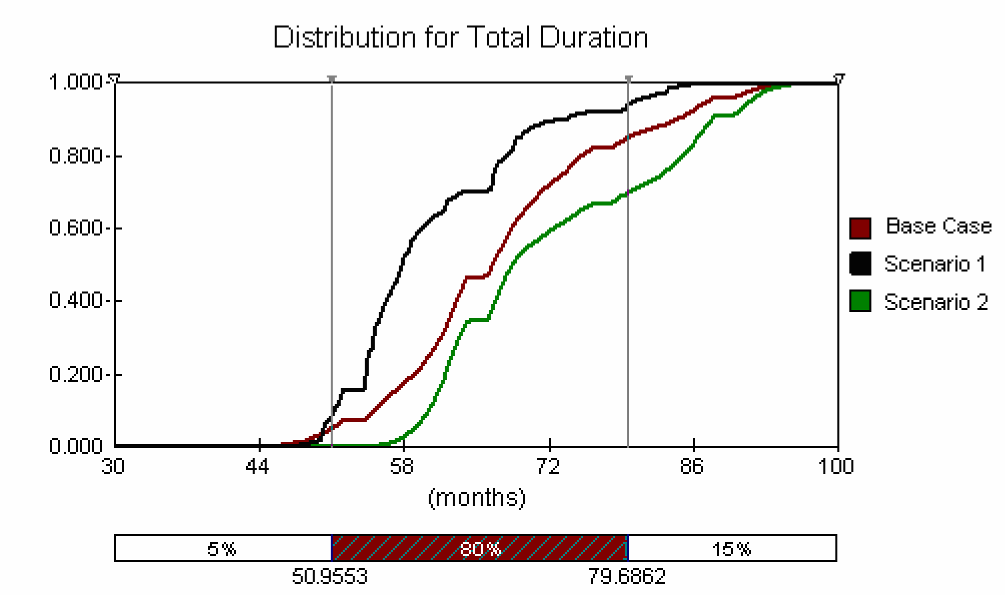


Figure 5-26: Probability Distributions for Project Duration

Base Case vs. Scenario 1 & 2

Figure 5-26 shows the CDF of the duration of the project for the base case and the scenarios described earlier. These curves are not as smooth as the ones obtained for costs; this happens because of the constraint that stipulates that construction during winter months must be suspended.

	Total Duration (months)		
	Base Case	**Scenario 1**	**Scenario 2**
Mean	67.35	60.66	72.17
Minimum	39.23	43.34	51.03
Maximum	97.82	87.73	99.26
Std Dev	10.63	8.78	10.93
Variance	112.99	77.09	119.37
Mode	62.03	54.40	62.03
5th Perc.	50.96	50.03	58.86
95th Perc.	87.38	80.23	91.48

Table 5-11: Probability Distribution Characteristics for Project Duration Base Case vs. Scenario 1 & 2

The favorable characteristics of Scenario 1 in Figure 5-23 define a more optimistic CDF of the project duration. This is confirmed by the table above where not only the mean of that distribution has decreased but also its standard deviation. On the other hand, the unfavorable conditions of Scenario 2 presented in Figure 5-25 generate a CDF with a longer mean duration and larger variance.

The ability to generate different scenarios or add acquired information to update the results of a risk analysis is one of the main benefits from the use of BBN's. This capability can be used for updating information while the project is in execution and new results generated can be used for forecasting performance at completion.

6. A Discussion on Probabilistic Project Performance Measurement and Forecasting

To manage a project efficiently decision makers need to continuously evaluate the current status of it to identify any problems so as to allocate immediately management attention and resources to align with project cost and schedule objectives.

Project performance measurement consists of determining, organizing and presenting cost, schedule and progress performance information in a way that project managers can have accurate and timely information to make informed decisions, analyze potential trade-offs and identify any corrective measures. Project performance measurement involves two aspects: progress monitoring and performance reporting.

Progress monitoring looks at actual performance data as they are compiled; it also involves looking forward and projecting where the project is going in terms of its compliance with the original plan.

Performance reporting involves collecting and disseminating project performance information. The process of performance reporting typically includes status reporting, progress reporting and forecasting. The status report describes where the project stands now, the progress report describes what the project team has accomplished, and the forecast report predicts future project status and progress at a given point of time or at completion.

Traditionally, project baselines used for project performance measurement are assumed to be deterministic, so are the available control methodologies. The emerging use of risk-based methodologies provides an opportunity to use probabilistic baselines not only for planning purposes but also for controlling efforts; however, there is hardly any research on how to incorporate probabilistic information within a formal control and performance forecasting methodology.

This chapter explores and discusses the implementation of a probabilistic approach for project performance measurement and forecasting.

6.1 Project Performance Control

While a project is in the execution phase, great effort is given to adhere to the project plan as closely as possible so initial agreements can be maintained and objectives accomplished. In reality, many factors affect the execution of a project and deviations from the plan are expected; however, it is crucial to have a control system to account for the impact of these deviations.

A project plan allows us to have a baseline that represents the expected performance at any point of time; so at any control point a project is expected to have achieved certain amount of work at an estimated cost. The objective of project control is to measure the actual values of these variables and determine if the project is meeting the targets of the project work plan, and make any necessary adjustments to meet project objectives. Therefore, the project control process involves the following activities (Hegazy 2002):

- Accurately follow the project plan

- Update the project plan based on new circumstances
- Monitor actual execution and keep track of resources
- Provide detailed progress reports, comparing actual versus planned progress
- At any stage during execution, forecast the cost at completion
- Take corrective actions at any stage to bring time and cost closer to the plan

If the above activities are successfully implemented through a formal control process the benefits to be observed while tracking performance objectives are:

- Early warning of a deteriorating situation creates an opportunity to do something about it before it is too late
- Accurate forecasting allows better decisions to be made about the course of the project
- Accurate forecasting allows better decisions to be made about matters outside the project which may be influenced by the progress of the project
- An open and verifiable view of progress improves sponsor confidence

6.2 Historic Development of Project Performance Measurement Methodologies

The fundamental concepts for project control come from two lines of thought, industrial engineering applications and project management.

In industrial engineering applications performance evaluation of line production processes are concerned with three figures: Planned output as standard cost rates, actual output at standard cost rates, and actual cost incurred. These performance metrics led to the concepts of efficiency for the process and for the cost incurred such as:

- Process efficiency: actual output at standard cost compared to planned output at standard cost
- Cost efficiency: actual output at standard cost compared to actual incurred cost

The formal definition for actual output at standard cost is what has actually been produced at the cost that was expected. In contrast to the line production concept, a project is considered as a unique endeavor; therefore, the actual output at standard cost represents a measure of the value of the actual progress, this metric has come to be known as earned value (EV).

In the project management arena, CPM and PERT methods were the first formal tools to plan and control projects (See Section 2.8.1 for CPM and PERT definitions). Project control was initially based only on variances between planned and actual costs, however, if a measure of work progress is not considered the results obtained can be misleading and might not reflect the true project status. For example, a project might show a positive cost variance *(planned cost > actual cost)* that would make us think that we are spending less than planned and therefore cost efficient; however, this positive variance could happed due to a different reason. For example, the progress of critical activities scheduled within the evaluation period might be delayed, so costs will be lower than planned but creating a delay in the whole project. This example illustrates the necessity of integrating not only the work progress of a project but also its schedule so a true status can be evaluated.

As a response to this problem, the Cost/Schedule Control Systems Criteria (C/SCSC) was introduced by the United States Department of Defense (DOD) in 1967. The C/SCSC incorporated the earned value metric and made it mandatory for all private contractors awarded a major systems contract or subcontract that exceeded established funding thresholds. This methodology was restricted to the acquisition of major systems by the US government while private parties did not embrace these criteria. The C/SCSC was a successful tool for the government since it permitted the oversight of contractor performance whenever the risks of cost growth rest with the contracting agency.

Most of the criticism for the C/SCSC and the non-adoption in private industry operations was due to strict criteria to be followed by contractors, the rigidity of the method and terminology that made the performance metrics more difficult to understand than what in reality they represented.

In 1995 the C/SCSC criteria was revisited to make it friendlier to users and more accessible to private industry so it can be applied not only to projects contracted by the government. This effort resulted in a new industry version called Earned Value Management (EVM) that was issued to the public in 1996 and adopted by the private sector as a viable and best-practice management tool.

Recent research publications acknowledge the benefits of the Earned Value approach to control project cost but also point out that this methodology does not reflect the real status of project schedule when the project is close to finalize or when the project passed already the completion date. As a response to this drawback an extension to EVM called Earned Schedule (ES) has emerged and gaining supporters rapidly. ES allows the use of time units for schedule control. This methodology will be explained in later sections.

In the following section the different performance methodologies are presented and their capabilities analyzed as well as the steps necessary for implementing the control system.

6.3 *Project Performance Measurement Methodologies*

6.3.1 Requirements for the Implementation of a Project Control Methodology

A control system makes use of the project schedule and work package cost information in order to establish a performance measurement baseline (PMB) to represent a time-phased budget plan against which project performance is measured. A PMB is formed by the costs assigned to scheduled work packages and applicable indirect costs; however, it does not include any management reserve or contingency.

In general, to implement a project performance control process the following steps should be followed:

- Develop a well-defined work WBS
- Develop a project schedule from the project WBS by integrating and sequencing the work to be performed using the Critical Path Method. The CPM network diagram shows the sequencing of activities or work packages

identified in the project WBS. The WBS also contains the duration and cost information for each work package and the relationship between expenditure and work to be produced.

- A well defined WBS allows using a work package as an activity of the diagram; however, depending on the size of the project it is necessary to combine several work packages into a single activity or vice versa.
- Establish a coding system to identify each component of the WBS so this information can be linked to a cost breakdown structure (CBS) for accounting use and control, and to organization breakdown structure (OBS) to assign responsibilities and coordinate resources. Most importantly, a coding system allows organizing and sorting information for reporting purposes. For definitions of CBS and OBS refer to Chapter 2.
- Measure the progress of the project, the actual cost and durations compared to their respective planned values depicted in PMB. Planned values represent cumulative planned costs, early start, late start of activities and target basis. Target basis include the percent-time and percent-cost distribution of each work package.

6.3.2 Establishing the Performance Measurement Baseline

The performance measurement baseline (PMB) represents a time-phased budget that is used as a basis against which to measure, monitor, and control cost performance of the project (Project Management Institute 2004). PMB is constructed using the cumulative costs linked to the project schedule as the primary tool for the schedule and cost control. The cumulative cost data is usually depicted as an S-curve to represent the planned cost to be incurred through the project life; see figure below.

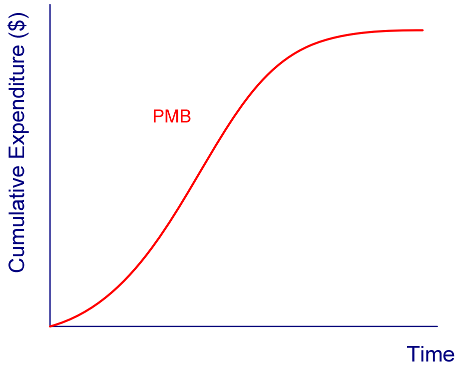


Figure 6-1: Performance Measurement Baseline

Once a PMB is established, it is considered a component of the project management plan and therefore a document that is available to all parties involved. In that regard, caution and thoughtfulness should be considered when defining it since this process allows certain flexibility that could impact the accuracy of results of the control method. This flexibility is built-in within the project schedule; activities that are not critical can be scheduled using their early start time, late start time or anytime in between.

Depending on the schedule selected to construct the PMB, the expenditure rate over time can vary considerably and therefore it could impact the results of its comparison against actual performance. This effect can be better shown in the figure below.

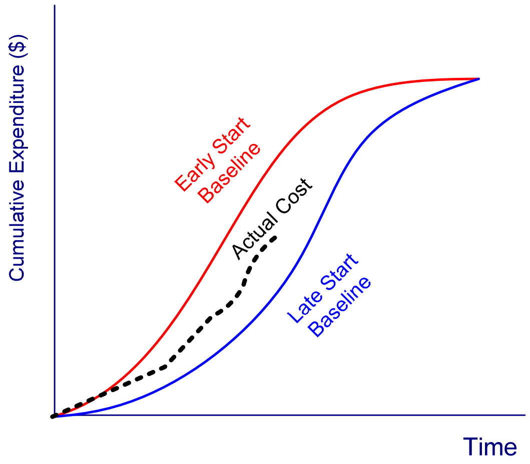


Figure 6-2: Effects of Using Activities' Early Start Time vs. Late Start Time on PMB

In Figure 6-2 we can observe that around the halfway point of completion of the project the planned cost value of the early start and the late start baselines clearly differs from each other; this creates a range of possible PMBs with the same final cost and time completion date. If the actual cumulative cost is within the limits of this range the value of cost variance can be positive or negative.

According to Fleming (1988) there are two other practices that can have a direct impact on the performance measurement accuracy and they are front loading and rubber baseline:

- Under front loading, the PMB happens when the baseline is generated by the contractor. In this scenario, a PMB is established with adequate budget allocated at the front-end, for near-term work, but the contract could be left with inadequate funds for the later, far-term effort. A latent overrun is thus solidly incorporated into a baseline plan. When contractors intentionally front load the baseline they do so with the belief or hope that subsequent changes in the statement of work will be sufficient to avoid an eventual overrun condition from surfacing. If this does not happen, overruns will be encountered on a contract which may otherwise have appeared to be in a good shape.

- A rubber baseline happens after the PMB is in place, usually during the early phases of contractor performance. As cost problems start to appear in performance, the contractor will attempt to shift allocated down-stream budget to the left, back into the current period in order to cover the current cost problems. The effect if allowed to happen is the same one as a front-loaded PMB.

The figure below shows the potential consequences of a front-loaded PMB and a rubber baseline on project total cost. The effect of these two practices is the delayed visibility of contract cost problems (Fleming and Koppelman 2005).

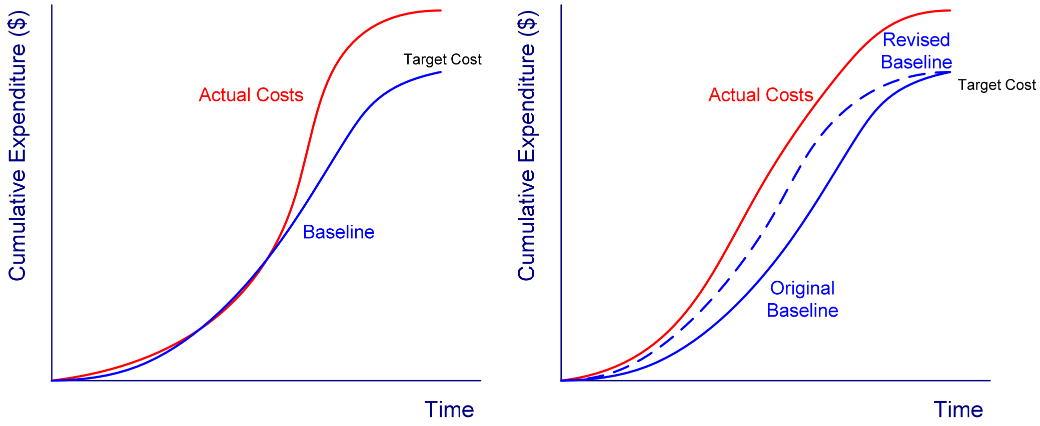


Figure 6-3: Effect of Front-Loaded PMB and PMB with “Rubber Baseline”

6.3.3 Measuring Work Progress and its Value

In general, the value of work performed or Earned Value (EV) is calculated by assessing the percent complete of a project activity multiplied by its estimated total cost. The EV for the entire project is just the summation of all work packages' EVs. This might seem a straightforward process; however, depending on the type of activity and its cost type, the procedure to calculate the value of the work performed varies. This section compiles the basic information to measure work progress from (Fleming 1988).

6.3.3.1 Direct Costs

The PMB is made up of the sum of direct cost of individual activities or work packages that are classified as:

- Discrete/Work activities
- Level of effort activities
- Apportioned activities

6.3.3.1.1 Discrete/Work Activity

Discrete/work activities represent a large portion of the activities of a project and they are classified in three categories: Activities that are completed and have earned 100% of its planned value, activities that have not started yet, and activities that are in execution with a certain percent of completion.

The major difficulty encountered in the determination of value of work performed is the evaluation of in-process work, in other words, work packages that have been started but have not been completed at the cutoff time of the report.

Six methods are recommended to measure the EV of this type of activities:

- 50/50 Technique: This technique is used for work packages with duration of not more than three control periods, preferably two maximum. 50% of the planned valued is earned when the activity starts and the balance is earned when the effort is completed. Variations of this technique use other percentage values such as 25/75, 40/60, etc.
- 0/100 Technique: This approach is best suited for work packages that are scheduled to start and complete within one control period. Nothing is earned when the activity starts, but 100% is earned when the effort is completed.
- Milestone Method: It is recommended when work packages exceed three or more months in duration. Work packages are divided up based on pre-established milestones and a weighted value is assigned to each milestone.
- Percent Complete: This approach requires a monthly estimate of the percentage of work completed of a work package in a cumulative basis.
- Equivalent and/or Completed Units: This method places a given value on each unit completed, or fractional equivalent unit completed. This method works best for fabrication or assembly endeavors that exceed two control periods.

- Earned Standards: Standards of performance of the task have to be established before execution using historical cost data, time and motion studies, etc. This is the most sophisticated approach and requires discipline by the contractor.

The first four methods described above correspond to engineering activities in which the effort is considered as a non-recurring type. A combination of these methods could be used depending on project characteristics and management policies.

6.3.3.1.2 Level of Effort (LOE) Activities

These types of activities are related with project administration and are more time-oriented than task-related. Examples include: project management, scheduling, contract administration, field engineering support, security, etc. Even though these functions are charged directly to a contract and last the full project duration, they have no measurable units.

In this case EV is always assumed to equal the planned value; however, this approach does not exclude the fact that cost variances can be observed, for example when more resources are consumed than planned.

6.3.3.1.3 Apportioned Effort Activities

Apportioned efforts have a direct intrinsic performance relationship to some other discrete activity treated as the reference base. An example of this type of activity is “construction inspection”, which direct time and value has a relationship to the “construction” labor and therefore can be express as a fraction of it. The percent complete of the apportioned efforts is the same as the reference base. Schedule variances behave similarly between the base and the apportioned effort; if the reference work package has a negative schedule variance, likewise, the later will reflect this negative condition. This is not the case for cost variances since actual cost can not be related to the work packages.

6.3.3.2 Other Direct Costs (ODC)

ODC covers things as travel, computer usage, and host of other activities chargeable directly to a contract, but excludes materials. The EV is set when either costs for these items are incurred, or when cost are recorded.

If the cost-incurred approach is used the actual cost is shifted to the earlier time frame to match the planned value and the EV, which is usually accomplished by using a commitment report. If the cost-recorded approach is used, the planned value is placed into a later time frame, to be in accordance with the time delay. Usually these costs are small compared to other categories such as labor and materials; they do not represent a major problem for the reporting and accounting purposes.

6.3.3.3 Indirect Cost Performance Measurement

Even though that a WBS does not include work packages’ indirect costs, it is necessary to have an estimation of their magnitude and how they are distributed in time, so they can controlled and compared against actual values. In general, the procedure avoids the creation of a cumbersome administrative effort. General guidelines are:

- The rates used for planned values and EVs should be identical
- The applied rate should be reconcilable with the bid rate
- The rate used for actual costs should liquidate the overhead pool on a current period basis and avoid significant year end adjustments.

6.3.3.4 Measurement of Design

Measurement of design is complicated because of the diversity of work that is involved and the different units used in the various activities; for example, design calculations, drawings and specifications write-up can be measured in different units.

One alternative is to use the percentage of completion of design work with a weighted multiplier assigned to design tasks to define the magnitude of effort that is required to complete each of them so a composite time-progress baseline can be constructed. Oberlender (2000) suggests the following formulas for measuring the value for work performed in design activities when the effort is estimated in work-hours.

$$\text{Earned work-hours} = \left(\text{Budgeted work-hours}\right) \times \left(\text{Percent complete}\right) \tag{6.1}$$

$$\text{Percent complete} = \frac{\text{Actual cost or work-hours to date}}{\text{Forecast at completion}} \tag{6.2}$$

6.3.4 Integrated Cost/Schedule/Work

In order to adequately relate cost, time and the amount of work performed the integrated Cost/Schedule/Work system was developed by the United States Department of Defense (US Department of Defense 1967). By measuring the amount of work and relating it to time and cost targets it is possible to obtain a better picture of the real status of a project. This control method integrates the three fundamental components of a project scope (work), budget (cost) and schedule (time). The following figure presents how these three performance metrics relate to each other.

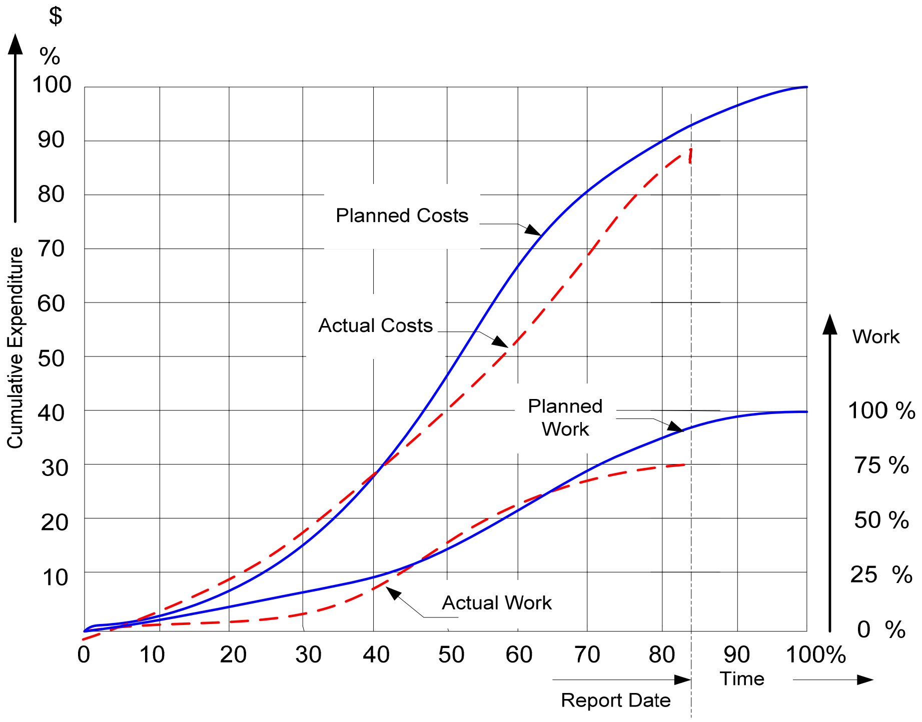


Figure 6-4: Integrated Cost/Schedule/Work Project Control

Figure 6-4 shows two planned S-curves; the first one depicts the cumulative planned cost in a time scale while the other presents the planned percentage of work completed by certain time. Actual costs and actual percent completion values are compared against planned baselines to draw conclusions about performance. Units for costs can be dollars or work-hours, for time is days, weeks or months, and the measure for work is a percentage of completion.

This methodology uses the following measures (Webb 2003):

- Actual cost of work performed (ACWP),
- Budgeted cost of work scheduled (BCWS), and
- Budgeted cost of work performed (BCWP)

ACWP represents the total of all expenditure on the project up to the report date; it is the summation of what has been actually spent irrespective of what has been planned or achieved.

BCWS represents the planned cost expenditure through the project life; it is the summation of all planned cost in the project up to the reporting date.

BCWP is the value of all the progress achieved on the project up to the report date and expressed in terms of the planned costs originally set out in the initial estimate. It represents what has been earned, not simply what has been spent. This measure is also called Earned Value.

These measures can be used to evaluate cost and schedule variances as well as performance ratios to evaluate project status. As mentioned, before this methodology was revised in 1995 and resulted in what is currently called Earned Value Management (EVM). The following section looks at the EVM approach and presents the calculation of performance indicators that are similar in nature to the ones used in the Cost/Schedule/Work method but updated with the EVM's terminology.

6.3.5 Earned Value Management

The PMBOK (Project Management Institute 2004) defines Earned Value Management (EVM) as a method that integrates scope, schedule, and resources for measuring project performance. It compares the amount of work that was planned with what has been spent and with what has been accomplished to determine cost and schedule performance. Earned Value Performance Measurement is a method of measuring and reporting project performance based on planned expenditure, actual expenditure and technical performance achieved to date. The EVM method provides values for variances and performance indices that can be used to assess current project status and performance, and predict future project performance based on past project performance and new information.

The analysis for computing Earned Value involves calculating three key values for each activity:

- Earned Value (EV), previously called BCWP, is the value of the work actually completed during a given period.
- The Planned Value (PV), previously BCWS, is the portion planned to be spent on the activity during a given period.
- The Actual Cost (AC), previously ACWP, is the total of costs incurred in accomplishing work on the activity during a given period. AC must correspond to whatever was budgeted for the PV and the EV.

Figure 6-5 depicts the relationship among PV, AC and EV and how these measures can easily indicate in a visual manner the status of a project.

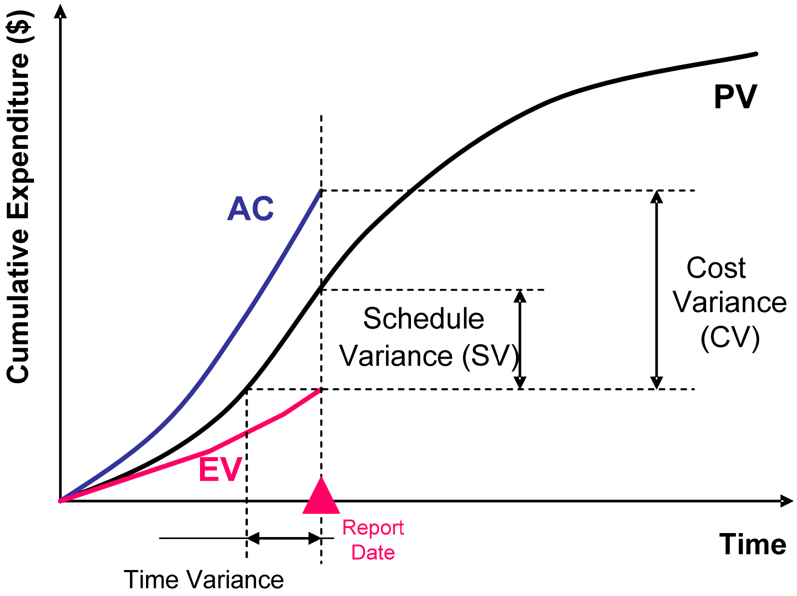


Figure 6-5: Project control using EVM

These three measures are used in combination to provide measures of whether or not work is being accomplished as planned. The most commonly used measures are the cost variance (CV) and the schedule variance (SV) and are computed as following:

$$CV = EV - AC \tag{6.3}$$

$$SV = EV - PV \tag{6.4}$$

According to EVM, positive variances are an indication that the execution of the project is doing better than planned; negative variances indicate that the project is in a poor position. These variances can be converted into efficiency indicators to reflect the cost and schedule performance of any project. These efficiency indicators are the cost performance index (CPI) and the schedule performance index (SPI) and are calculated as:

$$CPI = EV/AC \tag{6.5}$$

$$SPI = EV/PV \tag{6.6}$$

CPI is a fine indicator of cost efficiency since it is a ratio of the value created to the amount spent at a point in time on the project and is widely used to forecast project costs at completion. It shows the real worth that is being created by the project. The cumulative CPI is the sum of all individual EV budgets divided by the sum of all individual ACs.

SPI, on the other hand, is a schedule efficiency indicator that looks at the ratio of the earned valued created to the amount of value planned to be created at a point in time during the project. SPI is considered to be a measure of progress as it is using money as an analogue of time, which may not be strictly true (Webb 2003). SPI is commonly used in conjunction with the CPI to forecast the project completion estimates.

The measure that considers both indexes is called Critical Ratio (CR). The Critical Ratio is $CR = CPI \cdot SPI$ and represents the overall status of the project.

Index values greater than one indicate performance either in cost or schedule terms that is better than planned; values lower that one indicate a worse position. For example, a CPI value of 0.80 indicates that for every dollar spent only 80 cents worth of value is being created on the basis of the original budget.

One criticism against EVM is that schedule performance is not measured in time units, but rather in currency (i.e. dollars) or quantity (i.e. labor hours). For example, SV compares the value of the work performed against the planned cost at each reporting date; this can be become an obstacle for understanding how much behind or ahead of schedule a project is.

Another methodological problem of greater significance is observed when a project is completed behind schedule; at the completion date the SV still equals zero, and SPI equals one. Even though we know the project was completed late, yet the indicator values say the project has finished with perfect schedule performance.

Lipke (2003; 2004) states that schedule indicators of EVM fail to provide good information over the final third of a project and that they absolutely breakdown if the project is execution past its planned completion date.

As an alternative to solve this problem, Earned Schedule is emerging as a viable practice to measure schedule performance; this concept is presented in the following section.

6.3.6 Earned Schedule

Earned Schedule (ES) is an extension to Earned Value Management (EVM) and it was first introduced in (Lipke 2003) as an feasible alternative to traditional EVM's schedule performance indicators.

ES schedule performance indicators are time-based so its interpretation becomes easier. ES metrics for schedule variance and for the schedule performance index are SV(t) and SPI(t) respectively. ES renames the two traditional cost-based indicators SV and SPI as SV($) and SPI($), to indicate that they are in units of currency or quantity.

ES can be calculated as shown in Figure 6-6. The cumulative value of ES at actual elapsed time (AT) is found by using the earned value of the current report period to identify in which time increment of the planned value this cost value occurs. The value of ES is then equal to cumulative time to the beginning of that time increment plus a fraction of it; this fractional amount is equal to the portion of the EV at period extending into the incomplete time increment divided by the total PV for that same time period.

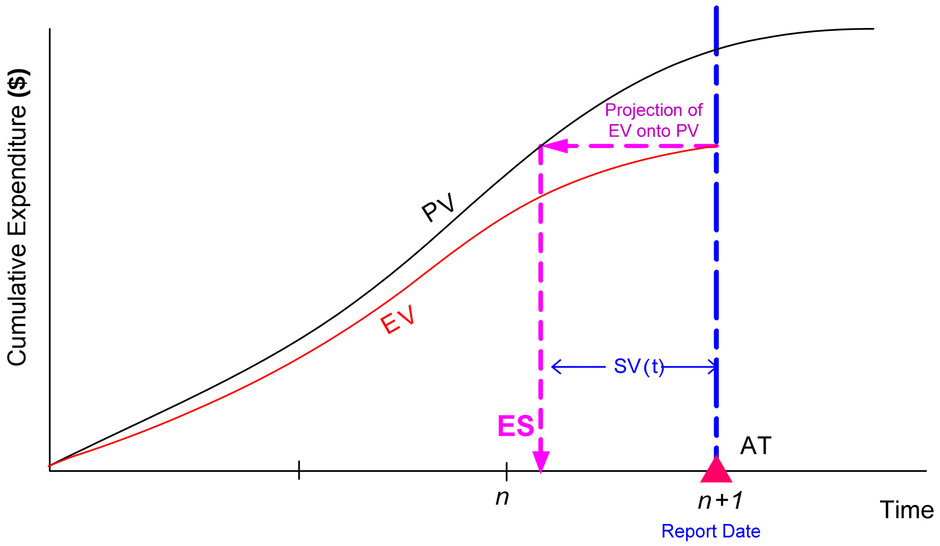


Figure 6-6: Earned Schedule

Having two consecutive control periods *n* and *n+1* (i.e. months *n* and *n+1*), ES can be expressed mathematically as:

$$ES_{n+1} = n + \frac{EV_{n+1} - PV_n}{PV_{n+1} - PV_n} \tag{6.7}$$

In the equation above the denominator of the fraction represents the dollar value of the amount of work that has been scheduled for $(n+1)^{st}$ period, while the numerator represents the dollar value of work done up to and including time *n+1* beyond what was scheduled for the period up to and including time *n*.

More details on the derivation of Equation (6.7) can be found in (Book 2006); however, the author fails to incorporate in his formulation a special case, which is when a project exceeds its planned schedule and the planned values of delayed activities have reached their budget at completion (BAC). If this situation is observed in a particular activity the denominator in the above equation becomes zero, so the equation to calculate its ES value should be modified as:

$$ES_{n+1,i} = \frac{EV_{n+1,i}}{PV_{n+1,i}} \cdot PD_i \tag{6.8}$$

where, i represents the delayed activity and PD_i its original planned duration.

Having defined ES we can now derive the corresponding time-based schedule indicators such as:

$$SV_{n+1}(t) = ES_{n+1} - AT_{n+1} = \frac{EV_{n+1} - PV_n}{PV_{n+1} - PV_n} - 1 \tag{6.9}$$

$$SPI_{n+1}(t) = \frac{ES_{n+1}}{AT_{n+1}} = \frac{n}{n+1} + \frac{EV_{n+1} - PV_n}{(n+1)(PV_{n+1} - PV_n)} \tag{6.10}$$

ES indicators provide status and predictive ability for analyzing a project schedule and their usage is analogous to their cost-based metrics used in EVM.

The application of ES methods does not require the collection of any new data since it only requires updated formulas. ES intends to provide a link between EVM and project schedule analysis. Henderson (Henderson 2004; Henderson 2005) claims that ES can be used for detailed schedule analysis and that it has the potential to improve both cost and schedule prediction

The figure below shows how the network of a project and its PMB are connected to ES. Regardless of the project's actual position in time, we have information about the portion of the planned schedule which should have been accomplished. The computed value of ES describes where the project should be in its schedule performance.

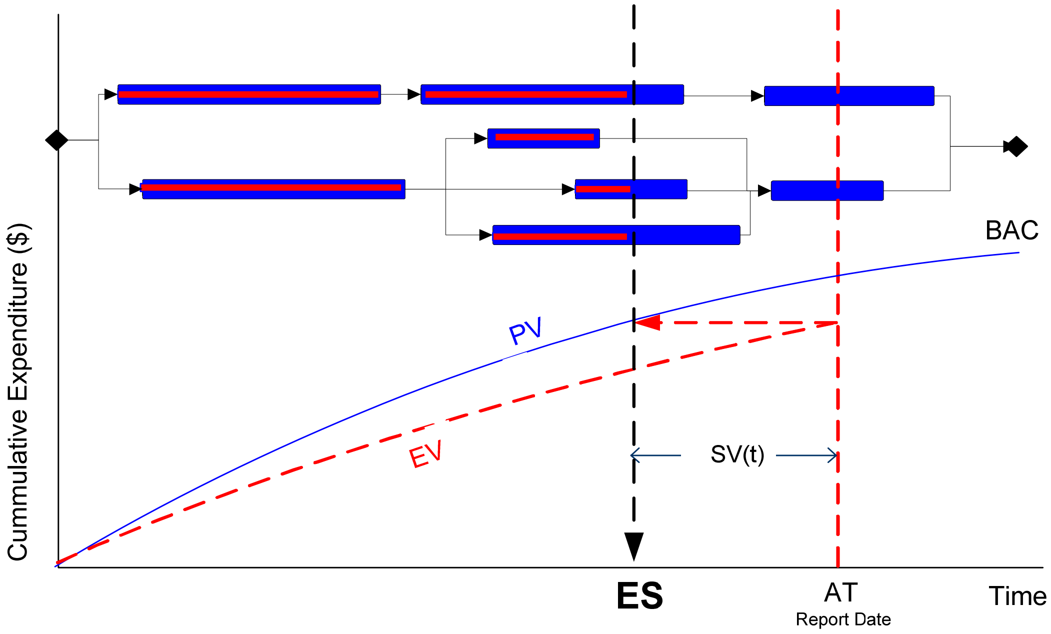


Figure 6-7: ES relating EVM to Schedule (Plan) from (Lipke 2003; Lipke 2004)

Figure 6-7 shows a desired adherence of the project execution to the activity sequences defined in the project plan; even though the project is behind schedule, project activities show the same level of completion as the activities that make up the plan portion attributed to the ES. In this situation EV metrics behave well, however if a more realistic situation like the one presented in Figure 6-8 occurred, EV is not being accrued in accordance with the plan generating misleading information that does not reflect the real status of the project.

A scenario such as the one observed in Figure 6-8 could occur when impediment or constraint conditions do not permit the normal execution of plan; project managers might be tempted to perform activities that are scheduled for later periods in an effort to accrue EV and show acceptable progress in performance reports. These activities are performed at risk since they can cause inefficiencies and rework due to new information acquired when predecessor activities are finished. This rework can clearly jeopardize cost objectives and that will be only observed later on when it occurs. ES will provide a better picture of the project status since it considers in its analysis the information of schedule objectives of report dates previous to the current control period.

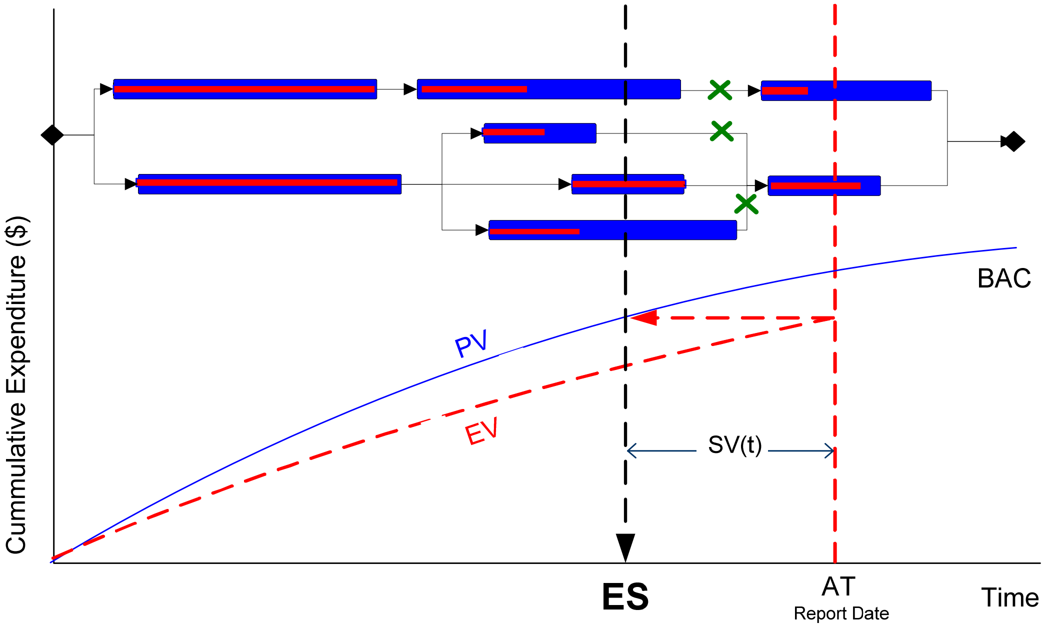


Figure 6-8: ES relating EVM to Schedule (Actual) from (Lipke 2003; Lipke 2004)

Lipke (2003; 2004) proposes a measure of schedule adherence such as:

$$P = \sum EV_j / \sum PV_j \tag{6.11}$$

where, PV_j is the planned value for activities associated with ES, and EV_j is the earned value at (AT) corresponding to and limited by planned activities, PV_j. P is a value that ranges from 0 to 1 and at project completion will equal 1. At any point in time, values closer to 1 show that a project is experiencing neither impediments nor overload of constraints and that management has applied discipline to the planned work process.

The adherence to the schedule characteristic, P, can be used with estimates of rework to calculate an effective earned value; details on its use go beyond the scope of this discussion.

6.4 *Forecasting Cost and Duration at Completion Using EVM and ES*

At any stage during project execution, project managers need first to evaluate the current status of a project to determine any deviations from the plan so they can forecast the final cost and completion date of the project; if the forecasted values are not aligned to project objectives corrective actions can be implemented.

Earned value performance metrics are used intensively to forecast future cost and time performance of a project. EVM allows to continuously monitor actual performance through efficiency rates such SPI and CPI and to identify performance trends that can influence future outcomes of the project.

In general, the quality of the forecasting methods presented in this section depends on three basic factors that are related with completeness of the project plan and organizational characteristics; these factors are:

- The quality of the project's baseline
- Actual performance against the approved baseline plan
- Management's discrimination to influence the final results

For a more detailed discussion on these factors refer to (Fleming and Koppelman 2005)

6.4.1 Estimating Cost at Completion

The forecast of the final cost of a project is called estimate at completion (EAC) and the cost of the remaining work is called estimate to complete (ETC). Therefore at any point in time the total project cost at completion is:

$$EAC = AC + ETC \tag{6.12}$$

ETC can be expressed as:

$$ETC = BAC - EV \tag{6.13}$$

So, (6.12) can be rewritten as:

$$EAC = AC + \left(BAC - EV\right) \tag{6.14}$$

The estimation of ETC can be greatly affected by how efficiently the project has been executed to date. So it is natural to think that the EVM efficiency metrics should be incorporated in the forecast formula (6.14) such as:

$$EAC = AC + \frac{\left(BAC - EV\right)}{pf} \tag{6.15}$$

where, *pf* is a performance factor that is driven by CPI and SPI.

Depending on the configuration of *pf*, three scenarios can be generated: best case, most likely, and worst case. Fleming and Koppelman (Fleming and Koppelman 2005) define these three scenarios with the following formulas:

- Low-end overrun-to-date or best case. Here *pf* of the remaining work is equal to 1. This formula is the same as (6.14) and assumes that any cost overrun to date will be carried to the project completion and it will not increase. This formula provides the minimum overrun floor that typically will not go away. This value is useful at early stages of project execution to communicate that there would be a variance from the cost target that would not be easy to recuperate.
- Middle range EAC or most likely. This formula makes use of the cumulative CPI up to the control date as the performance factor *pf*. The cumulative CPI has been shown to stabilize from as early as the 20%

completion point of a project and its use is considered as a reliable way to forecast EAC. Then, (6.15) is modified such as:

$$EAC = AC + \frac{(BAC - EV)}{CPI} \tag{6.16}$$

Alternatively, a short calculation version to evaluate EAC is:

$$EAC = \frac{BAC}{CPI} \tag{6.17}$$

Some practitioners suggest that a weighted aggregation of cumulative CPI and SPI represents a more realistic estimation of the most likely value of EAC; the suggested weights are 0.8 and 0.2 respectively such as:

$$EAC = \frac{BAC}{(0.8 \times CPI) + (0.2 \times SPI)} \tag{6.18}$$

- High-end range EAC or worst case. This formula uses the cumulative CPI times SPI as a way to incorporate into the analysis the schedule performance that have been observed up to date. This reasoning comes from the fact that project teams tend to use extra resources to bring back to schedule a project that is running late and therefore impacting its cost at completion and the CPI to be observed.

$$EAC = \frac{BAC}{Cum.\ CPI \times SPI} \tag{6.19}$$

6.4.2 Estimating Time to Completion

For the overall duration of a project Webb (2003) presents a formula for the estimated time to completion (ETTC) that consists of two parts: the time elapsed up to the reporting date plus the estimated additional time to complete the project assuming that trends seen to date continue.

ETTC is given by:

$$ETTC = AT + \frac{PD - \left(AT \times SPI\right)}{SPI} \tag{6.20}$$

where, AT is the actual elapsed time expended and PD is the planned duration. A simplification of (6.20) can also be used such as:

$$ETTC = \frac{PD}{SPI} \tag{6.21}$$

Once the planned duration of any activity or project has been exceeded the SPI becomes a measure of percentage completion, not schedule progress. Therefore, if the planned duration is exceeded, $AT > PD$, (6.20) and (6.21) should be respectively modified as:

$$ETTC = AT + \frac{AT - \left(AT \times SPI\right)}{SPI} \tag{6.22}$$

$$ETTC = \frac{AT}{SPI} \tag{6.23}$$

that is, the planned duration PD is substituted by AT.

These estimates are shown in the figure below where the straight line is drawn from the actual spend value to the predicted end conditions. These predictions do not provide information on the shape of the predicted S-curve since they do not consider the network structure or any rate of expenditure; they only represent point estimates obtained from simple linear expressions.

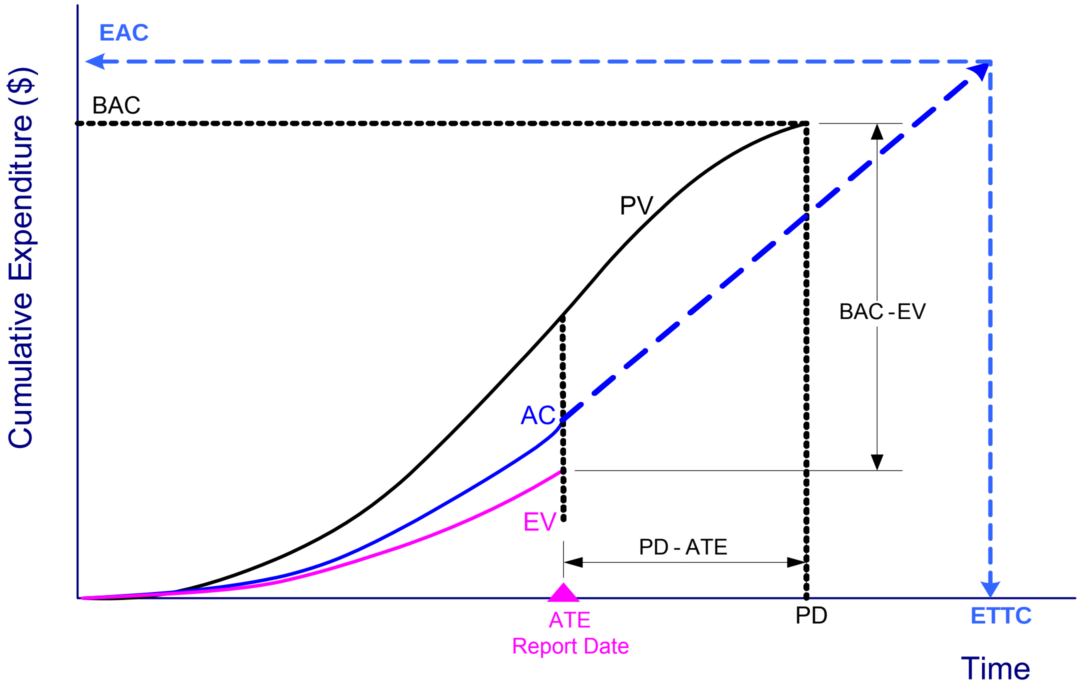


Figure 6-9: Forecasting Time and Cost at Project Completion using EVM Performance Metrics

The Earned Schedule method also provides formulas for predicting the project duration at completion using its time-based metrics. These predictive formulas look at the estimate of project duration at completion (EDAC) and at the estimate of completion date (ECD)

$$EDAC = \frac{PD}{SPI(t)} \tag{6.24}$$

$$ECD = \text{Project Start Date} + EDAC \tag{6.25}$$

The behavior of the EDAC and ECD is consistent with its EVM's cost-based equivalent EAC. According to (Henderson 2003; Henderson 2004; Lipke 2004) results of earned schedule metrics to forecast completion time seem to be satisfactory and provide better predictions than forecasting formulas that use only EVM metrics.

6.5 *Limitations of EVM and ES Methodologies*

The main challenge for implementing any control methodology is the fact that that cost and time can not be treated in the same way; when no work is done cost might stand still, but this is not true for time since it will go on whatever the project situation is. More important is to recognize that the total project cost is the sum of all the costs of the project activities; whereas this is not true for the project duration because the project duration is determined by the activities that are on the critical path.

One of the main problems of EVM and ES methodologies is the direct effect of non-critical activities in the schedule variance analysis. There could be situations when the critical path activities are right on track and non-critical activities are delayed within their allowed float; here the total planned value is greater than the earned value resulting in a misleading schedule indicator value (SV or SPI) that suggests that the project is late when in reality there is not enough information to confirm that result. Other circumstances might reflect that the project is on schedule even though that the critical path is lagging behind; this can happen because non-critical activities could be ahead of schedule increasing the project earned value.

These situations are better explained by the figure below, where a non-critical activity *i* can be executed anywhere within its allowed float without delaying the overall project completion; however, it actual execution date will be affecting the performance indicators.

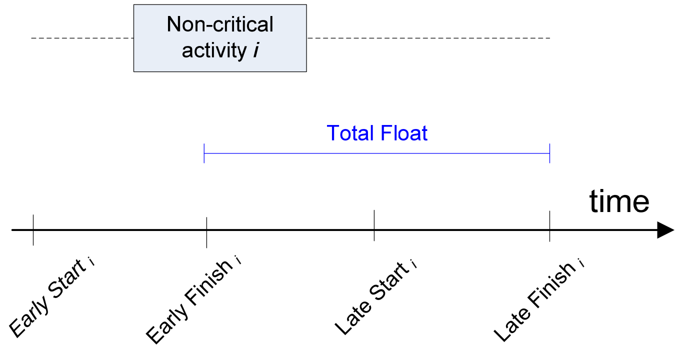


Figure 6-10: Effect of Non-Critical Activities in Performance Indicators

Another practice in project scheduling is the inclusion of time buffers or built-in float to safeguard project delays during execution; this practice can also mislead schedule performance metrics since it distorts of the true schedule position.

In reality a schedule variance represents the difference of what has been physically accomplished less what has been planned to be accomplished including critical and non-critical activities. This definition helps us conclude that schedule indicators may not indicate the true schedule position or may actually be reflecting a distorted picture of a project's true schedule condition.

Fleming and Koppelman (2005) recognize that EVM alone will not be sufficient to manage or predict a project's time objectives.

It is recommend that earned value analysis should be used in conjunction with the critical path method as a way to validate forecast dates of completion. With this joint analysis we can observe the possible scenarios presented in the table below, so the true status of the project can be assessed with confidence and more informed decisions made.

SPI	Total Float	Project Status
> 1	> 0	Ahead of Schedule
< 1	< 0	Behind Schedule
> 1	< 0	Critical path activities are behind schedule. Non-critical activities are ahead. May need to align resources.
< 1	> 1	Critical path activities are ahead schedule. Non-critical activities are behind. Could lead to creation of different critical paths.

Table 6-1: Using CPM and Earned Valued for Assessing Schedule Status

For the earned schedule analysis we recommend the evaluation of the status of the most probable critical path compared against the status of the entire project. Schedule performance indexes for the critical path and for the overall project can be compared as a way to uncover the true schedule status. The figure below is a tool that allows us to perform this analysis where the possible conditions of the project schedule can be exposed along its progression in time.

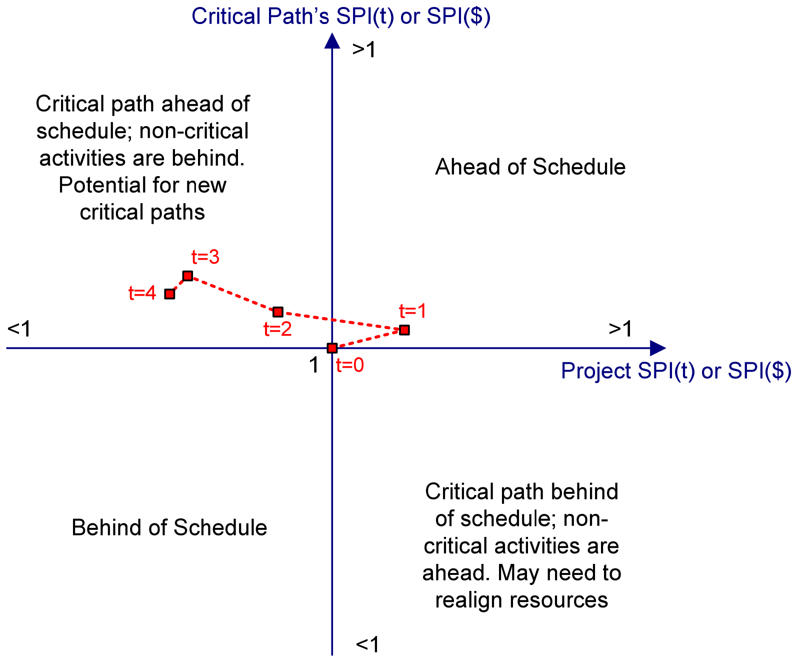


Figure 6-11: Comparing Schedule Metrics of the Critical Path and the Overall Project

When forecasting project performance at completion, the main weakness of EVM and ES techniques is the reliance on the assumption that future performance can be predicted based on past performance (Hillson 2004). Performance indexes and cost and schedule variances are used to predict final cost and completion times; however, there is no guarantee that deviations from a simple extrapolation of past performance would not occur. For example, Webb (2003) states that extensive research carried out on hundreds of projects within the US shows that EAC forecasts tend to be optimistic.

Project managers continuously use performance data to make decisions when deviations from the plan and undesirable predictions are observed. Therefore, not only actions taken by management could affect the remaining elements of a project but also opportunities or risks that could introduce variation and uncertainty into the performance prediction. These considerations make necessary the use of risk based methodologies to incorporate a forward view into the forecast of performance at completion given the actual status of a project.

6.6 Using Probabilistic Baselines for Project Control and Forecasting

Even though EVM is a very popular project control technique and even contractually mandatory in public funded projects, it presents limitations to incorporate variability and uncertainty that surrounds projects due to its deterministic nature.

As explained in Section 6.3.5, an output of the planning process is the project performance measurement baseline known as “S-curve”, which plots costs against time and provides a measure of cumulative expenditure at any period of time. EVM makes use of the PMB and actual report data to assess project status and forecast cost and duration at completion. However, the use of a deterministic baseline may have the potential to introduce biases and inaccuracy when measuring performance.

To control the project in more realistic fashion, we can make use of probabilistic baselines that take into consideration the effects of uncertainty and judgment. Although, risk based methodologies allow the construction of probabilistic S-curves that integrate cost and schedule, probabilistic control of project performance is a new concept; very few references can be found about this topic and among them we find (Barraza et al 2000, Barraza et al 2004, Hillson 2004). These authors suggest that a more practical way to represent time and cost S-curves is to convert them into "progress-based S-curves", so project performance can be assessed at different progress completion stages.

Progress-based S-curves or curves of work completed can be constructed using the critical path method and the cost and duration of project activities. In addition it is necessary to evaluate the percentage of planned work completion for project activities at different control periods. Figure 6-12, for example, shows probability distributions for project cost and duration at different stages of completion; where, PD represents the probability distribution of the project planned duration at completion while BAC represents the total project budget at completion.

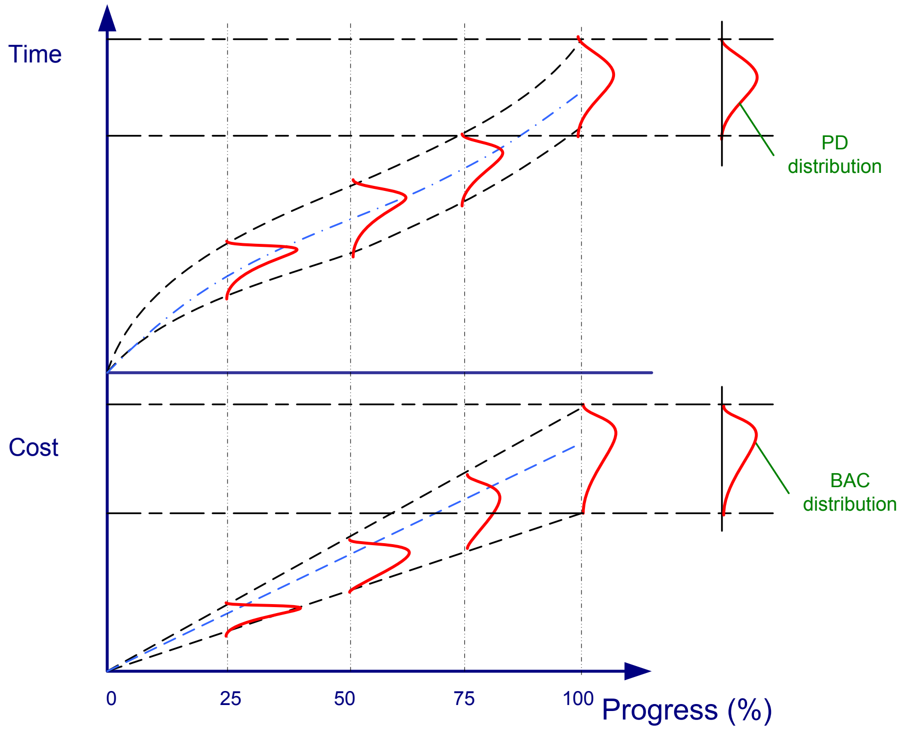


Figure 6-12: Probabilistic Baselines for Project Duration and Cost

The figure above shows that uncertainty about the cost and time elapsed distributions gets larger as the project develops; this happens because more work comes into play. What is interesting about this is that at any stage of project completion a probability distribution that describes the planned cost or time elapsed is available for control purposes; this creates a range of possible values throughout project progress for which statistics such as the planned mean, mode or the 5th and 95th percentiles can be obtained.

When a project enters into its execution phase, actual performance data can be acquired and compared against the statistics of the probabilistic PMB. Figure 6-13 provides a representation of the planned budget and duration probability distributions for the project as well as the information of elapsed time and actual cost. This information allows us, first to control if actual deviations are within acceptable ranges and also forecast and update time completion and cost distributions of the project.

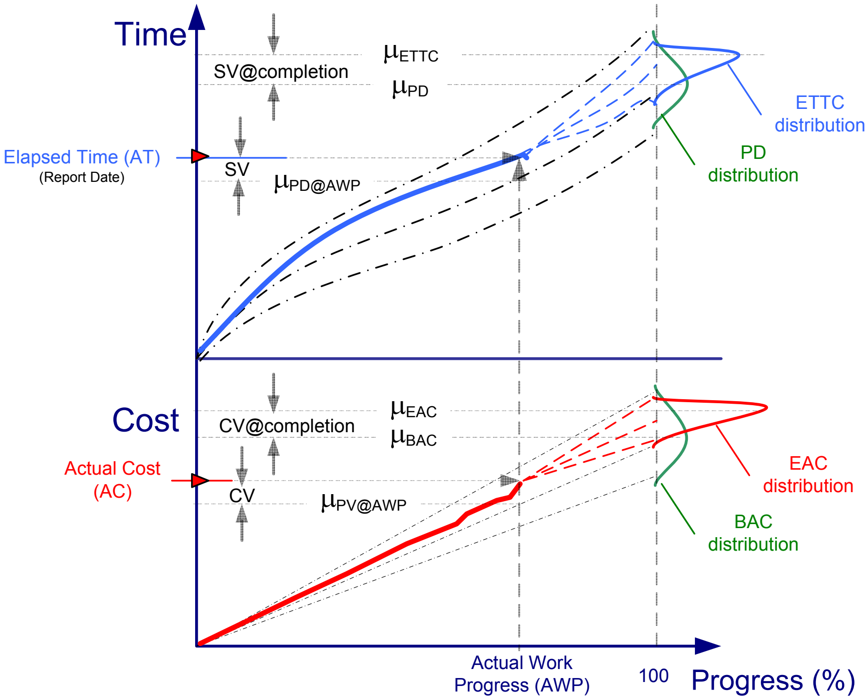


Figure 6-13: Probabilistic Performance Forecasting Using Probabilistic Baselines

The figure above compares the mean of the planned cost and time elapsed for a specific percentage of completion against actual performance data. This way cost and schedule variances can be evaluated not only at the control period but at completion. For example variances at any control date can be determined as follows:

$$CV = \mu_{PV@AWP} - AC \tag{6.26}$$

$$SV = \mu_{PD@AWP} - AT \tag{6.27}$$

where, CV is the cost variance, SV is the schedule variance, $\mu_{PV@AWP}$ is mean of the planned cost, and $\mu_{PD@AWP}$ is the mean of the elapsed duration at the actual project percent completion.

Given that actual information can be measured at any control period, what is left of the project can be incorporated into a risk analysis model, so cost and duration at completion can be updated and compared against initial performance goals and deviations from plan can be detected early enough. For example, cost and schedule variance at completion can evaluated using the following formulas:

$$CV_{\text{@completion}} = \mu_{BAC} - \mu_{EAC} \tag{6.28}$$

$$SV_{\text{@completion}} = \mu_{PD} - \mu_{ETTC} \tag{6.29}$$

where, μ_{BAC} is the mean of the budget at completion, μ_{EAC} is the mean of the estimate at completion, μ_{PD} is the mean of planned duration, and μ_{ETTC} is the mean of the estimated time to completion.

Barraza et al. (2000; 2004) explore the benefits of this type of analysis and layout a methodology that incorporates a probabilistic approach for project control and forecasting using EVM.

As we discussed earlier, the forecasting process could greatly benefit from a risk based methodology that brings into the analysis a forward looking perspective. The following section discusses how the BBN-MCS model developed in Chapter 4 can be integrated with control techniques to forecast performance at completion.

6.7 *Forecasting Project Performance at Completion Using the BBN-MCS Model*

As a project continues to develop over time, initial assumptions about the project change as well as additional information becomes available to the project team. These changes and this information potentially alter the project scope, design, and ultimately, cost and schedule. Updating allows the project team to re-baseline the risk assessment and benchmark the team's performance with respect to risk management (Roberds and McGrath 2006).

As a result of a project risk analysis, one can construct a probabilistic PMB that considers the possible combinations of project duration and cost at completion or at point in time of interest; an example of a probabilistic PMB can be observed in Figure 5-21.

A schematic representation of the possible S-Curves that are generated in a MCS model and create the probabilistic PMB is shown in the figure below.

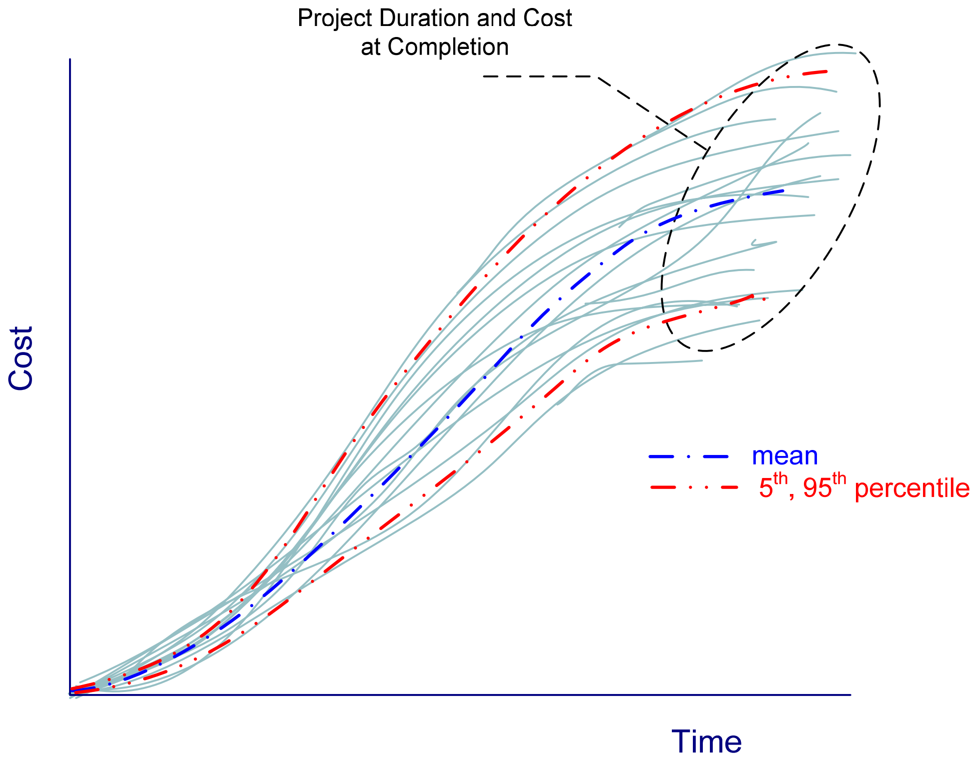


Figure 6-14: Probabilistic Performance Measurement Baseline (PMB)

At any point in time through the execution of a project, actual cost and time elapsed can be evaluated. This information and the progress activity data become the starting point for the integrated BBN – MCS model as shown in Figure 6-15.

Any qualitative evidence acquired or decisions made that are part of the project BBN's should be updated and added as actual observations to its corresponding BBN.

Also if any information has been acquired with respect to uncertainties that affect the cost estimate or activities (usually related with production) that are long enough to include various control periods, probability distributions for productivity, duration or cost can be updated using Bayesian approaches (Chung et al. 2006).

Activities that are in progress can either use EVM performance indexes to extrapolate their duration or use an updated distribution that describes the duration and cost of the work left.

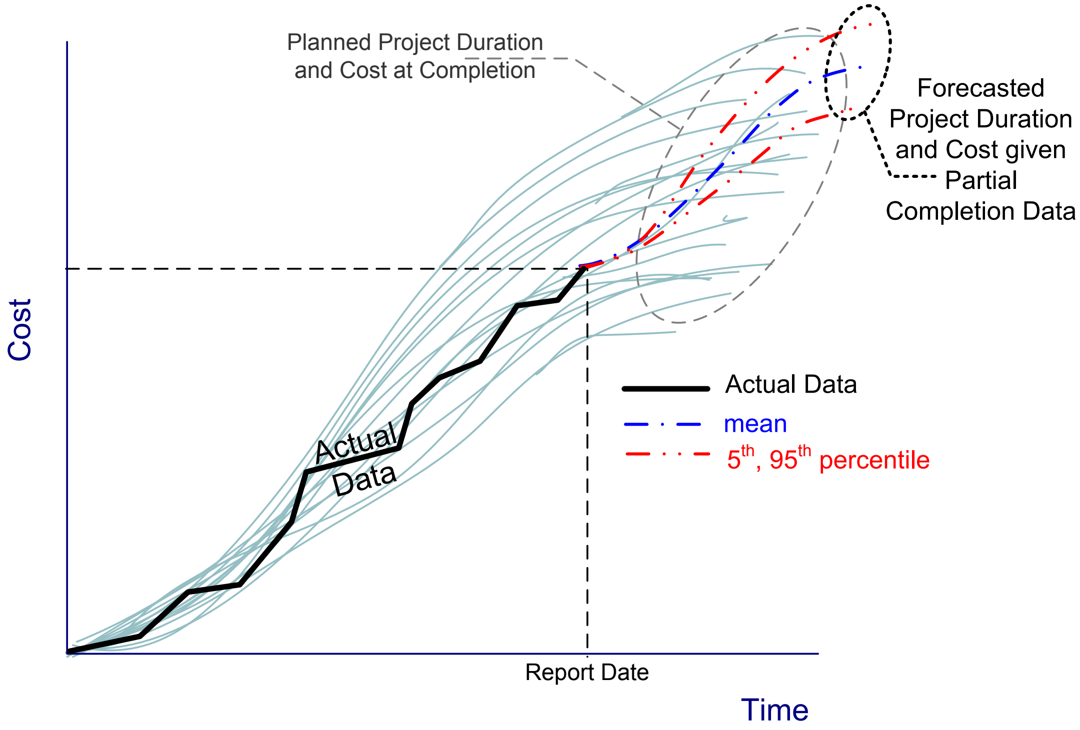


Figure 6-15: Forecasting Project Completion Given Actual Information

Once all required information has been updated, the risk model will simulate what is left of the project so the cost and duration at completion can be assessed probabilistically.

It should be noted that the new duration forecast looks at what is left to be executed from the project network; therefore, the prediction takes into consideration not only cost information but also the project schedule.

6.8 *Summary*

When using EVM or ES techniques special attention should be given to the status of the critical path; a more accurate approach should include a separate analysis for only critical activities contrasted to values for the whole project.

As reported in previous chapters, project planning benefits greatly from the use of risk based methodologies. However, a probabilistic view of project control will improve the quality of project status determination; it will also represent an improvement in the quality of cost and duration forecasts.

7. Conclusions and Future Directions

Several challenges motivated this research. The most important one was the difficulty to assess and include correlation among input variables in a viable way in a risk analysis model. Another challenge was the need to integrate the cost and schedule of a project so the estimated risk exposure is not underestimated and its joint effect is assessed. It also critical to recognize that qualitative evidence could affect the parameters of a risk model and create different scenarios that need to be considered when analyzing cost and schedule risk.

In this dissertation a methodology for project risk analysis using Bayesian networks within a Monte Carlo simulation environment has been developed to provide an alternative to these challenges.

The developed methodology advocates the use of a schedule-driven cost model where base value uncertainties and risk factors affect the deterministic project plan. Risk factors are defined in a risk register, which documents not only risks but also opportunities that affect the cost and/or duration of project activities.

The use of BBN's permits the incorporation of dependency and causality among risk factors. The MCS is used to model independent events, which are propagated through BBN's to assess dependent posterior probabilities of risks affecting project cost and time to completion. BBN's consider the effect of concurrent risks into the analysis and allow the incorporation of non-additive impacts.

BBN's also allow for the incorporation of qualitative considerations and project characteristics when soft evidence is acquired or when different scenarios need to be tested.

While the evaluation of qualitative characteristics provide a Top-Down view of the project, the assessment of uncertainties and risks affecting work packages represent an Bottom-Up approach; the use of the presented methodology creates a bridge between these two analyses, which are, most of the time, considered separately.

The results that are generated by the BBN-MCS model can also be used for project control. A probabilistic baseline can be determined and using current techniques such as EVM and ES, the performance of a project can be studied using a probabilistic framework. In this dissertation the limitations of current control methodologies were presented. The main drawback is that the structure of the project network and the status of critical activities are not considered in the analysis; this can create situations where performance indexes are unreliable. This research suggests that performance indexes should be calculated not only at a project level but also looking exclusively at the critical path of the project. More research is needed to determine a performance indicator that includes the structure and the status of the project network.

The BBN-MCS model has also proved to be a suitable tool for performance forecasting. A risk analysis model can be executed at any point of time during the execution of a project to study what remains of it; this brings a forward perspective into the forecast calculation what will be expressed in probabilistic terms.

As for future directions of research, it is necessary to explore the integration of BBN’s within the software packages used in project management. The burden of coding a project network and linking BBN's into the model could be avoided if a BBN–MCS module is created within a schedule software package; this will make the use of this methodology more appealing to project management practitioners. Other benefits of using schedule software packages include the use of complex logic constraints, calendars, and resources.

In this dissertation BBN's used nodes with categorical values and multinomial distributions; however, it is also possible to create BBN's with continuous valued nodes. The use of continuous variables will provide flexibility in the construction of complex models. Specifically, the arduous process of eliciting conditional states of multinomial variables could be alleviated. Moreover, the use of continuous variables will allow for a better representation of nodes that model risk impacts. Future research will look into incorporating continuous variables as nodes of BBN's.

It is also necessary to explore in more detail BBN's that represent specific industry needs; if data are available, better BBN's structures can be constructed using learning algorithms for specific industries such as construction, IT, etc. The goal of structure learning is to find a directed acyclic graph that best explains the data.

Finally, it would be also beneficial to investigate the accuracy of the reported results after projects are completed, so models can be calibrated and future results improved.

Appendix A. Summary of Base Cost Estimate

SUMMARY OF COST ESTIMATE

TOTAL CONSTRUCTION ITEMS (Sections 1 thru 8)	$	16,597,232
SALES TAX (8%)	$	1,327,779
PROJECT MANAGEMENT / PRELIMINARY ENGINEERING	$	4,309,501
TOTAL -RIGHT OF WAY COSTS	$	3,400,000
TOTAL -UTILITY RELOCATION COSTS	$	70,000
TOTAL PROJECT COSTS	$	25,704,512

	Quantity	Units	Unit Cost	Item Cost	Section Cost
ROADWAY/STRUCTURE ITEMS					
Section 1 Earthwork					
Pavement Removal (area not inc. with Roadway Exc.)		SY	7		
Retaining Wall Removal (area not inc. with Roadway Exc.)		LF	15		
Roadway Excavation	50,000	CY	10	500000	
Roadway Embankment	435,000	CY	8	3262500	
Clearing and Grubbing	18	Acre	1,800	32400	
Subtotal Section 1 Earthwork					**$ 3,794,900**
Section 2 Pavement (provide sketch of all layers for each type below)					
PCCP Mainline		SY	117		
HMA Mainline	19,800	Ton	55	1089000	
Crushed Surfacing Base Course	24,000	Ton	12	288000	
HMA Arterial		SY	49		
HMA Overlay (2" Depth)		SY	7		
Temporary Const. Pavement	1	LS	500,000	500000	
Concrete Sidewalk	4,500	SY	35	157500	
Diamond Grinding		Ln-Mile	100,000		
HMA Overlay Mainline		Ln-Mile	150,000		
Subtotal Section 2 Pavement					**$ 2,034,500**
Section 3 Drainage					
Conveyance	1	LS	70,550	70550	
Retention / Detention/Water Quality		LS			
Culvert Replacement		LS			
TESC (% of Sections 1-6 excluding TESC)	2%	of	13,101,285	262025.7	
Subtotal Section 3 Drainage					**$ 332,576**
Section 4 Specialty Items					
Retaining Walls -Soldier Pile w/ tiebacks (Cut > 15')		SF	129		
Retaining Walls -Soldier Pile w/o tiebacks (Cut < 15')		SF	84		
Retaining Walls -Special Soldier Pile w/o tiebacks		SF	109		
Retaining Walls -Soil Nail		SF	59		
Retaining Walls (MSE)		SF	45		
Retaining Walls (Cast-In-Place)		SF	59		
CaissonWalls		SF	129		
Sound Walls		SF	32		
CSS Wall Treatment		LS			
Highway Planting	1	LS	103,750	103750	
Wetland Mitigation	1	LS	850,000	850000	
Stream Mitigation		LS			
Subtotal Section 4 Specialty Items					**$ 953,750**
Section 5 Traffic Items					
Illumination -US XX / SR YY	1	LS	120,000	120000	
Illumination -H Rd	1	LS	100,000	100000	
Illumination -J Rd / Roundabout	1	LS	100,000	100000	
Conduit		LF	60		
Data Loop		LS	15,000		
Ramp Meter		Each	57,000		
Data Collector		Each	41,000		
CCTV Camera		Each	45,000		
VMS		Each	300,000		

Traffic Control/Staging (% Earthwork, Paving, Structures, Specialty)	10%	of	11,079,150	1107915		
Pavement Markings	1	LS	7,095	7095		
Signing Cantilever	1	Each	50,000	50000		
Signing Span		Each	150,000			
Signing -Miscellaneous (% of Overhead Signs)	25%	of	50,000	12500		
Traffic Signals -SR YY WB on/off ramps		Each	150,000			
ITS		Mile	1,000,000			
Guardrail	12,175	LF	17	206975		
32" Barrier	1,300	LF	100	130000		
Cement Concrete Curb and Gutter	9,110	LF	10	91100		
Roundabout Truck Apron (500 lf Inner & 440 lf Outer)	940	LF	25	23500		
Extruded Curb	500	LF	5	2500		
Subtotal Section 5 Traffic Items					**$**	**1,951,585**
Section 6 Structures						
SR YY: 3-Lane Structure	12,540	SF	160	2006400		
H Rd: 2-lane Structure+Bike lane	14,310	SF	160	2289600		
Subtotal Section 6 Structures					**$**	**4,296,000**
Section 7 Minor Items / Contigencies						
Minor Items (15% of Sections 1-6)	15%	of	13,363,311	2004496.6		
Subtotal Section 7 Minor Items					**$**	**2,004,497**
Section 8 Mobilization						
Mobilization (% of Sections 1-7)	8%	of	15,367,807	1229424.6		
Subtotal Mobilization					**$**	**1,229,425**
SALES TAX						
Sales Tax (% of Sections 1-8)	8%	of	16,597,232	1327778.6		
Subtotal Sales Tax					**$**	**1,327,779**
Section 9 Project Development Costs						
Preliminary Engineering	1	LS	1,000,000	1000000		
Preliminary Engineering -Spent to Date	1	LS		0		
Construction Administration	14%	of	17,925,010	2509501.5		
Environmental Documentation	1	LS	800,000	800000		
Subtotal Section 9 Project Development Costs					**$**	**4,309,501**
RIGHT OF WAY						
4 Interchange Parcels	1	LS	600,000	600000		
4 H Bridge Parcels	1	LS	2,100,000	2100000		
Wildlife Exchange	1	LS	400,000	400000		
RW Administration	1	LS	300,000	300000		
Subtotal Right of Way					**$**	**3,400,000**
Major Utility Relocations (incl. Engineering)						
Power Line Relocation @ Humorist	1	LS	70,000	70000		
Subtotal Utility Relocation					**$**	**70,000**

Appendix B. Project Risk Register

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
Construction					
C1	**Market Conditions – Uncertain Competition in Contracting Market** Separate from Market Conditions – Uncertainty in Escalation of Labor, Equipment, and Materials (risk C2) Function of: contracting market at time of bid, contract delivery method, contract size ($). Note that the team has said that their strategy is to not put the project out to Ad in the summer, which would most likely result in poor bids (this is built into the flow chart and model). Expect 3 bidders, but probably no more. Should be adequate competition with no significant issues.	All construction	100%	Normal (10th percentile = -2%; 90th percentile = +2%) of base construction cost Perfectly correlated across activities	Minor

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
-	**Market Conditions – Uncertainty in Cost Inflation of Labor, Equipment, and Materials** Separate from Market Conditions – Lack of Competition (risk C1) and Market Conditions – Structures Price Correction Per the CEVP Common Assumptions document, base cost escalation factors for construction and design activities are applied according to the WSDOT CCI tables as used in (Table 5-5: Annual Escalation Rates). However, there is considerable uncertainty in the future escalation rates due to regional, national, and global economic factors such as highway and non-highway construction spending, imports to China, commodity prices (iron and steel scrap, crude oil, cement, etc.), severe weather conditions, exchange rates, etc. This uncertainty is addressed as a market conditions risk factor (for escalation, separate from competition issues), which is implemented per the current recommended approach (based on historical FHWA data along with other factors.	Applies to all PE and construction activities, perfectly correlated	100% (Distribution)	See Section 5.4.1	Minor
Minor	**Delays in bid process** (other than related to market competition, which is captured separately)				

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
C2	**Construction Change Orders** (if not captured separately in individual risks) Uncertainty item representing an expected adjustment that will be made by the contractors in their bids to reflect the reality of change orders due to design errors and omissions and other changed conditions. Historical WSDOT data indicate that an average 3%-4% increase in project cost has been experienced due to contractor change orders resulting or design errors and omissions. This project has a lot of structures, which typically generate more changed conditions. Not much of this has been captured under separate construction risks, so include here.	All construction	100%	Uniform (3%, 4%) of base construction cost Perfectly correlated across activities	Captured elsewhere
-	**Extended Overheads** (i.e., additional Preliminary Engineering and Construction Engineering costs as a function of project delays) 1. Paid to contractor for non-contractor-controlled schedule delays: Cost per month = 5% of base construction cost / base construction duration. Assume that half of overall construction delay is not fault of contractor. Apply to construction Project Management activity. 2. WSDOT during construction: rate = CE base cost / base construction duration. Apply to construction PM activity. 3. WSDOT before construction: rate = PE base cost / base PE duration (flow chart start to Award date). Apply to pre-construction PM activity.	See left	Simulated in integrated cost/schedule model	See left	0

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
C3	**Uncertain construction staging / phasing** Base assumes 3 stages of construction as shown in flow chart (Figure 1). However, the project is early in design and alternative staging/phasing is possible. Includes contractor efficiency (including staging plan), labor availability, and weather variability. Exclusive of winter shutdowns	allocate across all three stages of construction	(extended overheads)	(extended overheads)	Normal dist (10th percentile = -3; 90th percentile = +3)
Minor	**Other construction duration uncertainty** (if not captured separately)				
Minor	**Work-window restrictions** ESA for migratory birds				
Design, Environmental, Permitting					

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
E1	**Uncertain configuration of SR-YY Interchange** Includes related potential changes in design, including related design and construction impacts (structures, earthwork, pavement, drainage, etc.). Excludes risks captured separately. Excludes potential gateway at SR-YY (captured under separate scope risk). Project has a preferred alternative and has undergone a VE study. However, project is only at 10% design and may evolve in response to a number of factors, primarily 4(f) avoidance. However, the configuration is also constrained by a number of factors. Uncertainties include (but are not limited to): • May have to accommodate future widening of US-XX (add extra lane in median; SR-YY structure over US-XX might have to be wider). Already being considered in the base. Minor cost. • Hood Park would like to modify entrance (relative to existing), but haven't formally proposed the change (no significant cost or schedule impact if not in wetland). Minor cost difference. • Right-angle crossing of US-XX could be skewed to reduce amount of property required from Reserve. Would impact bridge design (increased skew increases span length; if spans become too long, need to deepen structure) and walls. 20% chance of 2 month delay and net cost increase of $1M to Activity 15 (minor PE cost change). • Structure and foundation TS&L not established yet (captured in structures base uncertainty, Appendix A) • Issues related to protecting foundation (concrete) from contaminated groundwater (captured in structures base uncertainty, Appendix A)	15	20%	1	2

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
E2	**Uncertain TS&L for H Road overcrossing** Includes related potential changes in design, including related design and construction impacts (structures, earthwork, pavement, drainage, etc.). Excludes risks captured separately. Project has a preferred alternative and has undergone a VE study. However, project is only at 10% design. Uncertainties include (but are not limited to): 1. May have to accommodate future widening of US-XX (add extra lane in median; SR-YY structure over US-XX might have to be wider). Being considered in base design. Minor risk. 2. Modify alignment of H. Road over US-XX. Could change for various reasons – reduce ROW impacts, reduce overall cost, etc. Scenario: straighten alignment from proposed curved alignment. Summarize with the following potential (mutually-exclusive) outcomes: a. Base alignment, acquire full T-shaped property ($2.0M), land use does not change (base) b. Base alignment, acquire full T-shaped property, land use does change (value increases by 25%) c. Base alignment, don't have to acquire full T-shaped property (cost decreases by $0.85M), land use does not change d. Base alignment, don't have to acquire full T-shaped property (cost decreases by $0.85M), land use does change (value increases by 25%) e. Change to straight alignment (different ROW takes than in base but no cost difference, additional bridge and wall	20	Issue 2: Mutually exclusive outcomes: a. 31.5% b. 3.5% c. 31.5% d. 3.5% e. 30% Issue 3: 25%; however, this risk cannot occur if realize outcome E from Issue 2.	Issue 2: a. 0 (base) b. 0.5 c. -0.85 d. -0.45 e. 1.0 Issue 3: 0.15	minor

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
	cost, as well as utility relocation, incl grade issues) (cost increase of $1M) 3. Extend Humorist Road past S.L. Road: <u>25% chance of additional $0.15M (cannot occur if realize outcome E from Issue 2 above).</u> 4. Structure and foundation TS&L not established yet (captured in structures base uncertainty, Appendix A) 5. Issues related to protecting foundation (concrete) from contaminated groundwater (captured in structures base uncertainty, Appendix A) Note for 2. above: P[straight alignment] = 30%; P[partial take | base alignment] = 50%; P[change in land use] = 10%				
Minor	**Uncertainty in retaining walls** *In addition to base uncertainty, which is captured in Appendix A. Excludes uncertainty captured as part of interchange configuration uncertainty in separate risks(e.g., E1 and E2).* Base assumes no retaining walls. However, might replace embankment in some locations with wall. Captured under risks E1 and E2.				
E3	**Uncertainty in earthwork** *In addition to base uncertainty, which is captured in Appendix A. Excludes uncertainty captured as part of interchange configuration uncertainty in separate risks (e.g., E1 and E2).* Need 400k cy of fill, but only 80k cy available at old pit site on Reserve (old dam material) – although could be ESA issue. Maybe use excavated	20	70%	-0.375	Minor

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
	Boise Cascade fill. Base is $7.50/cy (embankment + compaction). Opportunity to save on excavation of existing alignment of SR-YY (that will be abandoned). Could reduce fill need by 50k cy (use at H Road).				
Minor	**Uncertainty in pavement** In addition to base uncertainty, which is captured in Appendix A. Excludes uncertainty captured as part of interchange configuration uncertainty in separate risks (e.g., E1 and E2).				
E4	**Uncertainty in drainage / stormwater management** *In addition to base uncertainty, which is captured in Appendix A. Excludes uncertainty captured as part of interchange configuration uncertainty in separate risks (e.g., E1 and E2)* . Base is $80k (mostly for structures, with pond in loop at SR-YY IC included in grading cost) and assumes no collection/detention/treatment and simply roadside runoff/infiltration for 27,000 sf of new impervious surface. Risk that conveyance and treatment may be required (catch basins, shoulder treatment for dispersion). e.g., 27,000 sf @ $8/sf for new impervious	15	60%	0.2	0
Minor	**Uncertainty in allowance for miscellaneous items** *In addition to base uncertainty, which is captured in Appendix A.*				

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
Minor	**Other design un certainty** *In addition to base uncertainty, which is captured in Appendix A. Excludes uncertainty captured as part of interchange configuration uncertainty in separate risks (e.g., E1 and E2)* .				
Minor	**Uncertain soft costs** *In addition to base uncertainty, which is captured in Appendix A. Excludes uncertainty captured as part of interchange configuration uncertainty in separate risks (e.g., E1 and E2).*				
E5	**Change in Seismic Design Standards** HQ Bridge representative says this risk applies to this project. **Issue 1**: From the CEVP Common Assumptions document: For this seismic zone, there would be a 7% increase in structures cost if this risk occurs. The probability of occurrence is 100% (it will ultimately occur, it's just a matter of when it will occur). The probability of occurrence is a function of time. The probability of occurrence in each time period, given the risk occurs (100% chance), is: • before June 2007: 0% • between June 2007 and June 2008: 50% • between June 2008 and June 2009: 10% • between June 2009 and June 2010: 40% **Issue 2:** Related to this risk for the bridges on this project, if seismic design criteria is implemented then 30% chance of ground improvement for liquefaction (at a cost of $500k/structure) Simulation note: Simulate when this risk occurs (set P(occurrence) on sheet	All construction activities with structures (perfectly correlated)	Distribution (see left)	See left	Minor

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
	Events to 100%, then use discrete distribution above (with dates translated to months after model start) to sample date of occurrence on sheet Cost Change). Compare simulated date of occurrence to Ad date for each construction package. If Ad date is after date of occurrence, then structures in that construction package are increased by 7% (plus related markups).				
E6	**Uncertain wetland mitigation** *In addition to base uncertainty, which is captured in Appendix A. Excludes uncertainty captured as part of interchange configuration uncertainty in separate risks(e.g., E1 and E2).* Impacts are not yet known, but suspect impacts will be greater than 0.5 acres of Class III (assume 5 acres). Won't mitigate on-site. Haven't identified suitable offsite mitigation site yet. Buffers and mitigation ratios are also uncertain (currently changing). Summarize with the following issues and uncertainties: 1. Wetland ROW: Base assumes that wetland mitigation ROW is included in land swap (i.e., no separate wetland ROW cost in base). Risk that might have to purchase site (6 acres at $5k/ac) for mitigation. 80% chance of $0.03M additional cost for wetland ROW. 2. Wetland construction: See base uncertainty. 3. Opportunity to save half the wetland construction cost by utilizing the Two Rivers mitigation site. 33% chance to save 50% of wetland construction cost (i.e., half of the wetland construction cost considering change from 2. above).	16	See left	See left	See left

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
Minor	**Uncertain noise walls** Base does not include noise walls. Walls may be required (low likelihood – not cost-effective). Particularly in SE quadrant of H Road Overcrossing.				
Minor	**Well-protection issues** Wells are for irrigation and are outside the project limits/impacts.				
E7	**Issues completing environmental documentation** 2003's corridor EA does not cover this project. Base assumes the appropriate documentation is a DCE with an 18 month schedule (which is believed to be a bit conservative) and $600k cost. Excludes issues related to land exchange/swap with Wildlife Reserve, which are captured separately because the base assumes a separate environmental process for the land swap. EA could be required for various reasons, such as issues related to gas stations at H. Road or wetland issues. Summarize the uncertainty with the following scenarios (potential mutually-exclusive outcomes from a rolled-up event tree, which captured the important dependencies explicitly): a. DCE completed ahead of schedule (save 3 months) b. DCE completed as assumed in the base c. DCE completed with delay (additional 3 months) d. EA required (instead of DCE) but simple and completed with no problems (additional 8 months and extra $200k). e. EA required but more complex / issues completing (additional 20 months	2	a. 28% b. 28% c. 14% d. 22.5% e. 7.5%	a. 0 b. 0 c. 0 (minor) d. 0.2 e. 0.5	a. -3 b. 0 (base) c. 3 d. 8 e. 20

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
	and extra $500k) P[not DCE] = 30% P[EIS|not DCE] = 25% P[DCE ahead of schedule|DCE] = 40% P[DCE on schedule|DCE] = 40% P[DCE behind schedule|DCE] = 20%				
Minor	**Delays getting design completed and/or approved** Base is 15 months for design and 6 months for PS&E. No design deviations are being requested. Sight distance issue for SR YY-IC – may need to alter design to get acceptable. Unlikely to include traffic signal. May have to raise grades to flatten vertical curve. Minor cost and time to rectify. Frontage road configuration (who pays, how they look) could take some time to resolve. No staffing, continuity, or management concerns.				
E8	**Access issues (hearing)** May have to provide emergency access for fire station to US-XX at H Road. Not sure how this access will provided. Could require room for acceleration and a crash gate. Access office does not like this alternative, and of questionable value (probably less than one minute difference in response time compared to using SRYY IC). 25% chance of additional $100k, with	20	25%	0.1	0

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
	no delay. Base assumes do not do this (abandon and culde-sac the existing road). Removing access to US-XX for gas stations and other properties in vicinity of H Road (reverse condemnation) covered elsewhere. Opposition from access hearing could delay DCE (covered in separate risk)				
E9	**Permitting issues** Base assumes 12 months and $200k. Individual 404 and 401 permits will drive the permitting schedule. Some uncertainty in permitting time due to wetland mitigation outcome, avoidance, etc.	8	a. 25% b. 50% c. 25%	minor	a. -3 b. 0 (base) c. 3
Minor	**4(f) issues** Cost and time included in environmental documentation base and risk. Sliver take of Hood Park (USACE), but re-doing their entrance and swapping land.				
E10	**Encounter unanticipated archaeological / cultural / historical site** Base includes $25k for cultural monitoring. Particularly near the Snake River. Not much excavation (mostly fill, which is less invasive). If encountered, unlikely to delay critical path (most likely can conduct study while work continues).	15	20%	0.025	0.5

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
Minor	**Encounter unanticipated contamination** Particularly at gas stations to be acquired. Some question whether WSDOT would have to remediate since not developing. No other significant concerns.				
Political and Other External Influences					
-	**Uncertainty in funding (amount and/or timing)** Project is "fully funded", although may need additional funding to cover recent escalation. Current funding level is $23.7M. If not enough, must request additional funding, which would be required prior to Ad. *Funding uncertainty is excluded from this CRA. The results are conditional on no funding delay*.				
-	**Issues involving Tribes** (other than included elsewhere, such as in environmental documentation risk) Currently partner with five tribes *Included in other risk re DCE*				
Minor	**Issues related to detour** Base includes overlay of S.L. Road (from SR-YY to H Road). May have to improve S.L. Bridge for use in detour, or make temporary connections/ramp				

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
	improvements to resolve detour issues.				
Minor	**Other issues (e.g., USFW, USACE)** Most issues are included in separate environmental risks. Other issues are minor.				
Right-of-Way					
-	**Uncertain cost escalation rate for ROW** Base escalation rate is 6%/year. Land use is established. Uncertainty in the average annual rate ranges from 4% per year to 10% per year (i.e., simulate the rate for one year and apply this rate to all years).				
R1	**Land swap with Wildlife Reserve** *In addition to base uncertainty, which is captured in Appendix A. Excludes uncertainty captured as part of interchange configuration uncertainty in separate risks (e.g., E1 and E2).* *Includes all pre-construction issues (design, ROW, permitting, environmental) related to this exchange.* Base assumes a separate environmental and ROW process from the rest of the project. Cannot purchase (not allowed by law). Could exchange land, but land has not been identified yet (have several ideas, such as the vineyard at north end of Reserve). An exchange would require US legislative action to modify the boundary of the Reserve.	See left	See left	See left	See left

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
	Independent issues: 1. Delay in legislative approval to alter the boundaries / conduct the land swap (base is 12 months – see flow chart). Discrete distribution for delay to Activity 7b: a. 35% chance of 0 delay b. 30% chance of +12 months c. 25% chance of +24 d. 10% chance of +36 2. Delay in reaching agreement / completing negotiation on the parcel to be exchanged. 40% chance of 4 month delay to Activity 7c. 3. WSDOT pays for USFW’s NEPA process. Included in base cost (even though separate from project environmental doc). Minor risk. 4. Acquire more than needed now for future use. Included in other ROW risk.				
Minor	**ROW from Port of Walla Walla** (south of US-XX for SR-YY IC and for J Road extension) Base assumes the Port will donate needed ROW (for Jantz and frontage roads) so that the Port can develop surrounding land after WSDOT builds roadway. WSDOT won’t build roads if Port doesn’t donate. Roads owned by Port who will transfer to county. Minimal risk to project.				

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
N/A	**Potential reverse condemnation for two gas stations at H Road** H Road is being re-aligned as it crosses over US XX to avoid having to take the two gas stations. However, loss of direct access to US XX might adversely impact the stations' business, resulting in litigation – costs associated with such litigation do not come from project budget. Hence, no cost risk. Potential delay issues are captured under separate risk to environmental documentation.				
-	**Uncertainty in main H Road ROW (T-shaped parcel)** *In addition to base uncertainty shown in Appendix A.* *Captured in risk E2*.				
R2	**Opportunity to swap land with USACE at Hood Park** (base = $100k)	6	75%	-0.1	0
N/A	**Opportunity to sell surplus land** However, any proceeds do not go back to project. Hence, not an opportunity to this project.				
Minor	**Other ROW uncertainty**				

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
Scope Changes (not captured separately)					
S1	**Gateway enhancement at SR-YY and other aesthetic treatments**	15 75%	0.2	(about 1%)	Minor
S2	**Pedestrian path improvements** Base includes only sidewalk connection between just north of roundabout to tie-in with J Road. But no formal connection with existing pedestrian path that crosses under US-XX at Snake River.	15	50%	0.1	Minor
Minor	**Additional ramp length** (included elsewhere or minor)				
Utilities					
-	**Relocation of High-Power Lines at H Road** Base assumes that WSDOT will not have to pay to relocate, but might have to. Included in U2.				
U1	**Encounter unknown utilities and/or damage existing utilities during construction, or have to pay for utility relocation** Relocation (base = $70k): OH high power lines	14	20%	0.2	Minor

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
	Gas line at SR-YY Irrigation system at H Road				
U2	**Planned utility relocations not completed on time**	14	20%	Minor	1
Minor and Unidentified Risks and Opportunities Aggregate effect of items labeled "Minor" above. "Major" means the items quantified above (i.e., all items other than those labeled "Minor" above)					
	Aggregate Minor Risks	Independently to all	50%	20% of sum of "major" risks to activity	20% of aggregate "major" risks to activity
	Aggregate Minor Opportunities	Independently to all	50%	20% of sum of "major" opportunities to activity	20% of aggregate "major" opportunities to activity
	Unidentified Risks	Independently to all	50%	20% of sum of "major" risks to activity	20% of aggregate "major" risks to activity

Item	Risk or Opportunity	Affected Project Activities	Probability of Occurrence	Cost Change (current $M)	Duration Change (months)
	Unidentified Opportunities	Independently to all	50%	20% of sum of "major" opportunities to activity	20% of aggregate "major" opportunities to activity

Notes:

1. All cost impacts are assessed in current terms. Cost escalation is handled automatically through the simulation model.

2. Except for "soft cost" uncertainties that are addressed separately, and unless noted otherwise, all cost impacts in this table are "fully loaded" with appropriate markups. Potential markups include items that may be treated as a percentage of the construction subtotal in the cost estimate, such as sales tax, mobilization, construction engineering, design, and allowances for miscellaneous items.

Bibliography

Abourizk, S. M., and Sawhney, A. (1993). "Subjective and Interactive Duration Estimation." *Canadian Journal Of Civil Engineering*, 20(3), 457-470.

Akintoye, A. S., and MacLeod, M. J. (1997). "Risk analysis and management in construction." *International Journal of Project Management*, 15(1), 31-38.

Al-Momani, A. (2000). "Construction Delay: a quantitative analysis." *International Journal of Project Management*, 18(1).

Attoh-Okine, N. O. (2002). "Probabilistic analysis of factors affecting highway construction costs: a belief network approach." *Canadian Journal of Civil Engineering*, 29(3), 369-374.

Back, W. E., Boles, W. W., and Fry, G. T. (2000). "Defining triangular probability distributions from historical cost data." *Journal of Construction Engineering and Management-ASCE,*, 126(1), 29-37.

Barraza, G. A., Back, W. E., and Mata, F. (2000). "Probabilistic monitoring of project performance using SS-curves." *Journal of Construction Engineering and Management-ASCE,*, 126(2), 142-148.

Barraza, G. A., Back, W. E., and Mata, F. (2004). "Probabilistic forecasting of project performance using stochastic S curves." *Journal of Construction Engineering and Management-ASCE,*, 130(1), 25-32.

Bedford, T., and Cooke, R. M. (2001). *Probabilistic risk analysis: foundations and methods*, Cambridge University Press, Cambridge, UK; New York, NY.

Beeston, D. (1986). "Combining risks in estimating." *Construction Management and Economics*, 4, 75-79.

Bhola, B., and Cooke, R. M. (1992). "Expert opinion in project management." *European Journal of Operational Research*, 57, 24-31.

Bier, V. (2004). "Implications of the research on expert overconfidence and dependence." *Reliability Engineering and System Safety*, 85, 312-329.

Birnie, J., and Yates, A. (1991). "Cost prediction using decision/risk analysis." *Construction Management and Economics*, 9, 171-186.

Book, S. A. (2006). ""Earned Schedule" and Its Possible Unrealiability." The Measurable News.

Bury, K. V. (1975). *Statistical models in applied science*, Wiley, New York.

Chapman, C. B., and Ward, S. (2003). *Project risk management: processes, techniques, and insights*, Wiley, Hoboken, NJ.

Chapman, R. J. (2001). "The controlling influences on effective risk identification and assessment for construction design management." 19(3), 147-160.

Charniak, E. (1991). "Bayesian Networks without Tears." AI Magazine, 50-63.

Chau, K. W. (1995a). "Monte Carlo simulation of construction costs using subjective data." *Construction Management and Economics*, 13(5), 369-383.

Chau, K. W. (1995b). "The validity of the triangular distribution assumption in Monte Carlo simulation of construction costs: empirical evidence from Hong Kong." *Construction Management and Economics*, 13, 15-21.

Chung, T. H., Mohamed, Y., and AbouRizk, S. (2006). "Bayesian Updating Application into Simulation in the North Edmonton Sanitary Trunk Tunnel Project." *Journal of Construction Engineering and Management*, 132(8), 882-894.

Clemen, R. T. (1987). "Combining Overlapping Information." *Management Science*, 33(3), 373-380.

Clemen, R. T., Reilly, T., and Clemen, R. T. (2001). "Making hard decisions with DecisionTools." Duxbury/Thomson Learning, Pacific Grove, CA.

Clemen, R. T., and Winkler, R. L. (1999). "Combining Probability Distributions From Experts in Risk Analysis." *Risk Analysis*, 19(2).

Cooke, R. M. (1991). *Experts in uncertainty: opinion and subjective probability in science*, Oxford University Press, New York.

Cooper, D. F., and Broadleaf Capital International. (2005). *Project risk management guidelines: managing risk in large projects and complex procurements,* J. Wiley, West Sussex, England; Hoboken, NJ.

Cooper, K. Q., and PA Consulting Group. (2004). "Toward a Unifying Theory for Compounding and Cumulative Impacts of Project Risks and Changes." PMI Research Conference, London, UK.

Cowell, R. G. (1999). *Probabilistic networks and expert systems*, Springer, New York.

DeGroot, M. H., and Mortera, J. (1991). "Optimal Linear Opinion Pools." *Management Science,* 37(5), 546-558.

Diaz, C. F., and Hadipriono, F. C. (1993). "Nondeterministic Networking Methods." *Journal of Construction Engineering and Management-ASCE,*, 119(1), 40-57.

Diekmann, J. E., and Featherman, W. D. (1998). "Assessing cost uncertainty: Lessons from environmental restoration projects." *Journal of Construction Engineering and Management-ASCE,*, 124(6), 445-451.

Elkjaer, M. (2000). "Stochastic budget simulation." *International Journal of Project Management*, 18(2), 139-147.

Eyers, K. (2001). "Belief network analysis of direct cost risk in building construction," University of Toronto, Toronto.

Fan, C. F., and Yu, Y. C. (2004). "BBN-based software project risk management." *Journal of Systems and Software*, 73(2), 193-203.

Fellows, R. (1996). "Monte Carlo simulation of construction costs using subjective data: comment." *Construction Management and Economics*, 14, 457-460.

Fente, J., Schexnayder, C., and Knutson, K. (2000). "Defining a probability distribution function for construction simulation." *Journal of Construction Engineering and Management-ASCE,*, 126(3), 234-241.

Flanagan, R., and Norman, G. (1993). *Risk management and construction*, Blackwell Scientific, Oxford; Boston.

Fleming, Q. W. (1988). *Cost/schedule control systems criteria: the management guide to C/SCSC*, Probus Pub. Co., Chicago, Ill.

Fleming, Q. W., and Koppelman, J. M. (2005). *Earned value project management*, Project Management Institute, Newtown Square, PA.

Flyvbjerg, B., Holm, M. K. S., and Buhl, S. L. (2003). "How common and how large are cost overruns in transport infrastructure projects?" *Transport Reviews*, 23(1), 71 - 88.

French, S. (1981). " Consensus of opinion." *European Journal of Operational Research*, 7, 332–340.

Garey, M. R., and Johnson, D. S. (1979). *Computers and Intractability: A Guide to the Theory of NP-Completeness*.

Genest, C., and Zidek, J. V. (1986). "Combining probability distributions. A Critique and annotated bibliography." *Statistical Science*, 1, 114-148.

Gido, J., and Clements, J. P. (1999). *Successful project management*, South-Western College Pub., Cincinnati.

Goossens, L. H. J., Cooke, R. M., and Kraan, B. C. P. (1998). "Evaluation Of Weighting Schemes For Expert Judgment Studies." *PSAM 4 Proceedings*, 1937-1942.

Hartford, D., and Baecher, G. (2004). *Risk and Uncertainty in Dam Safety,* Thomas Telford Ltd.

Hegazy, T. (2002). *Computer-based construction project management*, Prentice Hall, Upper Saddle River, N.J.

Henderson, K. (2003). "Earned Schedule: A Breakthrough Extension to Earned Value Theory? A Retrospective Analysis of Real Project Data." The Measurable News.

Henderson, K. (2004). "Further Developments in Earned Schedule." The Measurable News.

Henderson, K. (2005). "Earned Schedule in Action." The Measurable News.

Hillson, D. "Use a Risk Breakdown Structure (RBS) to Understand Your Risks." *Project Management Institute Annual Seminars & Symposium,* San Antonio,Texas,USA.

Hillson, D. "Earned Value Management & Risk Management: A practical synergy." *PMI Global Congress 2004 North America*, Anaheim USA.

Hulett, D. (2004). "Quantitative Risk Analysis Fundamentals." D. A. University, ed., Acquisition Community Connection.

Hulett, D. T. (1996). "Schedule Risk Analysis Simplified." *PM Network*, 23-30.

Hullet, D. T. (2002). "Integrated Cost and Schedule Project Risk Analysis."

Isidore, L. J., and Back, W. E. (2002). "Multiple simulation analysis for probabilistic cost and schedule integration." *Journal of Construction Engineering and Management-ASCE,*, 128(3), 211-219.

Isidore, L. J., Back, W. E., and Fry, G. T. (2001). "Integrated probabilistic schedules and estimates from project simulated data." *Construction Management and Economics*, 19, 417 - 426.

Jensen, F. V. (2001). *Bayesian networks and decision graphs*, Springer, New York.

Jouini, M. N., and Clemen, R. T. (1996). "Copula Models for Aggregating Expert Opinions." *Operations Research*, 44(3), 444-457.

Kahn, J. M. "A generative Bayesian model for aggregating experts' probabilities." *Proceedings of the 20th conference on Uncertainty in artificial intelligence table of contents*, Banff, Canada, 301-308.

Kahneman, D., Slovic, P., and Tversky, A. (1982). *Judgment under uncertainty: heuristics and biases*, Cambridge University Press, Cambridge; New York.

Kallen, M. J., and Cooke, R. M. (2002). "Expert aggregation with dependence." *Probabilistic Safety Assessment and Management*, 1287-1294.

Kamburowski, J. (1997). "New validations of PERT times." *Omega-International Journal Of Management Science*, 25(3), 323-328.

Lau, H. S., and Somarajan, C. (1995). "A Proposal On Improved Procedures For Estimating Task-Time Distributions In Pert." *European Journal Of Operational Research*, 85(1), 39-52.

Laufer, A. (1997). *Simultaneous management: managing projects in a dynamic environment*, AMACOM, New York.

Lee, D. E. (2005). "Probability of project completion using stochastic project scheduling simulation." *Journal of Construction Engineering and Management-ASCE,*, 131(3), 310-318.

Lichtenstein, S., Fischhoff, B., and Phillips, L. (1982). *Calibration of probabilities: the state of the art to 1980. In: Kahneman D, Slovic P, Tversky A, editors. Judgment under uncertainty: heuristics and biases.*

Linstone, H. A., and Turoff, M. (1975). *The Delphi method: techniques and applications*, Addison-Wesley Pub. Co. Advanced Book Program, Reading, Mass.

Lipke, W. (2003). "Schedule is Different." The Measurable News, 31-34.

Lipke, W. (2004). "Connecting Earned Value to the Schedule." The Measurable News.

Maio, C., Schexnayder, C., Knutson, K., and Weber, S. (2000). "Probability distribution functions for construction simulation." *Journal Of Construction Engineering And Management-ASCE,*, 126(4), 285-292.

Mak, S., and Picken, D. (2000). "Using risk analysis to determine construction project contingencies." *Journal of Construction Engineering and Management-ASCE,*, 126(2), 130-136.

Mak, S., and Raftery, J. (1992). "Risk attitude and systematic bias in estimating and forecasting." *Construction Management and Economics*, 10, 303-320.

Malcolm, D. G., Roseboom, J. H., Clark, C. E., and Fazar, W. (1959). "Application of technique for research and development program evaluation (PERT)." *Operations Research*, 7(5), 646-669.

McCabe, B., AbouRizk, S. M., and Goebel, R. (1998). "Belief networks for construction performance diagnostics." *Journal of Computing in Civil Engineering*, 12(2), 93-100.

McCabe, B., and Ford, D. "Using Belief Networks to Assess Risk." *Winter Simulation Conference*.

Mendel, M., and Sheridan, T. (1989). "Filtering Information from Human Experts." *IEEE Transactions on Systems, Man & Cybernetics*, 36, 6-16.

Meyer, M., and Booker, J. (2001). *Eliciting and analyzing expert judgment: a practical guide*, Society for Industrial and Applied Mathematics, Philadelphia.

Microsoft Corporation. (2001). "MSBNx: A Component-Centric Toolkit for Modeling and Inference with Bayesian Networks." Microsoft Research.

Microsoft Corporation. (2003). "Microsoft Office Professional Edition".

Moder, J. J., Phillips, C. R., and Davis, E. W. (1983). *Project management with CPM, PERT, and precedence diagramming*, Van Nostrand Reinhold, New York.

Morris, P. A. (1974). "DECISION ANALYSIS EXPERT USE." *Management Science*, 20(9).

Morris, P. A. (1977). "Combining Expert Judgments: A Bayesian Approach." *Management Science*, 23(7), 679.

Morris, P. A. (1983). "An axiomatic approach to expert resolution." *Management Science*, 29(24-32).

Mosleh, A., and Apostolakis. (1986). "The assessment of probability distributions from expert opinions with an application to seismic fragility curves." *Risk Analysis*, 6(4), 447-461.

Mosleh, A., Bier, V. M., and Apostolakis, G. (1988). "A Critique of Current Practice for the Use of Expert Opinions in Probabilistic Risk Assessment." *Reliability Engineering and System Safety*, 20, 63-85.

Nasir, D., McCabe, B., and Hartono, L. (2003). "Evaluating risk in construction-schedule model (ERIC-S): Construction schedule risk model." *Journal of Construction Engineering and Management-ASCE,*, 129(5), 518-527.

Newton, S. (1992). "Methods of analysing risk exposure in the cost of estimates of high quality offices." *Construction Management and Economics*, 431-449.

NRC U.S. Nuclear Regulatory Commission. (1989). "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants."

Oberlender, G. D. (2000). *Project management for engineering and construction*, McGraw-Hill, Boston.

Ouchi, F., and World Bank. (2004). *A literature review on the use of expert opinion in probabilistic risk analysis*, World Bank, Washington, D.C.

Palisade Corporation. (2004). "@RISK Risk Analysis Add-in for Microsoft Excel."

Pearl, J. (1988). *Probabilistic reasoning in intelligent systems: networks of plausible inference*, Morgan Kaufmann Publishers, San Mateo, Calif.

Pollack-Johnson, B., and Liberatore, M. J. (2005). "Project Planning Under Uncertainty Using Scenario Analysis." *Project Management Journal*, 36(1), 15-26.

Pontrandolfo, P. (2000). "Project duration in stochastic networks by the PERT-path technique." *International Journal of Project Management*, 18(3), 215-222.

Primavera Systems Inc. (2005). "Primavera Project Management 5.0"

Project Management Institute. (2004). *A guide to the project management body of knowledge: PMBOK guide*, Project Management Institute Inc., Newtown Square, PA.

Pulkkinen, U. (1993). "Methods for combination of expert judgments." *Reliability Engineering and System Safety*, 40(2), 111-118.

Pulkkinen, U. (1994). "Bayesian analysis of consistent paired comparisons." *Reliability Engineering and System Safety*, 43(1), 1-16.

Raftery, J. (1994). *Risk analysis in project management*, E & FN Spon, London; New York.

Raiffa, H. (1993). "Decision-Analysis - Introductory Lectures on Choices under Uncertainty (Reprinted from Decision-Analysis Introductory Lectures on Choices under Uncertainty, Pg 1-38)." *M D Computing*, 10(5), 312-328.

Ranasinghe, M. (1994a). "Contingencency allocation and management for building projects." *Construction Management and Economics*, 12, 223-243.

Ranasinghe, M. (1994b). "Quantification and management of uncertainty in activity duration networks." *Construction Management and Economics*, 12, 15-29.

Ranasinghe, M. (2000). "Impact of correlation and induced correlation on the estimation of project cost of buildings." *Construction Management and Economics*, 18(4), 395-406.

Ranasinghe, M., and Russell, A. D. (1992a). "Analytical approach for economic risk quantification of large engineering projects: validation." *Construction Management and Economics*, 10, 45-68.

Ranasinghe, M., and Russell, A. D. (1992b). "Treatment of correlation for risk analysis of engineering projects." *Journal of Civil Engineering Systems*, 9, 17-39.

Ranasinghe, M., and Russell, A. D. (1993). "Elicitation of subjective probabilities for economic risk analysis: an investigation." *Construction Management and Economics*, 11(5), 326-340.

Rao, G., and Grobler, F. P. "Integrated analyses of cost risk and schedule risk." *2nd Congress in Computers in Civil Engineering*, New York, 1404–1411.

Raz, T., and Michael, E. (2001). "Use and benefits of tools for project risk management." *International Journal of Project Management*, 19(1), 9 - 17.

Raz, T., Shenhar, A. J., and Dvir, D. (2002). "Risk management, project success, and technological uncertainty." *R & D Management*, 32(2), 101-109.

Roberds, W. J., and McGrath, T. C. "Qualitative Cost and Schedule Risk Assessment and Risk Management for Large Infrastructure Projects." *3rd Annual Conference of the PMI College of Scheduling*, Orlando, FL USA.

Ross, S. M. (2002). *Simulation*, Academic Press, San Diego.

Russell, S. J., and Norvig, P. (2003). *Artificial intelligence: a modern approach*, Prentice Hall/Pearson Education, Upper Saddle River, N.J.

Schexnayder, C., Knutson, K., and Fente, J. (2005). "Describing a beta probability distribution function for construction simulation." *Journal of Construction Engineering and Management-ASCE,*, 131(2), 221-229.

Sha'ath, K. K., and Singh, G. "A PC-Based Stochastic Project Scheduling and Costing Module." *Computing in Civil Engineering*, Washington, D.C., 9-16.

Smith, P. G., and Merritt, G. M. (2002). *Proactive risk management: controlling uncertainty in product development*, Productivity Press, New York.

Standish-Group. (1995). "The CHAOS Report."

Tah, J. H. M., and Carr, V. (2001). "Knowledge-based approach to construction project risk management." *Journal of Computing in Civil Engineering*, 15(3), 170-177.

Tah, J. H. M., Thorpe, A., and McCaffer, R. (1993). "Contractor project risks contingency allocation using linguistic approximation." 4(2-3), 281-293.

Terrell, D. (1998). "Biases in assessments of probabilities: New evidence from greyhound races." *Journal of Risk and Uncertainty*, 17(2), 151-166.

Touran, A. (1993). "Probabilistic Cost Estimating with Subjective Correlations." *Journal of Construction Engineering and Management-ASCE,*, 119(1), 58-71.

Touran, A. (1997). "Probabilistic model for tunneling project using Markov chain." *Journal of Construction Engineering and Management-ASCE,*, 123(4), 444-449.

Touran, A. (2003a). "Calculation of contingency in construction projects." *IEEE Transactions on Engineering Management*, 50(2), 135-140.

Touran, A. (2003b). "Probabilistic model for cost contingency." *Journal of Construction Engineering and Management-ASCE,*, 129(3), 280-284.

Touran, A., and Suphot, L. (1997). "Rank correlations in simulating construction costs." *Journal of Construction Engineering and Management-ASCE,*, 123(3), 297-301.

Touran, A., and Wiser, E. P. (1992). "Monte-Carlo Technique with Correlated Random-Variables." *Journal of Construction Engineering and Management-ASCE*, 118(2), 258-272.

US Department of Defense. (1967). "DODI 7000.2 Performance Measurement for Selected Applications."

van Dorp, J. R. (2004). "Statistical dependence through common risk factors: With applications in uncertainty analysis." *European Journal of Operational Research*, 161(1), 240-255.

van Dorp, J. R., and Duffey, M. R. (1999). "Statistical dependence in risk analysis for project networks using Monte Carlo methods." *International Journal of Production Economics*, 58(1), 17-29.

Vick, S. G. (2002). *Degrees of Belief: Subjective Probability and Engineering Judgment*, ASCE American Society of Civil Engineers.

Vose, D. (2000). *Risk analysis: a quantitative guide*, Wiley, Chichester; New York.

Wall, D. M. (1997). "Distributions and correlations in Monte Carlo simulation." *Construction Management and Economics*, 15(3), 241 - 258.

Wang, W. C. (2002). "SIM-UTILITY: Model for project ceiling price determination." *Journal of Construction Engineering and Management-ASCE,*, 128(1), 76-84.

Wang, W. C., and Demsetz, L. A. (2000a). "Application example for evaluating networks considering correlation." *Journal of Construction Engineering and Management-ASCE,*, 126(6), 467-474.

Wang, W. C., and Demsetz, L. A. (2000b). "Model for evaluating networks under correlated uncertainty - NETCOR." *Journal of Construction Engineering and Management-ASCE,*, 126(6), 458-466.

Webb, A. (2003). *Using earned value: a project manager's guide*, Gower, Aldershot, Hants, England; Burlington, VT.

Wilson, J. R., Vaughan, D. K., Naylor, E., and Voss, R. G. (1982). "Analysis of Space-Shuttle Ground Operations." *Simulation*, 38(6), 187-203.

Winkler, R. L. (1968). "The consensus of subjective probability distributions." *Management Science*, 15, 553 –567.

Winkler, R. L. (1981). "Combining Probability Distributions From Dependent Information Sources." *Management Science*, 27(4), 479-488.

Wiper, M. P., French, S., and Cooke, R. M. (1994). "Hypothesis-Based Calibration Scores." *The Statistician*, 43(2), 231-236.

World-Bank. (1984). "Tenth annual review of project performance audit results." Operations Evaluation Dept., Washington, D.C.

Worsham, J. P. (1980). *Application of the Delphi method: a selected bibliography*, Vance Bibliographies, Monticello, Ill.

WSDOT (2005). "CEVP® and Cost Risk Assessment (CRA)."

Yang, I. T. (2005). "Simulation-based estimation for correlated cost elements." *International Journal of Project Management*, 23(4), 275-282.

Zhang, Q. (1989). "A General-Method Dealing with Correlations in Uncertainty Propagation in Fault-Trees." *Reliability Engineering & System Safety*, 26(3), 231-247.