A Bayesian Model for Controlling Cost Overrun in a Portfolio of Construction Projects

A Dissertation Presented

by

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ABSTRACT

Planning and executing a successful capital project is one of the main objectives of every public agency. A successful capital project is defined as a project completed in accordance with a given scope, within budget, and on time. Due to risks associated with complex projects, an owner agency usually adds an amount known as contingency to the estimated project cost to absorb the monetary impact of the risks and to prevent cost overrun. However, studies show that large capital infrastructure projects, especially transit projects all around the globe have been mostly experiencing cost and schedule overruns. Despite all efforts and evolving new probabilistic methods to establish sufficient and optimum contingency budget, many agencies have not been able to provide adequate contingency for their large capital projects. For instance, nearly 50% of the large active transportation projects in the United States overran their initial budgets. Some agencies have reacted to this issue by employing approaches that result in too large a contingency budget. Having too much contingency can be just as undesirable as insufficient contingency, especially where the agency is dealing with a portfolio of projects rather than a single project. Assigning large contingencies will use up the agency's budget and will reduce the number of projects that may receive funding.

In this research, a new probabilistic model is proposed for calculation of contingency in a portfolio of construction projects. A Bayesian approach is used to update historical contingency values based on new project data that becomes available as construction projects are completed. Most agencies dealing with a portfolio of infrastructure projects should define the level of confidence γ for the portfolio budget based on available funding and the agency's policy goals. An important question is what level of confidence η is needed

at the individual project level to insure that the portfolio budget will not overrun with a probability of more than $1-\gamma$. This information is indispensable for the conduct of probabilistic risk assessment for individual projects.

The mathematical model developed in this research provides an analytical tool for calculating contingency levels in such a way to meet agency goals with respect to individual projects and the project portfolio. The model assumes a hybrid normal distribution for the cost of individual projects and uses the historical data to calculate the primary parameters of the model. The model defines the required confidence level for the risk assessment of individual project with respect to the desired confidence level for sufficiency of the portfolio budget. The required increase in the portfolio budget is calculated based on the desired confidence level. The correlation between costs of projects is recognized and a structured guideline along with a mathematical method is suggested for estimating correlation coefficients between costs of projects in the portfolio. To consider the recent performance of projects and to update model characteristics based on new project data that becomes available, a Bayesian approach is employed to update the model on regular intervals, such as once every two years. As more information becomes available, the required adjustment in portfolio budget will be reduced, because the accuracy of estimating the contingency is improved. The proposed model is an effective tool for the agencies to develop contingency budgets based on all the performance data historically available and the new data that becomes available in the future. Even though the proposed model is a generic model that can be used on any type of infrastructure projects, our emphasis in this research is mostly on transit projects. Because of this, the funding process for the Federal Transit Administration (FTA) is analyzed and the practical application of the model is based on transit projects' characteristics and costs.

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CHAPTER 1: INTRODUCTION

1.1   Overview

Risks and uncertainties associated with a project are impediments to reach an accurate cost estimate. Nearly 50% of the large active transportation projects in the United States overran their initial budgets (Sinnette 2004). To overcome the cost overrun issue, identifying project risk factors and cost escalation factors have been the subject of much research (Shane *et al* 2009; Flyvbjerg *et al* 2003; Pickrell 1990). For instance, Shane *et al* (2009) identified 14 risk factors classified in two categories: (1) Internal Sources such as bias, poor estimating, and contract document conflicts; (2) External Sources such as effects of inflation, market conditions, and unforeseen events/ conditions. To absorb the cost impact of these risk factors, a contingency budget is added to the total project budget. Contingency is defined as a reserve budget for coping with risks and uncertainties and to help keep the projects on budget. Contingency is traditionally estimated as a predetermined percentage of project base cost depending on the project phase. In recent years, some agencies have started conducting formal probabilistic risk assessment to estimate contingency budget rather than deterministic approach (Touran 2010; Molenaar 2005). However, to establish the contingency budget, an agency must make all efforts to set aside a budget which is optimized. This becomes more important when an agency is dealing with a portfolio of projects. Allocation of an excess budget for a project will use up the money that can be spent on other projects. For instance

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the current approach used by the U.S. Federal Transit Administration (FTA) to estimate the contingency budget in transit projects called Top-down Model is based upon a probabilistic method using lognormal distributions for different cost categories in the project. Our research shows the way that cost categories are ranged is very conservative resulting in a contingency budget far larger than what might be indeed needed (Bakhshi and Touran 2009).

1.2   Problem Identification

Planning and executing a successful capital project is one of the main objectives of every public agency. A successful capital project is defined as a project completed in accordance with a given scope, within budget, and on time. Cost overrun in capital projects can jeopardize project success and viability. It also redefines those projects that initially were promoted as effective vehicles to economic growth as possible impediments to such growth (Flyvbjerg *et al* 2003). Therefore, it is essential for agencies to keep their projects within budget if they want to ensure the successful completion of projects. Despite all claims regarding improved models, budget estimating for most capital projects especially transit projects have been constantly inaccurate for several decades (Touran 2010; Flyvbjerg 2006). To demonstrate this, we can refer to some research in which the transit projects have been studied:

1. Pickrell (1990): 9 out of 10 reviewed transit projects sponsored by the Federal Transit Administration (FTA) of the U.S. Department of Transportation (DOT) experienced cost overrun with the average of 50.06% from their cost estimate at the Alternative Analysis/Draft Environmental Impact Study (AA/DEIS);

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2. Flyvbjerg (2002): Flyvbjerg considered a sample of 258 transportation projects such as rail, fixed-link (tunnel and bridge), and road all around the world. On average, cost overrun occurred in 9 out of 10 projects. The average of cost overrun was 27.6% from the time that the project was approved for execution to the completion. Among them, 58 rail projects experienced the highest average of cost overrun of 44.7%;

3. FTA (2003c): 21 transit projects completed between 1990 and 2002 in the U.S. were reviewed in which 16 projects had cost overrun. On average, the sample of 21 projects showed 20.9% cost overrun compared with inflation-adjusted cost estimate at the AA/DEIS;

4. Booz.Allen.Hamilton (2005): They reviewed 28 transit projects in the U.S. They found that 26 out of 28 projects experienced cost overrun from the cost estimate at the AA/DEIS with the average of 36.3%;

5. FTA (2008): Another 21 transit projects completed between 2003 and 2007 in the U.S. were reviewed. For 17 of them, the inflation-adjusted costs at the AA/DEIS were reported. All 17 projects experienced cost overrun with the average of 40.2% higher cost compared to their inflation-adjusted costs at the AA/DEIS.

It should be mentioned that the Pickrell (1990), FTA (2003c), and FTA (2008) are three consecutive studies in which there is no repetitive project. Numerous observed cost overruns in capital projects suggest a need for developing an effective method for cost estimating and contingency allocation to control and prevent over budgeting issue. As it was mentioned earlier, this issue becomes even more important when an agency is dealing with a portfolio of projects where the cost overrun of one project can jeopardize the successful completion of other projects in the portfolio. In the context of this research, a portfolio of

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projects is a capital program consisting of several projects where the contingency is being established at the program level.

1.3   Research Objectives

In this research, the objective is to develop a new probabilistic model to effectively plan for projects' cost overruns in a portfolio with allocation of sufficient and optimized contingency budget while it has the potential to be updated. To this end, there have been three main objectives:

1. Calculating the required cost increase in the portfolio based on historical performance data;
2. Estimating the pairwise correlation coefficient between costs of projects in the portfolio using a proposed structured guideline and/or a mathematical method;
3. Updating the model using a Bayesian approach considering the performance of recently completed projects.

The proposed model is a significant improvement over the state of art in research at this point. Also, it is expected that after each time that the model is updated, the required increase (or decrease) in portfolio budget will be reduced, because the accuracy of estimating the contingency is improved.

1.4   Organization of the Dissertation

This dissertation is comprised of eight chapters and two appendices as follows.

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Chapter 1 introduces the scope of work and the objectives of this research. The synopses of all chapters are presented here.

Chapter 2 focuses on contingency definition and calculation. An extensive literature search was conducted and relevant information and data were collected. Contingency definition by different agencies is presented and discussed. An exhaustive list of common methods for calculating contingency budget is prepared and the methods are explained in detail. The methods are categorized in three main categories of: (1) Deterministic, (2) probabilistic, and (3) modern mathematical methods. At the end, the methods are compared and advantages and disadvantages of these methods are enumerated.

In *Chapter 3*, the regulatory characteristics of *New Starts* transit projects and their planning and budget development process are concisely discussed. The problem and issues in their cost estimating process such as escalation and contingency allocation are explained in more detail. This will help in setting the stage for developing a probabilistic approach for determining the required contingency for future projects.

In *Chapter 4*, the current budget estimating process to allocate contingency for transit projects in the U.S. and the U.K. are explained. Methods of contingency calculation and allocation in the U.S. and the U.K., known respectively as *Top-down* and the *Optimism Bias Uplifts*, are critically compared. Both methods are applied to the U.S. transit projects data and the results are discussed. The advantages and disadvantages of the two methods are highlighted. It is concluded that these methods do not provide an effective and optimum model for calculating the required contingency budget. The results also highlight the fact that developing a new method for calculating and allocating contingency budget is necessary and long overdue.

Chapter 5 describes the new probabilistic model proposed in this dissertation for contingency calculation in a portfolio of projects. This analytical method is developed using available historical data and assumes a hybrid normal distribution for cost of each project in the portfolio. This model can be applied to any set of projects that an agency desires to fund. It calculates the required increase in the budget in order to have a certain confidence for budget sufficiency. The model also can help the agency define the required level of confidence needed for risk assessment of individual projects with respect to the level of confidence associated with the portfolio budget. Then, a Bayesian approach for both independent and correlated cases is introduced to update the model in a specified time interval (for example, every two years) depending on the number of newly completed projects.

In *Chapter 6*, we first explain the common correlation coefficients used in construction industry such as Pearson and Spearman's Rank coefficients. Since in the proposed model we recognize the correlation between costs of projects, estimation of the pairwise correlation between costs of projects is required. Despite an intensive literature search, no previous work for estimating correlation between costs of projects where there is no historical data available was found; however, there were suggestions for subjectively estimating correlation coefficient between cost components in a project or activity durations (Cho 2006; Wang 2000; Touran 1993). We propose a systematic guideline for eliciting the correlation coefficient between costs of projects. To this end, a list of common risk factors that can affect any pair of projects are identified among cost risk factors presented in the literature. This list works as a baseline to qualitatively estimate the correlation using a set of suggested guidelines and thresholds. The proposed method is called *proposed structured guideline.*

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Furthermore, in Appendix B, a mathematical method is proposed for calculation of correlation coefficient where risk registers are available for projects.

Chapter 7 is dedicated to the application of the proposed model and verification of its effectiveness. To accomplish this, 31 transit projects constructed in the U.S. and sponsored by the Federal Transit Administration (FTA) are selected. These projects are divided into three different datasets: (1) Historical Dataset consisting of 22 projects completed prior to 2004, (2) First Dataset consisting of 5 projects completed in 2004, and (3) Second Dataset consisting of 4 projects completed in 2005 and 2006. Historical Dataset is used for initiating the model and calculating the primary parameters. To apply the model and realize the importance of accommodating the correlation, we consider two approaches. We first assume that projects in each dataset are statistically independent. In the second approach, the correlation among project costs is explicitly considered. Therefore, we recognize the correlation among projects in each dataset. Correlation coefficients between costs of projects in the datasets are estimated using the proposed structured guideline described in Chapter 6.

Chapter 8 is the conclusion chapter. It summarizes the findings of the research and makes specific recommendation for future research.

Appendix A lists the references used in this dissertation.

Appendix B proposes a mathematical method for calculating the pairwise correlation coefficient between costs of projects. This method is developed on the premise of breaking down the total project cost to a deterministic base cost plus a probabilistic contingency (sum of monetary impacts of risk factors). It uses the common risk factors between any pair of projects to calculate a pairwise correlation coefficient between costs of projects. A numerical

example using two hypothetical transit projects along with their risk registers is provided to illustrate the use of the proposed method.

CHAPTER 2: CONTINGENCY CALCULATION METHODS

2.1   Introduction

Owners usually need to have an accurate early cost estimate for their projects in order to provide sufficient budget for projects. A total cost of project is broken down to: (1) base cost, and (2) contingency cost. Base cost is the cost of project which is not including contingency (Touran 2006b). These are certain cost items of a project with a given scope necessary to physically deliver the project. Contingency is budget or time set aside to cope with uncertainties and risks during a project design and construction.

In this chapter, we first present several contingency definitions given by different agencies. Then an exhaustive list of available methods for estimating contingency budget is compiled and explained. At the end, these methods are compared.

2.2   Contingency Definitions

Project Management Institute (PMI 2004) delineates contingency as: "The amount of funds, budget or time needed above the estimate to reduce the risk of overruns of project objectives to a level acceptable to the organization." The Association for the Advancement of Cost Engineering (AACE 2010a) defines contingency as: "An amount added to an

estimate to allow for items, conditions, or events for which the state, occurrence, or effect is uncertain and that experience shows will likely result, in aggregate, in additional costs. Typically estimated using statistical analysis or judgment based on past asset or project experience." Moreover, it declares that contingency does not include costs caused by:

1. Major scope changes;
2. Extraordinary events such as major strikes and catastrophes;
3. Management reserves which is an amount added to an estimate to allow for discretionary management purposes outside of the defined scope of the project;
4. Escalation and currency effects.

Construction Industry Research & Information Association (CIRIA 1996) describes contingency as three basic types in construction projects: 1. Tolerance in the specification; 2. Float in the schedule; 3. Money in the budget. Also Schneck *et al* (2009) categorizes contingency in construction projects in: 1. Schedule contingency; and 2. Cost contingency. As is revealed by aforementioned contingency definitions, there is unanimity that contingency is considered in project management for managing risks and uncertainty associated with cost and schedule of a project. It should be noted that our focus in this research is on cost contingency. Therefore, hereafter contingency refers to cost contingency unless otherwise stated.

Since contingency is part of a project budget, this reveals the importance of estimating it as accurately as possible in the early stage of a project life. As the project progresses and the design details are decided, uncertainty associated with the project diminishes which means less contingency is required. Contingency is meant to keep the total project budget constant (Olumide *et al* 2010). In other words, by increasing the level of design and the clarity of

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scope, base cost should go up and contingency becomes less. When a project experiences cost overrun, one of the reasons could be insufficient established contingency budget to absorb cost growth (Baccarini 2006). This shows the importance of accurate contingency estimation in the early stages of project development. To establish a total project's budget, first the base cost is estimated. Then using a formal or informal risk assessment, the necessary contingency budget in accordance with the owner's (or in case of public projects, agency's) policy is added. Also, to consider the effect of inflation, market conditions, and variation in interest rate, the budget must be escalated. Escalation is usually not included in contingency (AACE 2010a; Moselhi 1997), because it is important to separate the cost of uncertainties resulting from inflation from uncertainties caused by technical difficulties, environmental issues, and administrative delays. The procedure to calculate total project cost (TPC) is depicted in the following diagram (Figure 2.1).
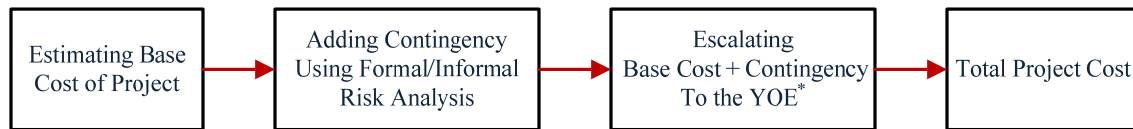
YOE: Year of Expenditure

Figure 2.1: Estimating Total Project Cost (TPC)

It should be noted that contingency can be seen from contractor's stand point and owner's stand point. Also, a close attention should be paid that project allowances are different from contingencies. Project allowances are estimates or plug numbers that estimator uses to account for project components that are hard to estimate either because the design is not complete or because based on available information an accurate estimate is not feasible (Touran 2006b). These allowances are undoubtedly part of project scope and must be incorporated in the base cost.

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2.3   Contingency Calculation Methods

As it was stated earlier, contingency is a budget for prevailing cost growth due to risks and uncertainties associated with a project. In other words, contingency is meant to offset the cost impact of uncertainties and risks that influence a project. This magnifies the importance of conducting a formal risk assessment to estimate as accurate as possible the contingency budget. Mak and Picken (2000) show the effectiveness of risk analysis to estimate contingency. They collected data on 332 building projects; among them 45 had used risk analysis. Defining a new variable DEVI, the ratio between the amount of contingency and the amount of variation at final cost, the hypothesis test that the mean of both groups were equal was rejected and they concluded that a significant improvement of resulted in contingency calculation by the use of risk analysis.

The Association for the Advancement of Cost Engineering (AACE 2008a) categorizes the methods to estimate risk cost and establish contingency in four major groups:

1. Expert judgment: An expert or a group of experts with strong experience in risk management and risk analysis define(s) the percentage of contingency for the project under consideration ;

2. Predetermined guidelines: A set of predetermined contingency values is provided for different key phases of certain project types;

3. Simulation analysis including range estimating and expected value: This method usually integrates expert judgment with an analytical model. Then a simulation process such as Monte Carlo simulation is employed to obtain probabilistic output;

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4. Parametric modeling: This method usually quantifies the amount of cost growth using risk drivers by the means of multi variable regression or artificial neural network;

Aforementioned methods will be explained in more detail in the following sections of the current chapter.

Schneck *et al* (2009) groups the methods of contingency calculation into:

1. Deterministic methods:

    1.1: An across-the-board percentage addition on the base cost estimate derived on the basis of intuition, experience, and historical data;

    1.2: Combination of line item specific contingencies with an overall unallocated contingency. The line item contingencies are based upon a combination of historical cost variance, project features, and identified risk of the project;

2. Probabilistic methods based on the statistical and probability analysis of project risk factors and estimation of project cost variance such as linear and nonlinear regression, the probability based Monte Carlo, and artificial neural network simulation.

Baccarini (2006) describes the traditional percentage as the most commonly used method in practice. He also mentions Monte Carlo simulation, regression analysis, and artificial neural networks as the methods that have gained prominence in recent times. Table 2.1 depicts several methods that Baccarini referred to in his review of the contingency concept.

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Table 2.1: Contingency Estimating Methods (Adopted from Baccarini 2006)

Contingency Estimating Methods	Reference (Example)
Traditional percentage	Ahmad 1992, Moselhi 1997
Method of Moments	Diekmann 1983; Moselhi, 1997, Yeo 1990
Monte Carlo Simulation	Lorance & Wendling 1999, Clark 2001
Factor Rating	Hackney 1985, Oberlander & Trost 2001
Individual risks – expected value	Mak, Wong & Picken 1998; 2000
Range Estimating	Curran 1989
Regression Analysis	Merrow & Yarossi 1990; Aibinu & Jagboro 2002
Artificial Neural Networks	Chen & Hartman 2000; Williams 2003
Fuzzy Sets	Paek, Lee, & Ock, 1993
Influence Diagrams	Diekmann & Featherman 1998
Theory of Constraints	Leach 2003
Analytical Hierarchy Process	Dey, Tabucanon & Ogunlana 1994

One should realize that the methods given by Baccarini in Table 2.1 are not completely different categories of models. For instance, range estimating can be categorized under Monte Carlo Simulation as it always needs random number generating for analysis. Also, artificial neural network and regression analysis are two subcategory of parametric modeling (AACE 2008a). The Methods mentioned by Baccarani (2006) will be covered in our exhaustive list of contingency estimation in the next sections.

In this research, we divide the common methods for establishing contingency budget into three main groups: 1. Deterministic methods; 2. Probabilistic methods, and 3. Modern mathematical methods. All other common methods will be explained as the subcategories of these three. Figure 2.2 depicts all common methods. These methods are described in detail in the following sections.
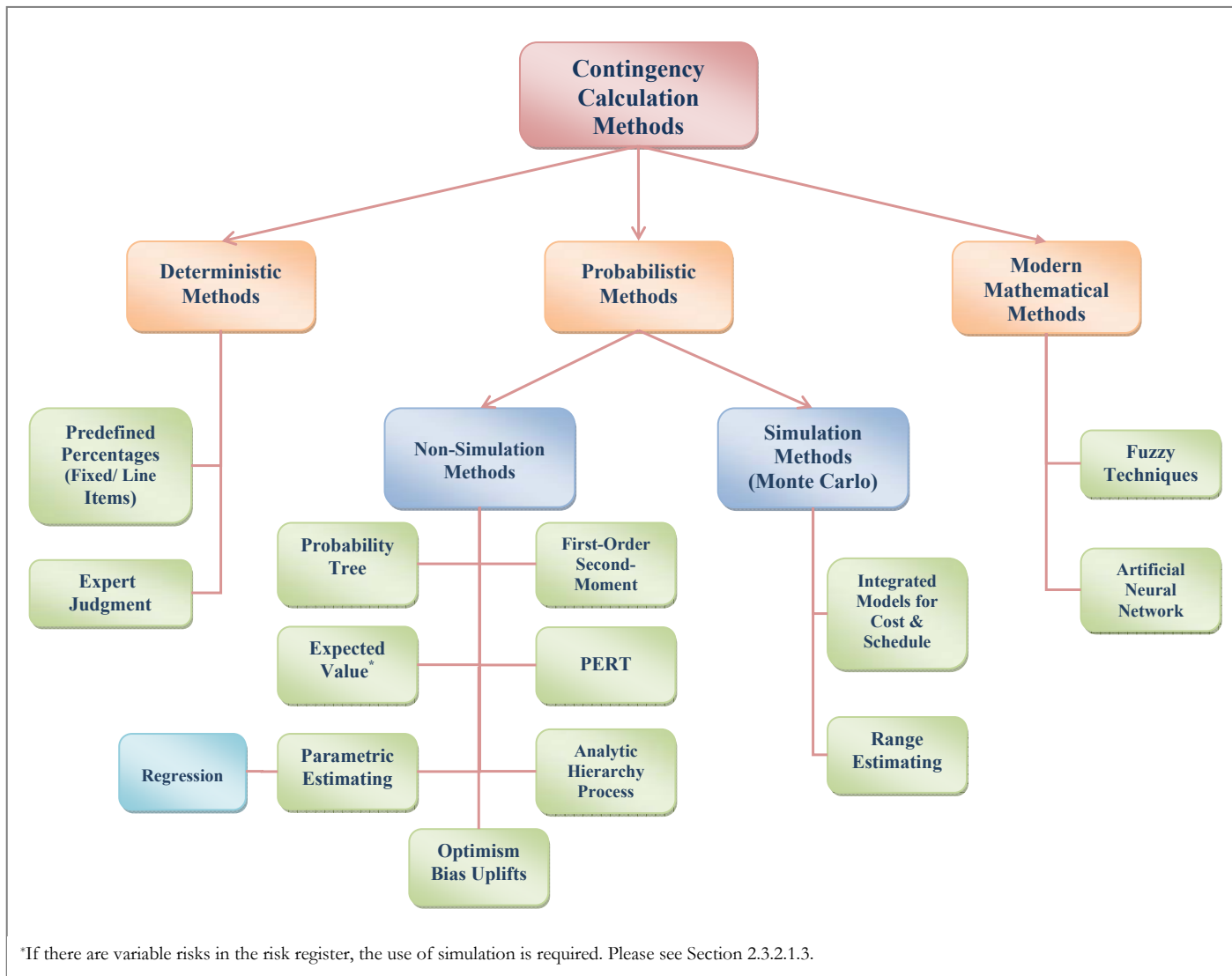
Figure 2.2: Contingency Calculation Methods

*If there are variable risks in the risk register, the use of simulation is required. Please see Section 2.3.2.1.3.

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2.3.1 Deterministic Methods

Deterministic methods are considered to be the simplest and most common methods used to establish contingency budget (AACE 2008a; Baccarini 2006; Touran 2003). These are used by owners when they do not want to apply a formal risk assessment on a project due to lack of time, size of project, or insufficient budget. The term deterministic implies that these methods offer a point estimate for contingency budget. In these methods usually a predetermined (guideline) or project oriented (expert judgment) percent of base cost depending on the project phase and development level is assigned as contingency budget. The percentages become smaller by the project development when more details are added in design and less uncertainties associate with project.

Even though deterministic approaches are simple and easy to apply, they have a main drawback. They cannot effectively address the risks specific to a project and consider the unique effects of project complexity, market condition, and location (Olumide *et al* 2010; AACE 2008a). Even in project oriented percentage where an expert or panel (estimator, engineer, or project manager) defines a unique percentage of base cost to allocate as contingency, this approach cannot be very effective since they do not implement a formal risk assessment to identify all risks and uncertainties associated to that certain project. Furthermore, the use of a fixed percentage does not provide information on the level of protection that this contingency is providing for the budget or schedule.

Even though in the recent years some agencies have started the use of probabilistic methods, deterministic methods are still employed by a most agencies. Olumide (2009) reports on a research led by Molenaar (NCHRP Project 08-60) in which 48 State Highway Agencies (SHA) were interviewed; it was revealed that the majority of these states are using

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deterministic contingency in their projects and a few of them uses formal risk assessment. 16 out of 48 SHAs were using predetermined contingency method in their projects. The result of these interviews is summarized in Table 2.2. Term range has been defined for those cost estimates that are delivered probabilistically which may be shown graphically with a probability curve.

Table 2.2: Percentage of SHAs that Using Range (Probabilistic) Estimating (Olumide 2009)

Project Development Phase	Never Use Ranges	Sometimes Use Ranges	Always Use Ranges
Planning	36%	55%	9%
Programming and Preliminary Design	53%	38%	9%
Final Design	70%	19%	11%

Table 2.2 shows that the number of agencies that always use probabilistic methods for cost estimating is relatively small. Table 2.3 summarizes various agencies practices in calculation of deterministic contingency. Parsons Jr. (1999) recommended a set of contingency values based on design completion stage for Waste Management (WM) projects of Department of Energy (DOE). Schneck *et al* (2009), Olumide *et al* (2010) and Olumide (2009) list a number of agencies such as AACE and States Department of Transportation (DOT) that employ deterministic methods for contingency allocation. These examples are summarized in Table 2.3.

Table 2.3: An Example of Agencies that use Deterministic Contingency

Agency	Contingency Required at Different Phases														
	Phase 1			Phase 2			Phase 3			Phase 4			Phase 5		
	Name	Design Compl	Cont. Val.	Name	Design Compl	Cont. Val.	Name	Design Compl	Cont. Val.	Name	Design Compl	Cont. Val.	Name	Design Compl	Cont. Val.
DOE, WM Projects	Planning	0-2%	50%	Conceptual	1-5%	40%	Title I	5-20%	30%	Title II	20-50%	15%	Construction	50-100%	5%
AACE	Exploration: Class V	0-2%	50%	Concept Definition: Class IV	1-5%	30%	Basic Engineering: Class III	5-20%	20%	Detailed Engineering: Class II	20-50%	15%	Construction: Class I	50-100%	5%
Louisiana DOT	Planning/ Environmental		30%	Preliminary Design		15%	Final Design		10%	Construction		5%			
Electric Power Research Institute	Class I: Simplified Planning	0-5%	30-50%	Class II: Preliminary Engineering	10-15%	15-30%	Class III: Detailed Engineering	25-35%	10-20%	Class IV: Finalized Engineering	60-100%	5-10%			
California DOT	Planning Estimates		25%	General Plan Estimates		20%	Marginal Estimate, Final Plans		5%						
Maryland DOT	Planning		35-40%	Programming and Preliminary		25-35%	Final Design		0-25%						
Florida DOT	Initial Cost Estimate		25%	Design Scope of Work		20%	Design Phase I	30%	15%	Design Phase II	60%	10%	Design Phase III	90%	5%

Olumide (2009) also mentions that Nevada, and Washington State DOTs are using contingency percentages similar to Caltrans (California DOT) given in Table 2.3.

Davis and Peng (2010) concluded that contingency percentages used by agencies are influenced by factors such as project stage, type, location, complexity and design quality. They summarize the percentages used for a normal (not complex) construction project in different phases in Table 2.4.

Table 2.4: Required Contingency in Different Phases of a Normal Construction Project (Davis and Peng 2010)

Required Contingency at Phase			
Planning	**Preliminary**	**Budget**	**Definitive**
25 to 35%	20 to 25%	10 to 20%	5 to 15%

Baccarini (2005) presented the results of a survey of 78 project practitioners participating in a project management conference regarding issues relating to project cost contingency. A key finding was that most practitioners were not aware that contingency is a risk management notion even though they knew it is a reserve budget. It is also found that 77% of practitioners were still using a deterministic percentage approach for estimating project cost contingency.

In summary deterministic methods can be summarized in two main categories which will be explained in the following sections.

2.3.1.1 Predefined Percentages (Fixed/Line Items)

This approach is the simplest method of contingency allocation. In this method, either an across-the-board predetermined (fixed) percentage of total project base cost or various percentages of line items will be added to the project budget as contingency. When contingency is added separately for each line item (allocated contingency), it can be an overall contingency as unallocated contingency added to the project budget on top of the allocated contingency. Each agency has its own set of guideline for contingency percentages. For instance, one can refer to Table 2.3 for a few examples of suggested percentages by different agencies. The suggested percentages are given for different key phases of a certain type of project and may be a single value or a range of values. Even though this method is simple and easy to apply, it does not consider the unique situation of each project and specific risk factors and uncertainties associated with every project. Moreover, it does not quantify the degree of confidence (confidence level) that the estimated contingency will provide against cost overruns.

2.3.1.2 Expert Judgment

The only difference of this method and predetermined percentage is that in this method there is not a set of predetermined percentages, but an expert or a group of experts with strong experience in risk management and risk analysis define(s) the percentage of contingency for the project under consideration. Even though this method can relatively considers the specific situation of each project by adding unique percentage for each project but it does not go through a formal and comprehensive risk assessment. Therefore, the contingency budget cannot be estimated adequately. Furthermore, similar to predefined

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percentage method, it does not provide the confidence level for the sufficiency of the estimated contingency.

2.3.2 Probabilistic Methods

The main difference between probabilistic methods and deterministic methods is that in probabilistic methods, uncertainties are explicitly modeled using appropriate statistical distributions (Touran 2006b). In deterministic methods the degree of confidence that the contingency will provide cannot be quantified against cost overruns (Davis and Peng 2010; Touran 2003). Also, it does not bring under consideration all risks and uncertainties that effect a project.

A cost estimate is considered as the prediction of the expected final cost of a project with a given scope and constructed during a certain time window (Dysert 2006). This definition discloses the probabilistic nature of cost estimate. Due to all uncertainties and risks associated with construction projects from errors in calculation to catastrophes affecting the project, finding the exact cost of a project is near to impossible. That is why a distribution or range can be more a realistic representation of project cost item. Using a cost distribution, one can define the level of confidence against different values of project cost. According to Moselhi (1997), contingency is an inverse function of risk that management accepts at an associated probability of cost overrun occurrence. The lower the taken risk of cost overrun occurrence is, the higher contingency budget will be required.

In probabilistic models the uncertainties and risks are incorporated within the cost estimate. The necessary contingency budget is estimated based on a desired confidence level determined by sponsor agency. A probabilistic method of contingency calculation uses

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formal risk analysis with probability concepts to model uncertainties affecting project cost and schedule (Touran 2006b). These types of models calculate a range of estimate rather than a point estimate. All mathematical operations such as addition, subtraction, multiplication, and other have to be performed on data ranges, and require the use of probability theory. Probabilistic models output which are distributions help the client understand the possible consequences of their decision where point estimate does not have this flexibility (AACE 2008b). Probabilistic risk assessment may employ a set of tools such as fault tree, probability tree, decision analysis, and Monte Carlo simulation (Touran 2006b). Probabilistic methods usually need more time and budget to conduct, and some agencies and most contractors are not willing to employ it on their normal projects. According to Smith and Bohn (1999) only contractors engaged in procurement of highly complex projects invest in formal risk analysis. In their study, they interviewed 12 contractors. The interviews revealed that none of them had the mathematical knowledge to calculate contingency.

Following sections explain the common practices of probabilistic contingency calculation in the construction industry.

2.3.2.1   Non-simulation Methods

This category includes the analytical methods in which risk assessment and contingency calculation are conducted without the use of simulation software packages. This is an advantage when an agency is not willing to invest on such software packages. However, these approaches are not suitable for large infrastructure projects where complex models are required. These models can be effective tools for the risk assessment of early phases of project developments such as conceptual or planning when project definition is not

complete. With the advent of the low-cost, personal computer-based, and powerful simulation software, the justification for the use of non-simulation approaches is reduced. However, the main weaknesses of simulation approaches, such as lack of a closed-form solution and the possibility of non-convergence of results remain.

Following are some examples of non-simulation methods.

2.3.2.1.1 Probability Tree

Probability trees provide a systematic method to transform individual risks each with a conditional expected value impact and probability of occurrence into an overall probability and expected value. This method is a diagrammatic representation of possible outcomes of consequence events. This model is not practical when the number of risks become large as the number of outcomes increases exponentially with the number of risks (Parsons *et al* 2004).

2.3.2.1.2 First-Order Second-Moment (FOSM)

FOSM methods are approximate methods to calculate the mean and standard deviation of complex functions. They usually linearize the function first using methods such as Taylor series about an appropriate point (usually mean) and then its first and second moments are obtained.

Let us assume that we have the different cost components of a project as a random vector $\underline{X}$ with mean vector $\underline{\mu}_{\underline{X}}$ and covariance matrix $\mathbf{V}$. If we consider total project cost Y as a nonlinear function of $\underline{X}$, we have:

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$$Y = g(\underline{X}) \tag{2.1}$$

The μ_Y and σ_Y^2 depend on the entire joint distribution of vector $\underline{X}$. Now, using the FOSM we can approximately estimate the mean and standard deviation of vector Y. The linearization of Y is conducted around $\underline{\mu}_X$ using Taylor series:

$$Y = g(\underline{X}) = g(\underline{\mu}_X) + \sum_{i=1}^{n} \frac{\partial g(\underline{X})}{\partial X_i}\bigg|_{\underline{X}=\underline{\mu}_X} (X_i - \mu_{X_i}) \tag{2.2}$$

Therefore with some approximation:

$$\mu_Y = g(\underline{\mu}_X) \tag{2.3}$$

$$\sigma_Y^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{\partial g(\underline{X})}{\partial X_i}\bigg|_{\underline{X}=\underline{\mu}_X} \frac{\partial g(\underline{X})}{\partial X_j}\bigg|_{\underline{X}=\underline{\mu}_X} Cov(X_i, X_j) \tag{2.4}$$

In Eq. (2.4), the values of $Cov(X_i, X_j)$ come from covariance matrix $\mathbf{V}$.

2.3.2.1.3   Expected Value

In this method first all significant risks in the risk register are identified. Risk register is a list of all risks/opportunities along with their impacts on cost/schedule of the project which is the important product of risk identification process (Touran 2006b). Then the risks need to be quantified by estimating the probability (likelihood) of risks' occurrence and impact of risks. The expected value of each risk is calculated by multiplying the probability of occurrence and its impact. If the all impacts are deterministic, the analysis can be done without simulation. However, most of the times it is not the case and the impact is uncertain

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and has a distribution. AACE (2009a) groups the risks that have deterministic impact as fixed (or deterministic) and those with uncertain impact as variable (or continuous). When the risks are variable or at least there is one, the use of Monte Carlo is required and this method should be considered as a simulation method. The correlation among the risks can be addressed while using Monte Carlo simulation. The contingency is considered to be the sum of all expected values and has a distribution (CDF) when the impacts are uncertain.

AACE (2209a) recommends that those risks that are being accepted by agency should be input to expected value analysis. Accepted risks are those that will remain part of the project scope and plan after mitigation and not being transferred or avoided. It also classifies the risk as significant when the expected value of risk affects the cost bottom line by more than $\pm0.5\%$ (called critical variance) at the conceptual estimate or $\pm0.2\%$ at the detailed estimate. If the risk is not significant it is dropped from further consideration in the analysis. The risk quantification is usually done in a workshop setting. The probability of risks' occurrence are estimated either using a percent point (or decimal point) or in preset qualification terms such as low, moderate, high, and very high. The advantage of preset qualification terms is that getting consensus on these terms among the participants is easier than specific probability percentages (AACE 2009a).

2.3.2.1.4   Program Evaluation and Review Technique (PERT)

Program Evaluation and Review Technique (PERT) is a project management method developed in 1957 which works for both schedule and cost of projects using central limit theorem (CLM). This method assumes a Beta distribution for the cost of each item which is approximated with a three point estimate: optimistic cost (lowest), most likely (target), and

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pessimistic (highest). These three points can be either estimated quantitatively using data from previous projects or qualitatively using expert knowledge and experience (Moselhi 1997). Yeo (1990) suggested a set of arbitrarily defined classes of risk given in Table 2.5 that can help estimator find the optimistic and pessimistic points based on an estimated cost item (target or most likely).

Table 2.5: A set of Arbitrary Classes of Risk (Yeo 1990)

Class of Risk	Definition of Parameters	Probable Error Range	
		Lowest Bound	Upper Bound
A	Reasonably Well Defined	-5%	+20%
B	Fairly Defined	-10%	+30%
C	Poorly Defined	-15%	+40%
D	Undefined	-20%	+50%

Having the three-point estimate of each cost item, mean and variance of cost item distribution can be calculated based on some assumptions in the PERT method as follows:

$$\bar{x} = \frac{x_a + 4x_m + x_b}{6} \tag{2.5}$$

$$v = \left(\frac{x_b - x_a}{6} \right)^2 \tag{2.6}$$

Where x_a is the optimistic estimate, x_b is the pessimistic estimate, x_m is the most likely estimate, $\bar{x}$ is the mean of distribution of cost item and v is its variance. Also, Yeo (1990) modifies the original variance equation according to a 5-95th percentile as follows:

$$v = \left(\frac{x_b - x_a}{3.2} \right)^2 \tag{2.7}$$

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PERT assumes that the cost items are independent of each other which is a drawback of this method. Therefore, when there are sufficiently large numbers of independent cost items (more than say five), the sum, based on central limit theorem (CLT) follows a normal distribution whose mean is the sum of all cost items' means and its variance is the sum of all cost items' variances. This distribution is used to define the required contingency budget for different probabilities that budget will not fall short.

Moselhi and Dimitrov (1993) suggested a probabilistic method similar to PERT which can accommodate the correlation among the project cost items. The mean in this method is similar to PERT but the variance is proved to be as follows regardless of the type of the marginal distributions of cost items:

$$V(C_{tot}) = \sum_{i=1}^{n} V(C_i) + 2\sum_{i=1}^{n} \sum_{j=i=1}^{n} \rho_{ij} \sqrt{V(C_i)} . \sqrt{V(C_j)} \qquad (2.8)$$

Where C_{tot} is the total cost of project comprised of n cost items (random variables) with known variances $V(C_i)$ and correlation matrix $R = \rho_{ij}, i, j = 1, 2, ..., n$.

Even though the modified PERT model proposed by Moselhi and Dimitrov accommodates the correlation among cost items and have preference over traditional PERT model, this is still cannot be considered theoretically accurate since it assumes that total cost has a normal distribution. This assumption is not true when cost items are not independent and correlation among them is observed.

2.3.2.1.5 Parametric Estimating

This method creates a relationship between an output which can be the cost overrun and inputs which can be a set of risk factors. This relationship is developed using historical data and methods such as multivariate regression analysis, artificial neural network, or even trial and error. Even though this method is simple and quick to apply, precaution is needed to select the risk factors that have predictable relationship with the outcome. First, parameters of the model which are risk factors such as scope definition, level of complexity, and size of project must be identified (AACE 2009b). It is recommended by AACE (2009b) that outcome is set as cost growth percentage relative to the base estimate excluding contingency. Data must be controlled to be free of any obvious and significant errors. After establishing all input and output parameters and collecting the necessary data, the relationship model can be constructed using either traditional multivariate regression analysis or more recent neural network methods.

The neural network methods are classified as Modern Mathematical Methods and will be explained in Section 2.3.3.2.

2.3.2.1.5.1 Regression

This type of parametric estimating has been used since 1970s. A review by Skitmore and Patchell in 1990 on cost modeling systems showed that use of regression analysis have been focused on finding the best predictors of bid price (Baccarini 2006). This model is more effective for the early cost estimate when there is not enough detail about the project. Using a sophisticated model at the early stages of project requires adding assumptions that add more uncertainty to the analysis and runs against the parsimony principle of regression

analysis. Ideally, the regression model must be sophisticatedly simple and without using unnecessary parameters should provide the best fit for the data at hand (Baccarini 2006). Regression method is recommended where there is a linear relationship between dependent (*e.g.* cost growth) and independent variables (risk factors). While the assumption of linearity is not necessarily true, it is commonly made.

Most of the time analysts need to have a distribution of possible outcomes in order to determine required contingency for acceptable levels of risk. AACE (2009b) suggests a simple method which is consistent with observed industry data to convert the calculated contingency value from regression analysis to a probability distribution. This method is based on two assumptions: cost outcomes (base cost plus contingency) are more or less normally distributed, and contingency is equal to standard deviation of the distribution. The mathematical explanation for these assumptions can be found in Rothwell (2005). This simple model helps the analyst form a normal distribution of cost where the mean of the distribution is the estimated base cost plus the contingency calculated from the regression model and its standard deviation is the contingency calculated from the regression model.

As an instance of the regression method, Kim and Ellis (2006) formed a model to estimate and predict cost contingency of transportation projects based on two factors: original contract amount, and estimated contingency amounts set by maximum funding limits. Florida Department of Transportation (FDOT) defines the maximum funding limit based on a percentage of original contract amount. For example, if the original contract amount is $5 million or less, the maximum funding limit is the minimum of 5% of the contract amount and $50, 000. Kim and Ellis (2006) used data from 79 Florida DOT projects to develop the

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model and 53 projects to validate it. Estimated contingency amounts were calculated using maximum fund limits of FDOT. The proposed model is:

$$\hat{Y}_i = 5017 + 0.88\hat{X}_1 + 0.00141\hat{X}_2 \qquad (2.9)$$

Where $\hat{Y}_i$ is the required contingency, $\hat{X}_1$ is the estimated contingency amount set by maximum funding limit, and $\hat{X}_2$ is the original contract amount. Their model has a coefficient of determination $R^2=0.84$ and the validation confirmed that it has the capability to estimate the contingency with good accuracy.

Creedy *et al* (2010) employed regression to check if there is any Pearson's correlation between cost overrun and risk factors for highway projects. They collected 231 highway projects data executed by Queensland Department of Main Road (QDMR) and completed between 1995 and 2003. Their study was comprised of two parts. First, they identified the risk factors contributing significantly to cost overrun from owners' view. For this purpose, they employed factor analysis (*i.e.* principal components analysis) and expert elicitation (*i.e.* nominal group technique). As a result of this part, they identified 11 factors such as design change, quality change, insufficient investigations and latent conditions contributed significantly in cost overrun. Then, they used multivariate regression analysis to identify direct correlations between cost overrun and factors such as geographical project type (urban/rural projects), project construction type, project delivery type, indexed project programmed cost (size of project), and identified risk factors in the previous part. They used forward and stepwise multivariate regression analyses and generated three identical models. They also employed backward analyses and generated 13 models. The coefficient of determination R^2 of models ranged from 0.019 to 0.061 and the models have not fitted the

data very well. Using developed mode, they concluded that there are no strong correlations between project type, work type, and project risk factors in producing cost overrun.

2.3.2.1.6 Analytical Hierarchy Process (AHP)

To assess the effect of risks on the projects, different methods have been proposed that utilize probability analysis and Monte Carlo simulation. However, there is not always quantitative detailed information available to us for developing such models. Therefore, the use of a subjective approach for project risk assessment sometimes becomes indispensable. The analytical Hierarchy Process (AHP) developed by Saaty (1980) presents a flexible and simple way of project risks analysis. The linguistic terms used in AHP allows risk analyst to include subjectivity, experience, and knowledge in an intuitive and natural way. This was first applied in the risk analysis by Mustafa and Al-Bahar in 1991 for the risk assessment of a construction project (Dey *et al* 1994).

In a method suggested by Dey *et al* (1994), first the whole project is classified according to the work breakdown structure (WBS). Risk analysis is performed separately for various work packages (WP). In each WP, risk factors and subfactors are identified and the overall risk of WP is calculated using the AHP. To allocate contingency budget they use two tiers. First, they implement the PERT approach suggested by Yeo (1990) for each WP to estimate the total cost distribution. Then using the overall risk of WP estimated from AHP, they find the appropriate targeted cost from the total cost distribution. The required contingency is the difference of the targeted cost and base cost.

2.3.2.1.7   Optimism Bias Uplifts

Optimism Bias Uplifts method (also known as Reference Class Forecasting) is a non-simulation probabilistic method developed by Flyvbjerg and COWI (2004) for the British Department for Transport (DfT) in effort to deal with optimism bias in capital project cost estimates. According to Flyvbjerg *et al* (2002; 2005) and Flyvbjerg (2006), psychological (optimism bias) and political explanations (strategic misrepresentation of costs due to political and organizational pressure) are responsible for much of the inaccuracy in transportation cost forecasting. Optimism bias and strategic misrepresentation are among the most difficult systematic risks to deal with (AACE 2009b).

In this method, transportation projects have been divided into a number of distinct groups. These groups include road, rail, fixed links (such as tunnel or bridge), buildings, and IT projects and have been selected in order to have statistically similar risk of cost overrun based on the study of an international database of 260 transportation projects. For each category, the probability distribution for cost overrun as the share of projects with a given maximum cost overrun was created. Having established the empirical cumulative probability distribution, uplifts are set up as a function of the level of risk that the DfT is willing to accept regarding cost overrun. "Uplift" is the term used to show the amount that the original estimate needs to be increased to arrive at the project budget for a given level of certainty with respect to cost adequacy. If the DfT wants to accept a higher risk, then a lower uplift is required. In this approach, it is assumed that the projects in future will behave similar to the past projects from a budgeting point of view. In other words, the improvement in cost containment in future projects is completely disregarded. Also, because the uplift values are

based on a relatively small number of projects (for example, the database is comprised of only 46 rail projects), serious error can potentially occur in the calculated uplifts.

In Chapter 4, the Optimism Bias Uplifts method using by the DfT in the U.K. is compared with a method practiced by the United States FTA for transit projects in the U.S.

2.3.2.2 Simulation Methods (Monte Carlo)

In this method usually expert judgment and an analytical method come together to reach a probabilistic output using a simulation routine (AACE 2008a). In many cases where the closed form equations are not available or due to several mathematical operations of distributions, analytical models become more complicated, simulation can help analyst find the probabilistic output. Touran (1993) declares that the use of simulation in most cases is indispensable because direct analytical approaches tend to be difficult and are sometimes infeasible. Monte Carlo is one of the most common simulation methods in the construction industry which is widely applied in risk analysis and contingency calculation. Monte Carlo methods rely on repeated random sampling of various cost distributions and basically need a computer to be applied. Monte Carlo refers to the famous Casino in Monte Carlo, Monaco, famed for gambling casinos and luxurious hotels (Clark 2001). The name connotes the uncertainty associated with gambling with modeling uncertainty. This method first was introduced by Stanislaw Ulam, a Polish mathematician.

The outcome of simulation should be evaluated to ensure it is reasonable (Clark 2001; Touran 2006b). When even an unrealistic model is developed, simulation can be conducted to reach some results which may be misleading. As simulation always "works" (*garbage in,*

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garbage out!) some people may distrust the results (Touran 2006b). Clark (2001) summarizes the steps needed to conduct a Monte Carlo simulation:

1. Prepare estimate and review it by a group meeting to get a precise estimate;

2. Conduct group Monte Carlo meeting to develop the data to conduct simulation;

3. Prepare and run Monte Carlo analysis;

4. Write report to management including recommended contingency.

One of the most common methods that employ Monte Carlo simulation is Range Estimating.

2.3.2.2.1   Range Estimating

This term was first coined by Curran (1976, 1989) and he even obtained a patent for the use of the term! In this method, first critical cost items are identified. The deterministic estimate of each critical cost item is considered as the most likely value. Next, the minimum and maximum values of the critical items are defined by a project group. At the end, with the help of Monte Carlo simulation the total cost cumulative distribution function (CDF) is calculated. This CDF is used to estimate the required contingency to reach the desired confidence level that budget will not fall short.

To identify the critical items, the Pareto's Law, the law of the significant few and the insignificant many, or what is known as 80/20 rule is employed (Moselhi 1997, AACE 2008b). It means 80% of the risks costs will be associated with 20% of cost items. In other words, 20% or fewer of the cost items are critical. AACE (2008b) explains the critical item as an item that its deviation from target can cause ±0.5% change (called critical variance) in the

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bottom line cost at the conceptual estimate or ±0.2% at the detailed estimate. Just those cost items identified as critical are ranged by a project team based on their knowledge and experience. AACE (2008b) recommends the probability range of 98% (1 to 99 percentile) for considering the extreme events. It also mentions that the minimum and maximum values are not comprised of events that would be considered way out of scope such as Acts of God or funding cuts which are outside of 1 to 99 percentile. Considering very rare events can lead to overstatement of the risks and consequently tie unnecessary contingency budget. After determining the range of critical cost items, all the required information is available to run a Monte Carlo simulation. The non-critical items are input in the analysis as the fixed (deterministic) values. Each critical item can have different probability density function (PDF) such as triangular, normal, lognormal, or Beta.[1] The selection of appropriate PDF for each cost item depends on how it fits the available data or meets the project group's belief. There are numerous commercial software packages such as @Risk and Cristal Ball that can help analysts apply Monte Carlo simulation. By adding all cost items (ranged and fix) and running the model for sufficient iterations (say 500 to 5000), the total project cost which is now a distribution (CDF) rather than a deterministic value, is calculated. This CDF describes the probability that total project cost as a random variable will be found at a value less than or equal to a certain number. Based upon the level of risk that agency desires to accept (80% is a common confidence level), the total project cost is selected from the estimated CDF. Defining 80% as the confidence level means that there is only 20% chance that the total project cost will go over the selected total project cost. The required contingency is the difference between the newly estimated cost and initially estimated cost before applying range estimating. The range estimating can be applied at any key phase of the project and

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[1] In Curran's approach, the CDF is confidential and the same CDF is apparently used for all critical cost items. Here, we are describing the concept of range estimating rather than the specific method used by Curran.

even during the construction phase at any certain period of time to release unnecessary contingency budget. Recently all software packages are capable to accommodate correlation among cost items by the means of Spearman Rank correlation method which will be explained in Chapter 5.

An example of this method is the technique used by the Federal Transit Administration (FTA 2007b) published in Project Guidance (PG)# 40 called Top-down model. In this guideline, the FTA requires a formal risk assessment for all new transit projects. In this method, various project cost components are treated as random variables and are ranged according to predetermined values to explicitly model the variability of each major cost component. Lognormal distribution is assumed for each cost category. The sum of these cost components will be a distribution that represents the total cost. This method will be explained in more detail and compared with the method used by British Department for Transport in Chapter 4.

2.3.2.2.2   Integrated Models for Cost and Schedule

The final costs and schedules for large infrastructure projects have been underestimated for the past decades (Flyvbjerg 2002). Even though it is obvious that cost estimate and schedule of construction projects are somehow related, cost estimating and probabilistic scheduling are often separately and independently applied (Isidore and Edward Back 2002). When there is no such a direct link between schedule and cost estimate of a project, the developed model cannot completely capture uncertainty and risk impacts associated with the project. Therefore, the calculated contingency budget may not be sufficient.

A model called ABC-Sim (Activity Based Costing Simulation) was developed by Isidore and Edward Back (2002) in which range estimating and probabilistic scheduling are applied simultaneously on an appropriately modeled construction project at the work breakdown structure (WBS) level. This model is based on discrete event simulation. Its main advantage over the traditional range estimating and probabilistic scheduling is that the model is capable of performing both range estimating and probabilistic scheduling simultaneously on a properly modeled construction project. Also, the model enables the analyst to find the project schedule value and its corresponding cost estimate value in each iteration of running model. After simulation, they use an analytical method to explain the relationship between the cost estimate and schedule data.

Roberds and McGrath (2006) suggested an integrated cost and schedule risk assessment approach for infrastructure projects. They discussed that most commercial software packages developed for conducting risk analysis using Monte Carlo simulation are not capable of conducting true probabilistic, risk based, integrated cost and schedule modeling. They suggested the use of general-purpose Monte Carlo simulation software such as @Risk for developing tailor-made spreadsheet-based models with following capabilities:

- Calculate the base project duration by considering activities relationships and critical path;

- Calculate base project cost by adding up all activities costs;

- Calculate cost escalation of each activity from current dollar to the year-of-expenditure (YOE) which is usually the mid-point of activity duration. The midpoint for a certain activity is calculated from the simulated start point and the total activity duration considering the uncertainty associated with the duration;

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- Incorporate uncertainties including risks and opportunities;

- Calculate total activity cost which is the sum of all escalated base activity costs plus all risks effects, and project duration.

Touran and Bakhshi (2010) introduced an integrated cost and schedule model for multi-year programs which considers uncertainties in cost, schedule, and escalation. This model uses Monte Carlo Simulation and considers Martingale series for modeling of escalation uncertainties. This Model is developed in an Excel spreadsheet; @Risk 5.0 (Palisade Corp 2008) is used for Monte Carlo simulation.

2.3.3 Modern Mathematical Methods

2.3.3.1 Fuzzy Techniques

Fuzzy set theory is a branch of modern mathematics that was first introduced by Zadeh in 1965 for modeling vagueness intrinsic in human cognitive process (Chan *et al* 2009). This is a method for capturing vagueness, uncertainty, imprecision, embedded human knowledge, human behavior, and intuition, and fuzzy logic enables computing with words where words are used instead of numbers (Sachs and Tiong 2009). In the risk assessment process when there is no statistical data available, opinions of experts with years of experience become very important. Experts can provide qualitative assessment of the risks. The conversion of these qualitative statements to numbers for estimating the uncertainty is not always easy. Fuzzy set theory is a mathematical tool that can help analyst quantify these linguistic terms (Choi *et al* 2004). Due to conceptual differences between fuzzy logic and probabilistic logic, Fuzzy technique has not been categorized into probabilistic methods. Even though both have

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values ranging between 0 and 1, fuzzy logic corresponds to degree of truth and probabilistic logic corresponds to probability (likelihood) (Buckley and Eslami 2002).

Sachs and Tiong (2009) develop a method for quantifying qualitative information on risk called Quantitative Qualitative Information on Risks (QQIR). In this method, fuzzy sets are used for capturing expert opinions and fuzzy weighted average method is employed for aggregating that information. The outcome of their model is a probability density function. Moreover Chan *et al* (2009) gives a review of fuzzy techniques in the field of construction management. It seems that the use of fuzzy sets and logics in the risk assessment and contingency calculation is becoming more widespread. As an example, Choi *et al* (2004) developed a risk assessment method for underground construction projects. The proposed model is comprised of four steps of identifying, analyzing, evaluating, and managing the risks inherent in construction projects and a risk analysis software is developed using uncertainty modeling based on fuzzy sets concept. In the analyzing step mentioned above, a fuzzy-based uncertainty model considers the uncertainty range involved in both probabilistic parameter estimates and subjective judgment. The final outcome of this model is a point estimate of total risk as the mean.

Also, Paek *et al* (1993) presented a model for pricing construction risks using fuzzy sets as a tool for contractors to assist them in deciding the bidding price of a construction project.

2.3.3.2   Artificial Neural Network

Artificial Neural Network (ANN) is an information processing technique that simulates human brain and its biological process (Chen and Hartman 2000). ANN uses a mechanism to learn from training examples and detect hidden relationships among data for generalizing

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solutions to future problems (Baccarini 2006). ANN is a better solution for modeling complex nonlinear relationships than conventional method such as nonlinear regression analysis (Chen and Hartman 2000). ANN uses a set of observations (input and output) to find the pattern called training example. After training, a network has the capability to estimate outputs quickly for new cases when fed only with their associated inputs (Moselhi *et al* 1993). Two drawbacks of ANNs are: analyzing and explaining the relationship between inputs and outputs is hard to accomplish because ANNs are essentially black-box methods (Chen and Hartman 2000); also selection of the consistence and unbiased inputs as the training data is really important because existence of bias in the training data is the major factor that limits the performance of an ANN (Touran and Lopez 2006; Chen and Hartman 2000).

As an example of this method, Chen and Hartman (2000) used ANN on the oil and gas projects. They selected projects performed by one organization in order to have as much consistency in practices as possible. They identified 19 risk factors for achieving successful budget and schedule performance. They nominated a group of 80 projects randomly divided for training, test, and production subsets with splits of 60/20/20 percent (48/16/16 projects). A commercial neural network development software package called NeuroShell 2 was used to implement training and develop the model. For cost performance model development, they used back propagation (BP) and general regression neural network (GRNN) algorithms. In the model trained with the BP, cost variance percentage (underrun/ overrun) of 75% (12 out of 16) production projects were predicted correctly. However, in four projects the model performed contrarily in which the difference between the actual cost overruns/ underruns and predicted ones were not over 23%. They also implemented a comparison on ANN and multiple linear regression analysis (MLR) by conducting MLR on

the same data. The comparison revealed that ANN outperformed MLR and can be used as a method of cost performance prediction with an acceptable accuracy.

2.4   Conclusion

Several contingency definitions were presented in this chapter. According to these definitions, there is consensus that cost contingency is a reserve budget for coping with monetary impacts of risks and uncertainties associated with a project. Therefore, if the impact of risks associated with a project can be estimated as accurate as possible, then the necessary contingency budget will be allocated accordingly. It should be noted that contingency budget is not intended to absorb the impacts of escalation, major scope changes, and extraordinary.

The most important and common methods to calculate contingency budget were introduced. The whole methods were classified into three main categories of: 1. deterministic, 2. probabilistic, and 3. modern mathematical methods. Deterministic methods are simple and easy to apply and consider to be still the most commonly used method. However, they are not capable of effectively addressing the risks specific to a project and reflect the unique characteristics of project such as complexity, market condition, and location. Also, the use of a fixed percentage does not provide information on the level of protection that this contingency is providing for the budget.

Probabilistic methods recognize the probabilistic nature of cost estimate by incorporating the uncertainties and risks within the cost estimate. Some agencies and most contractors are not willing to employ probabilistic methods on their normal projects because they usually need more time and budget to conduct. Unlike deterministic methods, the necessary

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contingency budget is estimated based on a desired confidence level determined by sponsor agency. Probabilistic methods are divided into two main categories: 1. Non-simulation methods, and 2. Simulation methods. Non-simulation methods are based on analytical methods and can employed with no need to software packages. This is an advantage when one is not willing to invest on such software packages. As it was mentioned, these models can be effective tools for the risk assessment of early phases of project developments such as conceptual or planning when project definition is not complete. However, these approaches are not suitable for large infrastructure projects where complex models are required. With the advent of the low-cost, personal computer-based, and powerful simulation software, the justification for the use of non-simulation approaches is reduced. Nevertheless, the main weaknesses of simulation approaches, such as lack of a closed-form solution and the possibility of non-convergence of results remain.

Two relatively new approaches in risk assessment: 1. fuzzy technique, and 2. artificial neural network (ANN) were classified as the third category of modern mathematical method. In risk assessment, fuzzy technique is used to quantify the qualitative assessment of risks provided by experts. Fuzzy technique mathematically helps analyst convert linguistic terms into numbers. ANN is a type of parametric estimate and uses a mechanism to learn from training examples and detect hidden relationships among data for generalizing solutions to future problems. ANN has proved better prediction for complex and nonlinear models.

CHAPTER 3: NEW STARTS PROJECTS

DEVELOPMENT

3.1   Introduction

The Federal government has provided a large portion of the Nation's capital investment in urban mass transportation especially in *new starts* projects since early 1970s (FTA 2002). New starts projects are new fixed guideway systems or extension to existing fixed guideway systems that might be eligible for the Federal financial support under 49 U.S.C. 5309 (United States Code: Title 49, Transportation, Subtitle III, General and Intermodal, Chapter 53, Public Transportation, Section 5309, Capital Investment Grants) if they meet certain criteria. Due to the fact that the demand for federal funds exceeded the supply, Urban Mass Transportation Administration (UMTA) (the predecessor to the Federal Transit Administration (FTA)) in the late 1970s established new policies to ensure that the available Federal funds would be used in the most prudent and effective manner. As part of this effort, UMTA developed Full Funding Grant Agreement (FFGA) as a contract between the Federal government and a transit agency. As time passed, UMTA/FTA gained more experience and the FFGAs became more sophisticated to protect the Federal government's interest. The FTA has prepared various manuals regarding project development and management to assure completion of high quality projects on time and within budget according to the scope.

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Despite all these precautions, we still see that the new starts projects suffer from cost overrun. In the current chapter, we briefly discuss the regulatory characteristics of new starts projects and their planning and development process. This will help in setting the stage for developing a probabilistic approach for determining the required contingency for future projects.

3.2   New Starts Projects Program

The Federal Transit Administration (FTA) has helped several local transit agencies get the Federal technical and financial support for locally planned, implemented, and operated fixed guideway transit projects such as heavy rail, light rail, commuter rail, and bus rapid transit systems. 49 C.F.R. §611 defines the New Starts Project as a new fixed guideway system, or an extension to an existing fixed guideway system. This part prescribes the process that local agencies (applicants/ grantees/ sponsors) must follow to be considered eligible for capital investment grants and loans through new starts program. Also, this part prescribes the procedures used by the FTA to evaluate proposed new starts projects as required by 49 U.S.C. 5309(e), and the scheduling of project reviews required by 49 U.S.C. 5328(a).

On August 10, 2005, President George W. Bush signed the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) as an amendment to Title 49. SAFETEA-LU authorized the Federal surface transportation programs for highways, highway safety, and transit for the 5-year period 2005-2009. SAFETEA-LU authorized $6.6 billion in new starts funding through fiscal year 2009 and has been extended to fiscal year 2010 in which Congress appropriated $2 billion for new starts funding (FTA 2010d).

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Prior to SAFETEA-LU, federal transit amendments were Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991 which authorized $5 billion over the 6 years in new starts funding and the Transportation Equity Act for the 21st Century (TEA-21) in 1998 which authorized nearly $218 billion in Federal funding for highway, highway safety and transit programs over six years.

3.3   New Starts Projects Development

SAFETEA-LU requires the FTA to evaluate and rate the projects requesting federal support and entering to the new starts program at specific key points of the project's planning and development. There are specific criteria that the FTA must consider before inputting a fixed guideway transit project into new starts program and entering into a long term commitment to a local agency. These criteria include project cost effectiveness, the transit supportiveness of existing and future land use, and local financial commitment. Evaluation of a candidate project's performance against the new starts criteria eventually results in an overall project rating of "Highly Recommended," "Recommended," or "Not Recommended."

Figure 3.1 depicts the procedure that the FTA must follow during the planning and project development of a new starts project. For entering into all key phases with the exception of alternative analysis (AA), the FTA must evaluate, rate and approve projects. AA and much of the preliminary engineering (PE) is conducted within the metropolitan planning process specified by SAFETEA-LU and the environmental review process as required by the National Environmental Policy Act of 1969 (NEPA). AA is a corridor-level analysis to address local requirement and is considered complete with the selection of a locally preferred alternative (LPA) to advance into PE. In the PE phase, the LPA is further developed and

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environmental impacts and mitigations are identified. The project scope is finalized and cost estimate is reasonably firm. Also, the financial plan with the majority of local funding commitment is allocated. The last phase of project development is final design (FD) in which the sponsor gets ready for construction and the FTA may enter into a multi-year financial commitment to fund the new start project known as the full funding grant agreement (FFGA).
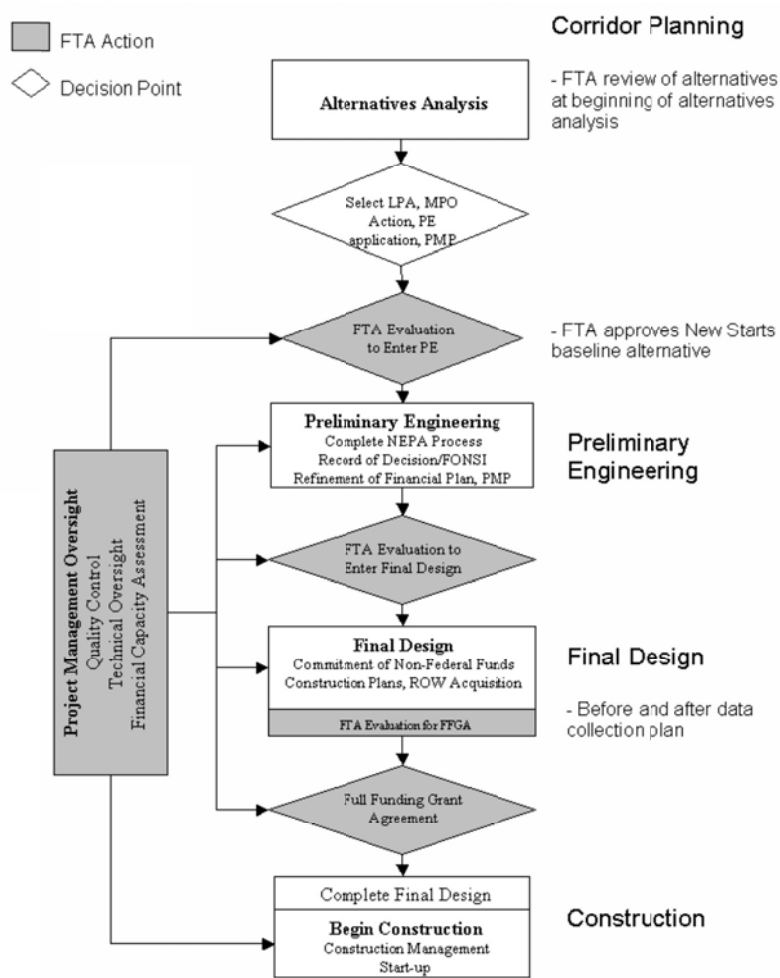
Figure 3.1: Planning and Project Development Process for New Starts Projects (FTA 2010c)

Project review and oversight by the FTA is conducted through Project Management Oversight Contractors (PMOCs) required by 49 C.F.R. § 633. PMOC role in a fixed

guideway transit project is to monitor and oversee the project's process to determine whether it is on time, within budget, in conformance with design criteria, constructed to approved plans and specifications, and is efficiently and effectively implemented. The FTA has documented procedures that the PMOCs must follow in each phase of project life in a set of Project Guidance (PG) manuals.

3.4   Full Funding Grant Agreement (FFGA)

Full Funding Grant Agreement (FFGA) is a contract between the FTA and a local transit authority (grantee) that establishes the FTA commitments to provide the Federal support for a new start project. According to Circular C5200.1A (Full Funding Grant Agreements guidance) by the FTA, FFGA defines the terms and conditions for Federal financial participation, describes the project, sets the maximum amount of Federal new starts funding for a project, stipulates project completion, and facilitates efficient management of the project in accordance with applicable Federal statutes, regulations, and policy. This is the point that the FTA contractually commits to a new start project.

The whole life cycle of a transit project development is divided into several phases as follows:

1. Alternative Analysis (AA) / Draft Environmental Impact Study (DEIS);

2. Preliminary Engineering (PE)/ Final Environmental Impact Study (FEIS);

3. Final Design (FD);

4. Full-Funding Grant Agreement (FFGA);

5. Construction;

6. Revenue Operation (RO).

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The FTA mostly enters into FFGA commitment after FD regardless of project delivery method such as design-bid-build (DBB), design-build (DB), or design-build-operate-maintain (DBOM) (FTA 2010e, and 2002). Before establishing the FFGA, the project management oversight contractor (PMOC) must go over a procedure to examine the Grantee's readiness to enter into a FFGA which protects the FTA's interests. The PG-52, Readiness to Execute FFGA (FTA 2010c), describes necessary review, analysis, and recommended procedures and reporting requirements that PMOC must follow. The final product of the PMOC is part of the package that is submitted to Congress. The FFGA readiness review is basically an update of earlier reviews and risk assessments performed at entry to both PE and FD.

Circular C5200.1A enumerates the reasons that may affect the length of time required for reaching the point to establish FFGA as follows:

1. Nature of the corridor;

2. Complexity of the project alternatives;

3. Magnitude and nature of potential environmental impacts;

4. Status of local planning data bases, e.g., socioeconomic, transportation systems data;

5. Quality of local analysis tools, e.g., travel demand forecasting, cost estimation;

6. Competence and motivation of local agency staff; and

7. Absence or presence of local consensus on how to proceed.

Aforementioned reasons will vary the time required to establish FFGA from the application submission.

3.5 Cost Estimation Methodology

Cost estimation is a progressive process that as a project develops from conceptual toward final design and project scope is better defined, it becomes more accurate. Grantees initially conduct cost estimation and the FTA controls the accuracy of cost estimates at entry to each key phase of project.

In transit projects, project costs are estimated from the bottom up using work breakdown structure (WBS). The WBS helps define all hard costs (what is to be built) and soft costs (management and administrative costs including fees, testing, etc.). Soft costs are typically 20% of a project cost (FTA 2003b), although it varies depending on project characteristics (TCRP 2010).

In 2005, the FTA started implementing a new format for cost estimates called the Standard Cost Categories (SCCs) for new starts projects. The FTA classifies all costs of a new start transit project into ten SCCs, SCC-10 to SCC-100. Figure 3.2 illustrates a typical SCC workbook. The SCC workbook is a project management tool and constructs a consistent format for the reporting, estimating, and managing of capital costs for new starts projects.

Standard Cost Categories for Capital Projects
(Rev. 11a, June 4, 2008)

10 GUIDEWAY & TRACK ELEMENTS (route miles)
- 10.01 Guideway: At-grade exclusive right-of-way
- 10.02 Guideway: At-grade semi-exclusive (allows cross-traffic)
- 10.03 Guideway: At-grade in mixed traffic
- 10.04 Guideway: Aerial structure
- 10.05 Guideway: Built-up fill
- 10.06 Guideway: Underground cut & cover
- 10.07 Guideway: Underground tunnel
- 10.08 Guideway: Retained cut or fill
- 10.09 Track: Direct fixation
- 10.10 Track: Embedded
- 10.11 Track: Ballasted
- 10.12 Track: Special (switches, turnouts)
- 10.13 Track: Vibration and noise dampening

20 STATIONS, STOPS, TERMINALS, INTERMODAL (number)
- 20.01 At-grade station, stop, shelter, mall, terminal, platform
- 20.02 Aerial station, stop, shelter, mall, terminal, platform
- 20.03 Underground station, stop, shelter, mall, terminal, platform
- 20.04 Other stations, landings, terminals: Intermodal, ferry, trolley, etc.
- 20.05 Joint development
- 20.06 Automobile parking multi-story structure
- 20.07 Elevators, escalators

30 SUPPORT FACILITIES: YARDS, SHOPS, ADMIN. BLDGS
- 30.01 Administration Building: Office, sales, storage, revenue counting
- 30.02 Light Maintenance Facility
- 30.03 Heavy Maintenance Facility
- 30.04 Storage or Maintenance of Way Building
- 30.05 Yard and Yard Track

40 SITEWORK & SPECIAL CONDITIONS
- 40.01 Demolition, Clearing, Earthwork
- 40.02 Site Utilities, Utility Relocation
- 40.03 Haz. mat'l, contam'd soil removal/mitigation, ground water treatments
- 40.04 Environmental mitigation, e.g. wetlands, historic/archeologic, parks
- 40.05 Site structures including retaining walls, sound walls
- 40.06 Pedestrian / bike access and accommodation, landscaping
- 40.07 Automobile, bus, van accessways including roads, parking lots
- 40.08 Temporary Facilities and other indirect costs during construction

50 SYSTEMS
- 50.01 Train control and signals
- 50.02 Traffic signals and crossing protection
- 50.03 Traction power supply: substations
- 50.04 Traction power distribution: catenary and third rail
- 50.05 Communications
- 50.06 Fare collection system and equipment
- 50.07 Central Control

60 ROW, LAND, EXISTING IMPROVEMENTS
- 60.01 Purchase or lease of real estate
- 60.02 Relocation of existing households and businesses

70 VEHICLES (number)
- 70.01 Light Rail
- 70.02 Heavy Rail
- 70.03 Commuter Rail
- 70.04 Bus
- 70.05 Other
- 70.06 Non-revenue vehicles
- 70.07 Spare parts

80 PROFESSIONAL SERVICES (applies to Cats. 10-50)
- 80.01 Preliminary Engineering
- 80.02 Final Design
- 80.03 Project Management for Design and Construction
- 80.04 Construction Administration & Management
- 80.05 Professional Liability and other Non-Construction Insurance
- 80.06 Legal; Permits; Review Fees by other agencies, cities, etc.
- 80.07 Surveys, Testing, Investigation, Inspection
- 80.08 Start up

90 UNALLOCATED CONTINGENCY

100 FINANCE CHARGES

Figure 3.2: Standard Cost Category (SCC) Workbook Using by the FTA

In the FFGA, there is a cost term called Baseline Cost Estimate (BCE). The BCE includes all costs necessary to complete the project with a given scope in the FFGA and is eligible for Federal assistance (FTA 2002). The BCE reflects escalation, contingencies, and schedule dates pertaining to the individual cost elements or contract units. Cost escalation can be calculated either based on year of expenditure or mid-point of construction. Contingency can be added to each line item, or added as a whole to the project cost estimate, or both. In the FFGA, the BCE is the Estimated Total Project Cost unless a grantee choose to pursue activities or pay for items within the project scope of work that are not eligible for Federal assistance; in this case, the Estimated Total Project Cost will be greater than the BCE. The estimated total project cost shows the total projected costs of the project at the time of the FFGA award (FTA 2002).

The Maximum Federal New Starts Financial Contribution is stipulated in the FGGA and signifies the limit on the amount of Section 5309 new starts funds that will be allocated to the Project. The Federal government has no obligation to provide further financial assistance for the project beyond the Maximum Federal New Starts Financial Contribution. If this budget is insufficient to complete the project, the grantee agrees to expeditiously finish the project and accepts sole responsibility for the payment of any cost overruns.

Even though the FTA accepts no responsibility for cost overruns, they closely review the cost estimates at entry to each key phase and right before the FFGA execution. There are also Project Guidance (PG) manuals to conduct risk assessment and estimate necessary contingency budget that the grantee is supposed to employ over the course of project development before and even after execution of the FFGA. This is done to prevent cost overrun that can jeopardize the on-time completion of project and tax payers' interests.

3.6   Risk Management and Contingency Allocation

As it was mentioned, contingency is a component added to the BCE which is intended to absorb the impacts of uncertainties and risk factors on projects. The FTA had established a set of predefined contingency amounts as percentage of total estimated cost for different phases of project development as follows (FTA 2003b):

1. Conceptual Design: 20% or higher

2. Preliminary Design: 10-20%

3. Definitive (75-100% Design): 5-15%

4. Detailed (Complete Plans, Specifications, and Estimate): 0-10%

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However, in late 2003, the FTA established a new guidance using an event-based analysis process entitled "Risk Assessment and Mitigation Procedures" as PG-22 (FTA 2003a). In this method, a risk register prepared during a risk workshop is used to estimate the required contingency. These are the items in the grantee's estimate that seem to vary significantly with anticipated ranges. Using a Monte Carlo simulation, the sum of all these risk factors is calculated. Since this method considers details and elemental events is called a bottom-up analysis.

Sillars and O'Connor (2008) described bottom-up analysis and showed that the costs were underestimated using this risk assessment approach. They analyzed the budget established using this procedure for three projects in detail. The result showed some variation between actual and predicted costs. However the study demonstrated the improvement on previous method where contingency was a set of subjective percentages mentioned above.

The observed variation in the actual and estimated cost of projects using the PG-22 motivated the FTA for developing a more conservative procedure in which projects were allocated larger contingencies to overcome uncertainties and risk events. To this end, in 2007 the PG-22 was superseded with the PG-40 (Risk Management Products and Procedures 2007) which is a holistic method and called the top-down model. The FTA found out that considering the individual risk events and not project risk as a whole may ignore some risk events that are individually insignificant but collectively have large impact on the total cost (Sillars and O'Connor 2008).

The top-down model considers the SCCs and ranges cost components using a set of predetermined coefficient. It assumes a lognormal distribution for each cost components and the sum of these cost components will be a distribution that represents the total cost.

However, in this method the way that cost categories are ranged is somewhat conservative resulting in a contingency budget far larger than previous approaches (Bakhshi and Touran 2009). It can be argued that using conservative contingencies is not prudent especially for an organization that is dealing with a portfolio of projects every year. This overestimation of contingency will use up the budget that can be spent on other projects waiting to enter into new starts program.

In the next chapter the top-down model is explained in more detail and is employed on a set of data as the current contingency estimation in the U.S. Also, the current technique used in the U.K. is explained and applied on a set of data. These two models are then analyzed and compared.

3.7   Estimating Escalation Costs

FTA requires that for each project, the cost escalation should be calculated and added to the budget. Association for Advancement of Cost Engineering (AACE) defines escalation as: "The provision in actual or estimated costs for an increase in the cost of equipment, material, labor, etc., over that specified in the purchase order or contract due to continuing price level changes over time. Inflation may be a component of escalation, but non-monetary policy influences, such as supply-and-demand, are often components." (ACCE 2010a)

Escalation is a risk factor and can have large impact on the cost estimate. The FTA study (2003c) in the review of 19 new starts projects found the inflation as the largest component of the difference in absolute dollars between the estimated cost and the final costs. As it was

mentioned earlier, the FTA requires local transit agencies to escalate construction costs to reflect predicted inflation (FTA 2003b). The escalation cost is reported as a separate budget line item. This requirement takes into consideration the fact that over time, materials and labor costs may rise due to general inflation. The FTA (2003b) mentions two methods to calculate the escalation costs. One is to estimate it by applying an assumed fixed annual percentage to probable construction costs through the mid-point of construction. This method does not need any knowledge regarding the distribution of project costs over time. It sets a single date which is the mid-point between the start and finish date of the construction phase. This method is not suitable when the cash flow or indices are not uniform over the course of construction phase (AACE 2010b). Another method which is a more sophisticated approach is to apply escalation by either individual construction contract or by trade item, *e.g.* bridge, track, signal, etc., and adjust to the predicted year of expenditure (YOE). This method breaks the whole expenditures over the course of construction phase in spending at a certain period of time such as monthly or yearly depending on the project's duration. Then each spending is escalated separately using proper cost indices and mid-point of that period. This method requires the knowledge of project cost distribution over time and is more accurate than mid-point construction phase (AACE 2010b).

In the studies where estimated costs are compared with actual costs, it is a common practice to adjust the estimated cost to mid-point of construction (*i.e.* constant) or year of expenditure dollars. Even though for each phase of New Starts project development, planning documents include capital cost estimates in escalated dollars, they may need to be adjusted when the projects' YOE or mid-point of construction has been changed from the plan. To do this, the actual inflation rates will be usually used for the adjustment.

However, this adjustment may cause some discrepancy in the reported cost overrun/ underrun of a project in various reports when there is no absolute methodology to follow. This can be due to using different indices or methods to escalate the costs. Figure 3.3 illustrates the effect of applying different methods to escalate project cost.
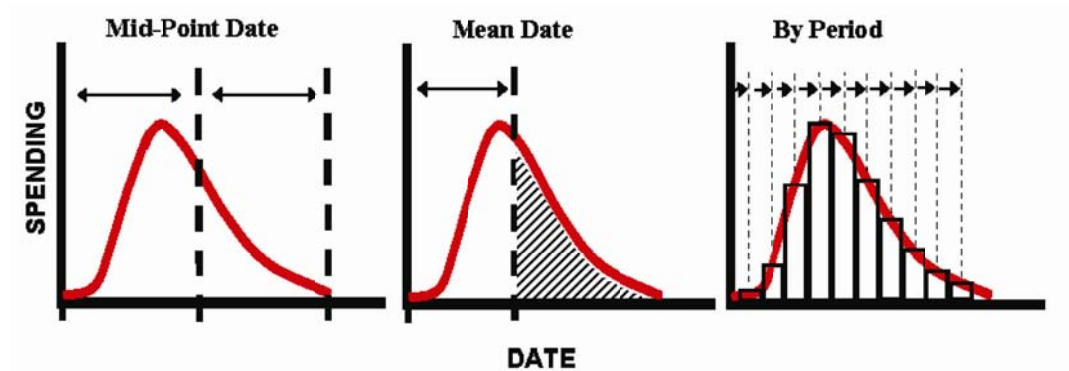
Figure 3.3: YOE and Mid-point of Construction Methods to Estimate Escalation (AACE 2010b)

When the project cost distribution over time is not symmetric and/or non-uniform, the results of cost escalation from YOE and mid-point of construction methods would be significantly different.

Using inconsistent indices is another issue in estimating cost escalation. Each cost index has different components and weightings. Therefore it is really important to escalate the cost of an activity/ trade using an index which indeed represents that type of activity/ trade. One of the widely used indexes in the construction industry is Construction Cost Index (CCI) presented quarterly by Engineering News-Record (ENR) for the average price of 20-city in the U.S. The latest CCI components are common labor 80%, steel 13%, lumber 6%, and cement 1%. ENR chose steel, lumber and cement because of their stable relationship to the nation's economy as well as playing a major role in construction (ENR 2009). ENR also

provides price data on 75 different building materials, in 20 major U.S. cities, plus Montreal and Toronto, on a monthly basis for over 50 years. Other than ENR, there are other sources such as R.S. Means, Marshall and Swift/Boeckh, and BNI Books that collect and report construction cost data. Also, there are agencies such as Office of Federal Housing Enterprise Oversight, and Bureau of Labor Statistics (BLS) that report cost index for various products. It is obvious choosing different cost indexes will result in different escalated costs.

As an example of discrepancy in selecting cost indexes, we can point out to two reports prepared for the FTA. The FTA (2008) suggested the following indices to estimate the escalation for different cost components: The CCI of ENR (20-city average) for construction costs, the Producer Price Index by BLS for metals and metals products, the national House Price Index by the Office of Federal Housing Enterprise Oversight for right-of-way costs, Employment Cost Index by BLS for all costs associated with Design, administration, project management and contingency. On the other hand, FTA (2003c) only used CCI of ENR for all cost components.

Thus, it is crucial for an agency to set forth a set of guidelines for using the escalation method and selecting the proper cost indexes. This will help an agency obtain a unique escalated cost estimate if it is prepared by different entities or at different times. Choosing optional cost index and/or escalation method will result in dissimilar escalated costs. This will also be a source of confusion for the researchers who want to study the project under consideration.

The following illustrates the discrepancy in the adjusted cost estimate of two transit projects presented in two different reports sponsored by the FTA. Atlanta North Line Extension and Portland Westside-Hillsboro MAX costs are reported differently in two relevant reports:

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Booz.Allen.Hamilton 2005, and FTA 2008. Costs in million dollars at the DEIS, FEIS, FFGA, and final cost are shown in the Table 3.1.

Table 3.1: Costs of Two New Starts Projects Reported in Two Different Reports Sponsored by the FTA

Project	Report	DEIS (Millions $)	FEIS (Millions $)	FFGA (Millions $)	Final Cost (Millions $)
Atlanta North Line Extension	Booz.Allen.Hamilton 2005	$422.4	$438.9	$381.3	$472.7
	FTA 2008	$439.5	$389.7	$352.0	$472.7
Portland Westside-Hillsboro MAX	Booz.Allen.Hamilton 2005	$531.9	$913.0	$910.2	$963.5
	FTA 2008	$559.3	$804.0	$886.5	$964.0

Table 3.1 depicts the impact of differently adjustment costs on the calculated cost overrun in various phases of projects. This can be a serious source of confusion and drawing wrong conclusion which leads to inefficient remedy. Therefore a close attention is required to establish a certain policy to escalate the costs which leads anyone estimating cost escalation to a unique cost at each stage of project development.

3.8   Previous Studies and Lessons Learned

Capital projects have been suffering from cost overrun and schedule delay over the past decades (Touran 2010; Flyvbjerg 2006). Researchers have shown that these are due to many different reasons including optimistic original estimates, lack of scope definition at the start of the project, scope creep during the project development phase caused by pressure from project stakeholders, errors in estimation, and lack of appropriate contingency budget

(Bakhshi & Touran 2009; Booz.Allen 2005; Flyvbjerg *et al* 2004). Transit projects are not an exception and have been mostly experiencing cost overrun. To identify the problems and control this issue, the FTA has conducted three exhaustive studies entitled Predicted and Actual Impacts of New Starts Projects in 1990 (Pickrell 1990), 2003 (FTA 2003c), and 2008 (FTA 2008). In these three reports, the FTA has analyzed the predicted costs (inflation-adjusted costs)/ridership and actual costs (as-built costs)/ ridership impacts of nearly 52 new starts projects. The predicted costs were adjusted to the mid-point of construction year dollars using industry accepted published inflation rates. The main purpose to conduct these studies was to evaluate the effectiveness of the procedures and technical methods used to develop the new starts projects.

Pickrell (1990) considered the cost of 10 new start projects and reviewed their actual costs with the predicted costs at AA/ DEIS. The total cost of these projects was $15.5 billion in 1988 dollars. It was found out that 9 out of 10 projects experienced overrun ranging from 13 to 106% with the average of 50.06% cost overrun. He concluded that main reasons for this overrun were optimistic original cost estimates, insufficient contingency, and delay in project startup, and delays in different points of projects' development.

The FTA (2003c) reviewed 21 additional projects completed between 1990 and 2002. The analysis showed that the projects on average suffered 20.9% cost overrun compared with inflation-adjusted estimated cost at the DEIS, 13.5% compared at the FEIS, and 7.3% at the FFGA.

In the latest study of predicted and actual impacts by the FTA (2008), 21 new starts projects completed between 2003 and 2007 were reviewed. On average, these projects had 40.2% higher cost compared to their inflation-adjusted cost at the DEIS, 11.8% higher at the FEIS,

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and 6.2% at the FFGA. The average length of time to open the projects for revenue service after selection of locally preferred alternative was about 7.9 years which didn't show significant change since 1990. Table 3.2 summarizes the results obtained from aforementioned studies by the FTA.

Table 3.2: Average Cost Overrun percentages of Three Different New Starts Projects Samples Compiled by the FTA at three Phases of Project Development

Study	No. of Projects	DEIS	FEIS	FFGA
Pickrell (1990)	10	50.1	N/A	N/A
FTA 2003	19	20.9	13.5	7.3
FTA 2008	21	40.2	11.8	6.2

Even though the results in Table 3.1 suggests some improvement in cost estimating over time, cost overrun still is an issue in capital projects specially in the early stage of project's planning and development (*i.e.* AA/DEIS).

3.9   Conclusion

In this chapter some regulatory specifications of new starts project, new fixed guideway systems or extension to existing fixed guideway systems, was explained. The planning and development of these projects and how they can get the Federal financial support under 49 U.S.C. 5309 was described.

The evolutionary practices of the FTA to assign contingency budget was discussed. The methods to escalate the capital cost estimate and the issues in this regard were explained. It

was concluded that a consistent policy is required for escalating project costs which leads anyone estimating cost escalation to a unique cost at each stage of project development.

 Three exhaustive studies by the FTA covering 50 new starts projects to evaluate the predicted and actual cost/ridership impacts were reviewed. It was found that despite all progress in the FTA's project development and management, projects are suffering from cost overrun. This suggests the need for a new solution to control/prevent cost overrun. In the following chapters a new method is proposed that can help agencies similar to the FTA to effectively decrease cost overrun in their portfolio of projects.

CHAPTER 4: COMPARISON OF BUDGET ESTIMATING FOR TRANSIT PROJECTS IN THE U.S. AND THE U.K.

4.1   Introduction

In this cahpter, the probabilistic approaches for cost estimating currently used in transportation industry are illustrated. We examine two probabilistic approaches to allocate contingency budget developed and used in the United States and United Kingdom. In the first approach, we review the method used by the Federal Transit Administration (FTA) of the U.S. Department of Transportation. The FTA requires a formal risk assessment for all new transit projects. In this method, various project cost components are treated as random variables and are *ranged* according to predetermined values to explicitly model the variability of each major cost component. The sum of these cost components will be a distribution that represents the total cost. In the second approach, the British Department for Transport suggests increasing project contingency in order to cope with the *optimism bias* in infrastructure transportation projects. This is done by considering a cumulative distribution function of the amounts of overruns in previous projects and specifying a confidence limit for the project at hand for establishing a revised budget.

The two methods discussed above have similarities; they both consider the probabilistic nature of the project costs and establish budget levels by explicitly considering this variability. These two methods are evaluated and a quantitative comparison of the results obtained by these methods is made. This is accomplished by analyzing the cost performance data of a group of major transit projects in the United States, applying the two methodologies, comparing and analyzing the results. The problem areas of these approaches are discussed and recommendations are made to optimize the use of these techniques.

4.2   Federal Transit Administration (Top-down) Model

4.2.1   Top-down Model Background

As it was stated in the previous chapter, the Federal Transit Administration (FTA) of the U.S. Department of Transportation (DOT) sponsors and provides technical support assistance to local transit authorities to carry out their transit projects. FTA, through a set of documented Project Guidance (PG) manuals and procuring the services of Project Management Oversight Contractors (PMOCs), provides oversight assistance to transit authorities. Among the PGs, PG-40 "Risk Management Products and Procedures" (March 2007) is used currently for conducting risk analysis of all new transit projects. This probabilistic risk assessment, referred to as top-down model, is a "holistic view of all risks associated with the projects" rather listing all risks in a risk register. FTA approach asserted that assessment of project risks considering discrete risk events could not capture the variability that is witnessed in current transit projects (Sillars and O'Connor 2008). The PG's stance was that to focus on significant but few risk items instead of project risk as a whole

may be masking risks that are unconsidered or individually small, but in total have a significant impact on the final cost.

4.2.2 Top-down Model Methodology

FTA classifies all costs of a new start transit project into ten Standard Cost Categories (SCC), SCC-10 to SCC-100 (Figure 4.1).

Standard Cost Categories for Capital Projects
(Rev. 11a, June 4, 2008)

10 GUIDEWAY & TRACK ELEMENTS (route miles)	40.06 Pedestrian / bike access and accommodation, landscaping
10.01 Guideway: At-grade exclusive right-of-way	40.07 Automobile, bus, van accessways including roads, parking lots
10.02 Guideway: At-grade semi-exclusive (allows cross-traffic)	40.08 Temporary Facilities and other indirect costs during construction
10.03 Guideway: At-grade in mixed traffic	**50 SYSTEMS**
10.04 Guideway: Aerial structure	50.01 Train control and signals
10.05 Guideway: Built-up fill	50.02 Traffic signals and crossing protection
10.06 Guideway: Underground cut & cover	50.03 Traction power supply: substations
10.07 Guideway: Underground tunnel	50.04 Traction power distribution: catenary and third rail
10.08 Guideway: Retained cut or fill	50.05 Communications
10.09 Track: Direct fixation	50.06 Fare collection system and equipment
10.10 Track: Embedded	50.07 Central Control
10.11 Track: Ballasted	**60 ROW, LAND, EXISTING IMPROVEMENTS**
10.12 Track: Special (switches, turnouts)	60.01 Purchase or lease of real estate
10.13 Track: Vibration and noise dampening	60.02 Relocation of existing households and businesses
20 STATIONS, STOPS, TERMINALS, INTERMODAL (number)	**70 VEHICLES (number)**
20.01 At-grade station, stop, shelter, mall, terminal, platform	70.01 Light Rail
20.02 Aerial station, stop, shelter, mall, terminal, platform	70.02 Heavy Rail
20.03 Underground station, stop, shelter, mall, terminal, platform	70.03 Commuter Rail
20.04 Other stations, landings, terminals: Intermodal, ferry, trolley, etc.	70.04 Bus
20.05 Joint development	70.05 Other
20.06 Automobile parking multi-story structure	70.06 Non-revenue vehicles
20.07 Elevators, escalators	70.07 Spare parts
30 SUPPORT FACILITIES: YARDS, SHOPS, ADMIN. BLDGS	**80 PROFESSIONAL SERVICES (applies to Cats. 10-50)**
30.01 Administration Building: Office, sales, storage, revenue counting	80.01 Preliminary Engineering
30.02 Light Maintenance Facility	80.02 Final Design
30.03 Heavy Maintenance Facility	80.03 Project Management for Design and Construction
30.04 Storage or Maintenance of Way Building	80.04 Construction Administration & Management
30.05 Yard and Yard Track	80.05 Professional Liability and other Non-Construction Insurance
40 SITEWORK & SPECIAL CONDITIONS	80.06 Legal; Permits; Review Fees by other agencies, cities, etc.
40.01 Demolition, Clearing, Earthwork	80.07 Surveys, Testing, Investigation, Inspection
40.02 Site Utilities, Utility Relocation	80.08 Start up
40.03 Haz. mat'l, contam'd soil removal/mitigation, ground water treatments	**90 UNALLOCATED CONTINGENCY**
40.04 Environmental mitigation, e.g. wetlands, historic/archeologic, parks	
40.05 Site structures including retaining walls, sound walls	**100 FINANCE CHARGES**

Figure 4.1: Standard Cost Categories (SCC)

Costs in SCC 90, Unallocated Contingency, and SCC 100, Financial Charges, are not considered in the top-down procedure. The remained categories should be carefully reviewed to identify all allocated contingencies and escalation. These contingencies and

escalation are removed from the estimate to arrive at the Base Cost Estimate (BCE) in each category which is not including contingency and escalation. The approach assumes that each cost category follows a lognormal distribution that can be identified by estimating the 10th and 90th percentile values of each cost component. The BCE is usually considered to be the 10th percentile of the lognormal distribution. The 90th percentile of the distribution is estimated from Eq. (4.1):

$$90^{th} \text{ Percentile of the Distribution} = \beta * 10^{th} \text{ Percentile of the Distribution} \qquad (4.1)$$

β is dependent on the level of risk in project delivery stages and ranges from 1.0 to 2.5 and above. A β value of 1.0 means that there is no risk associated with the BCE. The more the project progresses, the smaller the value of β. Having the 10th and 90th percentile of each cost components and using Lognormal Distribution equations, the mean and standard deviation of each cost component are calculated (Eqs. (4.2)-(4.7)). In these equations, μ and σ are parameters of the underlying normal distribution; mean and variance of the lognormal distribution are given in Eqs. (4.6) and (4.7).

$$x_a = \text{Optimistic Estimate} \% = \text{Cost of } 10^{th} \text{ Percentile in Each SCC} \qquad (4.2)$$

$$x_b = \text{Pesimistic Estimate} \% = \text{Cost of } 90^{th} \text{ Percentile in Each SCC} \qquad (4.3)$$

$$\mu = \frac{1}{2} Ln(x_a x_b) - \frac{[\phi^{-1}(a) + \phi^{-1}(b)]}{2} \sigma \qquad (4.4)$$

$$\sigma = Ln(\frac{x_a}{x_b}) / [\phi^{-1}(b) - \phi^{-1}(a)] \qquad (4.5)$$

$$Mean = e^{\mu + \sigma^2 / 2} \qquad (4.6)$$

$$Variance = e^{2\mu+\sigma^2}(e^{\sigma^2}-1) \tag{4.7}$$

The sum of these cost components that represents the total cost is calculated using the Central Limit Theorem and assuming normality for the sum of lognormal components. The cumulative distribution is formed once with the assumption that all cost categories are completely correlated, $r = 1.0$, and once with the assumption that there is no correlation, $r = 0$. Note that the assumption of normality is not correct when components are fully correlated. Indeed, it can be proven that the total will follow a lognormal distribution. A "First Order Approximation" distribution which is the final product of the proposed top-down approach is created by finding the one-third point of the total difference in variance between two aforementioned distributions. This process is applied at project cost components and several scenarios are run at the beginning of various project phases.

4.2.3 How to Assign β Values to Different SCCs at the Various Project Delivery Stages

Based on the historical data and lesson learned from previous transit projects, a set of recommended β values is suggested by PG-40. It is risk analyst's responsibility to find the most appropriate β factors to assign to each SCC considering the unique and specific characteristics of every project.

4.1 Requirement risks: those associated with definition of basic project needs and transit system requirements to meet those needs ($\beta \geq 2.5$);

4.2 Design risks: those involved with engineering design of the transit system ($2.5 > \beta \geq 2.0$);

4.3 Market risks: those associated with procurement of construction services and other system components $(2.0 > \beta \geq 1.75)$;

4.4 Construction risks: those associated with the actual construction of the systems $(1.75 > \beta \geq 1.05)$.

The guidelines provide specific β values to be applied to various Standard Cost Categories (SCC) of the transit project. The values of β may vary through project implementation at each key stage of project development. These recommendations would be used in the next section to assign the β's at three different stages of the project completion.

4.2.4   Applying the Top-down Model to U.S. Data

The value of β will vary from project to project and depending on the level of project development. As the project design progresses, the values of β tend to decrease. However, one can estimate an average β for the average transit project in the United States. The objective here is to calculate the average range for U.S. transit projects costs using the guidelines provided in PG-40. We have identified 51 transit projects in the U.S. (30 heavy rail and 21 light rail) for which actual costs were reported (Booz.Allen & Hamilton 2003 and 2004) according to SCC format. Using these cost data, the breakdown of costs for the average of these 51 transit projects are calculated for various cost categories. The result is illustrated in Figure 4.2.
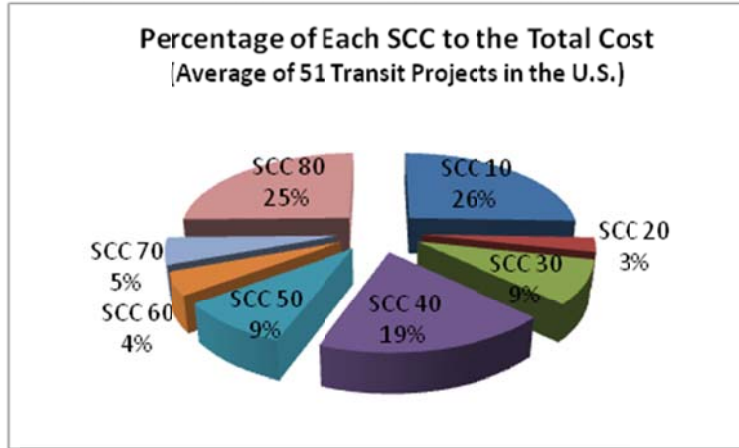
Figure 4.2: Percentage of Each SCC to the Total Cost

The β factors using the FTA recommendations are assigned for three different key phases of a project. These three phases are: Draft Environmental Impact Statement (DEIS), Preliminary Engineering (PE), and Final Design (FD). These phases are commonly used for transit project development in the U.S. and are roughly equivalent to Conceptual Design, Preliminary Engineering, and Final Design phases of a project development. These values are given in Table 4.1. It can be seen that following this procedure, for example at the PE stage, the average β value is 2.2. This means that the 90th percentile cost is more than twice as large as the 10th percentile cost.

Table 4.1: β Values Assigned to Each Cost Category at Three Key Phases of a Transit

Project

SCC	Average of 30 HRT Project	Average of 21 LRT Project	Average of 51 Transit Projects	% of Each SCC to Total Cost	Beta @DEIS	Beta @PE	Beta @FD
SCC 10	$191,915,256	$145,732,385	$172,660,755	25.55%	2.50	2.25	2.00
SCC 20	$20,763,234	$16,594,973	$19,427,829	2.88%	2.50	2.25	2.00
SCC 30	$61,752,584	$51,401,222	$58,640,064	8.68%	2.50	2.25	2.00
SCC 40	$179,590,760	$42,208,831	$125,482,165	18.57%	2.77	2.50	2.22
SCC 50	$62,638,602	$56,277,600	$61,219,753	9.06%	2.50	2.25	2.00
SCC 60	$26,399,332	$35,113,473	$30,587,258	4.53%	4.37	3.93	3.50
SCC 70	$38,409,454	$32,770,106	$36,809,117	5.45%	1.87	1.68	1.50
SCC 80	$198,569,935	$123,061,639	$170,827,849	25.28%	1.87	1.68	1.50
			Total		Weighted Average of Beta		
			$675,654,790	100%	2.44	2.20	1.96

For the average transit project, the 10th percentile is assumed to be the value of BCE and the 90th percentile is calculated using Eq. (4.1). Values of mean and standard deviation in each category are calculated using Eqs. (4.2)-(4.7).

Then, all SCCs are summed to generate Total Cost assuming independence and perfect correlation among cost BCEs. In both cases, following the FTA guide, the mean of the total cost is assumed to be a Normal distribution. The result is given in Table 4.2.

Table 4.2: 10th Percentile, 90th Percentile, Mean and Standard Deviation of Each Cost

Category

SCC	10th Percentile	DEIS Stage			PE Stage			FD Stage		
		90th Percentile	Mean	Std. Dev.	90th Percentile	Mean	Std. Dev.	90th Percentile	Mean	Std. Dev.
SCC 10	25.6%	63.9%	43.07%	15.90%	57.5%	40.30%	13.08%	51.1%	37.49%	10.33%
SCC 20	2.9%	7.2%	4.85%	1.79%	6.5%	4.53%	1.47%	5.8%	4.22%	1.16%
SCC 30	8.7%	21.7%	14.63%	5.40%	19.5%	13.69%	4.44%	17.4%	12.73%	3.51%
SCC 40	18.6%	51.4%	33.45%	13.84%	46.4%	31.30%	11.56%	41.2%	29.04%	9.26%
SCC 50	9.1%	22.7%	15.27%	5.64%	20.4%	14.29%	4.64%	18.1%	13.29%	3.66%
SCC 60	4.5%	19.8%	11.17%	7.00%	17.8%	10.35%	5.94%	15.8%	9.54%	4.96%
SCC 70	5.4%	10.2%	7.68%	1.90%	9.2%	7.21%	1.47%	8.2%	6.76%	1.08%
SCC 80	25.3%	47.3%	35.62%	8.83%	42.5%	33.45%	6.84%	37.9%	31.36%	4.99%
Total (Correlated)			165.73%	60.30%		155.12%	49.44%		144.43%	38.94%
Total (Independent)			165.73%	25.28%		155.12%	20.79%		144.43%	16.43%

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Following the top-down model process, cumulative normal distributions for each phase assuming completely correlated and independent are formed and the first order approximation curves are generated (Figure 4.3).
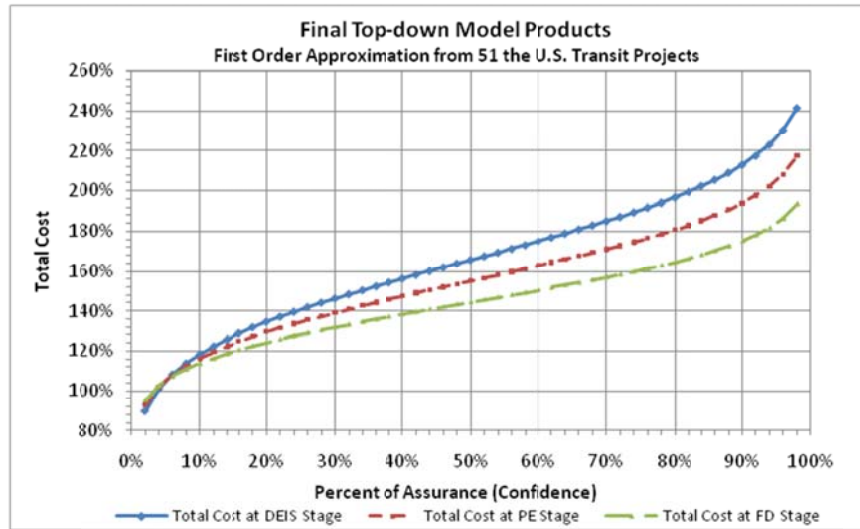
Figure 4.3: Final Top-down Model Curves (Total Required Budget) at Three Different Phases of a Transit Project

Using Figure 4.3, if an agency wants to establish project budget at the "Final Design" phase of a project, in order to have 85% confidence that the budget is sufficient, it should allocate a budget equal to 1.69 of initial cost estimate (Total BCEs). It should be noted that since in a transit project, a contingency budget is added to the Base Cost Estimate (BCE), and this contingency varies according to the project phase, the amount of uplift compared to the budgeted estimate should be smaller. For example, a typical contingency added to the BCE at the Final Design phase is about 10%. This means that according to the Optimism Bias Uplifts approach, this estimated budget should be increased by $1.69/1.1 = 1.54$ (or 54%). Since transit projects usually are costly, it means that the agency must provide and block a huge amount of money to ensure the sufficiency of budget. Figure 4.4 is a modified version

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of Figure 4.3. The X axis is converted to the "Acceptable Chance of Cost Overrun", 100% - Percent of Assurance (Confidence), and Y axis to "Required Uplift" (or the amount needed to be added to the base cost), Total Cost - 100%. This modification was done to make Figure 4.4 similar to the final product of British Department for Transport (Optimism Bias Uplifts) Model. We will be comparing the outcome of this analysis with the British approach later in this chapter. As an example, increasing the base budget by 69% (at the Final Design phase), will mean that there is a 15% chance that the budget would not be sufficient, *i.e.,* there will be a cost overrun.
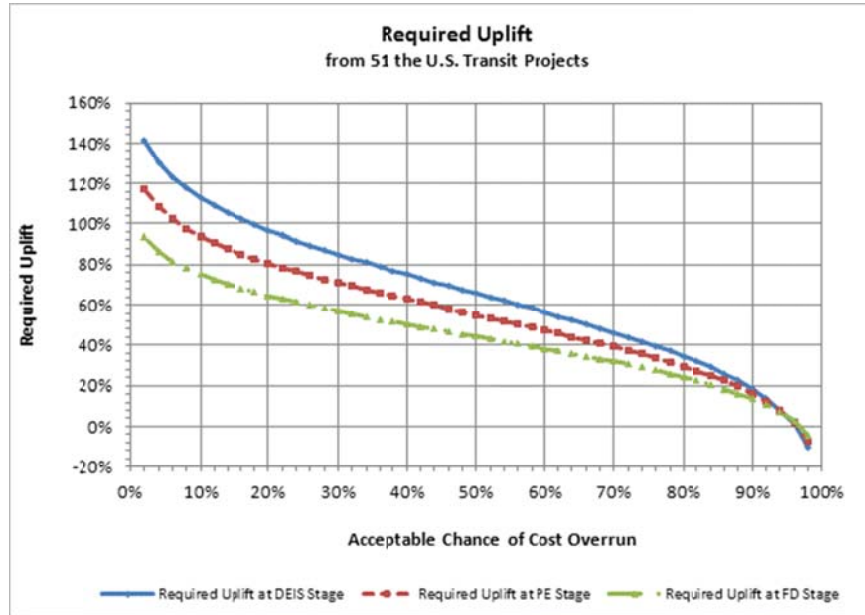
Figure 4.4: Converted Curves of the Top-down Model to Show the Required Uplift

4.3   The British Department for Transport (Optimism Bias Uplifts) Model

4.3.1   Optimism Bias Uplifts Model Background

The second approach examined for this research is the British Department for Transport approach in dealing with optimism bias in capital project cost estimates. This approach is based on work done by Flyvbjerg and COWI (2004) and reported by Flyvbjerg (2006). According to Flyvbjerg *et al* (2002; 2005) and Flyvbjerg (2006), psychological (optimism bias) and political explanations (strategic misrepresenting due to political and organizational pressure) are responsible for much of the inaccuracy in transportation cost forecasting. Reference class forecasting method is based on theories of decision-making under uncertainty. "Reference class forecasting does not try to forecast the specific uncertain events that will affect the particular project, but instead places the project in statistical distribution of outcomes from the class of reference projects." (Flyvbjerg 2006).

According to *Supplementary Green Book* (HM Treasury 2003): "There is a demonstrated, systematic tendency for project appraisers to be overly optimistic. To redress this tendency, appraisers should make explicit, empirically based adjustments to the estimates of a project's costs, benefits, and duration… It is recommended that these adjustments be based on data from past projects or similar projects elsewhere". To this end, the British Department for Transport (DfT) and HM Treasury published a guide: "Procedures for dealing with Optimism Bias in Transport Planning" based on the work conducted by Flyvbjerg and COWI to establish a guide for selected reference classes of transport infrastructure projects to prevent cost overrun. This approach is hereafter called "Optimism Bias Uplifts Model" method in this research.

4.3.2   The Optimism Bias Uplifts Model Methodology

In the DfT guide, transportation projects have been divided into a number of distinct groups. These groups include road, rail, fixed links, buildings, and IT projects and have been selected in order to have statistically similar risk of cost overrun based on the study of an international database of 260 transportation projects. In this chapter, we are interested in rail projects because the transit projects that we analyzed for the U.S. case were almost exclusively rail projects.

In the DfT guide, cost overrun is defined as the difference between actual cost (final cost) and estimated costs which is the forecasted costs at the time of approval of/decision to build a project in percentage of estimated costs. Where the approval point is not clear in the project planning process, the closest available estimate is used. For each category, the probability distribution for cost overrun as the share of projects with a given maximum cost overrun was created. Having established the empirical cumulative probability distribution, uplifts are set up as a function of the level of risk that the DfT is willing to accept regarding cost overrun. "Uplift" is the term used to show the amount that the original estimate needs to be increased to arrive at the project budget for a given level of certainty with respect to cost adequacy. If the DfT wants to accept a higher risk, then a lower uplift is required. The readers are referred to the British DfT (2004) and Flyvbjerg (2006) for a thorough description of the Optimism Bias Uplifts methodology.

4.3.3   Applying Optimism Bias Uplifts Model to U.S. Data

To generate a reference class, 22 transit projects across the U.S. were selected. The objective here is to apply the Optimism Bias Uplifts Model approach to these projects and then compare the results with the results of applying the USDOT approach to the same data. These projects were part of a study conducted under a research project where the co-author was a team member of the research group (Booz.Allen 2005). As part of this research effort, cost overruns for 22 major transit projects were calculated considering estimated budgets at various stages of these projects. For each project, the cost overrun/underrun was calculated at the DEIS, PE, and FD stages by comparing these estimates with actual cost of projects. Although, DfT calculates the cost overrun relative to the estimate at the point of approval of/decision to build, in order to compare FTA and DfT models, here cost overrun has been calculated at: DEIS, PE, and FD stages. PE can be considered equivalent to the time that British agencies prepare their initial budgets. In this way, we can compare these two models. It should be noted that the main criteria in selecting these 22 projects for inclusion in the original study was the availability of data. In other word, the research team was not trying to identify and select projects that were notorious for cost overrun or delay. Following the abovementioned process, the cumulative probability distribution for cost overrun as the percentage of projects with a given maximum cost overrun is formed (Figure 4.5); then the required uplift curve is calculated (Figure 4.6).
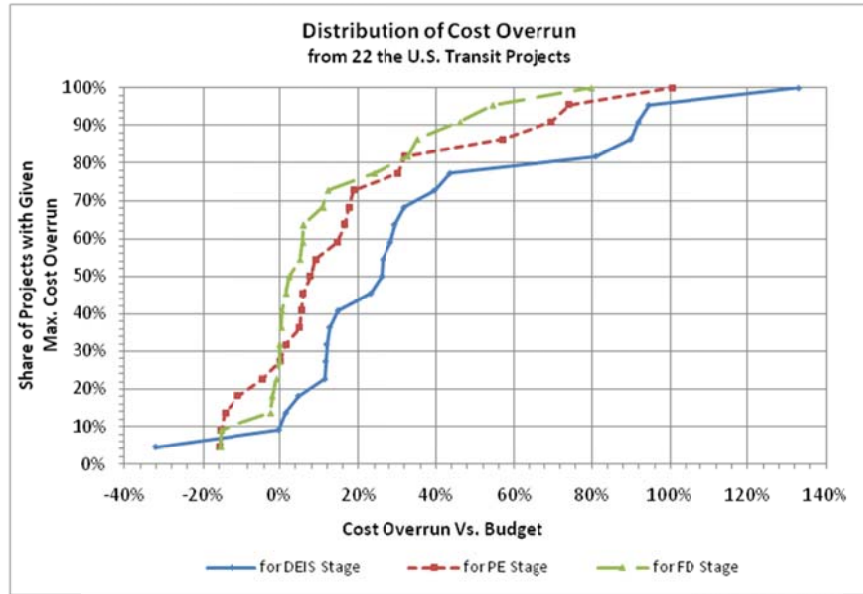
Figure 4.5: Probability Distribution of Cost Overrun at Three Different Stage of a Project
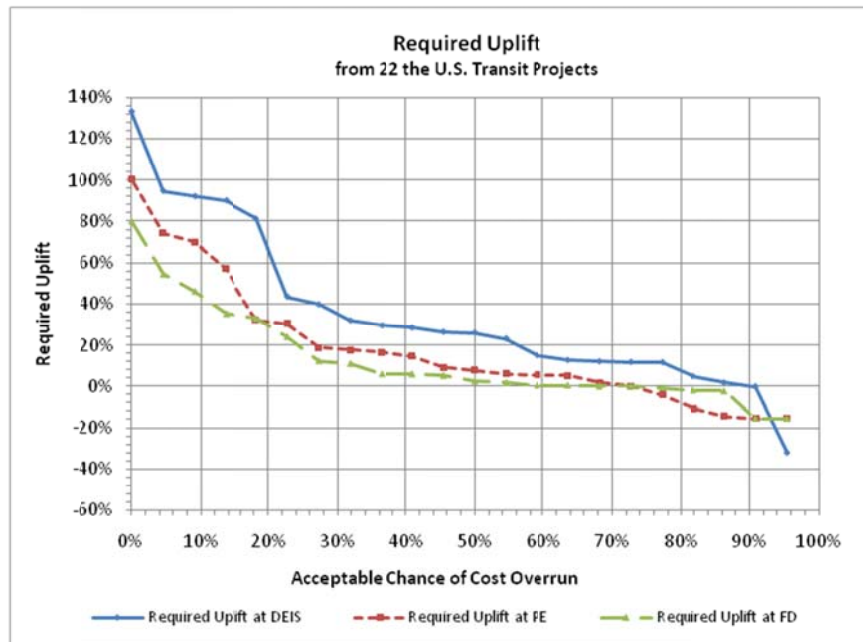
Figure 4.6: Required Uplifts at Three Different Stages of a Project

Figure 4.6 illustrates that based on the selected U.S. projects, if a transit agency decides to apply the method suggested by the DfT and to accept a 10% chance of cost overrun for its project, the required uplift is 91.61% at the DEIS phase, 67.36% at the PE phase, and

44.01% at the FD phase. It demonstrates that the more project progresses, due to the decreasing level of uncertainty, the less uplift is required.

4.5 Comparison of Top-down and Optimism Bias Uplifts Models

In previous sections, we applied two different probabilistic approaches to a group of transit projects in the U.S. Although, the Optimism Bias Uplifts approach used in the U.K. only considers the cost estimate at the approval of/decision to built stage of a project to calculate cost overrun, in order to evaluate β values of top-down model used in the U.S., we have calculated cost overrun at three phases of DEIS, PE, and FD. Comparing Figure 4.4 and Figure 4.6 shows that required uplift for 50% confidence at PE stage is 55.12% with top-down model and 7.70% with the Optimism Bias Uplifts approach. Table 4.3 lists the required uplift with 50% confidence at three stages of the project with two approaches.

Table 4.3: Required uplift with 50% Acceptable Chance of Cost Overrun with Two Approaches

Model	Required Uplift with 50% Confidence		
	DEIS	PE	FD
Top-Down approach	65.73%	55.12%	44.43%
Optimism Bias Uplifts approach	25.96%	7.70%	2.37%

Comparing these results show that the top-down approach established a much larger budget for the project. It should be realized that establishing too conservative a budget is not necessarily desirable because by tying excessive funds for projects, other candidate projects

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will be deprived of the necessary funds. From top-down Methodology, we remember that β is defined as the ratio between 90th percentile and 10th percentile of the cumulative cost distribution. So using data in Figure 4.5, we can construct equivalent β values for the Optimistic Bias approach by calculating the ratio between the 10th and 90th percentile points. In Table 4.4, the calculated β values are compared with weighted average of β values recommended by the top-down model (computed in Table 4.1).

Table 4.4: Comparison of the β Values in Two Approaches

Key Stages	Optimism Bias Uplifts			Top-down
	10th Percentile	90th Percentile	β	Weighted Average β
DEIS	1.001	1.916	1.91	2.44
PE	0.847	1.674	1.97	2.20
FD	0.872	1.440	1.65	1.96

As stated before, reviewing Table 4.4 shows that β values from Optimism Bias Uplifts approach where the data come from historical data are significantly smaller than the β recommended by the top-down approach. Looking at β s for Optimism Bias Uplifts approach illustrates that the values of β at PE stage is greater than DEIS where it should be normally smaller. This anomaly might be due to the nature of the projects in the sample and the relative small sample size. This is due to the greater number of projects that have had cost underrun at the PE stage possibly due to scope reduction.

4.6   Conclusion

Optimism Bias Uplifts and top-down approaches are suggested (and used) for transit project development in the U.S. and the U.K. Both these approaches have positive and negative aspects. First, the top-down model selects large values of β in order to prevent cost overrun which results in establishing a budget far larger than historical actual costs. Optimism Bias Uplifts approach is based on historical data but does not consider unique features and characteristic of individual projects. It gives an estimate of the actual cost based on a set of peer projects without considering the location and special condition of each projects. The positive aspect of both approaches is the explicit consideration of uncertainty in cost estimating and budgeting.

Our suggestion is to refine these approaches and come up with a probabilistic method that considers the unique characteristics of each project without tying up huge capital in order to prevent potential cost overruns. In this response, in the next chapter, we will develop a probabilistic model that calculates the required contingency budget for a portfolio of projects on top of the allocated contingency for individual projects.

CHAPTER 5: A HYBRID NORMAL MODEL FOR CALCULATING CONTINGENCY IN A PORTFOLIO OF PROJECTS

5.1   Introduction

As we discussed in the previous chapters, notwithstanding of all efforts and evolving new probabilistic methods to allocate sufficient and optimum contingency budget for capital projects, the research shows that cost overrun is still plaguing these projects. For instance in Chapter 4, it was shown that the FTA currently employs an approach that results in too large a contingency budget. Having too much contingency can be just as undesirable as insufficient contingency, especially where the agency is dealing with a portfolio of projects rather than a single project. Allocation of large contingencies will use up the agency's budget that can be spent on funding other projects and will reduce the number of projects that may receive funding.

In dealing with a portfolio of infrastructure projects, an agency should usually define the level of confidence γ for the portfolio budget based on available funding and the agency's policy goals (Touran 2006a). However, defining the required level of confidence η for conducting risk assessment at the individual project level is an important task in order to insure that the portfolio budget will not fall short with a probability of more than $1-\gamma$. Touran (2006a) suggested a mathematical model for establishing a minimum portfolio budget assuming a shifted exponential distribution for each project cost in the portfolio. It

did not include project cost correlations and this could underestimate the level of contingency calculated.

In response to imperfections associated with current contingency allocation methods, in this chapter, a new probabilistic model for contingency allocation in a portfolio of construction projects is proposed. The proposed model assumes a hybrid normal distribution for the cost of individual projects and uses the available historical data for initializing and calculating the primary parameters of the model. It estimates the required increase in the budget of portfolio in such a way to meet the agency goals with respect individual projects and the project portfolio. This is a dynamic models meaning that it is updated when the information of newly completed project becomes available. To this end, a Bayesian approach is employed to update the model based on the recently completed projects' performances on regular intervals, such as once every two years. It is expected that the required increase (or decrease) in portfolio budget will be diminished over the course of time by doing updating process. It is because the accuracy of estimating the contingency is improved. As an advantage of the model to be more accurate, correlation among the projects in the portfolio is recognized and accommodated in the proposed analytical model and Bayesian updating process. The basis of the model and updating procedure is developed in the current chapter. The suggested method to estimate the correlation between costs of projects will take up in the next chapter. Then in Chapter 7, the application and verification of the model is presented using a numerical example.

5.2 Basis of the Proposed Model

Even though the emphasis of this model is on transit projects, it is a mathematically flexible model that can be applied on any type of construction project.

To form truncated normal distribution of cost for each project, it is assumed that the probability of experiencing underrun m is α as the discrete portion of distribution. m is an arbitrary number based upon agency's objectives and α can be determined by reviewing the historical cost overruns/underruns. Figure 5.1 illustrates the hybrid normal $X \sim N(\mu', \sigma')$, where the normal component of the distribution is $N(\mu, \sigma)$.
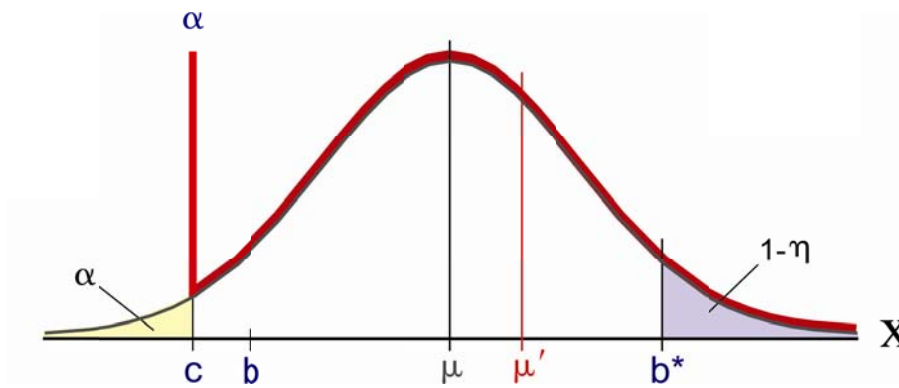
Figure 5.1: Hybrid Normal Distribution

We presume that there is a database of construction projects comprising of $i = 1, ..., n$ projects with the initial budget of b_i. It is found through this historical data that there is $\alpha\%$ chance to have m percent underrun and get the project done with $c_i = (1-m)b_i$. The model is constructed using the following parameters:

$b_i = $ Initial budget allocated for project i;

$x_i = $ Actual cost of project i;

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m = The maximum expected underrun;

c_i = Minimum expected project i cost which is $(1-m)b_i$;

α = Percent of projects in the historical data having underrun more than or equal to m;

δ = Cost overrun/underrun;

$\overline{\delta}$ = Average of cost overruns/underruns in the historical data;

$\overline{\sigma}$ = Standard deviation of cost overruns/underruns in the historical data;

β = Average rate of cost overrun/underrun relative to b which is $1+\overline{\delta}$;

ρ = Average rate of cost overrun/underrun relative to c which is $\beta/(1-m)$;

μ_i = Mean of underlying normal distribution in project i;

σ_i = Standard deviation of underlying normal distribution in project i;

μ_i' = Mean of hybrid normal distribution in project i;

σ_i' = Standard deviation of hybrid normal distribution in project i;

φ = A constant coefficient which is equal to σ_i'/c_i;

b_i^* = Revised budget of project i;

B = Sum of all individual initial budgets, $\sum b_i$;

η = Percent of confidence that individual projects' cost will not be more than b^*;

B^* = Sum of all revised individual budgets based on η, $\sum b_i^*$;

γ = Probability that portfolio of projects' cost will not be more than B^*;

Project cost X_i is defined as follows:

$$\begin{cases} P(X_i < c_i) = 0 \\ P(X_i = c_i) = \alpha \\ P(X_i > c_i) = 1 - \alpha \end{cases} \tag{5.1}$$

The Probability Distribution Function (PDF) which is a hybrid normal distribution is:

$$\begin{cases} f(x) = \alpha & for\ x_i \leq c_i \\ f(x) = \dfrac{1}{\sqrt{2\pi}\sigma_i} . e^{\frac{-(x_i - \mu_i)^2}{2\sigma_i^2}} & for\ x_i > c_i \end{cases} \tag{5.2}$$

The mean μ' and standard deviation σ' of hybrid normal can be calculated using the following equations (Walpole *et al* 2007):

$$\mu_i' = E(X_i) = \alpha.c_i + x_i \times \int_{c_i}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_i} . e^{\frac{-(x_i - \mu_i)^2}{2\sigma_i^2}} dx_i = \alpha.c_i + (1-\alpha).\mu_i + \frac{\sigma_i}{\sqrt{2\pi}} . e^{\frac{-[\Phi^{-1}(\alpha)]^2}{2}} \tag{5.3}$$

$$\begin{aligned} \sigma_i'^2 &= E(X_i^2) - \mu_i'^2 = \alpha.c_i^2 + x^2{}_i \times \int_{b_i}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_i} . e^{\frac{-(x_i - \mu_i)^2}{2\sigma_i^2}} dx_i - \mu_i'^2 \\ &= \alpha.c_i^2 - \mu_i'^2 + \frac{\sigma_i}{\sqrt{2\pi}} . [\sigma_i.\Phi^{-1}(\alpha) + 2\mu_i]. e^{\frac{-[\Phi^{-1}(\alpha)]^2}{2}} + (1-\alpha).(\sigma_i^2 + \mu_i^2) \end{aligned} \tag{5.4}$$

Where:

$$\Phi^{-1}(\alpha) = \frac{c_i - \mu_i}{\sigma_i} \tag{5.5}$$

is the inverse of cumulative function for standard normal distribution. β is the average rate of cost overruns/underruns and can be calculated from the historical data as:

$$\beta = 1 + \overline{\delta} = 1 + \frac{1}{n}.\sum_{i=1}^{n} \frac{x_i - b_i}{b_i} \tag{5.6}$$

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In other words:

$$\mu_i' = \beta.b_i \qquad (5.7)$$

Also, we can define:

$$\mu_i' = \rho.c_i \qquad (5.8)$$

and knowing that $c_i = (1-m).b_i$, we have:

$$\mu_i' = \beta.b_i = \rho.c_i \rightarrow \rho = \frac{\beta.b_i}{c_i} \quad \Rightarrow \quad \rho = \frac{\beta}{1-m} \qquad (5.9)$$

By rearranging Eq. (5.5), mean of the underlying distribution is:

$$\mu_i = c_i - \sigma_i.\Phi^{-1}(\alpha) \qquad (5.10)$$

By substituting Eq. (5.10) and (5.8) in Eq. (5.3) and rearranging, the standard deviation of underlying distribution is found:

$$\sigma_i = \frac{(1-\rho).(1-m).b_i}{(1-\alpha).\Phi^{-1}(\alpha) - \dfrac{e^{\frac{-[\Phi^{-1}(\alpha)]^2}{2}}}{\sqrt{2\pi}}} \qquad (5.11)$$

Reviewing Eq. (5.4) shows that all terms of $\sigma_i'^2$ are comprised of a constant coefficient times c_i^2. Therefore, $\sigma_i'^2$ can be written in the form of:

$$\sigma_i'^2 = \varphi^2.c_i^2 \xrightarrow{\ or\ } \sigma_i' = \varphi.c_i \qquad (5.12)$$

Where φ is a constant coefficient for all values of σ_i' and c_i and using Eq. (5.4) and (5.12), it can be computed. Referring to Figure 5.1, if a budget $b_i^* > b_i$ for each project is selected, the chance of shortfall of budget would be limited to η. So:

$$P(X_i \le b_i^*) = F(b_i^*) = \alpha + \Phi(\frac{b_i^* - \mu_i}{\sigma_i}) - \Phi(\frac{c_i - \mu_i}{\sigma_i}) = \alpha + \Phi(\frac{b_i^* - \mu_i}{\sigma_i}) - \alpha = \eta \quad (5.13)$$

If we rearrange Eq. (5.13), we obtain:

$$b_i^* = \mu_i + \sigma_i.\Phi^{-1}(\eta) \tag{5.14}$$

We know that the original portfolio budget is:

$$B = \sum b_i = \sum \frac{c_i}{(1-m)} = \frac{1}{(1-m)}\sum c_i \xrightarrow{Then} \sum c_i = (1-m).B \tag{5.15}$$

Using Eq. (5.14), (5.15) and substituting μ_i by Eq. (5.10), the new portfolio budget can be computed as follows:

$$\begin{aligned}B^* &= \sum b_i^* = \sum[\mu_i + \sigma_i.\Phi^{-1}(\eta)] = \sum[c_i - \sigma_i.\Phi^{-1}(\alpha)] + \sum[\Phi^{-1}(\eta).\sigma_i] \\ &= (1-m).B + [\Phi^{-1}(\eta) - \Phi^{-1}(\alpha)].\sum \sigma_i\end{aligned} \tag{5.16}$$

Substituting Eq. (5.11) in Eq. (5.16), the ratio of B^* / B is found as follows:

$$\frac{B^*}{B} = (1-m).\left[1 + \frac{(1-\rho).[\Phi^{-1}(\eta) - \Phi^{-1}(\alpha)]}{(1-\alpha).\Phi^{-1}(\alpha) - \dfrac{e^{\frac{-[\Phi^{-1}(\alpha)]^2}{2}}}{\sqrt{2\pi}}}\right] \tag{5.17}$$

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Now, we assume that the total cost of all projects in the portfolio is T. If we consider that all projects in the portfolio are *independent*, then T based upon Central Limit Theorem will follow an approximate normal distribution with the mean μ_T and the variance σ_T^2 as follows:

$$T = \sum X_i \xrightarrow{\;CLT\;} T \sim N(\mu_T, \sigma_T^2) \tag{5.18}$$

$$\mu_T = \sum \mu_i' = \sum (\rho.c_i) = \rho.(1-m).B \tag{5.19}$$

$$\sigma_T^2 = \sum \sigma_i'^2 = \sum (\varphi.c_i)^2 = \varphi^2.\sum c_i^2 \xrightarrow{\;Then\;} \sigma_T = \varphi.\sqrt{\sum c_i^2} \tag{5.20}$$

However, sometime projects in the portfolio are highly correlated and by ignoring the correlation, we will underestimate the results. The correlation becomes more important here since we are dealing with a portfolio of projects funding with the same agency and somewhat similar characteristics (such as being contemporaneous and all being transit projects). This magnifies the importance of correlation.

When there is correlation among the projects μ_T will not change and can be calculated using Eq. (5.19), but σ_T^2 will be different. The distribution of total cost is no longer a normal distribution. If all projects are perfectly correlated ($\rho = 1.0$) then the total cost has the distribution of each single projects which is a hybrid normal here. However, assumption of normality is a good approximation for the total cost especially for small correlation values. To calculate the variance of total cost of projects where they are correlated, we have:

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$$\sigma_T^2 = \sum \sigma'^2_i + 2\sum_{i<j}\sum_j \rho_{ij}\sigma'_i\sigma'_j = \sum (\varphi.c_i)^2 + 2\sum_i\sum_j \rho_{ij}(\varphi.c_i).(\varphi.c_j) \xrightarrow{\text{Then}}$$

$$\sigma_T = \varphi.\sqrt{\sum c_i^2 + 2\sum_{i<j}\sum_j \rho_{ij}c_i c_j} \tag{5.21}$$

Defining γ as the percent of confidence that portfolio of projects cost will not be more than

B^*, we have:

$$P(T < B^*) = \Phi(\frac{B^* - \mu_T}{\sigma_T}) = \gamma \tag{5.22}$$

Rearranging Eq. (5.21) and using Eq. (5.19) and (5.21), we have:

$$\Phi^{-1}(\gamma) = \frac{B^* - \mu_T}{\sigma_T} \xrightarrow{\text{Then}} \frac{B^*}{B} = \rho.(1-m) + \frac{\varphi.\Phi^{-1}(\gamma)}{B}.\sqrt{\sum_{i=1}^n c_i^2 + 2\sum_{i<j}^n\sum_j^n \rho_{ij}c_i c_j} \tag{5.23}$$

By equating Eqs. (5.17) and (5.23), one can find the γ values for different η values as

follows:

$$\gamma = \Phi\left\{\frac{(1-m).(1-\rho).B}{\varphi.\sqrt{\sum_{i=1}^n c_i^2 + 2\sum_{i<j}^n\sum_j^n \rho_{ij}c_i c_j}}\left[1 + \frac{[\Phi^{-1}(\eta) - \Phi^{-1}(\alpha)]}{(1-\alpha).\Phi^{-1}(\alpha) - \frac{e^{\frac{-[\Phi^{-1}(\alpha)]^2}{2}}}{\sqrt{2\pi}}}\right]\right\} \tag{5.24}$$

Rearranging Eq. (5.24) gives:

$$\eta = \Phi\left\{\Phi^{-1}(\alpha) + \left[(1-\alpha).\Phi^{-1}(\alpha) - \frac{e^{\frac{-[\Phi^{-1}(\alpha)]^2}{2}}}{\sqrt{2\pi}}\right]\left[\frac{\varphi.\sqrt{\sum_{i=1}^{n}c_i^2 + 2\sum_{i<j}^{n}\sum_{j}^{n}\rho_{ij}c_ic_j}.\Phi^{-1}(\gamma)}{(1-m).(1-\rho).B} - 1\right]\right\}$$

$$(5.25)$$

If we assume that we have n identical projects, Eq. (5.24) and (5.25) can be rewritten as follows:

$$\gamma = \Phi\left\{\frac{(1-\rho).n}{\varphi.\sqrt{n+2\sum_{i<j}^{n}\sum_{j}^{n}\rho_{ij}}}\left[1 + \frac{[\Phi^{-1}(\eta) - \Phi^{-1}(\alpha)]}{(1-\alpha).\Phi^{-1}(\alpha) - \frac{e^{\frac{-[\Phi^{-1}(\alpha)]^2}{2}}}{\sqrt{2\pi}}}\right]\right\}$$

$$(5.26)$$

$$\eta = \Phi\left\{\Phi^{-1}(\alpha) + \left[(1-\alpha).\Phi^{-1}(\alpha) - \frac{e^{\frac{-[\Phi^{-1}(\alpha)]^2}{2}}}{\sqrt{2\pi}}\right]\left[\frac{\varphi.\Phi^{-1}(\gamma).\sqrt{n+2\sum_{i<j}^{n}\sum_{j}^{n}\rho_{ij}}}{(1-\rho).n} - 1\right]\right\}$$

$$(5.27)$$

Flowchart shown in Figure 5.2 illustrates the procedure of how to employ the proposed model.

Budget Contingency in a Portfolio of Projects
Using Hybrid Normal Distribution

Historical Data

Decide on the maximum expected underrun (m)

Using dataset, find the percent of projects (α) having actual costs of less than (1-m)*b

Using dataset, find the average rate of cost overrun (β) where $\mu'=\beta*b$, Eq. (5.6)

Calculations

Compute B*/B for different ηs using Eq.(5.17)

Compute η for different levels of γ, using Eq. (5.25)

Compute φ, a constant coefficient which is equal σ'/b, using Eqs. (5.4) and (5.12)

Calculate the average rate of cost overrun relative to c, using: $\rho=\beta/(1-m)$ where $\mu'=\rho'c$, Eq. (5.8)

Analysis

Constructing B*/B and η for different levels of γ, an agency can find the required amount of additive budget for portfolio of projects in order to be γ% confident that there would be no budget shortfall for portfolio and η% for individual projects

Bayesian Updating

Collecting newly completed projects' cost overruns/underruns, δ

Updating the average of cost overrun/underrun using Bayesian approach, Eq. (5.40) or Eqs. (5.45) and (5.46)

Calculating new α and β using Eqs. (5.47) and (5.48)

Parameters Description

b_i = Initial budget allocated for project i;

x_i = Actual cost of project i;

m = The maximum expected underrun;

c_i = Minimum expected project i cost which is $(1-m).b_i$;

α = Percent of projects in the historical data having underrun more than or equal to m;

δ = Cost overrun/underrun;

$\bar{\delta}$ = Average of cost overruns/underruns in the historical data;

$\bar{\sigma}$ = Standard deviation of cost overruns/underruns in the historical data;

β = Average rate of cost overrun/underrun relative to b which is $1+\bar{\delta}$;

ρ = Average rate of cost overrun/underrun relative to c which is $\beta/(1-m)$;

μ_i = Mean of underlying normal distribution in project i;

σ_i = Standard deviation of underlying normal distribution in project i;

μ'_i = Mean of hybrid normal distribution in project i;

σ'_i = Standard deviation of hybrid normal distribution in project i;

φ = A constant coefficient which is equal to σ'_i/c_i;

b_i^* = Revised budget of project i;

B = Sum of all individual initial budgets, $\sum b_i$;

η = Percent of confidence that individual projects' cost will not be more than b_i^*;

B^* = Sum of all revised individual budgets based on η, $\sum b_i^*$;

γ = Probability that portfolio of projects' cost will not be more than B^*;

Figure 5.2: Procedure for Applying the Proposed Model

5.3   Bayesian Approach for Updating the Model

An agency employing the proposed model is expected to experience less cost overrun in the newly funded projects. Since the model has been constructed based on limited observed

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data, it can help decrease the level of overrun/underrun and is not expected to eradicate the overruns in the first attempt. Therefore the model needs to be updated in a yearly or biyearly basis depending on the number of completed projects. To this end, a Bayesian updating approach is proposed to update the model as the information regarding the costs of new projects becomes available. The Bayesian approach helps by using the new data to augment historical data to arrive at revised, more accurate predictions.

The Bayesian approach systematically combines the prior knowledge as to a fact and recent observations and helps the analyst make decision using all source of available information. Using Bayesian, even subjective judgments based on intuition, experience, or indirect information can be integrated formally with observations to make interference. This is something which is not possible in classical statistical approach which uses sample statistics as the estimator of parameters. The Bayesian probability of an event A, signifies the degree of belief or confidence in that event's occurrence based on prior information and observed data whereas classical probability refers to the actual probability of the event and is not concerned with observed behavior.

Ang and Tang (2007) identifies two broad source of uncertainties: 1. Aleatory and 2. Epistemic. The aleatory uncertainty is associated with the inherent variability of information (being intrinsically unpredictable) and the epistemic uncertainty is associated with imperfections in our knowledge or capability to make prediction. Only aleatory uncertainty is acknowledged in classical statistics, whereas the Bayesian approach encompasses both kinds of uncertainty equally well. The Bayesian approach systematically updates existing aleatory and epistemic uncertainties as new data for each type becomes available.

All in all, the Bayesian approach for updating the proposed model will benefit the agency by using all available information in a systematic way. It brings into consideration new observations that become available one by one whereas the other methods just consider the overall mean and standard deviation of sample.

5.3.1 Fundamental of Bayesian Approach

Let us suppose that the possible values of a parameter θ are a set of discrete values $\theta_i = 1, 2, ..., k$ with prior relative likelihoods $p_i = P'(\Phi = \theta_i)$. Also, ε denotes the observed outcome of the experiment. Now, the prior assumptions on parameter θ may be modified formally through the Bayes' theorem. The Bayesian approach in discrete cases is defined as (Ang and Tang 2007):

$$P''(\Theta = \theta_i) = \frac{P(\varepsilon|\Theta = \theta_i)P'(\Theta = \theta_i)}{\sum\limits_{i=1}^{k} P(\varepsilon|\Theta = \theta_i)P'(\Theta = \theta_i)} \tag{5.28}$$

Where:

$P(\varepsilon|\Theta = \theta_i)$ is the likelihood of the experimental outcome ε if $\Theta = \theta_i$, that is the conditional probability of obtaining a particular experimental outcome assuming that the parameter is θ_i.

$P'(\Theta = \theta_i)$ is the prior probability of $\Theta = \theta_i$, that is prior to the availability of the experimental information ε.

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$P''(\Theta = \theta_i) = P(\Theta = \theta_i | \varepsilon)$ is the posterior probability of $\Theta = \theta_i$, that is the probability that has been revised in light of the experimental outcome ε.

Extending Eq. (5.28) to continuous cases, assume that Φ is the random variable for the parameter of a distribution whose prior distribution (PDF) is $f'(\theta)$. The probability that Φ will be between θ_i and $\theta_i + \Delta\theta$ is $f'(\theta_i).\Delta\theta$. Figure 5.3 illustrates the distribution of θ. Again assume that ε is an observed experimental outcome and the prior distribution $f'(\theta)$ can be modified with this extra information employing the Bayes' theorem. Therefore the probability of having θ_i between θ_i and $\theta_i + \Delta\theta$ in light of the new observation ε is (Ang and Tang 2007):

$$f''(\theta_i).\Delta\theta = \frac{P(\varepsilon|\theta_i).f'(\theta_i).\Delta\theta}{\sum_{i=1}^{k} P(\varepsilon|\theta_i).f'(\theta_i).\Delta\theta} \qquad (5.29)$$
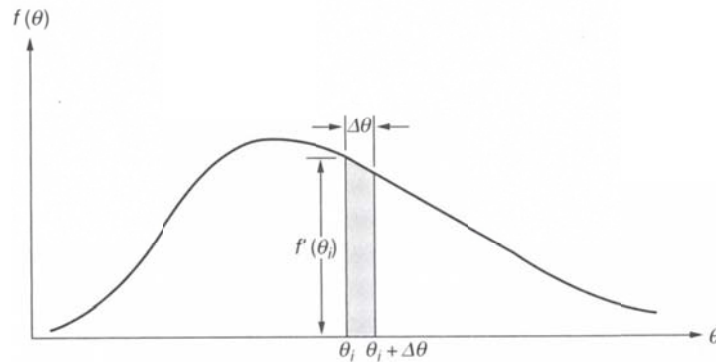
Figure 5.3: Prior Distribution of Parameter θ (Ang and Tang 2007)

Where $P(\varepsilon|\theta_i) = P(\varepsilon|\theta_i < \theta \leq \theta_i + \Delta\theta)$. In the limit, Eq. (5.29) becomes:

$$f''(\theta_i) = \frac{P(\varepsilon|\theta).f'(\theta)}{\int_{-\infty}^{\infty} P(\varepsilon|\theta).f'(\theta)d\theta} \qquad (5.30)$$

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In Eq. (5.30) $P(\varepsilon|\theta)$ is the likelihood of observing the outcome ε where the value of distribution parameter is θ. Hence $P(\varepsilon|\theta)$ is a function of θ and is known as the likelihood function. The denominator is independent of θ and is just a constant to normalize the equation in order to make the $f''(\theta)$ a proper PDF. So, Eq. (5.30) can be rewritten as:

$$f''(\theta) = k.L(\theta).f'(\theta) \qquad (5.31)$$

Where:

$$k = [\int_{-\infty}^{\infty} P(\varepsilon|\theta).f'(\theta)d\theta]^{-1} \text{ is the normalizing constant;} \qquad (5.32)$$

$L(\theta) = $ the likelihood of observing the experimental outcome ε assuming a given θ, the parameter of the distribution.

Eq. (5.31) can be used to update the proposed model in the light of new information acquired through newly completed projects in a certain period of time. Here θ is considered to be the average of cost overruns/underruns $(\bar{\delta})$ required to calculate the parameters β and ρ of the model. Eq. (5.31) can be rewritten as follows:

$$f''(\bar{\delta}) = k.L(\bar{\delta}).f'(\bar{\delta}) \qquad (5.33)$$

5.3.2   Bayesian Approach for k Independent Projects

Let's presume that k new projects are completed. Assuming these k new projects with the cost overrun/underrun of δ_j are completely independent of each other, the probability of

observing $\delta_1, ..., \delta_k$ coming from a population Δ having an underlying normal distribution $N_\Delta(\overline{\delta}, \overline{\sigma})$ with the mean of $\overline{\delta}$ and the known standard deviation of $\overline{\sigma}$ is:

$$P(\delta_j = \delta_1, ..., \delta_k | \overline{\delta}) = \prod_{j=1}^{k} N_\Delta(\delta_j | \overline{\delta}, \overline{\sigma}).d(\delta) \qquad (5.34)$$

Since we do not know the standard deviation of the population, $\overline{\sigma}$ is assumed to be the standard deviation of cost overruns/underruns of k observed projects σ. Therefore, the likelihood function can be written as:

$$L(\overline{\delta}) = \prod_{j=1}^{k} N_\Delta(\delta_j | \overline{\delta}, \overline{\sigma}) = \prod_{j=1}^{k} \frac{1}{\sqrt{2\pi}.\sigma} \exp\left[-\frac{1}{2}.\left(\frac{\delta_j - \overline{\delta}}{\sigma} \right)^2 \right] \qquad (5.35)$$

It should be noted that Eq. (5.35) is the product of k PDFs of normal distributions which is the function of $\overline{\delta}$. It is known that the product of k normal PDFs with means μ_i and standard deviations σ_i is also a normal PDF with the mean μ_L and standard deviation σ_L as follows (Bolstad 2007):

$$\begin{cases} \mu_L = \dfrac{\displaystyle\sum_{i=1}^{k} (\mu_i / \sigma_i^2)}{\displaystyle\sum_{i=1}^{k} 1/\sigma_i^2} \\ \sigma_L = \dfrac{1}{\sqrt{\displaystyle\sum_{i=1}^{k} 1/\sigma_i^2}} \end{cases} \qquad (5.36)$$

Hence, the likelihood function can be written as:

$$L(\overline{\delta}) \propto N\left(\delta_L, \sigma_L\right) = N\left(\frac{\sum_{j=1}^{k}\left(\delta_i / \sigma^2\right)}{\sum_{j=1}^{k}\left(1/\sigma^2\right)}, \frac{1}{\sqrt{\sum_{j=1}^{k}\left(1/\sigma^2\right)}}\right) = N\left(\frac{\delta_1 + ... + \delta_k}{k}, \frac{\sigma}{\sqrt{k}}\right) \tag{5.37}$$

To find the likelihood function, we can take either analytical approach using Eq. (5.37) or a numerical approach. The posterior distribution is now the product of likelihood $L(\overline{\delta})$ and prior $f'(\overline{\delta})$. If the prior is a normal PDF such as:

$$f'(\overline{\delta}) \sim N(\delta', \sigma') = \frac{1}{\sqrt{2\pi}.\sigma'}\exp\left[-\frac{1}{2}\left(\frac{\overline{\delta} - \delta'}{\sigma'}\right)^2\right] \tag{5.38}$$

Then the posterior has also a normal PDF. In this case the posterior has a mean and standard deviation as follows (Ang and Tang 2006):

$$f''(\overline{\delta}) = k.L(\overline{\delta}).f'(\overline{\delta}) \sim N(\delta'', \sigma'') \tag{5.39}$$

$$\begin{cases} \delta'' = \dfrac{\delta_L.(\sigma')^2 + \delta'.(\sigma_L)^2}{(\sigma')^2 + (\sigma_L)^2} = \dfrac{\left(\dfrac{\delta_1 + ... + \delta_k}{k}\right).(\sigma')^2 + \delta'.\left(\dfrac{\sigma}{\sqrt{k}}\right)^2}{(\sigma')^2 + \left(\dfrac{\sigma}{\sqrt{k}}\right)^2} \\[6mm] \sigma'' = \dfrac{\sigma'.\sigma_L}{\sqrt{(\sigma')^2 + (\sigma_L)^2}} = \dfrac{\sigma'.\left(\dfrac{\sigma}{\sqrt{k}}\right)}{\sqrt{(\sigma')^2 + \left(\dfrac{\sigma}{\sqrt{k}}\right)^2}} \end{cases} \tag{5.40}$$

Eq. (5.40) in conjunction with Eq. (5.37) shows that the posterior mean δ'' approaches the mean of observations (sample mean) for relatively large number of observations k. Also, it is found that the standard deviation of posterior distribution σ'' is always smaller than standard deviation of prior distribution σ'.

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In this research, both likelihood and posterior distributions of $\overline{\delta}$ are calculated using Eqs. (5.37) and (5.40). These same values can be calculated using a numerical approach as well.

5.3.3 Bayesian Approach for k Correlated Projects

So far we were assuming that the k newly completed projects were independent and there is no correlation among the cost overruns/underruns of these projects. Now, we consider the case where there are dependencies among the collected projects for updating. We know that to conduct analysis with correlated cost overruns/underruns, joint density function is required. The probability distribution of each cost overrun/underrun is the marginal distribution. When the cost overruns/underruns are independent, the product of their marginal distributions gives their joint density function. In the previous section where we assumed independence among projects, we saw that the probability of observing cost overruns/underruns $\delta_1, ..., \delta_k$ coming from a population Δ having an underlying normal distribution $f_\Delta(\delta)$ with the mean of $\overline{\delta}$ and the known standard deviation of $\overline{\sigma}$ is the product of probability of observing each δ_k individually given the population information. If the projects are not independent, knowing the marginal distributions of cost overruns/underruns is not sufficient to obtain their joint density function. Multivariate normal distribution is the special case in which the only information is required other than marginal distribution of each random variable is the values of covariance among the variables (Rowe 2003). When there is a multivariate normal distribution, each of its marginal variables by itself is normally distributed. The converse however is not generally true (Kurtner *et al* 2005). Despite this, we have made a simplifying assumption that the joint

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density function of the cost overruns/underruns to be a multivariate normal distribution. The multivariate normal PDF is (Springer 1979):

$$f(\delta_1, ..., \delta_k) = \frac{\left|V^{-1}\right|^{1/2}}{(2\pi)^{n/2}} . \exp\left[-\frac{1}{2}.(\delta - \bar{\delta})' . V^{-1}.(\delta - \bar{\delta})\right] \qquad (5.41)$$

Where all bold letters represent a matrix/vector and:

$\boldsymbol{\delta} = (\delta_1, ..., \delta_k)^T$ are the cost overruns/underruns of k newly completed projects (T denotes the transpose of matrix).

$\bar{\boldsymbol{\delta}} = (\bar{\delta}_1, ..., \bar{\delta}_k)^T$ are the means of each cost underruns/overruns distribution. Since it was assumed that all these k projects are coming from a normal population with the mean $\bar{\delta}$, $\bar{\boldsymbol{\delta}}$ can be written as $\bar{\boldsymbol{\delta}} = (\bar{\delta}, ..., \bar{\delta})^T$.

V is the variance-covariance matrix which is a symmetrical ($k \times k$) matrix as follows:

$$V = \begin{bmatrix} \sigma_1^2 & \rho_{12}\sigma_1\sigma_2 & \rho_{13}\sigma_1\sigma_3 & ... & \rho_{1k}\sigma_1\sigma_k \\ \rho_{21}\sigma_2\sigma_1 & \sigma_2^2 & \rho_{23}\sigma_2\sigma_3 & ... & \rho_{2k}\sigma_2\sigma_k \\ - & - & - & ... & - \\ - & - & - & ... & - \\ \rho_{k1}\sigma_k\sigma_1 & \rho_{k2}\sigma_k\sigma_2 & \rho_{k3}\sigma_k\sigma_3 & ... & \sigma_k^2 \end{bmatrix} \qquad (5.42)$$

ρ_{mk} is the correlation coefficient between project m and k. σ_j is the standard deviation of cost overrun/underrun of project j. Again, since it was assumed that all k projects are coming from a unique normal population with the standard deviation of $\bar{\sigma}$, all σ_j $(i = 1, ..., k)$ in the matrix V are equal to $\bar{\sigma}$. Since we do not know the standard deviation

of the population, $\overline{\sigma}$ is assumed to be the standard deviation of cost overruns/underruns of k observed projects σ.

$\left|\mathbf{V}^{-1}\right|$ is the determinant of matrix $\mathbf{V}^{-1}$ which is the inverse of matrix $\mathbf{V}$.

One should note that Eq. (5.41) is the joint probability function of project cost overruns. In other words, assuming that $\overline{\boldsymbol{\delta}}$ and $\mathbf{V}$ are known, the probability of observing $\boldsymbol{\delta} = \left(\delta_1, ..., \delta_k\right)^T$ is found. However in Bayesian updating we need to find the likelihood of having $\overline{\boldsymbol{\delta}} = \left(\overline{\delta}, ..., \overline{\delta}\right)^T$ as the parameter of distribution when we have observed $\boldsymbol{\delta} = \left(\delta_1, ..., \delta_k\right)^T$. Therefore Eq. (5.41) can be used to obtain the likelihood function of $\overline{\boldsymbol{\delta}}$ which is the function of just $\overline{\delta}$ as follows (Rowe 2003):

$$L(\overline{\delta}_1, ..., \overline{\delta}_k) = L(\overline{\delta}, ..., \overline{\delta}) = \frac{\left|\mathbf{V}^{-1}\right|^{1/2}}{(2\pi)^{n/2}} . \exp\left[-\frac{1}{2}.\left(\delta - \overline{\delta}\right)'.\mathbf{V}^{-1}.\left(\delta - \overline{\delta}\right)\right] \tag{5.43}$$

Having the likelihood function and assuming a prior distribution $f'(\overline{\delta})$ like Eq. (5.38), the posterior distribution $f''(\overline{\delta})$ is a normal shape as follows:

$$f''(\overline{\delta}) = k.L(\overline{\delta}_1, ..., \overline{\delta}_k).f'(\overline{\delta}) \sim N(\delta'', \sigma'') \tag{5.44}$$

In the correlated case, to calculate mean and standard deviation (δ'', σ'') of $f''(\overline{\delta})$, only numerical approach is available to us and there is no close form formula. To this end, a range of possible $\overline{\delta}$ is selected. It is obvious that $\overline{\delta}$ cannot be less than -100% as it is practically impossible that a project have underrun of its whole budget. To be conservative, the range is assumed to be from -99.99% to 200% with the pace of 0.001. These values are input in Eqs. (5.38) and (5.43) to respectively calculate the correspondence prior PDF value,

$f'(\overline{\delta})$ and likelihood value, $L(\overline{\delta}_1,...,\overline{\delta}_k)$ of each possible $\overline{\delta}$. It should be noted that for the values of $\overline{\delta}$ outside the range of [-99.99%, 200%], the $L(\overline{\delta})$ and accordingly $f''(\overline{\delta})$ become too small so that they can be ignored from the analysis without any significant impact.

Reviewing Eq. (5.43), it is found that the term in the exponential function is the product of three $(1 \times k)$ and $(k \times k)$ and $(k \times 1)$ matrices which results in a polynomial function of $\overline{\delta}$. It means that Eq. (5.43), for any $\overline{\delta}$, gives a scalar likelihood value. Having variance-covariance matrix, $L(\overline{\delta}_1,...,\overline{\delta}_k)$ can be easily calculated by any available mathematical package such as MATLAB.

Multiplying of the prior PDF and likelihood values of each $\overline{\delta}$ gives $f''(\overline{\delta})$ which is the posterior PDF value of $\overline{\delta}$ before normalization (the area under the curve is not equal one). Both curves $L(\overline{\delta}_1,...,\overline{\delta}_k)$ vs. $\overline{\delta}$ and $f''(\overline{\delta})$ vs. $\overline{\delta}$ are needed to be normalized.

To calculate δ'' and σ'', the area under the curve of $f''(\overline{\delta})$ vs. $\overline{\delta}$ after normalizing is assumed to be divided to t narrow rectangles. The area of each rectangle is the probability of having the $\overline{\delta}_{(mid)j}$ (midpoint of the rectangle j). Then:

$$\delta'' = E(\overline{\delta}) = (\overline{\delta} : f''(\overline{\delta}) \text{ is } Maximum) \tag{5.45}$$

$$\sigma''^2 = E(\overline{\delta}^2) - (E(\overline{\delta}))^2 = \sum_{j=1}^{t} \overline{\delta}^2_{(mid)j}.P(\overline{\delta}_{(mid)j}) - \delta''^2 =$$

$$\frac{1}{\sum_{j=1}^{t} \left[\overline{\delta}_{(mid)j}.f''(\overline{\delta}_{(mid)j})\right]}.\left[\sum_{j=1}^{t} \overline{\delta}^2_{(mid)j}.\left(\overline{\delta}_{(mid)j} - \overline{\delta}_{(mid)j-1}\right)f''(\overline{\delta}_{(mid)j})\right] - \delta''^2 \tag{5.46}$$

The term $\sum_{j=1}^{t}\left[\overline{\delta}_{(mid)j}.f''\left(\overline{\delta}_{(mid)j}\right)\right]$ in Eq. (5.46) is to normalize the posterior distribution and plays the role of k in Eq. (5.44).

5.4   Updating the Primary Parameters of the Proposed Model

In Section 5.3.2 (for independent projects) and Section 5.3.3 (for correlated projects), using Bayesian approach and having the information of newly completed projects the distribution of $\overline{\delta}$, the average of cost overruns/underruns, was updated and posterior distribution $f''(\overline{\delta}) \sim N(\delta'', \sigma'')$ was calculated.

The mean δ'' and standard deviation σ'' of the posterior distribution is now used to update the primary parameters of the proposed model α, β, and ρ as follows:

$$\alpha_{new} = P(x < -m) = P(Z < \frac{-m-\delta''}{\sigma''}) = \Phi(\frac{-m-\delta''}{\sigma''}) \tag{5.47}$$

$$\beta_{new} = 1 + \delta'' \Rightarrow \rho_{new} = \frac{\beta_{new}}{1-m} \tag{5.48}$$

where Φ is the cumulative function for standard normal distribution. The proposed model is updated by $\alpha_{new}, \beta_{new}$, and ρ_{new} values and becomes ready to be applied to any prospective set of projects which are in budget allocation process.

5.5   Summary

In this chapter, a new probabilistic model was proposed for budget allocation in a portfolio of projects. The model assumes hybrid normal distribution for cost of projects and utilizes available historical data. Then, a Bayesian approach is employed to update the model as more projects are completed and new information becomes available. The proposed model first helps an agency to find the required portfolio's budget increase in order to have a certain confidence γ that the budget will be sufficient. Also, the model gives the required confidence level η to conduct risk assessment at individual project level to insure that the portfolio budget will not overrun with a probability of more than $1 - \gamma$. The model can be updated with the information of newly completed projects on a regular basis. Bayesian updating is applied considering two different approaches: 1. independent projects; and 2. correlated projects.

In Chapter 7, application of the proposed model with a numerical example is explained in detail.

CHAPTER 6: SUGGESTED METHOD TO ESTIMATE CORRELATION BETWEEN PROJECTS' COSTS

6.1 Introduction

One of the important steps in a probabilistic risk assessment is the recognition of the statistical correlation among cost components. Ignoring the correlation results in an underestimation of total cost variance. This may lead to underestimation of contingency budget for the desired confidence level. The effect of correlation on the total construction cost variance has been the emphasis of numerous papers in the past 20 years (Ince and Buongiorno 1991; Touran and Wiser 1992; Wall 1997; Touran and Suphot 1997; Ranasinghe 2000). To consider correlation among cost components, two major issues are noteworthy:

1. Measure of dependence between components where there is not sufficient historical cost data; and

2. Implementation of correlation where correlation matrix is not mathematically true.

In this chapter, a structured guideline is proposed for more accurate or at least more consistent subjectively estimating of correlation coefficients between costs of two construction projects where there is no historical data available. Furthermore, the

mathematical characteristics of a correlation matrix are explained and the methods to make it a mathematically true matrix are discussed.

6.2   Measure of Dependence

When two or more random variables do not vary independent of each other, the measure of their dependence is measured by correlation coefficients. There are several correlation coefficients to measure this relationship among which Pearson Coefficient and Spearman's Rank Correlation Coefficient are the most commonly used in construction research and practice.

6.2.1   Pearson Coefficient

Pearson coefficient measures the degree of linear relationship between variables. It ranges from -1 to +1. If a variable is a linear function of another variable with both variables changing in the same direction, this coefficient is 1 and if they move in opposite directions this coefficient is -1 (perfect correlation). A coefficient of 0 means that there is no linear relationship between variables. It should be noted that coefficient of 0 is not an indication of independence. However, the inverse is correct and the coefficient of two independent random variables is 0. If we assume X and Y are two random variables with the mean μ_X, μ_Y and standard deviation of σ_X, σ_Y respectively, Pearson coefficient is defined as follows:

$$\rho_{X,Y} = \frac{Cov(X,Y)}{\sigma_X.\sigma_Y} = \frac{E[(X - \mu_X).(Y - \mu_Y)]}{\sigma_X.\sigma_Y} \tag{6.1}$$

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Substituting estimates of the covariance and variance based on a given sample, Pearson coefficient is calculated from Eq. (6.1):

$$\hat{\rho}_{x,y} = \frac{\sum_{i=1}^{n}(x-\bar{x})(y-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x-\bar{x})^2} \cdot \sqrt{\sum_{i=1}^{n}(y-\bar{y})^2}} \tag{6.2}$$

Where $\bar{x}$ and $\bar{y}$ are sample means for variables X and Y.

6.2.2 Spearman's Rank Correlation Coefficient

Spearman's rank correlation coefficient ranges between -1 to +1. This is a non-parametric measure of statistical dependence between two variables and is an indication of correlation between ranks of the values of random numbers instead of correlation between values. It evaluates how well the relationship between two variables can be described using a monotonic function. To find the rank correlation between a set of sample (x, y) observed from random variables X and Y, one first needs to sort the x values in descending or ascending order and assign a rank R_i to each row, and then corresponding y values are ranked S_i among all y. The Spearman's rank correlation can be calculated using Eq. (6.3) (Kurowicka and Cooke 2006):

$$\hat{\rho}_{x,y} = \frac{\sum_{i=1}^{n}(R_i - \bar{R})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n}(R_i - \bar{R})^2} \sqrt{\sum_{i=1}^{n}(S_i - \bar{S})^2}} \tag{6.3}$$

Where n is the number of observed values, and $\overline{R}$ and $\overline{S}$ are the rank means in the sample of n observations. In summary, Pearson correlation is a measure of linear relationship between variables while Spearman rank correlation is a measure of monotonosity (Iman and Conover 1982).

6.3 Subjective Estimate of Correlation

Several researchers have shown that the effect of excluding correlation in cost or schedule estimation is significant (Ince and Buongiorno 1991; Touran and Wiser 1992; Wall 1997; Touran and Suphot 1997; Ranasinghe 2000; Yang 2006). The problem is that usually there is no sufficient historical data to help estimate the correlation coefficients. Most of the time in construction we do not have access to the detailed data about cost items or activity durations to find their relationships. In such a case, subjective estimates of correlation elicited from the experts are used (Touran 1993; Wang and Demsetz 2000; Cho 2006). To this end, building a system to gather the qualitative information and convert them to quantitative values is required. When there is not enough data to calculate the correlation coefficient, the estimator can provide some qualitative values using his or her judgment or by asking the experts. It is neither accurate nor reasonable to ask non-experts to provide a number between -1 to +1 as an estimate of the correlation coefficient for two variables under question. Most people even experts do not know how to interpret the numerical magnitude of correlation while they may be more familiar with terms such as *very low, low, moderate, high*, and *very high* as correlation terms. The challenge is to start from a qualitative estimate of the correlation coefficient and turn it into a numerical value for conducting the statistical analysis.

Touran (1993) suggested a convenient system to quantify the subjective correlations. He recommended that experts can estimate the correlation in three levels of weak, moderate, or strong based on previous experience which could vary from project to project depending on the circumstances. The proposed correlation coefficients for different levels are as follows:

Weak: 0.15 which is the midpoint of 0 to 0.3;

Moderate: 0.45 which is the midpoint of 0.3 to 0.6;

Strong: 0.80 which is the midpoint of 0.6 to 1.0.

Touran (1993) applied both calculated correlation coefficients and suggested subjective coefficients in numerous construction cost examples to compare the resulting total cost CDFs (Cumulative Distribution Functions). It was shown that the actual CDFs were very close to the CDFs using suggested subjective correlation. It should be noted however that in order to have a mathematically correct and applicable correlation matrix, the matrix must be positive semidefinite. The use of qualitative or subjective correlation coefficients (or even calculated correlation coefficients from relatively small samples) may lead to a correlation matrix that may not be positive semidefinite. This issue and available methods to resolve it are discussed in detail in the following section.

Another suggested method for finding the correlation between durations of activities in a CPM network is to use the concordance probability. Cho (2006) employed concordance probability, the idea proposed by Gokhale and Press (1982), in conjunction with a three-step questionnaire to estimate correlation coefficients between activity durations. In this method, for two dependent random variables, a bivariate normal density is assumed and a conditional probability called concordant is required. For variables X and Y having two independently observed pairs (X_1, Y_1) and (X_2, Y_2), the concordance probability is:

$$C\_\Pr = \Pr(Y_2 > Y_1 | X_2 > X_1) \qquad\qquad (6.4)$$

The concordance probability is a monotone increasing function of correlation coefficient. Figure 6.1 explicates the relationship between concordance probability and correlation coefficient.
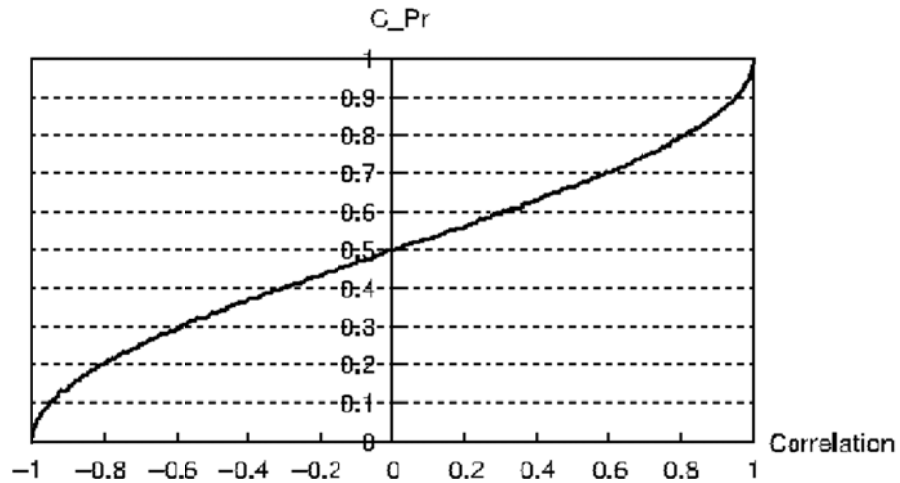
Figure 6.1: Relationships of Correlation Coefficient and Concordance Probability (Cho 2006)

Having concordance probability and using Figure 6.1, the correlation coefficient is found for any pair of variables. Cho suggested a three-step method to successfully elicit the correlation coefficient of the duration of two activities A and B, as follows:

1. Asking the experts to determine the mean duration and the standard deviation for each activity. In case of multiple experts, either simple average or weighting average is used;

2. Asking the experts whether the pair of activities is influenced by the common environmental risks or shares human resources. If the answer is "No", the

correlation is 0; otherwise, if there is a dependency feeling between two activities, it should be proceeded to step 3;

3. Asking the experts in what fraction of the cases he/she would expect that the duration of activity B will be longer than its expected duration, given that the duration of activity A is longer than its expected duration. Having this fraction as the concordance probability and using Figure 6.1, the correlation coefficient is found.

6.4   Proposed Structured Guideline (PSG) to Elicit Correlation

Even though the correlation among cost items has a significant impact on the total cost distribution as it was stated earlier, few studies exist that have focused on precisely measuring the correlation between costs. In this research as we are dealing with the portfolio of projects rather than individual projects, the correlation among projects becomes an important issue which needs to be studied. There is a need for some guidelines for estimating the correlation coefficient as accurately as possible among each pair of projects in the portfolio (or construction program). A simple approach is to apply a subjective coefficient by the judgment of the estimator or a panel of experts using terms such as *low, moderate*, and *high* and then convert them to pre-specified numerical values. Example of this subjective correlation is what Touran (1993) suggested and was explained earlier. Chau (1995) used a similar qualitative assessment method for estimating degree of dependence.

In case of more than one estimator or expert, the average of values can be used. However, this method cannot be very precise since the experts may ignore some important characteristics that cause strong correlation among the cost of two projects. Having a

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systematic and consistent approach can improve the precision of correlation estimate. Here a structured guideline is proposed for more accurate or at least more consistent estimating of correlation coefficients between costs of two construction projects.

6.4.1 Identifying Common Risk Factors

As it was mentioned earlier, correlation between two variables is the degree to which there is a linear relationship between them and coefficient measures the strength of that linear relationship. Based on this definition, what is needed to find the correlation among the cost of two projects in the lack of historical data, is to consider all the common factors that can influence the cost of the projects under consideration. Reviewing all the effective factors and analyzing those that are in common can help find an approximate estimate for the correlation coefficient with a good degree of accuracy. In this way, the expert estimating the correlation coefficient can be ensured that he/she is not missing any significant factor that can establish correlation among two projects. To this end, first two relatively comprehensive sources of cost risk factors: 1. Touran (2006b), and 2. Shane *et al* (2009), were identified. In these two sources, authors have compiled all the risk factors that can affect the cost of a project. Both of these sources emphasize transportation projects that make them especially relevant to this dissertation. These sources are reviewed in depth to identify the risk factors that can affect a group of projects and increase or decrease their costs.

Touran (2006b) provides a risk catalog based on several sources that its main purpose is to help the CM agency dealing with project owners. However this risk checklist provides a listing of the typical factors affecting the risks associated with a project. Similar or related risks are grouped according to their general theme or source and are arranged in a roughly

chronological order. The project life cycle is divided into the following phases based on Construction Management Association of America (CMAA) life-cycle breakdown:

1. Pre-design phase; 2. Design phase; 3. Bid and award phase; 4. Construction phase;

5. Post-construction phase.

This risk catalog is reviewed precisely to select those factors that potentially can have common influence on all projects in a portfolio rather than to be specific to a project. These factors with some modifications are classified based on their types and given in Table 6.1.

Table 6.1: Identified Common Cost Factors for All Construction Projects (Adapted from Touran 2006b with Some Modifications)

No	Classification	Risk Factor
1	Regulatory Conditions	Statutory/regulatory constraints (federal, state, or local)
2		Delay in federal approvals
3		Environmental and ADA regulations/requirements
4		Taxes and duties
5	Financial Conditions	Federal political climate
6		Bond market and rates
7		Exchange rate
8		Inflation rate
9		Interest rate
10	Market Conditions	Number of bidders
11		General economic climate that can affect bidding behavior
12		Availability of suppliers and subcontractors
13		Unemployment rate in construction trades
14		Material and energy prices
15		Material shortages and large price increases
16		Adequacy of marketplace supply (special items)
17		Sole source equipment and service providers
18		Opportunity for equipment discounts (concurrent projects/clients)

In another extensive research conducted by Shane *et al* (2009), an anthology of individual cost increase factors were identified through an in-depth literature review. The authors list 18 primary factors in two internal and external classifications which impact the cost of all types of construction projects. These factors were verified by interviews with 20 state highway agencies. In this classification those factors that contribute to cost escalation and are controlled by the agency/owner are internal, while factors existing outside the direct control of the agency/owner are classified as external. For our purpose, to find the correlation among two projects, both internal and external factors should be reviewed. Table 6.2 shows the identified cost factors by Shane *et al*.

Table 6.2: Identified Common Cost Factors for All Construction Projects (Adopted from Shane *et al* 2009)

No	Classification	Risk Factor
1	Internal	Bias
2		Delivery/procurement approach
3		Project schedule changes
4		Engineering and construction complexities
5		Scope changes
6		Scope creep
7		Poor estimating
8		Inconsistent application of contingencies
9		Faulty execution
10		Ambiguous contract provisions
11		Contract document conflicts
12	External	Local concerns and requirements
13		Effects of inflation
14		Scope changes
15		Scope creep
16		Market conditions
17		Unforeseen events
18		Unforeseen conditions

Table 6.1 and 6.2 together give a reasonably exhaustive source of all cost escalation factors for each individual project. As we are interested in those factors that can impact a pair of projects, these two sources are reviewed to eliminate repetitive factors and those factors which cannot concurrently affect a pair of projects. In this proposed approach, factors with negligible common effect are removed because of the approximate nature of the approach. Table 6.3 illustrates 12 factors that this author believes should be considered during correlation estimation for a pair of projects. These are the factors that if they occur in project A, they can *potentially* impact project B.

Table 6.3: Recommended Common Cost Factors in Correlation Estimation for a Pair of Projects

No	Common Risk Factor	Project	
		A	B
1	Optimistic estimating (Bias)		
2	Lack of experience with delivery/ procurement method		
3	Statutory/ regulatory constraints (federal, state, or local)		
4	Environmental regulations and requirements		
5	Political climate		
6	Bond market and rates		
7	Exchange rate		
8	Inflation/interest rate		
9	Number of bidders		
10	Unemployment rate in construction trades		
11	Material and energy prices		
12	Sole source equipment and service providers		

We now have a list of the common risk factors. We have tried to consider risk factors that are more or less independent of each other, otherwise the effect of some factors will be counted more than once. Below a brief explanation of each factor is given:

1. _Optimistic estimating (Bias):_ Large projects tend to be underestimated due to optimistic estimation (Flyvbjerg 2006). Most people, especially those championing projects, have a tendency to see the future events in a more favorable light than the actual experience. Thus, when an estimator is preparing a project budget, he may underestimate costs due to this optimism and not considering all the important factors that may go wrong in the project. Also, this bias can have political reason to increase the likelihood of approving the project for being funded.

2. _Lack of experience with delivery/ procurement method:_ Project delivery methods, DBB (design-bid-build), DB (design-build), and CMR (construction manager at risk) along with procurement methods LB (low bid), BV (best value) and QBS (qualifications based selection) distribute the risk among the contract parties. The risks are supposed to be transferred to the party who can handle and manage the risks most effectively. If the party is unable to manage the risks properly this will increase the project costs. So, when an agency is using a delivery system other than the traditional DBB, depending on previous experience with the alternative delivery method, the project cost may increase.

3. _Statutory/ regulatory constraints (federal, state, or local):_ New statutes/regulations may be imposed by federal, state, or local governments which may require even major changes in project design. This will affect project costs or duration that has indirect impact on project cost. For instance, the Aviation and Transportation Security Act (ATSA) passed by congress in November 19, 2001 after terrorist attack in September 11, 2001 made several

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changes in airports' design to increase the measure of security. For analyzing this risk factor, the geographical locations of the two projects under consideration are really important meaning both projects must be under similar constraints.

4. *Environmental regulations and requirements:* This risk factor is similar to the risk factor No. 3, but is only limited to the constraints imposed by environmental regulations and requirements. These are the constraints to mitigate the impact of projects on the local societal environment as well as the natural environment. This factor is again important when it can affect both projects under consideration.

5. *Political climate:* Changing the political climate may cause some alterations that impact a project and result in cost increase. For instance political climate in state level or federal level may lead to expedite the finishing of transit projects which may cause cost growth.

6. *Bond market and rates:* Any changes in the bond market will have a direct impact on project cost. If bond rates go up nationwide, so we can expect to see cost growth in any pair of projects under consideration. Many of the local bonds would have rates that are affected by the financial health of the issuing agency. In such cases, of course the bond rates are independent from each other for projects in different states.

7. *Exchange rate:* This factor is important when projects have items imported from another country. For example, if we are analyzing correlation among two projects that have vehicles manufactured in Canada, if dollar becomes weaker against the Canadian currency, the exchange rate becomes a common cost growth factor on both projects.

8. *Inflation/interest rate:* When inflation/interest rate is higher than what is anticipated during project cost estimate, this becomes a major factor. This factor is more important

when we are dealing with multi-year projects (Touran and Bakhshi 2010). For the applications considered in this dissertation, this risk factor may be the most important cause of cost correlation because the portfolio consists of contemporaneous projects.

9. Number of bidders: When the number of bids that an agency receives for a project is low, it means there is little competition and that project cost goes up. This happens when the project is complex, too large and/or the risks associated with the project are much greater than usual. Economic conditions can have an effect on the number of bidders as well. Usually tough economic times will result in an increase in the number of bidders as was evidenced in the current economic recession. Even obtaining payment/performance bonds for this type of projects is not easy for every contractor.

10. Unemployment rate in construction trades: Low unemployment rate and wage have inverse relationship. When the unemployment rate increases up to a certain point, the wages go down. This is another effective escalation factor that should be considered.

Blanchflower and Oswald (1990) used Britain and the U.S. data to form a wage curve. They found out that in both Britain and the U.S. there is a wage curve that has a negative gradient over low levels of unemployment. However they concluded these curves become flat once sufficiently large unemployment rate reached. The British wage curve was minimized at 13% while the U.S. curve was minimized at 10%.

11. Material and energy prices: When the price of key materials and/or energy items change, it has a direct impact on the project cost. For instance if the price of cement increases significantly and both projects under consideration have considerable amount of cement, this factor must be considered as a common risk factor in both projects. Also, most of the time scarcity of materials is followed by large price increases. For example if for some

reason steel shortage happens in the market, its price would dramatically increase. Therefore two projects under consideration in which huge amounts of steel are consumed, will experience cost growth and this factor is a common risk factor in both projects.

12. Sole source equipment and service providers: When the agency requires supplies or services which are available from only one source, and no other suppliers or services will satisfy its requirements due to unique features or functions, this will be considered as sole source equipment or service providers. If similar conditions affect both projects under consideration, this factor must be considered in the analysis of correlation coefficient.

6.4.2   Subjectively Estimating the Correlation

It should be noted that factors given in Table 6.3 are the common escalation factors in each project; but, it does not mean if a factor impacts project A it would necessarily impact project B as well. For instance, Material and Energy Prices is a risk factor that can potentially impact any project. Two projects are considered for correlation analysis. Both projects may need a certain type of material that has increased in price. However, project A is a design-build contract where the design-builder has already submitted his firm bid. So while project B may receive higher bids because of material price, project A would be unaffected as far as the owner is concerned. In this case this factor will not change the degree of dependency between cost of project A and B. Also, it is important to find out to what degree these common risk factors that are influencing both projects. In other words, the share of each risk factor can be different from project to project. For example, project A is affected by sharp increase in price of copper, however, project B is not affected because the amount of copper used in that project is much less compared to project A. It can be plausible that only

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two or three common factors can cause a large correlation for more than one project depending on the magnitude of their effect.

In the proposed approach, an expert needs to go over the factors given in Table 6.3 for each pair of projects and check if it will impact both projects for the same reasons. The estimate of correlation coefficient should be an expert decision considering these common risk factors. These factors help expert consider the causes of dependency. So what is suggested here is that the analyst uses the common risk factors as the causes of creating correlation and his/her expert judgment to estimate a subjective degree of correlation between pairs of projects. These subjective degrees are suggested to be: *none or independent, small, moderate*, and *large* correlation. Previous research has suggested numerical values for these qualitative correlations. As an example, for quantification of these statements, Cohen (1988) suggests a threshold as follows:

1. Large: 0.5;

2. Moderate: 0.3;

3. Small: 0.1.

These values tend to underestimate the effect of correlations. Touran and Wiser (1992) showed that correlation among various cost categories in building projects can be as high as 0.80. Further Touran (1993) suggested using three correlation values of 0.15, 0.45 and 0.8 and reproduced results close to actual correlations between project costs. The author of this dissertation suggests the following thresholds based on other relevant studies, the subject matter and the ability of experts to *feel* the difference between various magnitudes when they are quantifying the correlation:

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1. Large or strong correlation: Ranges from 0.7 to 1.0 and should be assigned as 0.85;

2. Moderate correlation: Ranges from 0.4 to 0.7 and should be assigned as 0.55;

3. Small or weak correlation: Ranges from 0.1 to 0.4 and should be assigned as 0.25;

4. None or independent: Ranges from 0 to 0.1 and should be assigned as 0.

These values are slightly larger than those suggested by Touran (1993) and hence more conservative, but are justified given the lack of data regarding large transit projects which are the subject of this dissertation. It should be noted that the correlation coefficient of 0.85 among costs of two projects is very high and can rarely happen.

In Appendix B, a mathematical method is suggested to calculate the pairwise correlation coefficient between costs of projects in which the risk registers (a list of probable risk factors along with their monetary impacts) are available.

6.4.3   Delphi Method for Improving the Subjectively Estimated Correlation

The accuracy of estimate can be improved by considering the opinion of a panel of experts instead of a single expert. There are three major methods to elicit experts' judgments: interactive group, Delphi, and individual interview (Meyer and Booker 2001). We suggest the use of Delhi method because of its well-known characteristic to avoid biases arising from group interactions.

The Delphi method is a structured communication technique to elicit a panel of experts' judgment on an issue. This method is comprised of repeated solicitations of questions

through mail or email from the panel. The experts' opinion on an issue is collected by a moderator (facilitator) in two or more rounds until reaching a consensus. After the first round of collecting opinions, the moderator prepares an anonymous summary of the collected opinions from the experts in the panel along with the given reasons they provided for their judgments. In the next round of collecting data, this summary is distributed among the same experts and they are encouraged to revise their previous opinion in light of other experts' judgments. After a few rounds, a consensus should be achieved or at least the dispersion of opinions becomes less. This method was first developed by Rand Corporation for Air Force in the early 1950s (Chan *et al* 2001).

The panel usually consists of a number of experts selected based on their experience and knowledge on the issue under consideration. Panel members are anonymous to each other in the whole process and only moderator communicates with them. The moderator creates the questionnaire, distributes and collects them, and answers the questions of the panel members.

In the context of estimating correlation between costs of projects using our suggested method, we can use the Delphi method to increase the accuracy of the estimate. Hallowell and Gambatese (2009) suggested the use of Delphi method for interpretive reasoning which involves the recognition of pattern, spatial relationships, correlations and casual relationships.

The moderator can select a panel of experts who have enough knowledge about the projects under consideration and are also familiar with the correlation concept. The moderator must develop a questionnaire including the brief explanation of the suggested method, the list of projects, and a matrix for inputting pairwise correlation along with a section to provide the

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reason to select that correlation value. After the first round, the moderator should average all answers on pairwise correlations and round them up to the closest number in the four suggested correlation coefficient in the previous section (*i.e.,* 0, 0.25, 0.55, or 0.85). The reason for that is we ask the experts to select the correlation coefficient from among these four predetermined values. Therefore, for the next round, the correlation coefficient must be in the predetermined format to enable the expert to possibly revise its previous opinion by comparing it with the outcome of all panel members. This process can go on until it reaches a steady point and a consensus is arrived on the estimated correlation coefficients.

6.5   Implementation of Correlation

6.5.1   Characteristics of Correlation Matrices

The process described in the previous section is based on expert judgment considering the common risks impacting the cost of each pair of projects. After correlation coefficients are estimated in this way, the correlation matrix should be tested to ensure that the matrix is mathematically a correct correlation matrix. The correlation among each pair of projects may appear to be rational; however, the whole system represented by correlation matrix might be inconsistent. Covariance matrix and correlation matrix as the normalized covariance matrix must be either a positive definite or positive semidefinite matrix (Koch 1999; Pearson 2002). Before taking up this concept, some matrix definitions will be explained that are required for better understanding of the following sections.

Eigenvector and Eigenvalue

If A is an $n \times n$ matrix and if x is a non-zero vector such that $Ax = \lambda x$, where λ is a scalar, then x is an eigenvector of matrix A with corresponding eigenvalue λ. Any eigenvalue λ satisfies the nth degree polynomial equation $\det(A - \lambda I) = 0$. This equation is called the characteristic equation of matrix A. We thus have n eigenvalues which may not be all distinct and n corresponding eigenvectors (Bell 1975).

Also, it is known that if A is symmetric, then $\det(A) = \prod_{i=1}^{n} \lambda_n$.

Positive Semidefinite Matrix

A symmetric matrix $A \in \Re^{n \times n}$ is positive semidefinite if $x^T A x \geq 0$ for every $x \in \Re^n$ and is denoted by $A \succeq 0$. When A is positive semidefinite, we can say (Berman *et al* 2003):

1. All the eigenvalues of A are nonnegative;

2. An $n \times n$ lower triangular real matrix L exists such that $A = LL^T$. This is called Choleski decomposition;

3. $\det(A) \geq 0$.

Determinant of a lower or upper triangular or diagonal matrix is equal to the product of the diagonal elements of the matrix (Bell 1975).

Positive Definite Matrix

This is a special case of positive semidefinite matrix. An $n \times n$ positive semidefinite matrix A is completely positive if and only if it is a nonsingular matrix and matrix A is nonsingular

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if and only if the determinant of the matrix is not equal to zero. This means $x^T A x > 0$ for every $0 \neq x \in \Re^n$. When A is positive definite, we can say (Berman *et al* 2003):

1. All the eigenvalues of A are positive;

2. $A = LL^T$ where L is a nonsingular lower triangular matrix (Choleski decomposition);

3. $\det(A) > 0$.

6.5.2 Controlling Consistency of Correlation Matrices

A correlation matrix needs to be consistent which means the possible simultaneous correlation relationships between three or more variables must exist. Inconsistency happens when a matrix cannot meet the positive semidefinite or definite criteria. This issue is magnified when most of the correlations among the variables are relatively large (Touran 1993). The requirement for being positive semidefinite or definite first needs to be tested and once it is satisfied, one can be confident that the correlation matrix used in the analysis indeed represents a relationship that would be possible among random variables. To this end, a couple of methods based on the characteristics of semidefinite matrices have been suggested to test if the correlation matrix is a positive semidefinite matrix. There are also suggested algorithms to make the correlation matrix or covariance matrix a positive semidefinite matrix when it cannot satisfy the requirements with the lowest impact on the original values.

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Suggested Methods:

Fishman (1978) suggested an algorithm based on Choleski decomposition to test if the covariance matrix is positive definite or not. If Choleski decomposition exists for a matrix it means that the matrix is either positive definite or semidefinite. Fishman algorithm to decompose $\Sigma = BB^T$ is as follows where Σ is the covariance matrix of n variables, σ_{ij} denotes entries in matrix Σ and b_{ij} denotes entries in matrix B:

$$b_{i1} = \frac{\sigma_{i1}}{\sqrt{\sigma_{11}}} \quad \text{for } i = 1, ..., n \tag{6.5}$$

$i = 2$:

$$b_{ii} = \sqrt{\sigma_{ii} - \sum_{j=1}^{i-1} b_{ij}^2} \tag{6.6}$$

If $i = n$, then computation of matrix B is complete. If not, increment i by 1:

$$i \longrightarrow i+1, \quad b_{ij} = \frac{\sigma_{ij} - \sum_{m=1}^{j-1} b_{im}.b_{jm}}{b_{jj}} \quad \text{for } j = 2, ..., i-1 \tag{6.7}$$

Matrix Σ cannot be decomposed if the term under the root in Eq. (6.6) is negative; in other words b_{ii} becomes imaginary. If covariance matrix is tested for being positive definite, then this term must be positive and for positive semidefinite it must be non-negative.

To remedy this problem, Touran (1993) suggested that all correlation coefficients (not covariances) should be reduced by about 1% and then matrix B recalculated to see if all b_{ii} entries become real. If some entries still remain imaginary, the process of reducing

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correlation coefficients should be repeated until there is no imaginary entry anymore. However, the final adjusted correlation matrix would be different from the original matrix.

Ince and Buongiono (1991) suggested Scheuer and Stoller algorithm which is completely similar to Fishman algorithm for testing for positive definiteness and deriving the elements b_{ij} in Choleski decomposition. They also recommended that whenever the term under the square root is not positive the corresponding variance factor σ_{ii} must be increased by:

$$\Delta = \sum_{j=1}^{i-1} b_{ij}^2 - \sigma_{ii} + \varepsilon_i \tag{6.8}$$

where ε_i is an arbitrarily small number that can restore positive definiteness to the covariance matrix. This can be interpreted as a situation where the originally specified variances of one or more variables are too small in relation to the larger variances of other variables (Ince and Buongiono 1991).

Most of mathematical software packages such as MATLAB can do Choleski decomposition and when the matrix is not a positive definite or semidefinite it alerts the user that decomposition is not possible. Also simulation software packages check the consistency of input correlation matrix using different algorithms. In case of inconsistency, they usually offer to resolve the issue by creating a new matrix that is as close as possible to the original one and meets the requirements. For instance, @Risk developed by Palisade Corporation uses the eigenvalue characteristic of a positive semidefinite matrix to check the consistency of the entered correlation matrix. As it was mentioned earlier, the eigenvalues of a positive semidefinite matrix are greater than or equal to zero. If @Risk determines the entered matrix is invalid, it implements a three-step process to make it consistent:

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1. It first finds the smallest eigenvalue λ_1 of the correlation matrix C;

2. Using the transformation:

$$C' = C - \lambda_1.I \qquad\qquad (6.9)$$

Where C is the entered correlation matrix, C' is the transformed correlation matrix, and I is the identity matrix, it shifts the eigenvalues so that the smallest eigenvalue becomes 0;

3. Using another transformation:

$$C'' = (1/1 - \lambda_1).C' \qquad\qquad (6.10)$$

It divides all the diagonal terms of C' by $(1 - \lambda_1)$ to make the diagonal values equal to 1. This matrix has the smallest eigenvalue equal to zero.

Therefore, using one of the abovementioned methods the correlation matrix can be tested and adjusted to ensure a consistent correlation matrix.

6.6 Summary

In this chapter, the effect of correlation on total portfolio's budget variance was described. Correlation coefficients in construction costs for measuring the degree of dependence between two variables were explained. Lack of historical data to mathematically calculate correlation was considered to be a major issue in construction projects. Subjective estimate and qualitatively assessment of correlation were described as a solution when there is no sufficient data available to calculate correlation.

A new method called proposed structured guideline (PSG) was introduced to help estimators or experts to estimate the correlation coefficient between costs of pair of projects in a reasonable and systematic fashion. In order to do that two exhaustive sources of risk factors were identified and a short list of 12 common risk factors that can affect the cost of any two projects under consideration were determined. A set of guidelines was developed that can help the estimator or the expert first qualitatively estimates the correlation and then by the means of predetermined coefficient figures converts the qualitative term into a correlation coefficient.

Moreover, the characteristics of correlation matrix were described and the methods to convert a matrix to a positive semidefinite matrix were discussed.

CHAPTER 7: APPLYING THE PROPOSED MODEL

7.1 Introduction

The proposed model is a mathematically flexible model that can be applied to any portfolio of projects. Different agencies may have different policies for cost estimating process and budget development that may require a certain point in time to use the model. The model may be used to improve the budget of each project in a portfolio at any key stage of project development such as conceptual design, preliminary engineering, or final design. However, the use of the model is contingent upon availability of historical data. An agency needs to have historical cost estimates at the point that they are seeking to employ the model along with actual final costs. For instance, if an agency intends to use the proposed model after finishing the final design, they need to have access to a set of projects whose estimated costs at the final design and their actual final costs are available. This data forms the first step of the model where the mean and standard deviation of cost overruns/underruns are defined.

After collecting historical data and calculating the mean and standard deviation of cost overruns/underruns, the model will be ready to be applied on any set of projects in a portfolio. The model will calculate the required budget increase/decrease based on the past projects' performances. Then by finishing new projects and receiving more information, the model is updated and becomes ready to be applied on another prospective portfolio of projects.

7.2 Application of the Model by an Owner Agency

We will now demonstrate the application of the model by an owner agency. We will use the Federal Transit Administration (FTA) as a case in point. As it was stated earlier in Chapter 3, the FTA financially and technically supports local transit agencies for major capital investment in new fixed guideway system such as rapid rail, light rail, commuter rail, exclusive bus/high occupancy vehicle lanes, or ferry service or an extension to an existing fixed guideway system. The FTA financial assistance to local transit agencies happens through an agreement called Full Funding Grant Agreement (FFGA). This is the point that the FTA commits contractually to provide the agency with Federal funds. Each year based on the amount of available funds for *new starts projects* under the 49 U.S.C. 5309 Major Capital Investment Program, a number of transit projects are selected and reported to the Congress through Annual Report on Funding Recommendations for approval. These annual reports are prepared for each fiscal year. Therefore, it is of high importance to have accurate cost estimates for all projects in the portfolio of projects in a certain fiscal year. Cost overrun of projects and providing more funds will jeopardize the on time completion of projects, and incur more expenses to the tax payers. Thus it is important for the FTA to have a precise estimate of project's cost before tying themselves to the FFGA contracts.

The proposed model can greatly help the FTA adjust the projects' cost estimates based on past projects' performances. In the proposed approach, first the preparation of a set of historical projects' data including cost estimate at the FFGA and actual final cost (as-built cost) is required. Using this data, mean and standard deviation of cost overruns/underruns in the historical data set is determined. Based on this, the parameters of the model are calculated and the model can be applied on the first set of projects recommended in the

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upcoming annual report to the Congress. The model may advise to increase or decrease the total portfolio budget. Then all projects' cost estimates are modified using the calculated increase/ decrease factor. The new adjusted cost estimates must be considered by the FTA to establish the FGGAs. Henceforth, every single year or two, when the new projects are completed and new data becomes available, the model will be updated using the suggested Bayesian approach. The updating incorporates the performance of recently completed projects in the model. However, it will take a few years until the actual costs of projects used in the proposed model become available and their cost overruns/underruns input to the model. The model is updated in the regular intervals and performances of the projects completed are input in the model. The hope is to see the cost overrun and/or underrun close to zero after a few iterations.

In the following sections, the application of the model through a numerical example using transit capital cost data is illustrated and the ability and effectiveness of the model to control cost overrun in a portfolio of projects is verified.

7.3 Selecting Data to Find the Initial values of α and β

To show the application and effectiveness of the model, in this chapter the model is applied to a set of transit capital cost data. For this purpose, a set of 28 transit projects (Booz Allen Hamilton 2005) is selected. These projects have been funded by the Federal Transit Administration (FTA) of the U.S. Department of Transportation in the past twenty years (Table 7.1).

Table 7.1: List of 28 Transit Projects Adopted from Booz Allen Hamilton (2005)

ID	Case Study Projects	Mode	Procurement Approach	Project Setting	Year Completed	Panel Selected
1	Atlanta North Line Extension	Heavy rail	DBB	Extension	1999	X
2	Boston Old Colony Rehabilitation	Heavy rail	DBB	Rehab.	1997	
3	Boston Silver Line (Phase 1)	Busway	DBB	New Start	2004	X
4	Chicago Southwest Extension	Heavy rail	DBB	Extension	1989	
5	Dallas South Oak Cliff Extension	Light rail	DBB	Extension	2002	X
6	Denver Southwest Line	Light rail	DBB	Extension	1999	X
7	Los Angeles Red Line MOS 1	Light rail	DBB	New Start	1991	
8	Los Angeles Red Line MOS 2	Light rail	DBB	Extension	1994	
9	Los Angeles Red Line MOS 3	Light rail	DBB	Extension	1995	
10	Minneapolis Hiawatha Line	Light rail	DB	New Start	2004	X
11	New Jersey Hudson-Bergen MOS1	Light rail	DBOM	New Start	2000-2002	X
12	New York 63rd Street Connector	Heavy rail	DBB	Extension	2001	X
13	Pasadena Gold Line	Light rail	DB	Extension	2003	X
14	Pittsburgh Airport Busway (Phase 1)	Busway	DBB/DB/DBOM	New Start	2000-2002	X
15	Portland Airport MAX Extension	Light rail	DB	Extension	2001	X
16	Portland Banfield Corridor	Light rail	DBB	New Start	1984	
17	Portland Interstate MAX	Light rail	CMR	Extension	2004	X
18	Portland Westside/Hillsboro MAX	Light rail	DBB	Extension	1998	
19	Salt Lake North-South Line	Light rail	DBB	New Start	1999	X
20	San Francisco SFO Airport Ext	Heavy rail	DBB/DB	Extension	2003	X
21	San Juan Tren Urbano	Heavy rail	DB/DBOM	New Start	2005	
22	Santa Clara Capitol Line	Light rail	DBB	Extension	2003	
23	Santa Clara Tasman East Line	Light rail	DBB	Extension	2001	
24	Santa Clara Tasman West Line	Light rail	DBB	Extension	1999	
25	Santa Clara Vasona Line	Light rail	DBB	Extension	2004	
26	Seattle Busway Tunnel	Busway	DBB	New Start	1990	
27	St Louis Saint Clair Corridor	Light rail	DBB	Extension	2000	
28	Washington Largo Extension	Heavy rail	DBB/DB	Extension	2004	X

Reviewing Table 7.1 discloses that 22 out of 28 projects have been completed before 2004, 5 projects in 2004 and 1 project in 2005. We set aside the 22 projects as historical data to find the primary values for α and β used in the model. Then the model is applied to the set of 5 projects completed in 2004 to see the effect of model on cost overruns/underruns. In the next step, the model is updated with the actual costs of these 5 projects. To perceive the dynamic characteristic of the model by the means of Bayesian updating over time, we further identified three transit projects that were completed in 2005 and 2006. Therefore a set of 4 new observed projects are created to be used for applying the model and conducting Bayesian updating.

From this point on, for consistency and ease of referencing, we call the set of 22 projects "Historical Dataset", the set of 5 projects "First Dataset", and the set of 4 more recent projects "Second Dataset".

Cost overrun/underrun of each project is defined to be the percent of difference between actual final cost (as-built cost) and estimated cost at the end of final design (FD), when in transit projects Full Funding Grant Agreement (FFGA) is established by the FTA. For the process of transit project approval and funding by the FTA, please refer to Chapter 3. Cost overrun/underrun data for 28 projects in Booz Allen Hamilton (2005) report is illustrated in Table 7.2.

Table 7.2: Cost Overrun/underrun of 28 Transit Projects Adopted from Booz Allen Hamilton (2005)

ID	Case Study Projects	Planning/ DEIS (1)	Change from Planning to Preliminary Engineering		PE/ FEIS (2)	Change from Preliminary Engineering to Final Design		Final Design/ FFGA (3)	Change from Final Design to Construction		Final Cost (4)	Total Change from Earliest Estimate to Final Cost	
		Millions YOE$	Millions YOE$	%	Millions YOE$	Millions YOE$	%	Millions YOE$	Millions YOE$	%	Millions YOE$	Millions YOE$	%
1	Atlanta North Line Extension	$422.4	$16.5	3.9%	$438.9	($57.6)	-13.1%	$381.3	$91.4	24.0%	$472.7	$50.2	11.9%
2	Boston Old Colony Rehabilitation	$447.2	$28.9	6.5%	$476.1	$75.8	15.9%	$551.9	$13.1	2.4%	$565.0	$117.8	26.3%
3	Boston Silver Line (Phase 1)	$318.1	$66.3	20.8%	$384.4	$29.0	7.5%	$413.4	$191.0	46.2%	$604.4	$286.3	90.0%
4	Chicago Southwest Extension	$453.0	$43.0	9.5%	$496.0	($145.1)	-29.2%	$350.9	$123.7	35.2%	$474.6	$21.6	4.8%
5	Dallas South Oak Cliff Extension	$347.1	$170.1	49.0%	$517.2	$0.0	0.0%	$517.2	($80.0)	-15.5%	$437.2	$90.1	26.0%
6	Denver Southwest Line	$138.0	$14.1	10.2%	$152.1	$24.3	15.9%	$176.3	$0.8	0.4%	$177.1	$39.1	28.3%
7	Los Angeles Red Line MOS 1	n/a	--		$695.8	$264.5	38.0%	$960.3	$529.9	55.2%	$1,490.1	$794.4	114.2%
8	Los Angeles Red Line MOS 2	n/a	--		$1,116.6	$408.0	36.5%	$1,524.6	$397.0	26.0%	$1,921.6	$805.0	72.1%
9	Los Angeles Red Line MOS 3	n/a	--		$1,113.3	$232.3	20.9%	$1,345.6	($118.0)	-8.8%	$1,227.6	$114.3	10.3%
10	Minneapolis Hiawatha Line	$581.0	($32.4)	-5.6%	$548.6	$126.8	23.1%	$675.4	$39.9	5.9%	$715.3	$134.3	23.1%
11	New Jersey Hudson-Bergen MOS1	$775.0	($136.4)	-17.6%	$638.6	$353.5	55.4%	$992.1	$120.9	12.2%	$1,113.0	$338.0	43.6%
12	New York 63rd Street Connector	$488.4	$49.5	10.1%	$537.9	$107.1	19.9%	$645.0	($12.7)	-2.0%	$632.3	$143.9	29.5%
13	Pasadena Gold Line	$997.5	($193.7)	-19.4%	$803.8	($109.9)	-13.7%	$693.9	($16.3)	-2.3%	$677.6	($319.9)	-32.1%
14	Pittsburgh Airport Busway (Ph 1)	$170.2	$115.0	67.6%	$285.2	$41.6	14.6%	$326.8	$0.0	0.0%	$326.8	$156.6	92.0%
15	Portland Airport MAX Extension	$125.0	$0.0	0.0%	$125.0	$0.0	0.0%	$125.0	$2.0	1.6%	$127.0	$2.0	1.6%
16	Portland Banfield Corridor	n/a	--		$214.0	$72.5	33.9%	$286.6	($39.8)	-13.9%	$246.8	$32.8	15.3%
17	Portland Interstate MAX	$313.4	$16.5	5.3%	$329.8	($15.0)	-4.5%	$314.9	$34.5	11.0%	$349.4	$36.0	11.5%
18	Portland Westside/Hillsboro MAX	$531.9	$381.1	71.6%	$913.0	($2.8)	-0.3%	$910.2	$53.3	5.9%	$963.5	$431.6	81.1%
19	Salt Lake North-South Line	$276.9	$8.7	3.1%	$285.6	$26.4	9.2%	$312.0	($0.2)	-0.1%	$311.8	$34.9	12.6%
20	San Francisco SFO Airport Ext.	$1,175.3	($1.4)	-0.1%	$1,173.9	($6.9)	-0.6%	$1,167.0	$383.2	32.8%	$1,550.2	$374.9	31.9%
21	San Juan Tren Urbano	$965.0	$157.0	16.3%	$1,122.0	$128.0	11.4%	$1,250.0	$1,000.0	80.0%	$2,250.0	$1,285.0	133.2%
22	Santa Clara Capitol Line	n/a	--		$147.1	$12.7	8.6%	$159.8	$2.7	1.7%	$162.5	$15.4	10.5%
23	Santa Clara Tasman East Line	$197.7	$78.1	39.5%	$275.9	($0.8)	-0.3%	$275.1	$1.1	0.4%	$276.2	$78.5	39.7%
24	Santa Clara Tasman West Line	$251.3	$76.5	30.5%	$327.8	$4.7	1.4%	$332.5	($51.9)	-15.6%	$280.6	$29.4	11.7%
25	Santa Clara Vasona Line	n/a	--		$269.1	$44.5	16.5%	$313.6	$3.2	1.0%	$316.8	$47.8	17.7%
26	Seattle Busway Tunnel	$314.1	$45.6	14.5%	$359.7	$35.7	9.9%	$395.4	$215.7	54.6%	$611.1	$297.0	94.6%
27	St Louis Saint Clair Corridor	$337.3	$39.4	11.7%	$376.7	($37.5)	-10.0%	$339.2	($2.7)	-0.8%	$336.5	($0.8)	-0.2%
28	Washington Largo Extension	$397.1	$36.8	9.3%	$433.9	$0.0	0.0%	$433.9	$22.1	5.1%	$456.0	$58.9	14.8%
	Sum	$10,023.0	$979.1	9.8%	$14,558.0	$1,612.0	11.1%	$16,169.9	$2,903.8	18.0%	$19,073.8	$5,494.9	37.7%
	Unweighted Average			15.3%			9.5%			12.2%			36.3%

To verify the assumption of normality, a test of goodness of fit using @Risk (Palisade Corp. 2008) software is conducted on 22 cost overruns/ underruns of Historical Dataset. The test using the Chi-squared statistic passed at 1% level of significance (P-value= 0.0219). Figure 7.1 depicts the superposition of the normal distribution on the original data histogram.
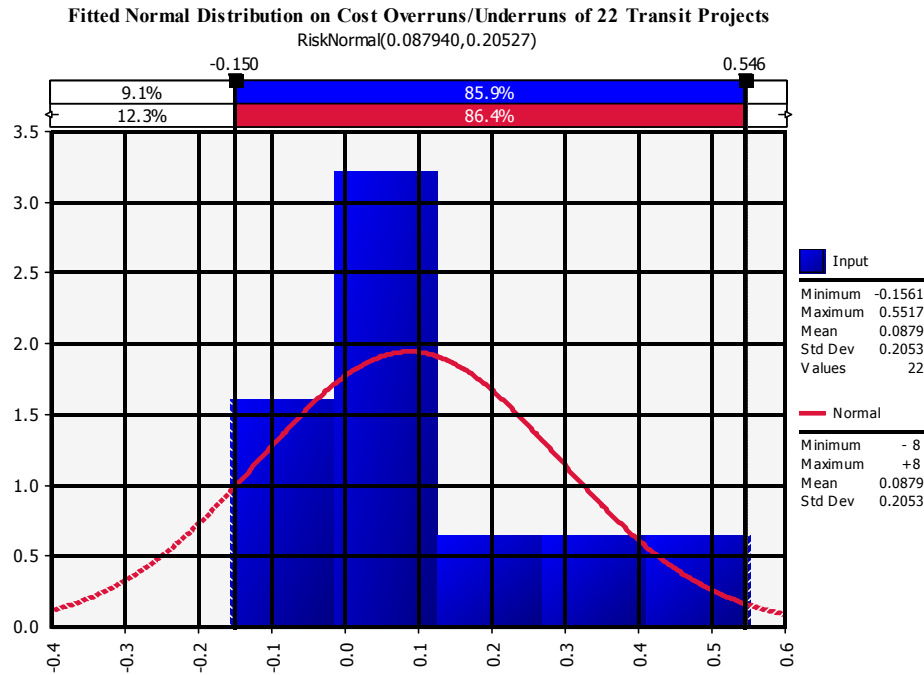
Figure 7.1: Fitting the Normal Distribution on 22 Transit Projects (Historical Dataset)

Figure 7.1 demonstrates the limitation in the cost underrun values. It means that in the real world we are dealing with projects that their costs would not be less than a certain value. This certain value can be approximated using historical data. Reviewing the historical data, we assume that the FTA defines $m = 15\%$ as the maximum expected underrun. Using Figure 7.1, it is found that the value of α corresponding with $m = 15\%$ is $\alpha = 9.1\%$ and the average of cost underruns/overruns is $\overline{\delta} = 8.79\%$; thus $\beta = 1.0879$ and $\rho = 1.0879/(1 - 0.15) = 1.2799$.

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In the following sections, we first introduce the First and Second Dataset in more detail and estimate the correlation between projects of each dataset. Then the model will be applied to the datasets. To highlight the impact of correlation, we first apply the model presuming that all projects are statistically independent of each other. Later, we will recognize estimated correlation between projects. Correlation coefficients are estimated using the Proposed Structured Guideline (PSG) described in Chapter 5.

7.4 Selecting Data (First Dataset) to Apply the Model for the First Time

After estimating values of α and β from the historical data, the model is ready to be applied on any prospective set of projects. As it was mentioned earlier, a set of 5 transit projects completed in 2004 from Booz Allen Hamilton (2005) called First Dataset is selected to apply the model for the first time. These projects with estimated cost at the FFGA and actual final cost and percent of cost overrun/ underrun are summarized in Table 7.3.

Table 7.3: Dataset of Five Transit Projects for Applying the Model for the First Time (First Dataset)

Proj. ID	Project Name	State	Completed Year	Mode	Delivery Method	Cost at FFGA in M$	Actual Cost in M$	Cost Overrun/ Underrun
1	Boston Silver Line (Phase 1)	MA	2004	Busway	DBB	$413.4	$604.4	46.2%
2	Minneapolis Hiawatha Line	MD	2004	Light Rail	DB	$675.4	$715.3	5.91%
3	Portland Interstate MAX	OR	2004	Light Rail	CMR	$314.9	$349.4	10.96%
4	Santa Clara Vasona Line	CA	2004	Light Rail	DBB	$313.6	$316.8	1.02%
5	Washington Largo Extension	DC	2004	Heavy Rail	DB	$433.9	$456.0	5.09%

7.4.1   Case Study Projects in the First Dataset

The projects in the First Dataset have been selected from Booz Allen Hamilton (2005) and the following information is gathered from that report. This information forms the basis for estimating the correlation coefficients among project costs. These projects were built at about the same time and all of them were completed and went into revenue in 2004. This is important because it can show that they have been under similar economical conditions in terms of inflation and escalation.

Below, each project is briefly described. This information will later be used to estimate the pairwise correlation coefficients.

Project 1- Boston Silver Line (Phase 1):

This is a 1.5 mile underground Bus way. Boston Silver line Phase 1 was developed by Massachusetts Bay Transportation Authority (MBTA) and is comprised of a 1 mile, 3 station tunnel between South Station and the World Trade Center. The project included the procurement of 32 vehicles and the construction of a new vehicle maintenance facility. The project delivery method used for this project was design-bid-build (DBB).

The total cost for the Silver Line project was estimated to be $413.4 million at the Full Funding Grant Agreement (FFGA) phase, but grew to $604.4 million upon completion. The cost increase was due to schedule delays and changes in unit cost and scope. The midpoint of construction from 1995 was shifted to 2002 resulting in an increase in project costs of about $99.1million. The remaining increase was due to changes in unit cost and scope. Factors contributing to delays were identified to be coordination problems on the joint construction contracts with the Central Artery/Tunnel project, complication with the design

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for relocating utilities, and differing site conditions. Land acquisition costs were also higher than what was originally estimated.

Project 2- **Minneapolis Hiawatha Line:**

Metro Transit of Minneapolis-St. Paul Metropolitan Council, Minnesota Department of Transportation (MnDOT), Metropolitan Airports Commission (MAC), and Hennepin County constructed an 11.9 mile light rail transit line connecting downtown Minneapolis, Minneapolis/St. Paul International Airport, and the Mall of America. This is the first LRT line built in Minnesota and the project experienced political pressures during its planning. Hiawatha Line project included a 1.5 mile tunnel, 26 light rail vehicles, and 17 stations. The project delivery method used for this project was design-build (DB).

After the feasibility study and the Final Environmental Impact Statement (FEIS) in 1985, the project was halted when the "Legislature prohibited any expenditure of public funds on light rail transit". However this constraint was removed before entering into the FFGA and did not affect the cost estimate at that point.

The Hiawatha Line project was estimated as \$675.4 million total cost at the FFGA stage, but was completed for \$715.3 million. An FFGA was signed for the project for \$675.4 million in January 2001 with revenues service scheduled for December 2004. Construction started on the Hiawatha Corridor LRT in January 2001. The project faced a challenge in acquiring land from five federal agencies because each agency had a different structure and rule for land transfer. Eventually all the right-of-way (ROW) was acquired and deals were made with the agencies without any cost increase. The major cost increase happened due to re-alignment at the Mall of America. The re-alignment provided better access (and more ridership) at the Mall of America and increased ridership. The cost increase included \$18.8 million for design

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and construction, $11.8 million for additional right-of-way costs, additional local contribution of $3.6 million, additional $2.8 for management and administration, additional insurance of $2.8 million, and additional contingency of $1.5 million. This project experienced one year of delay after final design during the construction phase.

Project 3- Portland Interstate MAX:

This is a 5.8 mile interstate Metropolitan Area Express (MAX) light rail line. It tied into the existing MAX Blue Line at Rose Quarter. Interstate MAX used innovative, green construction practices not previously widely applied to light rail construction. The project delivery method used for this project was Construction Manager at Risk (CMR).

The Interstate MAX project total cost was estimated at $314.9 million at the FFGA stage, but was completed for $349.4 million. The project schedule remained constant throughout project development, and the project was completed on time. Despite an increase in the fleet size during final design, cost containment during construction was made possible by value engineering, utilizing the CMR delivery method, bringing the construction contractor early into the design phase, and using innovative construction practices and materials. Alignment costs went down during final design, but up again during construction. Construction costs were also impacted by the need to close the MAX Blue Line for a brief period while existing tracks were raised and realigned. During the closure, buses shuttled MAX riders around the area.

Project 4- Santa Clara Vasona Line:

This is a 5.2 mile light rail extension constructed by Santa Clara Valley Transportation Authority (VTA). Santa Clara Vasona Line includes 0.18 miles of subway alignment, 0.1 miles elevated and the rest at-grade. There are eight stations, seven at-grade and one

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elevated. The project objectives were to provide service between downtown San Jose and town of Campbell and to ease traffic on adjacent freeways and surface streets. The project delivery method used for this project was design-bid-build (DBB).

The total cost estimate for Vasona project was $313.6 million at the FFGA stage, and was completed for $316.8 million. The project schedule remained constant throughout project development, and the project was completed on time. From planning to operations, project scope quantities remained constant, while cost increases totaled about $47.8 million. Only $3.2 million cost increase happened after final design/FFGA. The growth is attributed in part to several requirements imposed by third parties, such as additional requirements by Union Pacific Railroad (UPRR) as part of the right-of-way (ROW) purchase for existing freight track relocation and reconstruction. ROW purchase cost from UPRR was also higher than the original budget. Similarly, 496 feet of guideway required elevation after the California Public Utilities Commission (CPUC) disapproved of at-grade crossing at Hamilton Avenue. In addition, the Hamilton station had to be elevated as a result of the guideway being elevated. Utility relocation was more significant than envisioned in the original budget and required additional construction management resources to limit schedule slippage.

Project 5- Washington Largo Extension:

This was a 3.1 mile heavy rail extension led jointly by the Maryland Transit Administration (MTA) and the Washington Metropolitan Area Transit Authority (WMATA). The 3.1 mile path included tunnel and surface segments, 2 new stations, and the purchase of 14 heavy rail vehicles. The stations provide 2,700 park-and-ride spaces. The MTA developed the project

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through preliminary engineering and WMATA accepted responsibility for managing the final design and construction activities, using a design-build (DB) construction method.

The cost estimate of this project at the FFGA stage was $433.9 million and the actual cost at completion was $456.0 million. The planned opening of the project shifted multiple times, from 2003 during planning, to 2005 during preliminary engineering, and to 2004 during final design through actual opening in 2004. However, the project schedule was not delayed after final design during construction phase. Changes in scope and unit cost caused cost increase in the project.

7.4.2 Estimating Correlation between Projects in the First Dataset Using the PSG

To calculate the correlation coefficient among each pair of projects in the First Dataset using the proposed structured guideline (PSG), precise knowledge of every project is required. What has been compiled in the previous section is not covering all aspects of the projects' information necessary to complete the PSG table. Since we lack detailed information on each project, we may not be able to go over all twelve common risk factors in the PSG method. An agency's expert who has access to all contract documents of the projects in hand can review all twelve common risk factors and estimate the correlation with a better accuracy.

It should be noted that the estimation of the correlation should happen at the time of the FFGA. Many of the risk factors described in the projects descriptions were not known at the time of the FFGA. The correlation evaluation is performed by going through the 12 factors given in Table 6.3. The relevant factors are discussed in the following.

It is presumed that all five projects had optimistic estimating and that they were underestimated. Flyvbjerg (2006) declares that there is a demonstrated, systematic tendency for project appraisers in large public projects to be overly optimistic. Projects 2, 3 and 5 were using alternative delivery method. Hiawatha Line was the first LRT project in Minneapolis in which they did not have much experience. For Washington Largo Extension, MTA had experience with design-build in Central LRT Project Phase II constructed in 1997. Given the variety of the delivery methods used and the experience of transit agencies, it seems that the assumption of independence is not unrealistic.

Due to September 11, 2001 terrorist attack, the risk of security enhancement and changing the alignment to protect Federal lands may arise. Despite this, due to geographic dispersity of these projects, we could not identify any one regulation or incidence that would affect more than any one of these projects concurrently. Also, there is no evidence that any environmental regulation has affected the projects after completing the final design.

The bond rating in each state is established based on that state's creditor situation. However, as all five projects are contemporary, bond rate would incur some correlation between costs of the five projects. Rail cars of projects 2, 3, 4, and 5 could have been imported from overseas or Canada. Inflation also can create some degree of correlation between the projects as they are contemporary.

Now, Table 7.4 is completed on the basis of the gathered information in accordance with the criteria explained in the PSG method (Sections 6.4.1 and 6.4.2). The correlation magnitudes are first identified, and then they are converted to the correlation coefficients using the proposed conversion threshold.

Table 7.4: Finding the Correlation Coefficients among Projects in the First Dataset

Correlation	Projects									
	1, 2	1, 3	1, 4	1, 5	2, 3	2, 4	2, 5	3, 4	3, 5	4, 5
Correlation Magnitude (Qualification)	Weak	Weak	Weak	Weak	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Correlation Coefficient (Quantification)	0.25	0.25	0.25	0.25	0.55	0.55	0.55	0.55	0.55	0.55

The correlation matrix estimated here then need to be checked for being positive semidefinite. This control is conducted in the next section.

7.4.3 Positive Semidefinite Check for the Correlation Matrix in the First Dataset

We remember that a matrix is positive semidefinite if and only if all eigenvalues of the matrix are non-negative. With the help of MATLAB programming language, this condition is checked first and if the matrix is not positive semidefinite, it is restored using @Risk algorithm explained in Chapter 5.

The correlation matrix of the projects in the First Dataset estimated in the previous section is labeled C_1 where projects with ID 1 to 5 are arranged from left to right and top to down which is:

$$C_1 = \begin{bmatrix} 1.00 & 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & 1.00 & 0.55 & 0.55 & 0.55 \\ 0.25 & 0.55 & 1.00 & 0.55 & 0.55 \\ 0.25 & 0.55 & 0.55 & 1.00 & 0.55 \\ 0.25 & 0.55 & 0.55 & 0.55 & 1.00 \end{bmatrix} \tag{7.1}$$

Using MATLAB, five eigenvalues of matrix C_1 are calculated:

$$\lambda_1 = 0.4500; \quad \lambda_2 = 0.4500; \quad \lambda_3 = 0.4500; \quad \lambda_4 = 0.8603; \quad \lambda_5 = 2.7897 \tag{7.2}$$

Since all five eigenvalues of correlation matrix C_1 are positive, therefore the matrix can be considered as a mathematically true correlation matrix.

7.5   Selecting Data (Second Dataset) to Apply the Model for the Second Time

To show the effectiveness and dynamic characteristic of the model over the course of time, we employ the model on another set of projects. For this purpose, a set of four projects were identified that were completed in 2005 and 2006 (Annual Report on New Starts (FTA 2010a), Capital Cost Database (FTA 2010b), and Booz Allen Hamilton (2005)). These projects are summarized in Table 7.5 and called Second Dataset.

Table 7.5: Dataset of Four Transit Projects for Applying the Model for the Second Time
(Second Dataset)

Proj. ID	Project Name	State	Completed Year	Mode	Delivery Method	Cost at FFGA in M$	Actual Cost in M$	Cost Overrun/ Underrun
1	Chicago CTA Blue Line (Douglas) Rehabilitation	IL	2006	Heavy Rail	DBB	$482.6	$419.61	-13.05%
2	Northern New Jersey Hudson-Bergen MOS-II	NJ	2006	Light Rail	DBOM	$1,215.4	$1,218.47	0.25%
3	San Diego Mission Valley East	CA	2005	Light Rail	DBB	$431.0	$504.01	16.94%
4	San Juan Tren Urbano	PR	2005	Heavy Rail	DB	$1,250.0	$2,250.0	80.00%

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7.5.1   Case Study Projects in the Second Dataset

This dataset is chosen to apply the model for the second time after updating the model by the actual data of completed projects in the First Dataset. This will help demonstrate the effectiveness and dynamic characteristics of the model.

The projects in the Second Dataset are selected from Annual Report on New Starts (FTA 2010a) and Booz Allen Hamilton (2005). Followings are brief explanations for each project of the Second Dataset. This data forms the basis for estimating the correlation coefficients among them. The main criteria for selecting these projects have been the availability of the required cost data.

Project 1- Chicago CTA Blue Line (Douglas) Rehabilitation:

The Douglas Branch Line of Chicago Transit Authority (CTA) is a heavy rail originally built in the early 20th century. This line serves one of the most economically distressed areas in Chicago. The rehabilitation project reconstructed 6.6 mile length of the existing line which was comprised of extensive work on eight CTA rail stations (six elevated and two at-grade), five miles of track, signal and communications equipment, traction power system and infrastructure rehabilitation. The project delivery method used for this project was design-bid-build (DBB).

The total capital costs for the proposed project were estimated to be $482.6 million but it was completed with $419.6 million. The FTA issued a Finding of No Significant Impact on the Environmental Assessment (EA) in April 2000. Following to Environmental Assessment process, the FTA approved the project into final design in June 2000. The FFGA between the FTA and CTA was reached in January 2001 and the FTA committed $320.1 million in Section 5309 New Starts funds to the project. The contractor of this project was

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Kiewit/Delgado, AJV (A Joint Venture) with $317 million construction contract. The project started at Pulaski station on September 10, 2001 and was completed on January 8, 2005. The project is anticipated to have 6,000 daily new riders in the year 2020.

Project 2- Northern New Jersey Hudson-Bergen MOS-II:

The Northern New Jersey Hudson-Bergen MOS-II (Minimum Operable Segment - II) of the New Jersey Transit Hudson-Bergen is a 5.1 mile light rail system with seven stations. This project is part of a three phase project. The whole Hudson-Bergen Light Rail Transit (LRT) system is a 20.1 mile, 30 station LRT project. It runs from the Vince Lombardi Park-and-Ride lot in Bergen County to West Fifth Street in Bayonne in Hudson County. The MOS-I is 10.3 mile, MOS-2 is 5.1 mile, and MOS-3 is a 4.7 mile system. This line provides transit service for one of the highest residential densities in the region. It also serves the Manhattan central business district by providing connections to ferry and commuter rails. MOS-II was in fact negotiated as a large *change order* to MOS-I project. MOS-II was a DBOM (design- build- operate- maintain) project which is unusual for transit projects in the United States, however, the agency had sufficient experience with this delivery system because MOS-I was DBOM also.

The total capital cost for MOS-II was estimated at $1,215.40 million. The FEIS for the full Hudson-Bergen LRT project was issued in August 1996. A Finding of No Significant Impact on the EA was issued by the FTA in June 1999. Full Funding Grant Agreement for MOS–II between the FTA and New Jersey Transit was reached in November 2000. The FTA committed $500 million of Section 5309 New Starts funds. The issuance of the FFGA at that time provided NJ Transit with the authority to borrow funds to begin construction while the MOS-I was being completed, under the same turnkey contract. This was an

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advantage which allowed that the entire Hudson-Bergen project to be constructed at a lower cost by preventing the considerable costs associated with stopping and then restarting a major construction project MOS-II was completed in 2005 and is anticipated to serve 34,900 average weekday riders in 2010.

Project 3- San Diego Mission Valley East:

San Diego Mission Valley East light rail transit (LRT) was an extension of existing Blue Line executed by The Metropolitan Transit Development Board (MTDB) with a length of 5.9 mile. The project extended the existing system from the Mission San Diego Trolley Station east of Interstate 15 to the City of La Mesa in which it connects to the existing Orange Line near Baltimore Drive. The project was comprised of the construction of four new stations at Grantville, San Diego State University, Alvarado Medical Center and 70th Street, and served two existing stations at Mission San Diego and Grossmont Center. The project had elevated, at-grade, and tunnel (400 ft) portions, 11 new low-floor railcars, and provided two park-and-ride lots and a new access road between Waring Road and the Grantville Station. The project delivery method used for this project was design-bid-build (DBB).

Total capital cost was estimated at $431 million. The project is anticipated to serve approximately 10,800 average weekday riders in 2015. A Major Investment Study/Draft Environmental Impact Statement (MIS/DEIS) was completed in May 1997. The FEIS was completed, and a Record of Decision was issued by the FTA in August 1998. The FTA and MTDB reached a FFGA on June 22, 2000. The FTA committed a total of $330 million in Section 5309 New Starts funds to the project. In July 2005, the project was completed and called Green Line.

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Project 4- San Juan Tren Urbano:

This was the first fixed guideway mass transit system in Puerto Rico. This heavy rail system consisted of 10.7 miles of track and 16 stations, and 74 vehicles. The project owner was the Puerto Rico Highway and Transportation Authority (PRHTA). It is a rapid rail line between Bayamon Centro and Sagrado Corazan area in the metropolitan San Juan area. The system is comprised of double-track lines. This project used design-build (DB) delivery method.

The total project cost at the FFGA was estimated to be $1,250 million but it was completed with $2,250 million. Due to increased cost of this project, PRHTA reduced its budget for other transportation projects in the area, such as a planned transportation building.

After establishing the FFGA , three Environmental Assessments were prepared that revised the alignment at the Villa Nevarez station and added two new stations in Rio Piedras at the University of the Puerto Rico and in Hato Rey. Two new stations along the line were added to the plan and a previous station was realigned. Also, 10 cars were added to the original plan. Tren Urbano also experienced 4 years of delay in the construction phase and went to revenue in 2005. A multitude of issues including the use of design-build, local contractors, and several changes in scope caused the vast cost overrun.

7.5.2 Estimating Correlation between Projects in the Second Dataset Using the PSG

Due to lack of detailed information as to each project in the Second Dataset, similar to what we did for calculating correlation coefficients in the First Dataset, we take into consideration just those common risk factors for which the data is available. Once again it should be

noticed that an agency's expert who has access to the all contract documents of the projects in hand can review all twelve common risk factors identified in the PSG method and estimate the correlation with a better accuracy.

One should remember that the estimation of the correlation should happen at the time of the FFGA when many of the risk factors described in the projects descriptions were not known. The correlation evaluation is performed by going through the 12 factors given in Table 6.3 and the relevant factors are discussed in the following.

According to Flyvbjerg (2006), there is a demonstrated, systematic tendency for project appraisers in large public projects to be overly optimistic. Therefore, it is presumed that all four projects had optimistic estimating and that they would be underestimated. Projects 2 and 4 were using alternative delivery method. However, New Jersey Transit Agency had experience in DBOM delivery method as they had constructed Hudson-Bergen MOS-I with the same delivery method. Therefore because of variety of the delivery methods used and the experience of transit agencies, it seems that the assumption of independence is not unrealistic.

Due to the September 11, 2001 terrorist attack, the risk of security enhancement and changing the alignment to protect Federal lands may arise. Despite this, due to geographic dispersity of these projects, we could not identify any one regulation or incidence that would affect more than any one of these projects concurrently. Also, there is no evidence that any environmental regulation has affected the projects after completing the final design.

The bond rating in each state is established based on that state's creditor situation. However, as all four projects are more or less contemporary, bond rate would incur some correlation between costs of the five projects. Rail cars of all projects could have been imported from

overseas or Canada. Inflation also can create some degree of correlation between the projects as they are contemporary.

Now, Table 7.6 is completed on the basis of the gathered information in accordance with the criteria explained in the PSG method (Sections 6.4.1 and 6.4.2). The correlation magnitudes are first identified, and then they are converted to the correlation coefficients using the proposed conversion threshold.

Table 7.6: Finding the Correlation Coefficients among Projects in the Second Dataset

Correlation	Projects					
	1, 2	1, 3	1, 4	2, 3	2, 4	3, 4
Correlation Magnitude (Qualification)	Moderate	Moderate	Weak	Moderate	Weak	Weak
Correlation Coefficient (Quantification)	0.55	0.55	0.25	0.55	0.25	0.25

The positive semidefiniteness of the estimated correlation matrix for the projects in the Second Dataset is checked in the next section.

7.5.3 Positive Semidefinite Check for the Correlation Matrix of the Second Dataset

We first need to calculate all eigenvalues of the correlation matrix estimated in the previous section to see if it has any negative eigenvalues. With the help of MATLAB programming language, this condition is checked first and if the matrix is not positive semidefinite, it is restored using @Risk algorithm explained in Chapter 5.

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The correlation matrix of the projects in the Second Dataset estimated in the previous section is labeled C_2 where projects with ID 1 to 4 are arranged from left to right and top to down which is:

$$C_2 = \begin{bmatrix} 1.00 & 0.55 & 0.55 & 0.25 \\ 0.55 & 1.00 & 0.55 & 0.25 \\ 0.55 & 0.55 & 1.00 & 0.25 \\ 0.25 & 0.25 & 0.25 & 1.00 \end{bmatrix} \tag{7.3}$$

Using MATLAB, four eigenvalues of matrix C_2 are calculated:

$$\lambda_1 = 0.4500; \quad \lambda_2 = 0.4500; \quad \lambda_3 = 0.8500; \quad \lambda_4 = 2.2500 \tag{7.4}$$

Since all five eigenvalues of correlation matrix C_2 are positive, therefore the matrix is mathematically a true correlation matrix.

7.6   Methodology Assumed for Applying the Proposed Model

Let us assume that the FTA is going to allocate budget for the projects in the First Dataset and wants to know the required portfolio budget increase. Also, they are interested in knowing the level of confidence η which is needed at the individual project level to insure that the portfolio budget will not overrun with a probability of more than $1 - \gamma$. The model is fed by $\alpha = 9.1\%$, $\beta = 1.0879$ and $\rho = 1.2799$ values calculated from the Historical Dataset in Section 7.3 and the required portfolio budget increase is calculated.

We will multiply the original cost estimates at the FFGA by the calculated increase factor to get the adjusted cost estimate at the FFGA. This means that the FTA has used the model and increased the required total budget for the portfolio. Then cost overruns/ underruns in

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the First Dataset are computed with respect to the adjusted cost estimates at the FFGA. These cost overruns/ underruns are served as the new observations to update the model. Updating the model results in new α_{new1} and β_{new1} values. At this point, the model has been updated and is ready to be applied on the next dataset which is the Second Dataset. It is expected that the local agencies will improve the accuracy of the cost estimate over time. To incorporate this fact, we increase the cost estimate at the FFGA of the projects in the Second Dataset using the previously calculated increase factor. This reflects the improvement of the cost estimates by local agencies over the course of time. Once again, the model is applied on the adjusted cost estimates in the Second Dataset. The new increase factor is estimated. Similar to the process applied on the First Dataset, the model is updated using the cost overruns/ underruns in the Second Dataset and α_{new2} and β_{new2} values are computed. These new values can be used on any prospective set of projects in the future.

7.7 Applying the Model Assuming Independence Cost Data

In order to show model application, we apply the model to the collected data assuming independence between project costs. Later, this assumption is relaxed and we will consider cost correlations.

7.7.1 Applying the Model on the First Dataset (Independent Case)

From Historical Dataset (Section 7.3), $\alpha = 9.1\%$, $\beta = 1.0879$, and $\rho = 1.2799$ were estimated. Using Eqs. (5.4) and (5.12), $\varphi = 0.1875$ is calculated. Then by the means of Eq.

(5.25), the corresponding η s for different γ s are calculated. This is done for γ between 5% and 95% and the result is depicted in Figure 7.2.
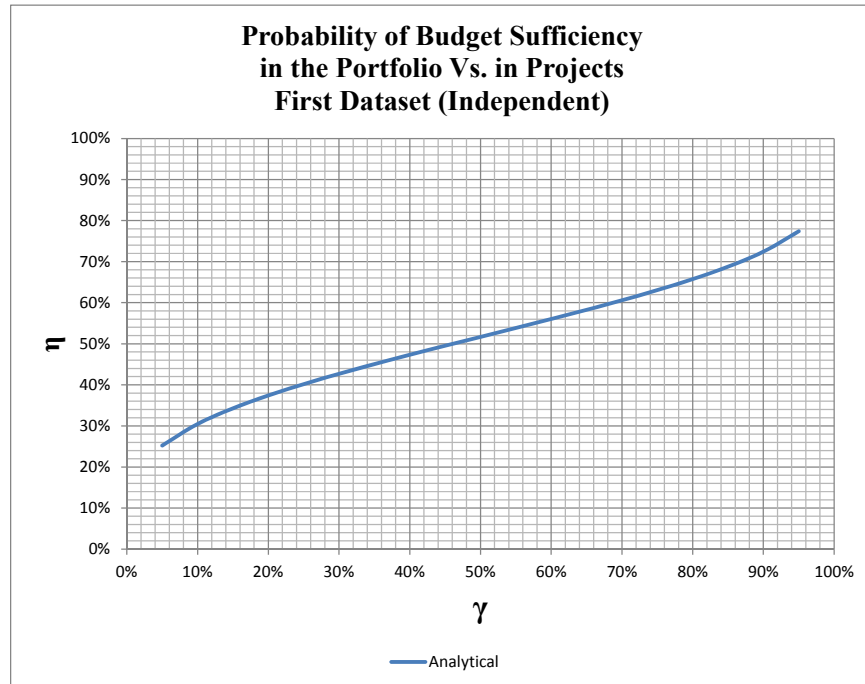
Figure 7.2: Probability of Budget Sufficiency in the Portfolio of Independent Projects (γ) *vs.* in Individual Projects (η)

Then, Eq. (5.17) is employed to compute the required percent increase in portfolio budget based on the η values found from Eq. (5.25). The required percent increase in budget is graphed versus γ and shown in Figure 7.3. In order to make sure that the results are accurate, we simulated the model to find increasing factor which is superimposed on the analytical curve found using the analytical approach. These two curves are very similar.
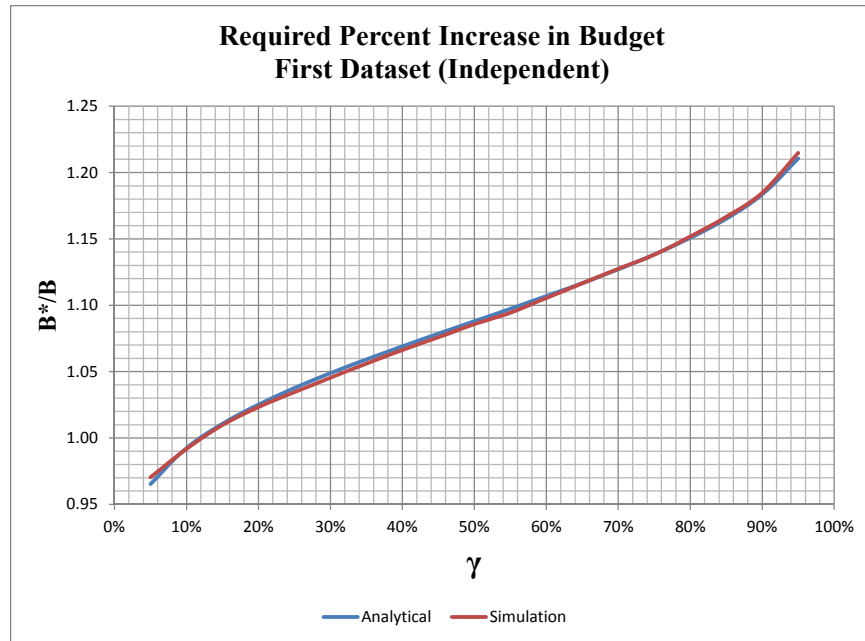
Figure 7.3: Required Percent Increase in Budget (B^*/B) *vs.* Probability of Budget

Sufficiency in the Portfolio of Independent Projects (γ)

For example, one can see in Figure 7.2 that if the FTA wants to have 85% confidence that allocated budget for the portfolio of projects will not fall short, it needs to consider a minimum level of confidence of 68.78% $\cong$ 69% in each individual project risk assessment. Also, Figure 7.3 illustrates that the FTA needs to increase the portfolio budget by 16.52% in order to have 85% level of confidence that the budget for the portfolio is sufficient.

This finding is significant because none of the existing approaches that are used for probabilistic contingency analysis provides a method for calculating the percent increase over existing portfolio budget levels to achieve a certain confidence level in individual projects.

In Table 7.7, a comparison is made between the actual cost overrun/underrun of projects in the First Dataset and cost overrun/underrun if the budget had been adjusted with the

estimated increasing factors. Even though the required budget increase in the portfolio can be distributed differently between the projects, we assume all will be increased proportionally by multiplying the required increase factor ($B^*/B = 1.1652$) by the cost at the FFGA to reach Adjusted Cost at the FFGA.

Table 7.7: Comparison of Cost Overrun/Underrun of Projects in the First Dataset Using the Proposed Model (Independent Assumption)

Proj. ID	Cost at the FFGA (in M$)	Adj. Cost at the FFGA (in M$)	Actual Cost (in M$)	Cost Overrun/Underrun	
				Actual	Adjusted
1	$413.40	$481.71	$604.40	46.20%	25.47%
2	$675.40	$786.99	$715.30	5.91%	-9.11%
3	$314.90	$366.93	$349.40	10.96%	-4.78%
4	$313.60	$365.42	$316.80	1.02%	-13.30%
5	$433.90	$505.59	$456.00	5.09%	-9.81%
Total	$2,151.20	$2,506.64	$2,441.90	13.84%	-2.31%

Table 7.7 shows that if the FTA had used the proposed model to allocate budget for five new projects, they could prevent occurring cost overrun of 13.84% with experiencing -2.31% cost underrun. We expect by updating the model and considering the performance of the recently completed projects, we reach more accurate and optimized increasing factor for budgeting of future projects.

7.7.2 Updating the Model Using the First Dataset Projects (Independent Case)

In this step, we use the information collected from completed projects in the First Dataset to update the model. The cost overruns/ underruns of five projects are considered new observations and serve to form the underlying distribution. The prior distribution is the normal distribution fitted on the histogram of 22 cost overruns/ underruns in the Historical Dataset with the mean of 8.79% and standard deviation of 0.2053.

Considering 85% confidence as a reasonable level, we found that 16.52% increase on the total budget was required. By means of Bayesian updating and recent performance of the transit projects sponsored by the FTA, the α and β of the model can be updated.

The prior distribution comes from the Historical Dataset as follows:

$$f'(\bar{\delta}) = N(0.0879, 0.2053) = \frac{1}{\sqrt{2\pi}(0.2053)} \exp\left[-\frac{1}{2}\left(\frac{\bar{\delta}-0.0879}{0.2053}\right)^2\right] \tag{7.5}$$

Five new observations are the cost overruns/underruns of projects with adjusted cost at the FFGA using 16.52% increasing factor shown in Table 7.7. Using Eq. (5.37), the joint likelihood function, the product of five individual normal PDFs, is calculated:

$$L(\bar{\delta}) \propto N\left(\frac{\delta_1+...+\delta_k}{k}, \frac{\sigma}{\sqrt{k}}\right) = N(\frac{0.2542-0.0911-0.0478-0.1330-0.0981}{5}, \frac{0.1582}{\sqrt{5}})$$
$$= N(-0.0231, 0.0708)$$

$$\tag{7.6}$$

To find the posterior distribution, Eq. (5.40) is used:

$$\begin{cases} \delta'' = \dfrac{\delta_L.(\sigma')^2 + \delta'.(\sigma_L)^2}{(\sigma')^2 + (\sigma_L)^2} = \dfrac{-0.02313 \times (0.2053)^2 + 0.0879 \times (0.0708)^2}{(0.2053)^2 + (0.0708)^2} = -1.13\% \\ \sigma'' = \dfrac{\sigma'.\sigma_L}{\sqrt{(\sigma')^2 + (\sigma_L)^2}} = \dfrac{0.2053 \times (0.0708)}{\sqrt{(0.2053)^2 + (0.0708)^2}} = 0.0669 \end{cases}$$

$$(7.7)$$

Prior, likelihood, and posterior distributions of cost overrun/ underrun are shown in Figure 7.4.
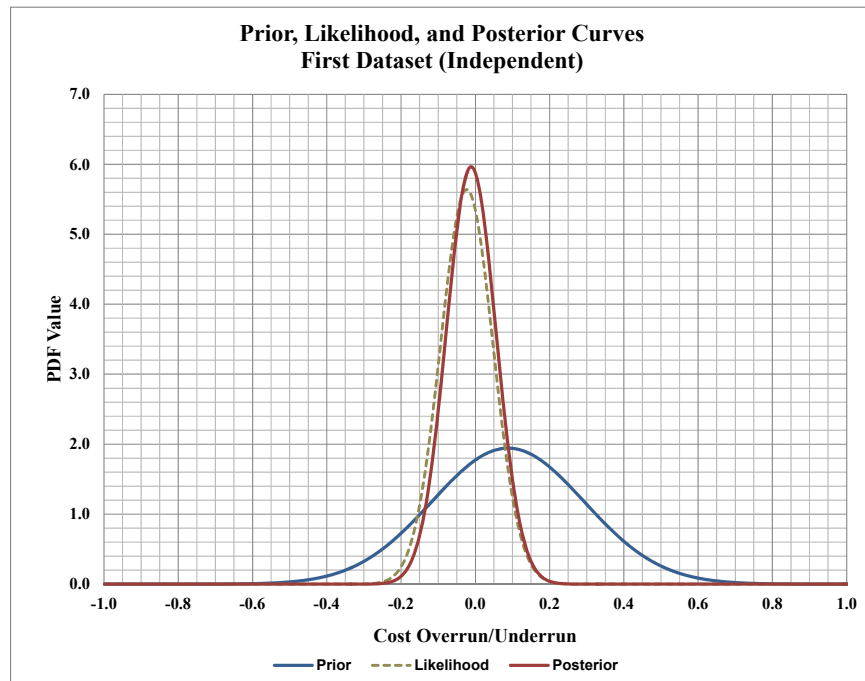
Figure 7.4: The prior, likelihood, and posterior distributions of cost overrun/ underrun

Using Projects in the First Dataset (Independent Assumption)

The posterior distribution parameters can now be used to update α, β and ρ parameters considering $m = 15\%$:

$$\alpha_{new1} = P(x < -m) = P(Z < \frac{-m-\delta''}{\sigma''}) = \Phi(\frac{-0.15 + 0.0113}{0.0669}) = 1.90\%$$

$$\beta_{new1} = 1 + \delta'' = 1 + (-0.0113) = 0.9887 \Rightarrow \rho_{new1} = \frac{\beta_{new1}}{1-m} = \frac{0.9887}{0.85} = 1.1632$$

(7.8)

Replacing the new values of parameters (α_{new1}, β_{new1} and ρ_{new1}) in the model, it is ready and updated to be applied to any future dataset. The updated model is applied to the Second Dataset in the next section.

7.7.3   Applying the Model on the Second Dataset (Independent Case)

Now, we assume that the FTA is budgeting for four new projects (with data provided in the Second Dataset, Table 7.5) and wants to establish the required portfolio budget increase and level of confidence η needed at the individual project level to insure that the portfolio budget will not overrun with a probability of more than $1 - \gamma$.

It should be noted that the projects in the Second Dataset have been estimated with procedures similar to those used for estimating projects in the First Dataset. In other words no improvement has been made in cost estimation for the Second Dataset compared with the First Dataset. Therefore to reflect the impact of the model we increase the cost estimate at the FFGA of all projects in the Second Dataset by the increasing factor estimated in the previous section 16.52% $(B^*/B = 1.1652)$.

From updating process, we have $\alpha = 1.90\%$, $\beta = 0.9887$. By selecting $m = 15\%$ as the maximum expected underrun, $\rho = 1.1632$ (Eq. 7.8). Using Eqs. (5.4) and (5.12), $\varphi = 0.0771$ is calculated. Then by the means of Eq. (5.25), the correspondent η s for

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different γs are computed. For γ between 5% and 95%, η is calculated and the result is graphed in Figure 7.5.
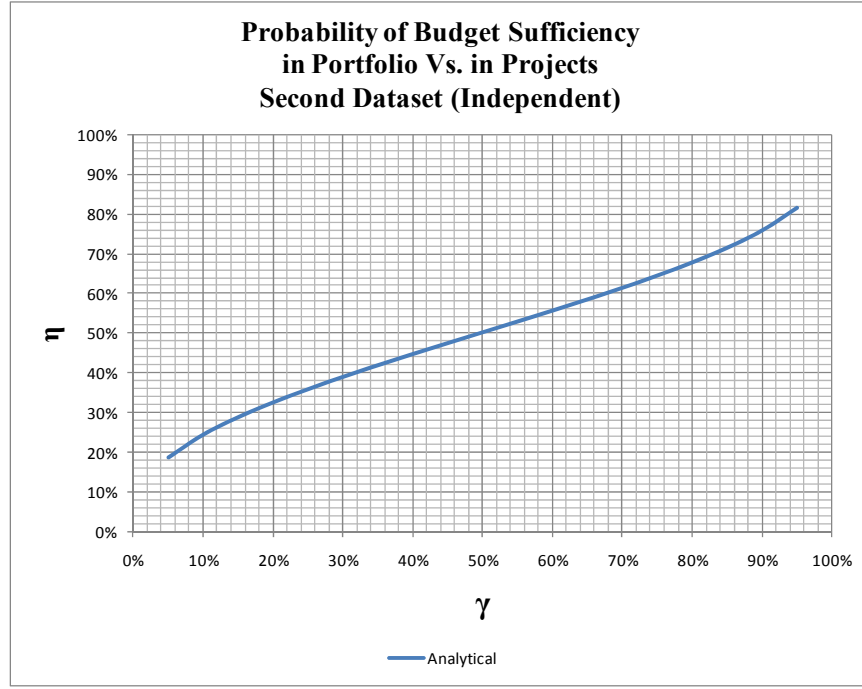
Figure 7.5: Probability of Budget Sufficiency in the Portfolio of Independent Projects (γ) *vs.*

in Individual Projects (η)

Then, Eq. (5.17) is employed to compute the required percent increase in portfolio budget based on the η values found from Eq. (5.25). The required percent increase in budget is shown versus γ values in Figure 7.6. Again to ensure the correctness of calculations, we simulated the model to find the increasing factor. Simulation results are superimposed on the analytical curve found from equations as described above. These two curves are almost identical.
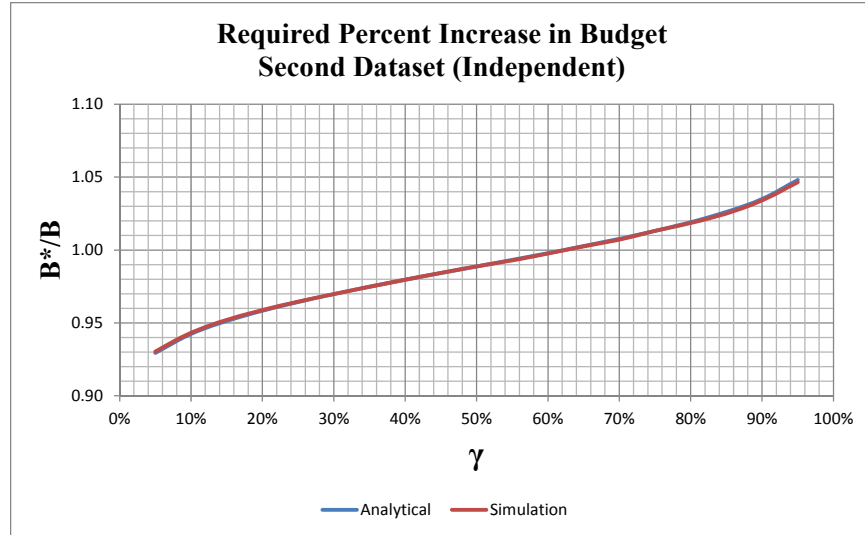
Figure 7.6: Required Percent Increase in Budget (B^*/B) *vs.* Probability of Budget

Sufficiency in the Portfolio of Independent Projects (γ)

From Figure 7.5, one can see that if the FTA wants to have 85% confidence that allocated budget for portfolio of projects in the Second Dataset will not fall short, it needs to consider 71.49% $\cong$ 71% level of confidence in each individual project risk assessment. Also, Figure 7.6 illustrates that the FTA needs to increase the portfolio budget by 2.61% in order to have 85% level of confidence that the budget for portfolio is sufficient.

In Table 7.8, to verify the effectiveness of the model, a comparison is made between the actual cost overrun/underrun of projects in the Second Dataset and cost overrun/underrun if the budget had been adjusted with the estimated increasing factors. It was found that to have 85% confidence that the budget will not fall short, the FTA needs to increase the portfolio budget by 2.61%. Thus the adjusted cost at the FFGA using the proposed model will be higher than the original cost estimate by:

$$Adj.Factor_{Ind.} = 1.1652 \times 1.0261 = 1.1956 \qquad (7.9)$$

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Table 7.8: Comparison of Cost Overrun/Underrun of Projects in the Second Dataset Using

the Proposed Model

Proj. ID	Cost at FFGA (in M$)	Adj. Cost at FFGA (in M$)	Actual Cost (in M$)	Cost Overrun/Underrun	
				Actual	Adjusted
1	$482.6	$577.02	$419.61	-13.05%	-27.28%
2	$1,215.4	$1,453.20	$1,218.47	0.25%	-16.15%
3	$431.0	$515.33	$504.01	16.94%	-2.20%
4	$1,250	$1,494.57	$2,250.00	80.00%	50.54%
Total	$3,379.0	$4,040.12	$4,392.09	21.04%	1.23%

Table 7.8 shows that if the FTA had used the proposed model to allocate budget for the four new projects, they could reduce the cost overrun from 21.04% to 1.23%. This result verifies how effective the model can be to control the cost overrun while is not overallocating the budget.

7.7.4   Updating the Model Using the Second Dataset (Independent Case)

Once again, we use the information of completed projects in the Second Dataset to update the model for the second time. The cost overruns/ underruns of the four projects are considered new observations and serve to form the underlying distribution.

The prior distribution is the posterior distribution calculated in Section 7.7.2 as follows:

$$f'(\bar{\delta}) = N(-0.0110, 0.0669) = \frac{1}{\sqrt{2\pi}(0.0669)} \exp\left[-\frac{1}{2}\left(\frac{\bar{\delta} + 0.0110}{0.0669} \right)^2 \right] \qquad (7.10)$$

New observations are the adjusted cost overruns/underruns of four independent projects in the Second Dataset given in Table 7.8. Using Eq. (5.37), the joint likelihood function, the product of four individual normal PDFs, is calculated:

$$L(\bar{\delta}) \propto N\left(\frac{\delta_1 + ... + \delta_k}{k}, \frac{\sigma}{\sqrt{k}}\right) = N(\frac{-0.2728 - 0.1615 - 0.0220 + 0.5054}{4}, \frac{0.3444}{\sqrt{4}}) \quad (7.11)$$
$$= N(0.0123, 0.1722)$$

To find the posterior distribution, Eq. (5.40) is used:

$$\begin{cases} \delta'' = \dfrac{\delta_L.(\sigma')^2 + \delta'.(\sigma_L)^2}{(\sigma')^2 + (\sigma_L)^2} = \dfrac{-0.0123 \times (0.0669)^2 - 0.0110 \times (0.1722)^2}{(0.0669)^2 + (0.1722)^2} = -0.79\% \\ \\ \sigma'' = \dfrac{\sigma'.\sigma_L}{\sqrt{(\sigma')^2 + (\sigma_L)^2}} = \dfrac{0.0699 \times (0.1722)}{\sqrt{(0.0669)^2 + (0.1722)^2}} = 0.0624 \end{cases}$$

$$(7.12)$$

Prior, likelihood, and posterior distributions of cost overrun/ underrun are shown in Figure 7.7.
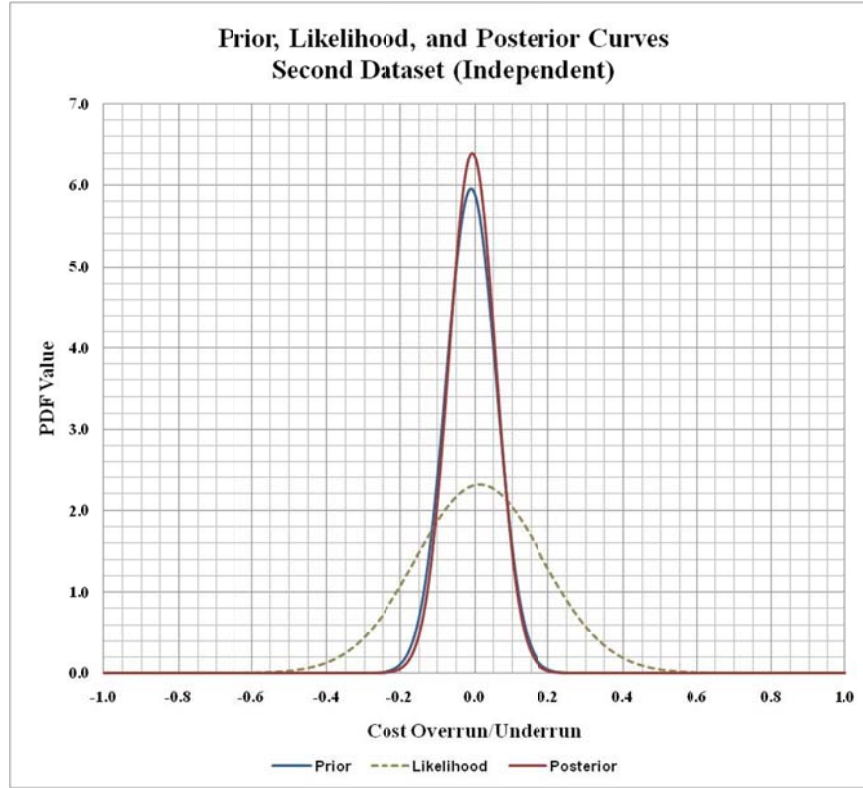
Figure 7.7: The prior, likelihood, and posterior distributions of cost overrun/ underrun

Using Projects in the Second Dataset (Independent Assumption)

It can be seen that in this second round of updating, the prior and posterior distributions are much more similar. This process fine tunes the accuracy of estimates as more updates are implemented. The posterior distribution parameters can now be used to update α, β and ρ parameters considering $m = 15\%$:

$$\alpha_{new2} = P(x < -m) = P(Z < \frac{-m - \delta''}{\sigma''}) = \Phi(\frac{-0.15 + 0.0079}{0.0624}) = 1.14\%$$

$$\beta_{new2} = 1 + \delta'' = 1 + (-0.0079) = 0.9921 \Rightarrow \rho_{new2} = \frac{\beta_{new2}}{1 - m} = \frac{0.989}{0.85} = 1.1672$$

(7.13)

The values of α_{new2}, β_{new2} and ρ_{new2} must be used to apply the model on any prospective dataset in the future, assuming independence between cost estimates.

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7.8   Applying the Model Assuming Correlated Cost Data

In this section, the application of the model is repeated on both the First and Second Datasets recognizing correlation between projects. The correlation coefficients were already estimated in Sections 7.4.2 and 7.5.2.

7.8.1   Applying the Model on the First Dataset (Correlated Case)

From Historical Dataset (Section 7.3), we have $\alpha = 9.1\%$, $\beta = 1.0879$, and $\rho = 1.2799$. Using Eqs. (5.4) and (5.12), $\varphi = 0.1875$ is calculated. To use Eq. (5.25), we need to have the correlation coefficient matrix C_1 which was estimated before (Sections 7.4.2). Therefore by means of Eq. (5.25), the correspondent η s for different γ s from 5% to 95% are calculated. The result is graphed in Figure 7.8.
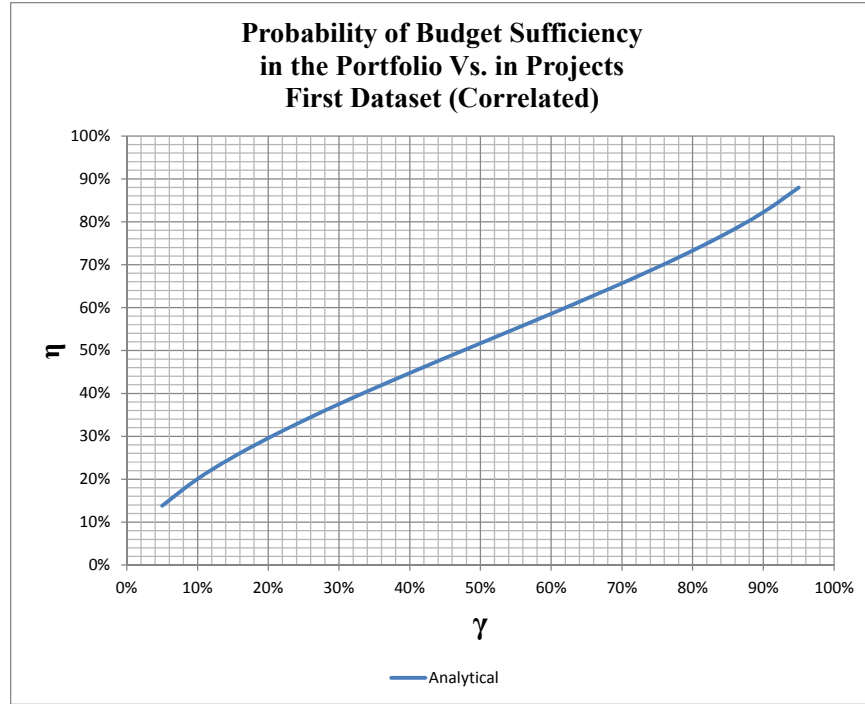
Figure 7.8: Probability of Budget Sufficiency in a Portfolio of Correlated Projects (γ) *vs.* in

Individual Projects (η)

Similar to independent projects, the estimated values of η for different γ s are used in Eq. (5.17) to compute the required percent increase in portfolio budget. The required percent increase in budget is graphed versus γ and shown in Figure 7.9. Again, we used simulation to check the accuracy of proposed analytical method. Required B^*/B factor values found from simulation and proposed analytical method are superimposed and shown in Figure 7.9. It is clear that two curves are very similar.

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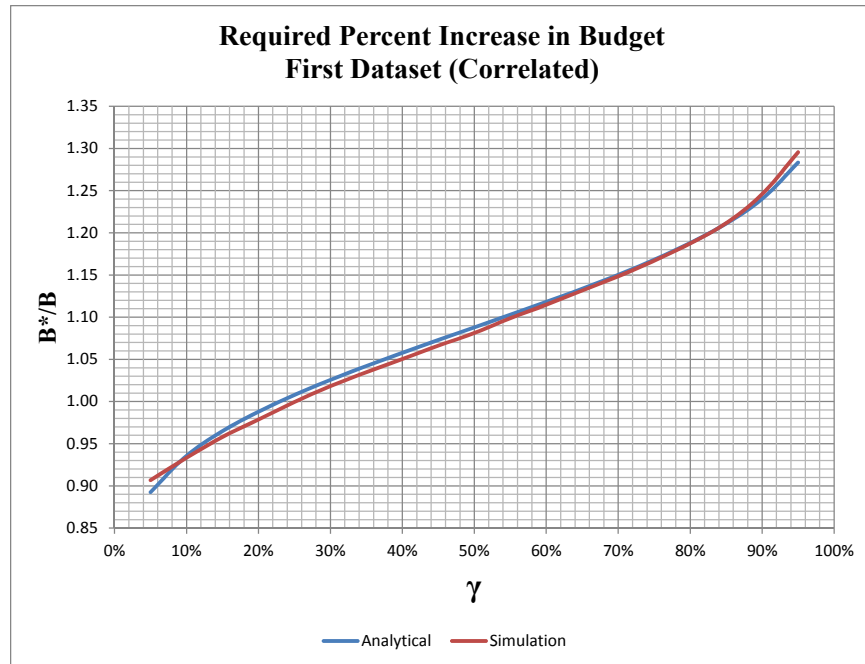
Figure 7.9: Required Percent Increase in Budget (B^*/B) *vs.* Probability of Budget

Sufficiency in the Portfolio of Correlated Projects (γ)

Reviewing Figure 7.8, one can see that if the FTA wants to have an 85% confidence that allocated budget for the portfolio of correlated projects will not fall short, it needs to consider 77.48% $\cong$ 77% level of confidence in each individual project risk assessment. This is about 8% more than what was calculated when projects were independent. Also, Figure 7.9 illustrates that the FTA needs to increase the portfolio budget by 21.11% in order to have an 85% level of confidence that the budget for the portfolio is sufficient. This is 4.59% more than what was required for the independent case.

Therefore, it is found that the results from correlated assumption are more conservative than independent case. In Table 7.9, the actual cost overruns/underruns of projects in the First Dataset and cost overruns/underruns if the budget had been adjusted with the estimated

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increasing factor are compared. By increasing the cost estimates at the FFGA by the required

increasing factor of 21.11% $(B^*/B = 1.2111)$, we reach Adjusted Cost at the FFGA.

Table 7.9: Comparison of Cost Overrun/Underrun of Projects in the First Dataset Using the

Proposed Model (Correlated Projects)

Proj. ID	Cost at the FFGA (in M$)	Adj. Cost at the FFGA (in M$)	Actual Cost (in M$)	Cost Overrun/Underrun	
				Actual	Adjusted
1	$413.40	$499.83	$604.40	46.20%	20.72%
2	$675.40	$816.61	$715.30	5.91%	-12.55%
3	$314.90	$380.74	$349.40	10.96%	-8.38%
4	$313.60	$379.17	$316.80	1.02%	-16.58%
5	$433.90	$524.6	$456.00	5.09%	-13.22%
Total	$2,151.20	$2,605.22	$2,441.90	13.84%	-6.00%

Table 7.9 shows if the FTA had used the proposed model to allocate budget for five new

projects, they could have ended up with an average 6.00% cost underrun instead of 13.84%

cost overrun. It is expected that by updating the model and considering the performance of

the recently completed projects, we can reach more accurate and optimal increasing factor

for budgeting of future projects.

7.8.2 Updating the Model Using the First Dataset (Correlated Case)

Here the estimated correlation matrix between the projects is incorporated in the updating

analysis. It should be noted that the Eq. (5.40) (to analytically calculate the mean and

standard deviation of the posterior distribution) is not valid anymore because of dependency

among the projects. Therefore the only feasible approach is the numerical procedure. The prior distribution from the Historical Dataset is the same as given in Eq. (7.5). Five new observations are the cost overruns/underruns of projects with adjusted cost at the FFGA using 21.11% increasing factor with the average of -6.00% and standard deviation of 0.1522.

First, we need to find the variance-covariance matrix V_1 correspondent with correlation matrix C_1 which is positive semidefinite. We know that:

$$V_1 = \sigma . C_1 . \sigma = \begin{bmatrix} 0.1522 & 0 & 0 & 0 & 0 \\ 0 & 0.1522 & 0 & 0 & 0 \\ 0 & 0 & 0.1522 & 0 & 0 \\ 0 & 0 & 0 & 0.1522 & 0 \\ 0 & 0 & 0 & 0 & 0.1522 \end{bmatrix} \times \begin{bmatrix} 1.00 & 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & 1.00 & 0.55 & 0.55 & 0.55 \\ 0.25 & 0.55 & 1.00 & 0.55 & 0.55 \\ 0.25 & 0.55 & 0.55 & 1.00 & 0.55 \\ 0.25 & 0.55 & 0.55 & 0.55 & 1.00 \end{bmatrix} \times \sigma$$

$$= \begin{bmatrix} 0.0232 & 0.0058 & 0.0058 & 0.0058 & 0.0058 \\ 0.0058 & 0.0232 & 0.0127 & 0.0127 & 0.0127 \\ 0.0058 & 0.0127 & 0.0232 & 0.0127 & 0.0127 \\ 0.0058 & 0.0127 & 0.0127 & 0.0232 & 0.0127 \\ 0.0058 & 0.0127 & 0.0127 & 0.0128 & 0.0232 \end{bmatrix}$$

(7.14)

Where σ is a diagonal matrix whose entries are the standard deviation of cost overrun/ underrun of five observed projects.

Using Eq. (5.41) and MATLAB, the likelihood values for the various values of $\bar{\delta}$ ranging from -99.99% to 200% with the pace of 0.001 are calculated. The posterior is computed using Eq. (5.44) and the numerical method explained previously, in an Excel spreadsheet. Using Eqs. (5.45) and (5.46), the mean and standard deviation of the posterior distribution are calculated:

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$$\begin{cases} \delta'' = 1.30\% \\ \sigma'' = 0.0965 \end{cases} \tag{7.15}$$

Prior, likelihood, and posterior distributions of cost overrun/ underrun are shown in Figure 7.10.
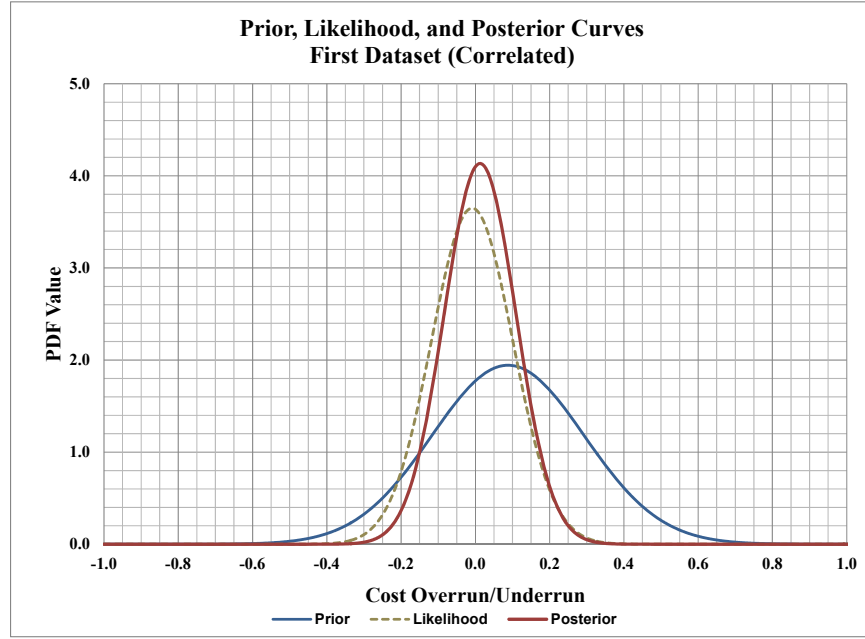
Figure 7.10: The prior, likelihood, and posterior distributions of cost overrun/ underrun

Using Projects in the First Dataset (Correlated Assumption)

The posterior distribution parameters can now be used to update α, β and ρ parameters assuming $m = 15\%$:

$$\alpha_{new1} = P(x < -m) = P(Z < \frac{-m - \delta''}{\sigma''}) = \Phi(\frac{-0.15 - 0.0130}{0.0965}) = 4.55\%$$

$$\beta_{new1} = 1 + \delta'' = 1 + 0.0130 \Rightarrow \rho_{new} = \frac{\beta_{new1}}{1 - m} = \frac{1.013}{0.85} = 1.1918 \tag{7.16}$$

Replacing the new values of parameters in the model, it is ready and updated to be applied on any future dataset to estimate the new η and B^*/B.

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7.8.3 Applying the Model on the Second Dataset (Correlated Case)

From updating process (Section 7.8.2), we have $\alpha = 4.55\%$, $\beta = 1.0130$. By selecting $m = 15\%$ as the maximum expected underrun, $\rho = 1.1918$.

Like Section 7.7.3 where the projects assumed to be independent, it should be noted that the projects in the Second Dataset have been estimated with the similar manner in the past. Therefore to reflect the impact of the model and improvement in the cost estimate, we increase the cost estimate at the FFGA of all projects in the Second Dataset by increasing factor $21.11\%\,(B^{*}/B = 1.2111)$ estimated in Section 7.8.1.

Correlation coefficients are added to the model using correlation matrix C_2''. Using Eqs. (5.4) and (5.12), $\varphi = 0.1078$ is calculated. Then by the means of Eq. (5.25), the correspondent η s for different γ s are computed. For γ between 5% and 95%, η is calculated and the result is graphed in Figure 7.11.
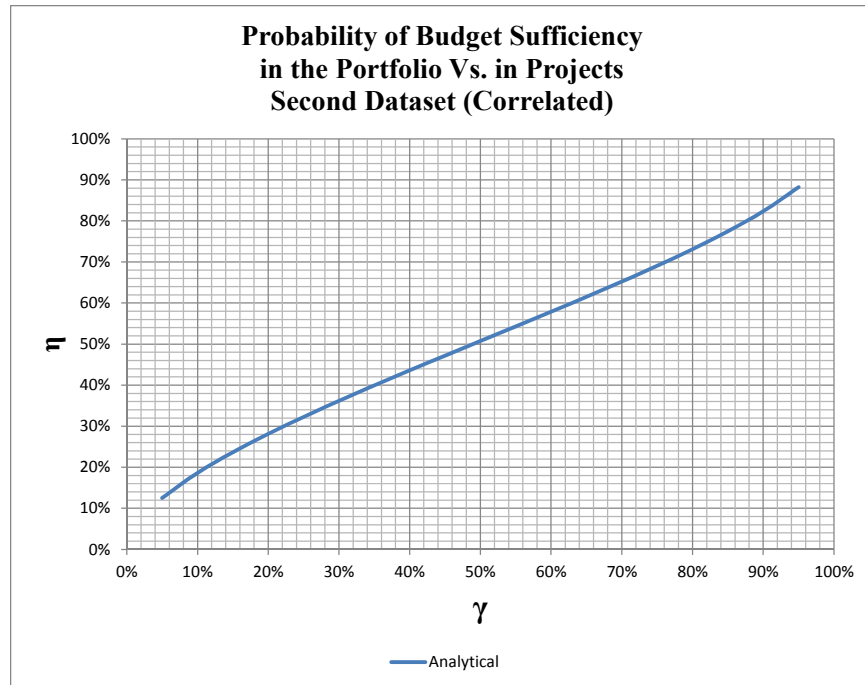
Figure 7.11: Probability of Budget Sufficiency in the Portfolio of Correlated Projects (γ) *vs.*

in Individual Projects (η)

Like independent projects, the estimated values of η for different γ s are used in Eq. (5.17) to compute the required percent increase in portfolio budget. The required percent increase in budget is shown versus γ values in Figure 7.12.
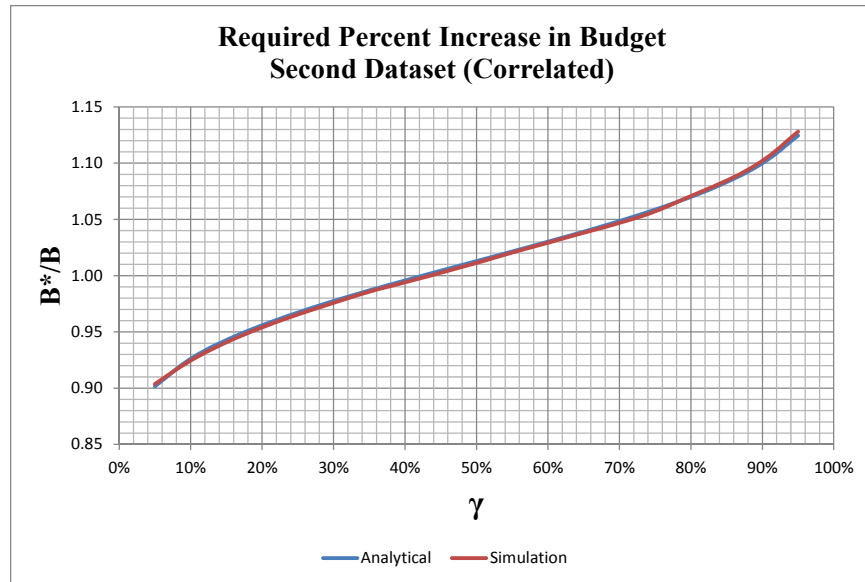
Figure 7.12: Required Percent Increase in Budget (B^*/B) *vs.* Probability of Budget

Sufficiency in the Portfolio of Correlated Projects (γ)

Again we use simulation to check the accuracy of proposed analytical method. Required increasing factor curves found from simulation and proposed analytical method are superimposed in Figure 7.12. The two curves are very close together. This comparison suggests that the normality assumption is not adding significant error to the analytical model.

Reviewing Figure 7.11, one can see that if the FTA desires an 85% confidence that allocated budget for portfolio of the correlated projects will not fall short, it needs to consider 77.48% $\cong$ 77% level of confidence in each individual project's risk assessment. This is about 6% more than when we assumed that the projects are independent. Also, Figure 7.12 illustrates that the FTA needs to increase the portfolio budget by 8.32% in order to have 85% level of confidence that the budget for portfolio is sufficient. This is 5.71% more than required increasing factor for independent projects in the portfolio of the Second Dataset.

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In Table 7.10, to verify the effectiveness of the model, a comparison is made between the actual cost overrun/underrun of projects in the Second Dataset and cost overrun/underrun if the budget had been adjusted with the estimated increasing factors. It was found that to have 85% confidence that the budget will not fall short, the FTA needs to increase the portfolio budget by 8.32%. Thus the adjusted cost at the FFGA using the proposed model will be higher than the original cost estimate by:

$$Adj.Factor_{Cor.} = 1.2111 \times 1.0832 = 1.3118. \tag{7.17}$$

Table 7.10: Comparison of Cost Overrun/Underrun of Projects in the Second Dataset

Using the Proposed Model (Correlated Projects)

Proj. ID	Cost at FFGA (in M$)	Adj. Cost at FFGA (in M$)	Actual Cost (in M$)	Cost Overrun/Underrun	
				Actual	Adjusted
1	$482.6	$633.08	$419.61	-13.05%	-33.72%
2	$1,215.4	$1,594.38	$1,218.47	0.25%	-23.58%
3	$431.0	$565.39	$504.01	16.94%	-10.86%
4	$1,250	$1,639.77	$2,250.00	80.00%	37.21%
Total	$3,379.0	$4,432.62	$4,392.09	21.04%	-7.73%

Table 7.10 shows if the FTA had used the proposed model to allocate budget for four new projects, they could have 7.73% underrun in average instead of experiencing 21.04% overrun. This shows the effectiveness of the model to keep the portfolio within budget.

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7.8.4 Updating the Model Using the Second Dataset (Correlated Case)

For the correlated approach, the prior distribution is the posterior distribution calculated in Section 7.8.2 as follows:

$$f'(\bar{\delta}) = N(0.0130, 0.0965) = \frac{1}{\sqrt{2\pi}(0.0965)}\exp\left[-\frac{1}{2}\left(\frac{\bar{\delta}-0.0130}{0.0965}\right)^2\right] \qquad (7.18)$$

New observations are the adjusted cost overruns/underruns of four correlated projects in the Second Dataset given in Table 7.10. First, we need to find the variance-covariance matrix V_2 correspondent with correlation matrix C_2. We know that:

$$V_2 = \sigma.C_2.\sigma = \begin{bmatrix} 0.3139 & 0 & 0 & 0 \\ 0 & 0.3139 & 0 & 0 \\ 0 & 0 & 0.3139 & 0 \\ 0 & 0 & 0 & 0.3139 \end{bmatrix} \times \begin{bmatrix} 1.00 & 0.55 & 0.55 & 0.25 \\ 0.55 & 1.00 & 0.55 & 0.25 \\ 0.55 & 0.55 & 1.00 & 0.25 \\ 0.25 & 0.25 & 0.25 & 1.00 \end{bmatrix} \times \sigma$$

$$= \begin{bmatrix} 0.0985 & 0.0542 & 0.0542 & 0.0246 \\ 0.0542 & 0.0985 & 0.0542 & 0.0246 \\ 0.0542 & 0.0542 & 0.0985 & 0.0246 \\ 0.0246 & 0.0246 & 0.0246 & 0.0985 \end{bmatrix} \qquad (7.19)$$

Where σ is a diagonal matrix whose entries are the standard deviation of cost overruns/underruns of the four observed projects.

Using Eq. (5.41) and MATLAB, the likelihood values for the various values of $\bar{\delta}$ ranging from -99.99% to 200% with the pace of 0.001 are calculated. The posterior is computed using Eq. (5.44) and the numerical method explained previously, in an Excel spreadsheet. Using Eqs. (5.45) and (5.46), the mean and standard deviation of the posterior distribution are calculated:

$$\begin{cases} \delta'' = 1.10\% \\ \sigma'' = 0.0888 \end{cases} \tag{7.20}$$

Prior, likelihood, and posterior distributions of cost overrun/ underrun are shown in Figure 7.13.
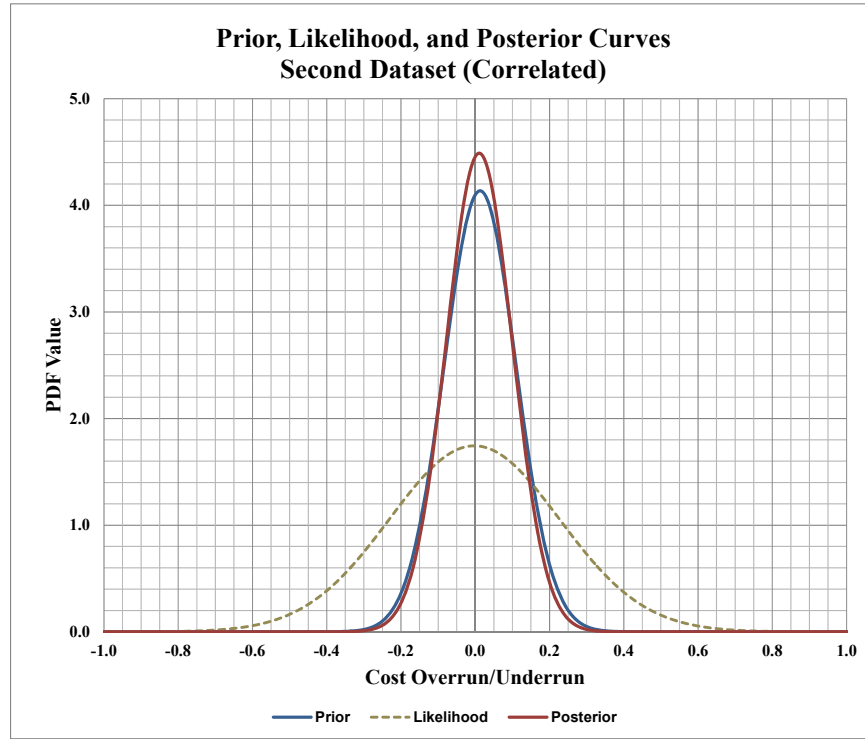
Figure 7.13: The prior, likelihood, and posterior distributions of cost overrun/ underrun Using Projects in the Second Dataset (Correlated Assumption)

The posterior distribution parameters can now be used to update α, β and ρ parameters considering $m = 15\%$:

$$\alpha_{new2} = P(x < -m) = P(Z < \frac{-m - \delta''}{\sigma''}) = \Phi(\frac{-0.15 - 0.0110}{0.0888}) = 3.50\%$$

$$\beta_{new2} = 1 + \delta'' = 1 + 0.0110 = 1.0110 \Rightarrow \rho_{new2} = \frac{\beta_{new2}}{1 - m} = \frac{1.0110}{0.85} = 1.1894 \tag{7.21}$$

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The values of α_{new2}, β_{new2} and ρ_{new2} must be used to apply the model on any prospective dataset whose projects are correlated.

7.9　Sensitivity Analysis for Cost Correlation Impact on Required Percent Increase in Budget

In this section, we carry out a sensitivity analysis (SA) to evaluate the contribution of cost correlation to the variability of required percent increase in budget (B^*/B). To this end, we perform a screening method in which the cost correlation matrices are changed and the output of the model is monitored.

Conducting the SA requires a set of possible cost correlation matrices. In the previous sections, we estimated the correlation between project costs of the First Dataset (C_1) and the Second Dataset (C_2). To create the sets of possible inputs, we need to develop new correlation matrices. Therefore, we multiply each *pairwise correlation* in matrix C_1 and C_2 to a set of multipliers. These multipliers must be selected in a manner that the new generated correlations are not greater than 1.0.

Considering the correlation coefficients in matrices C_1 and C_2, we selected the set of multipliers as {1.5, 1.0, 0.5, 0}. It is obvious that the multiplier of zero to all pairwise correlations in matrices C_1 and C_2 results in an identity matrix which is the previously calculated independent case. Moreover, the multiplier of 1.0 makes no changes and it is again the original correlated case. Thus, two new scenarios are added with multiplier of 0.5 and 1.5. The newly generated matrices are checked to be positive semidefinite matrices. The

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control showed that the matrices are indeed positive semidefinite and no transformation is required. All steps explained in Section 7.8 is repeated once with new matrices $0.5 \times C_1$ and $0.5 \times C_2$ and once with $1.5 \times C_1$ and $1.5 \times C_2$. The required percent increase in budget (B^*/B) for the First Dataset and the Second Dataset is estimated and depicted in Figures 7.14 and 7.15 for all four scenarios.
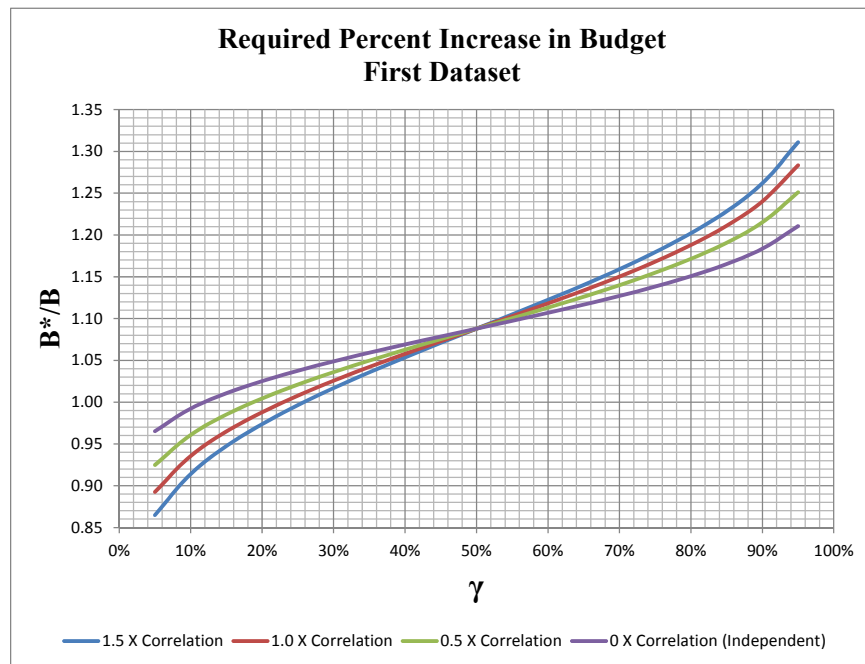
Figure 7.14: Required Percent Increase in Budget for the First Dataset Considering Four

Different Correlation Matrices
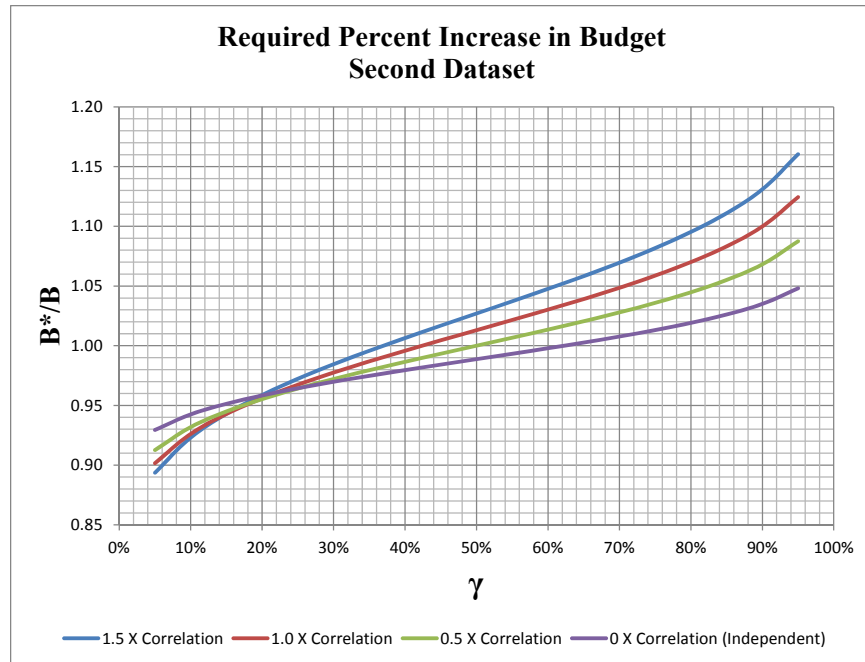
Figure 7.15: Required Percent Increase in Budget for the Second Dataset Considering Four

Different Correlation Matrices

Figures 7.14 and 7.15 show the effect of various correlations on the required percent budget increase. For instance, for the First Dataset if the sponsor wants to have 85% budget sufficiency confidence and ignore the correlation among the project costs, the model shows 16.52% required budget increase, while considering the $1.5 \times C_1$ correlation matrix results in a 22.85% required budget increase. This is 6.33% difference which is translated into $136 million extra budget. This reveals the importance of recognition of correlation in the model. Therefore, in order to allocate as accurate as possible contingency budget for a portfolio, the precise estimation of correlation between costs of projects is imperative.

7.10   Analysis of Results

In this chapter, a comprehensive numerical example was presented to illustrate the application and effectiveness of the proposed model to decrease the cost overrun in the portfolio of projects over time. To this end, three different datasets of transit projects were chosen: 1. Historical Dataset comprised of 22 projects finished before 2004 to find the initial α and β to prepare the model for applying on any prospective dataset; 2. First Dataset including five projects completed in 2004 to apply the model for the first time and updating the model; 3. Second Dataset including four projects completed in 2005 and 2006 to apply and update the model for the second time.

To apply the model, two different approaches were considered: 1. we assumed independence among projects' costs; 2. the correlations between projects in applying and updating were recognized and estimated using the Proposed Structured Guideline (PSG). The results from applying the proposed model on aforementioned datasets are summarized in Table 7.11. Column "Actual Cost Overrun/ Underrun" depicts the actual mean and standard deviation of cost overruns/ underruns in three datasets. Column "Adjusted Cost Overrun/ Underrun" shows the mean and standard deviation of cost overrun/ underrun if the model had been applied to the data. The last Column "Updated Cost Overrun/Underrun" presents the mean and standard deviation of cost overruns/underruns after using the Bayesian updating which will prepare the model for the next application.

Table 7.11: Summary of the Results from Applying the Proposed Model on Transit Projects

Data	Approach	α	β	For $\gamma = 85\%$		Actual Cost Overrun/ Underrun		Adjusted Cost Overrun/ Underrun		Updated Cost Overrun/ Underrun	
				B^*/B	η	$\overline{\delta}$	$\overline{\sigma}$	$\overline{\delta}_{Adj.}$	$\overline{\sigma}_{Adj.}$	δ''	σ''
Historical Dataset	N/A	N/A	N/A	N/A	N/A	8.79%	0.2053	N/A	N/A	N/A	N/A
First Dataset	Ind.	9.10%	1.0879	1.1652	69%	13.84%	0.1844	-2.31%	0.1582	-1.13%	0.0669
First Dataset	Cor.	9.10%	1.0879	1.2111	77%	13.84%	0.1844	-6.00%	0.1522	1.30%	0.0965
Second Dataset	Ind.	1.90%	0.9887	1.0261	71%	21.04%	0.4118	1.23%	0.3444	-0.79%	0.0624
Second Dataset	Cor.	4.55%	1.0130	1.0832	77%	21.04%	0.4118	-7.73%	0.3139	1.10%	0.0888
Prospective Dataset	Ind.	1.14%	0.9921								
Prospective Dataset	Cor.	3.50%	1.0110								

One can see that the required adjustment in the value of factor B^*/B and cost overrun/ underrun are diminished after each updating. For example, with the independent approach B^*/B (for 85% confidence) was decreased from 1.1652 for the First Dataset to 1.0261 for the Second Dataset. Also, in the First Dataset the model was able to decrease the cost overrun from 13.84% to -2.31%. This improvement continues in the Second Dataset where the cost overrun goes down from 21.04% to 1.23%. Moreover, the model shows that in order to have 85% confidence that the portfolio budget for the First Dataset is sufficient, each individual project in the portfolio needs to be assessed with $\eta = 69\%$ where this is $\eta = 71\%$ for the Second Dataset.

With the correlated approach, for the First Dataset they could have ended up with a 6.00% cost underrun instead of the actual 13.85% cost overrun by assigning increasing factor of 1.2111 to the budget and individual risk assessment confidence level of 77%. For the Second Dataset, the model could have brought down the cost overrun of 21.04% to 7.73% cost underrun by assigning increasing factor of 1.0832 and individual risk assessment confidence level of 77%.

In summary, Table 7.11 illustrates the improvement that can be gained through applying this model over a period of time to control cost overrun and provide adequate budget in the project portfolio. One can notice that in this example, the independent approach is more successful in controlling cost overrun and allocating optimized contingency than the correlated approach. However, it may not be the case for all situations. Therefore, in order to be realistic and more conservative, the consideration of correlation between project costs is encouraged.

7.11   Summary

This chapter demonstrates the application and success of the model through a numerical example of transit projects. First a general procedure that an owner agency such as the FTA should take to apply the proposed model in their budget development procedure was elucidated. To explain the application and verify the effectiveness of the model, three different datasets of transit projects were introduced called: Historical (including 22 transit projects), First (including five transit projects), and Second Datasets (including four transit projects). Historical Dataset was used to estimate the initial parameters of the model. Then the First and Second Datasets were employed for applying and updating the model

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considering two different assumptions: 1. assuming independent projects, and 2. assuming correlation among the projects' costs in each dataset were recognized. A brief description of projects in the First and Second Datasets was given and pairwise correlation coefficients of projects were estimated. The outcomes for two different approaches were summarized in Table 7.11 which depicts the success of the model in predicting and controlling cost overrun over time.

CHAPTER 8: CONCLUSION

8.1   Summary of the Completed Work

Most large infrastructure projects have been suffering from cost overruns. A method has been established to calculate an optimum contingency budget to protect the project against cost overrun, while not tying an excessive budget that can be used on other projects. This becomes more important when an agency is dealing with a portfolio of projects. Even though all suggested methods in this dissertation are applicable for any agency, our emphasis has been mostly on transit projects since they are usually costly (several hundred million dollars), complex and have been plagued by cost overrun.

In an attempt to identify the drawbacks in the current methods of contingency allocation in transit agencies, the current methods used in the U.S. (Top-down method) and the U.K. (Optimism Bias Uplifts method) were discussed and compared in Chapter 4. The analysis revealed that the way that projects are ranged in Top-down model is conservative, resulting in tying large sums of money to a project which can be used for other projects. The Optimism Bias Uplifts approach used in the U.K. adds a contingency budget to the base cost of projects by only considering the historical performance of that type of projects (*i.e.* transit, road, etc.). This means the unique features and characteristics of each project do not have any impact on contingency allocation. Furthermore, the historical data is used in a statistical sense, requiring large datasets. The U.K. method is based on only 46 transit projects

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(including metro, light rail, bus lines, and conventional rail projects). In reality, due to the wide differences between transit projects, very few of these projects can be considered similar and hence following the same statistical distribution.

The shortcomings of the abovementioned approaches was the motivation to develop a probabilistic method that not only considers the historical performance of typical projects but also brings into consideration the unique feature of the projects by individual project risk assessment. The proposed model uses a hybrid normal distribution and utilizes historical data to assist the agencies to find the optimum required increase in the portfolio budget based on the desired confidence level. It is a dynamic model that is updated when new information regarding newly completed projects becomes available. It also considers the correlation among costs of projects in order to estimate more precise contingencies. Another advantage of the model is that it enables the agency to identify the required confidence level for risk assessment in individual project level with respect to the desired confidence level for portfolio of projects.

The advantages of the proposed model for allocation of contingency for portfolio of projects can be summarized as:

1. Considering the historical performance of typical projects;
2. Allowing for the unique features of each project through individual risk assessment of projects;
3. Defining the required confidence level for risk assessment of individual project with respect to the desired confidence level for sufficiency of portfolio budget;
4. Flexibility for updating using a Bayesian approach when new projects are completed and new performance data becomes available;

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5. Accommodating the correlation among project costs in order to obtain more accurate results;

6. The approach is a completely analytical approach not based on simulation; therefore closed form solutions are developed that will eliminate the errors resulting from the use of simulation modeling; further, there is no need for investing in Monte Carlo simulation software packages. Furthermore, errors inherent in simulation approaches such as nonconvergence of results will be eliminated.

The performance of the model was investigated using cost data from 32 transit projects sponsored by the Federal Transit Administration (FTA) divided into three sets. The Historical Dataset was used for initializing of the model and estimating the primary parameters of the model. Then, the model was applied to the First and Second Datasets. To identify the impact of correlation, the model is first applied to the datasets assuming statistically independent projects. Then, the correlation between projects in each dataset is recognized and estimated using the PSG method developed in this research and described in Chapter 6.

Even though in these cases the independent approach showed better success in controlling cost overrun and allocating optimized contingency, it may not be the case for all situations. Therefore, we encourage agencies to consider the correlation between projects in order to be realistic and more conservative.

8.2 Limitations of the Proposed Model

To develop the proposed model, we made some assumptions for developing a complete analytical model. These assumptions can be summarized as follows:

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1. We assumed that the population of cost overruns/underruns has a normal distribution. While this assumption may not be very accurate as projects are not fully identical, this is required to develop an analytical model. Using this assumption, we employed a hybrid normal distribution to range the cost of projects;

2. As part of the model development, we added up the cost of projects in the portfolio and calculated mean of total cost μ_T and standard deviation σ_T. Then, we assumed a normal distribution for the total cost where the projects can be correlated. However, we explained, since in reality all projects in a portfolio may not be strongly correlated, this assumption will not cause significant error to the model. This was confirmed with the given numerical example in Chapter 7. For instance, to calculate the required percent increase in budget for the First Dataset, we simulated the model and superimposed the results on the analytical curve (Figures 7.3 and 7.9). It was found that both curves were very similar. Since the simulation considers the exact shape of the total cost distribution, the similarity of the results justifies the use of a normal distribution for modeling total cost of the portfolio.

Other than aforementioned assumptions, we can identify two more limitations in the application of the model as follows:

1. The model needs historical data to be trained first, and then is applied to a prospective portfolio of projects. To obtain the immediate and precise results from the model, having the historical data is indispensable. However, in the absence of that information, the model is still utilizable. Let us consider that there is an agency with no former knowledge about the cost performance of their projects. However, they have recently completed a few projects. These projects can be used as new observations in the

Bayesian updating section of the proposed model. The agency can use a defuse distribution as the prior distribution of cost overruns/underruns, calculate the posterior distribution and continue the procedure thereafter;

2. Implementing the model procedure in agencies' budget development process could be a challenging task. It may not be an easy task to convince an agency to add the proposed model in their budget development procedures.

8.3   Recommended Works for Future

We suggest the current effort can be expanded in the following areas in the future:

1. All the discussions in this research were limited to the budget contingency. Therefore it would be a valuable effort to develop a similar method for schedule contingency allocation for a portfolio of projects where the relationships between the projects are specified;

2. The distribution assumed for the cost of project in the model is a hybrid normal distribution. It is suggested to evaluate other distributions such as lognormal. The challenge here is to keep the model completely analytical; in order to keep the model analytical, the choice of distributions become limited. Of course using simulation modeling other distributions can also be used;

3. Even though an Excel spreadsheet in conjunction with MATLAB was created for applying the model to the numerical example presented in Chapter 7, development of a user friendly software program which can accommodate any number of projects without need of MATLAB is suggested. In this way, an agency can use the model easily and more conveniently;

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4. In Appendix B, a mathematical method is presented for estimating the value of Pearson correlation coefficient between project costs. A comparison between this method and the proposed suggested guideline (PSG) in Chapter 6 for the same projects by different experts is suggested.

   The PSG provides a list of 12 common risk factors that can potentially affect any pair of project. An expert or a panel of experts should first identify the common risk factors affecting both projects under consideration from the list. After that, using a set of suggested guidelines and thresholds, the correlation coefficient is estimated. On the other hand, the proposed mathematical method (Appendix B) is an analytical tool which needs the project's risk register. For any pair of projects, the common risk factors in their risk registers are identified. Then, using the computational approach suggested in Appendix B the correlation coefficient between project costs is calculated. Comparison of correlation coefficients calculated with these two approaches can help identify estimation problems and may lead to development of simple practical approaches for estimating correlation coefficients accurately;

5. In Chapter 3, we discussed using different methods for estimating cost escalation and employing various cost escalation indices by agencies. It was shown that the inconsistency in use of these methods and indices result in reporting of dissimilar project costs for the same project in different studies. Therefore, the importance of improving the current budget development guideline for agencies such as the FTA is recognized.

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APPENDIX B: A PROPOSED MATHEMATICAL METHOD FOR CALCULATING COST CORRELATION

B.1   Introduction

One problem facing the modeler in using the approaches described in this research is estimating the correlation coefficient between project costs. As was described in this dissertation, the most common approach is to provide subjective estimates of correlation coefficient. This of course while better than ignoring correlation, may be subject to inaccuracy and estimator's bias. No analytical approach for calculating correlations was found even after an exhaustive search in civil engineering, construction, and management literature. In order to alleviate this problem, this appendix proposes a mathematical model developed by the author for the calculation of correlation coefficient between project costs.

B.2   Basis of the Method

Here a mathematical method is proposed to calculate the Pearson Correlation Coefficient between costs of two projects. This method is based on the premise of breaking down the total cost of project to: (1) base cost, and (2) risks cost. Base cost is the cost of project which is not including contingency (Touran 2006b). These are costs for items with a high degree of

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certainty and which are necessary for delivering the project. Risk costs on the other hand, are costs that are uncertain in nature and may or may not affect the project. The costs of risks are usually allowed for by budgeting a contingency set aside to cope with uncertainties and risks during a project design and construction. Using this definition, let us define the total cost of project as:

$$X_i = B_i + \sum_{j=1}^{n_i} R_{ij} \tag{B.1}$$

Where X_i denotes total cost, B_i denotes the base cost of project i and R_{ij} represents the monetary impact of risk factors $(j = 1, 2, ..., n)$ for project i which can be random variables or even deterministic. The summation is the required contingency budget for project i.

To estimate the correlation coefficient between costs of two projects, let us assume two projects with the following total costs:

$$X_1 = B_1 + \sum_{j=1}^{n_1} R_{1j} \tag{B.2}$$

$$X_2 = B_2 + \sum_{j=1}^{n_2} R_{2j} \tag{B.3}$$

Risk factors in both projects can be divided into two parts: (1) common risk factors (CR) and (2) special risk factors (SR). CR risk factors are those that if they occur in project 1, they will potentially happen in project 2. SR risk factors are those that are not likely to happen in both projects. Therefore the costs can be rewritten as:

$$X_1 = B_1 + \sum_{k=1}^{m_1} CR_{1k} + \sum_{l=1}^{p_1} SR_{1l} \tag{B.4}$$

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$$X_2 = B_2 + \sum_{k=1}^{m_2} CR_{2k} + \sum_{l=1}^{p_2} SR_{2l} \tag{B.5}$$

Where $m_1 = m_2 = m$ and $m_1 + p_1 = n_1$ and $m_2 + p_2 = n_2$. To estimate the correlation coefficient, we need to calculate the covariance between X_1 and X_2:

$$COV(X_1, X_2) = COV(B_1 + \sum_{k=1}^{m_1} CR_{1k} + \sum_{l=1}^{p_1} SR_{1l}, B_2 + \sum_{k=1}^{m_2} CR_{2k} + \sum_{l=1}^{p_2} SR_{2l}) \tag{B.6}$$

Expanding the above, we have:

$$COV(X_1, X_2) = COV(B_1, B_2) + COV(B_1, \sum_{k=1}^{m} CR_{2k}) + COV(B_1, \sum_{l=1}^{p_2} SR_{2l}) +$$
$$COV(\sum_{k=1}^{m} CR_{1k}, B_2) + COV(\sum_{k=1}^{m} CR_{1k}, \sum_{k=1}^{m} CR_{2k}) + COV(\sum_{k=1}^{m} CR_{1k}, \sum_{l=1}^{p_2} SR_{2l}) \tag{B.7}$$
$$+ COV(\sum_{l=1}^{p_1} SR_{1l}, B_2) + COV(\sum_{l=1}^{p_1} SR_{1l}, \sum_{k=1}^{m} CR_{2k}) + COV(\sum_{l=1}^{p_1} SR_{1l}, \sum_{l=1}^{p_2} SR_{2l})$$

We note that covariance between two constants or a constant and a variable is equal to zero. Thus:

$$COV(X_1, X_2) =$$
$$COV(\sum_{k=1}^{m} CR_{1k}, \sum_{k=1}^{m} CR_{2k}) + COV(\sum_{k=1}^{m} CR_{1k}, \sum_{l=1}^{p_2} SR_{2l}) + \tag{B.8}$$
$$COV(\sum_{l=1}^{p_1} SR_{1l}, \sum_{k=1}^{m} CR_{2k}) + COV(\sum_{l=1}^{p_1} SR_{1l}, \sum_{l=1}^{p_2} SR_{2l})$$

To calculate the above covariances, we need to make some assumptions.

We recognize the correlation between analogous common risk factors such as (CR_{11}, CR_{21}) and (CR_{12}, CR_{22}) in two projects. All other combinations of common risk factors such as (CR_{11}, CR_{22}) or (CR_{12}, CR_{23}) are assumed to be independent meaning the covariance is zero. We also consider that there is no correlation between all combinations of special risk

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factors in two projects (SR_{1l}, SR_{2l}). We also assume that there is no correlation between common risk factors and special risk factors of the two projects. The abovementioned independence assumptions are justified as no relationship exists between those combinations of risk factors. In other words, if one occurs in Project 1, we cannot have any prediction on occurrence of the other one in Project 2. Therefore, the assumption of independence (or covariance of zero) is rational and adequate.

Knowing the fact that:

$$\rho_{x,y} = \frac{COV(x, y)}{\sigma_x.\sigma_y} \implies COV(x, y) = \rho_{x,y}.\sigma_x.\sigma_y \tag{B.9}$$

Where $\rho_{x,y}$ is the correlation coefficient between x and y. Thus we have:

$$
\begin{aligned}
COV(X_1, X_2) &= COV(\sum_{k=1}^{m} CR_{1k}, \sum_{k=1}^{m} CR_{2k}) = \\
&COV(CR_{11}, CR_{21}) + COV(CR_{12}, CR_{22}) + ... + COV(CR_{1m}, CR_{2m}) = \\
&\rho_{CR_{11}, CR_{21}}.\sigma_{CR_{11}}.\sigma_{CR_{21}} + \rho_{CR_{12}, CR_{22}}.\sigma_{CR_{12}}.\sigma_{CR_{22}} + ... + \rho_{CR_{1m}, CR_{2m}}.\sigma_{CR_{1m}}.\sigma_{CR_{2m}} = \\
&\sum_{k=1}^{m} (\rho_{CR_{1k}, CR_{2k}}.\sigma_{CR_{1k}}.\sigma_{CR_{2k}})
\end{aligned}
\tag{B.10}
$$

We know that:

$$\sigma_{X_1}^2 = \sum_{j=1}^{n_1} \sum_{t=1}^{n_1} Cov(R_{1j}, R_{1t}) \xrightarrow{\text{If all risks are independent}} \sigma_{X_1}^2 = \sum_{j=1}^{n_1} \sigma_{R_{1j}}^2 = \sum_{k=1}^{m_1} \sigma_{CR_{1k}}^2 + \sum_{l=1}^{p_1} \sigma_{SR_{1l}}^2$$

$$\tag{B.11}$$

and:

$$\sigma_{X_2}^2 = \sum_{j=1}^{n_2} \sum_{t=1}^{n_2} Cov(R_{2j}, R_{2t}) \xrightarrow{\text{If all risks are independent}} \sigma_{X_2}^2 = \sum_{j=1}^{n_2} \sigma_{R_{2j}}^2 = \sum_{k=1}^{m_2} \sigma_{CR_{2k}}^2 + \sum_{l=1}^{p_2} \sigma_{SR_{2l}}^2$$

$$\tag{B.12}$$

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Therefore:

$$\rho_{X_1,X_2} = \frac{COV(X_1,X_2)}{\sigma_{X_1}.\sigma_{X_2}} = \frac{\sum_{k=1}^{m}(\rho_{CR_{1k},CR_{2k}}.\sigma_{CR_{1k}}.\sigma_{CR_{2k}})}{\sqrt{\sum_{j=1}^{n_1}\sum_{t=1}^{n_1}Cov(R_{1j},R_{1t})}.\sqrt{\sum_{j=1}^{n_2}\sum_{t=1}^{n_2}Cov(R_{2j},R_{2t})}} \quad\quad (B.13)$$

Using Eq. (B.13), one can calculate the correlation coefficient among costs of any pair of projects with an acceptable degree of accuracy.

Due to common characteristics of the analogous common risk factors in two projects, if we assume perfect correlation with correlation coefficient of 1.0 among them, Eq. (B.13) can be simplified to:

$$\rho_{X_1,X_2} = \frac{\sum_{k=1}^{m}(\sigma_{CR_{1k}}.\sigma_{CR_{2k}})}{\sqrt{\sum_{j=1}^{n_1}\sum_{t=1}^{n_1}Cov(R_{1j},R_{1t})}.\sqrt{\sum_{j=1}^{n_2}\sum_{t=1}^{n_2}Cov(R_{2j},R_{2t})}} \quad\quad (B.14)$$

B.3   Numerical Example

Here to illustrate the application of the model, two hypothetic contemporary projects along with their identified risks are presented. Then using the mathematical model, the correlation between costs of two projects is estimated.

Figure B.1 shows a hypothetical transit project with 26 identified risks/opportunities with the total monetary impact of \$26,101,022 and standard deviation of \$4,212,370. Figure B.2 depicts the risks/opportunities identified for the second hypothetical transit project with the total impact of \$31,726,409 and standard deviation of \$5,033,372. Both risk assessments

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have been conducted after final design in 2005, with the expected starting construction phase in 2005.

The goal is to estimate the correlation between costs of these two projects using the proposed mathematical method.

		Risk/Opportunity Impact				
Risk ID	**Risk/Opportunity Event**	**5%**	**Most Likely**	**95%**	**Mean**	**Std. Deviation**
Project Name: Hypothetical Transit Project 1				**Construction Start Date:** 3/7/2005		
Location: Las Vegas, NV				**Risk Anaylisis at Phase:** Final Design		
Project BC: $432,027,078				**Risk Anaylisis Date:** 7/19/2004		
P1.R01	Owner directed change	$0	$2,400,000	$4,800,000	$2,400,005	$1,433,071
P1.R02	Utility relocation variation	-$3,500,000	$0	$5,000,000	$594,238	$2,543,428
P1.R03	Remaning property acquistions	-$250,000	$2,500,000	$4,000,000	$2,004,386	$1,276,672
P1.R04	Environmental risks	$500,000	$1,250,000	$2,500,000	$1,448,164	$599,768
P1.R05	Proximity to existing structures	$100,000	$250,000	$500,000	$289,633	$119,956
P1.R06	City restrictions	$0	$1,093,580	$2,187,159	$1,093,579	$653,008
P1.R07	Design change for column location	$25,000	$50,000	$100,000	$59,916	$22,568
P1.R08	Daily lane closures and their frequency	$0	$250,000	$500,000	$250,001	$149,277
P1.R09	Design changes/City requirements	$0	$243,201	$486,402	$243,200	$145,222
P1.R10	Estimate deviation (pessimistic estimate)	-$1,000,000	$1,950,000	$4,000,000	$1,593,473	$1,496,211
P1.R11	Permanent barriers	$0	$1,500,000	$2,000,000	$1,102,344	$607,475
P1.R12	Parking space construction	$0	$250,000	$300,000	$170,134	$92,235
P1.R13	Traffic signal modifications	$0	$1,642,000	$1,970,400	$1,117,440	$605,814
P1.R14	Site conditions (geotech), environmental risk	$100,000	$250,000	$500,000	$289,632	$119,953
P1.R15	Locomotives uncertainty due to exchange rate	$1,500,000	$2,750,000	$5,000,000	$3,146,460	$1,051,004
P1.R16	Additional surveying required	$25,000	$75,000	$200,000	$104,786	$52,920
P1.R17	Potential RTC caused project delay	$601,865	$1,203,730	$2,407,460	$1,442,458	$543,316
P1.R18	Fire Protection - NFPA 130	$0	$180,000	$300,000	$156,229	$89,823
P1.R19	Credit for Station Connector	$0	$0	$2,400,000	$983,528	$754,226
P1.R20	Potential increase in insurance cost	$0	$1,687,500	$3,375,000	$1,687,490	$1,007,617
P1.R21	Emergency walkway lighting	$0	$1,000,000	$2,400,000	$1,158,447	$717,949
P1.R22	Additional fare collection equipment	$0	$200,000	$300,000	$160,335	$90,274
P1.R23	Escalation from Sep 30,04 to NTP of Mar 05	$0	$2,375,000	$4,750,000	$2,374,999	$1,418,171
P1.R24	Effect of potential delay	$742,761	$1,485,523	$2,971,046	$1,780,141	$670,491
P1.R25	Scope change for additional oversight and Before & After study	$200,000	$350,000	$500,000	$350,002	$89,568
P1.R26	V/E Study	$50,000	$100,000	$150,000	$100,000	$29,856
Total					**$26,101,022**	**$4,212,370**

Figure B.1: The Risk Register for the First Hypothetical Transit Project

Risk ID	Risk/Opportunity Event	Risk/Opportunity Impact			Mean	Std. Deviation
		5%	Most Likely	95%		
P2.R01	Design uncertainty	$2,650,000	$4,650,000	$6,650,000	$4,649,995	$1,194,219
P2.R02	ADA Compliance	$297,000	$330,000	$396,000	$343,090	$29,790
P2.R03	Opportunity (only half of platform built)	$3,095,000	$3,439,000	$4,127,000	-$3,575,446	$310,536
P2.R04	Archaelogy finds	$125,000	$250,000	$500,000	$299,582	$112,839
P2.R05	Deviation from estimate (pessimistic estimate)	-$55,000	$2,650,000	$4,750,000	$2,410,396	$1,436,191
P2.R06	Fiber optics purchase and install	$480,000	$500,000	$900,000	$653,672	$131,579
P2.R07	Potential cost overrun on track costs	$100,000	$5,566,100	$9,276,833	$4,870,713	$2,746,972
P2.R08	Opportunity that less than 100% of line is born by MTA	$100,000	$1,000,000	$1,500,000	-$841,420	$420,409
P2.R09	Risk of property price needed to create wetlands	-$1,500,000	$0	$1,000,000	-$198,096	$748,515
P2.R10	Support and setup facility	$0	$150,000	$250,000	$130,191	$74,853
P2.R11	Appraisal services ranged	$225,000	$600,000	$900,000	$570,299	$201,705
P2.R12	Prpoperty acquistion	$5,390,000	$6,200,000	$9,440,000	$7,168,499	$1,238,819
P2.R13	Locomotives uncertainty due to exchange rate	$3,500,000	$6,500,000	$8,750,000	$6,202,936	$1,569,747
P2.R14	Bid uncertainty	-$1,440,000	$0	$2,880,000	$571,178	$1,299,918
P2.R15	Overrun on the rehab cars and uncertainty on car cond	$0	$2,750,000	$5,400,000	$2,710,410	$1,612,218
P2.R16	Spare parts	$961,200	$2,352,000	$5,140,800	$2,906,525	$1,257,736
P2.R17	Variability of engineering services	-$1,507,800	$0	$1,507,800	$13	$900,331
P2.R18	Escalation	$0	$3,250,000	$5,500,000	$2,853,873	$1,645,963
Total					$31,726,409	$5,033,372

Figure B.2: The Risk Register for the Second Hypothetical Transit Project

First, two risk registers shown in Figure B.1 and B.2 are compared to recognize the common risk factors in both risk registers. The common risk factors have been highlighted in the figures. These are risks with IDs P1.R10, P1.R15, and P1.R23 in Project 1 corresponding with P2.R05, P2.R13, and P2.R18 in Project 2. The standard deviation of all risks can be found in the last column of risk registers. It should be noted that no correlation is appeared to be between the risk factors in each project. Because of this, independence is assumed between these risk factors. Hence, standard deviations of total costs are calculated using Eqs. (B.11) and (B.12) and are presented in the last row of risk registers ($4,212,370 and 5,033,372). The analogous common risks in two projects are assumed to be fully correlated

$(\rho = 1.0)$. Using Eq. (B.14) the correlation coefficient between costs of two projects is estimated:

$$\rho_{X_1, X_2} = \frac{1496211 \times 1436191 + 1051004 \times 1569747 + 1418171 \times 1645963}{4212370 \times 5033372} = 0.289 \quad \text{(B.15)}$$

This method is very simple to apply on large projects where the risk register for these types of projects is mostly available. Please note that currently, the FTA requires each New Starts transit project to go through a complete risk analysis and hence the risk register should be prepared for each new project. The analyst should be careful to select the common risk factors correctly. This is the most important step in the application of the method. Since the correlation estimation is usually required between costs of similar projects in a portfolio, the agency can publish a template or a risk catalogue. As a result of this practice, the recognition of common risk factors becomes more accurate and straight-forward.