A COMPARISON OF FUZZY INDICES WITH MONTE CARLO SIMULATIONS FOR RISK ASSESSMENT AT THE PRELIMINARY STAGES OF TRANSIT PROJECT PLANNING

By

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Master of Science in Environmental Protection

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Szczecin, Poland

2004

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2006

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ACKNOWLEDGMENTS

I wish to express my sincere appreciation to my major advisor, Dr. William McTernan for his wise supervision, constructive guidance, assistance and friendship. My sincere appreciation extends to my other committee members, Dr. John Veenstra and Dr. Dee Ann Sanders, whose assistance and friendship are also invaluable.

I would also like to give my special thanks to my husband, Aaron, for his encouragement at times of difficulty in this effort. Thanks also go to my parents for their love, support and guidance throughout the entire period of my education

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I. INTRODUCTION

The research described in this paper addresses a Federal Transit Agency (FTA) concern associated with their mandated environmental requirements. To address the environmental risks to a project, FTA employs a risk assessment for its major capital investments, known as New Starts projects (*McTernan et al., 2004*). Traditional environmental impact assessment conducted by FTA follows the National Environmental Policy Act (NEPA) guidelines and typically occurs after significant elements of the transit project have been defined. This occurs at approximately the 60% completion level of project planning and design (Borinsky, pers. com., 2005). However, previous efforts have shown that the present approach of identifying environmental issues late in the process frequently can result in schedule and/or cost slippage resulting from environmental concerns that go undetected until late in the project cycle. This can significantly alter project schedules and increase costs, as well as incurring undue adverse public response to the potential project. Therefore, FTA had decided that the identification of the environmental risks that can impact a project should begin at the pre-planning stage and continue throughout project delivery until completion of construction.

FTA proposed to create an environmental risk assessment protocol for major transit investments to aid the project developers in identification of these environmental areas of concern that can adversly impact project's schedule and/or cost if not identified early in the planning process. FTA has contracted with the Oklahoma Transportation

Center (OTC) to develop a tool to aid their staffers and future contractors in identifying these environmental issues. This tool, intended for the preliminary stage of project planning, will allow the transit agencies to select and to evaluate mode and corridor alternatives while identifying critical areas of environmental concern and determining which alternatives have the lowest potential impact on project completion. It will also address and supply information on mitigation of identified risks to avoid and/or decrease cost overruns and schedule delays (*McTernan et al., 2004*).

The goal of this Master's research was to develop a compatible environmental risk assessment protocol for major transit investments for an early stage of overall project planning. The resultant assessment can be employed to identify critical issues and events, which if left unattended, would result in significant scope changes and/or schedule delays and possible cost increases. Identification of these risks early in project development can minimize the probability of cost overruns and schedule delays and can predict other adverse incidents before they occur. In addition, the possible impacts of risk mitigation were analyzed.

The research addressed seven areas of environmental concern identified by FTA, as follows:

- Noise pollution
- Historical resources
- Parkland protection
- Endangered species
- Environmental justice
- Wetlands

- Property acquisition (*McTernan et al., 2004*)

In addition to the seven areas of environmental concern, four modes of transportation were analyzed: light rail, commuter rail, heavy rail and buses.

To meet the objectives of the project the Oklahoma Transportation Center (OTC) research group developed an environmental risk assessment protocol structured in the form of risk assessment matrices (RAM). The RAM method is a common approach in ecological/environmental evaluation and risk assessment. It is a concise tool for gathering information to prioritize assets, identify mitigation needs and develop response and recovery plans.

The first step in developing risk matrices was identification of all risk events that could potentially be associated with a project. The risk matrices contain markers and descriptors divided among cost and schedule slippage with and without mitigation. In the next step, the risk levels were determined based on the severity and likelihood of occurrence of each event. Both risk events and their relative impact levels were developed in a group effort of OTC and FTA personnel. The method used in this study in the RAM was based on the index approach where relative risk was gauged on a user supplied scale from one to ten. Index methods are frequently employed in situations were limited input information is available or where a high level of quantitative characterization of the output is not required (*Daniels at al, 1995-96*). Obviously, in case of alternatives screening in the preplanning stage of the project, both of these arguments apply.

During a previous research effort by OTC personnel, the RAM's were proven to be an effective tool for environmental risk assessment at the pre-planning stage

(*McTernan et al, 2005*). They were successful in distinguishing between different alternatives. The results obtained from the RAM analysis, however, are just single value risk indices and they do not provide enough information for efficient decision-making. The single value indices are burdened with uncertainty associated with the assessment of the situation at the early stage of the project. The uncertainty in a risk analysis is due to the randomness inherent to the system, and due to the assessor's understanding and judgment of the system (*Quelch et al., 1994*). Given a very early stage of overall project planning, where minimal information is available and is routinely accompanied by significant uncertainty, it would be misleading to supply a single value result instead of indicating a range of possible outcomes. Therefore, an effort to include and evaluate the uncertainty in the risk assessment process was undertaken, which is the focus of this thesis.

Two alternative simulation methods were considered to address the uncertainty in these estimates: Monte Carlo analysis and fuzzy sets theory. Monte Carlo simulation is a statistical method developed in the 1940s, named for Monte Carlo, Monaco, where the primary attraction is casinos containing games of chance, such as roulette wheels, dice, and Jackpot machines. The random behavior in games of chance is similar to how Monte Carlo simulation selects the input values at random to simulate the model. When you roll a die, you know that a value between 1 and 6 will come up, but you do not know which for any particular roll. It is the same with the variables that have a known range of values but an uncertain value for any particular time or event (*Decisioneering.com, 2005*).

Monte Carlo simulation is a sampling technique used for generating results that depend on variables or parameters represented as probability distributions. It selects the input values at random to simulate the model, where the variables have a known range of values but an uncertain value for any particular time or event (*Decisioneering.com, 2005*). As such, Monte Carlo analysis incorporates the variability of outcomes inherent to range of possible scenarios, as well as the uncertainty associated with these assessments (*Hayse, 2000*).

Monte Carlo analysis proves statistically that with enough sampling iterations one can accurately create an output realization distribution which is representative of the entire range of possible realization outputs. However, the accuracy of the result depends on how precisely all input parameters' distributions are defined. In many cases, unfortunately, there are not enough data available to determine accurately input probability density functions. Moreover, the number of iterations needed to generate a precise output distribution is usually extensive, effecting the application of MC simulation to early stage project planning where numerous alignment and modes may be under consideration. Nevertheless, Monte Carlo analysis is a widely used method for incorporating parameter uncertainty in quantified risk assessment.

The alternative method to Monte Carlo simulations that was considered for this effort is the fuzzy sets theory. Fuzzy sets were first introduced in 1965 by Lotfi A. Zadeh (*1965*). He proposed to use them for description of imprecisely defined classes or sets that play an important role in human thought process and communication. The theory of fuzzy sets is intended for development of concepts and techniques for dealing with sources of uncertainty or imprecision that are of non-statistical nature (*Quelch et al., 1994*).

Zadeh (*1965*) writes:

> The notion of a fuzzy set provides a convenient point of departure for the construction of a conceptual framework which parallels in many respects the framework used in the case of ordinary sets, but is more general than the latter and, potentially, may prove to have a much wider scope of applicability, particularly in the fields of pattern classification and information processing. Essentially, such a framework provides a natural way of dealing with problems in which the source of imprecision is the absence of sharply defined criteria of class membership rather than the presence of random variables.

Since the fuzzy sets theory was first introduced, it has developed into a broad field of mathematics with applications in various areas. Several texts have been published describing the fundamental concepts and more complex issues and applications (*Zimmermann, 1985; Klir at al., 1995; Kaufman et al., 1991; Terano et al, 1992*). Recently, numerous studies have been done on utilization of fuzzy sets theory in decision support tools for risk assessment. Xu et al. (*2003*), developed a fuzzy expert system in assessing operational risk of software; and de Siqueira Campos et al. (*2005*), presented a decision support method for environmental impact assessment using a fuzzy logic approach.

Monte Carlo and fuzzy set approaches will be applied to the previously established matrix risk assessment protocol to incorporate and evaluate project uncertainty. Basic computer software utilized in this research includes Microsoft® Excel 2000 spreadsheets, and @RISK 4.5 advanced risk analysis for spreadsheets.

II. MONTE CARLO SIMULATIONS

Monte Carlo Simulation enables characterization of uncertainties in risk assessment. To conduct probabilistic modeling using Monte Carlo analysis each of the input parameters is assigned a probability distribution function (pdf) that represents the uncertainty in the parameter characterization. The output from the model is calculated by randomly selecting a value from the probability distributions for each of the input parameters. The model is run repetitively and the outputs from each run of the model are saved. Instead of obtaining a single risk estimate to represent the model output, a set of sample results is obtained that can present the output as a frequency distribution or a cumulative density function. In Figure 1 a schematic description of the Monte Carlo method for uncertainty analysis is presented. Four random input variables with defined distributions are inputs to a model with one stochastic output. The results from Monte Carlo simulation can be summarized using typical statistics such as mean and variance. When applied to risk assessments, the output can be used to determine central tendencies (expected values) as well as low- and high-end risks with probabilities of occurrence.

Monte Carlo analysis consists of three major steps:

- defining statistical distributions of input parameters,
- simulating the model, and
- analyzing the results from the simulations.

These steps are described in detail in the following sections.

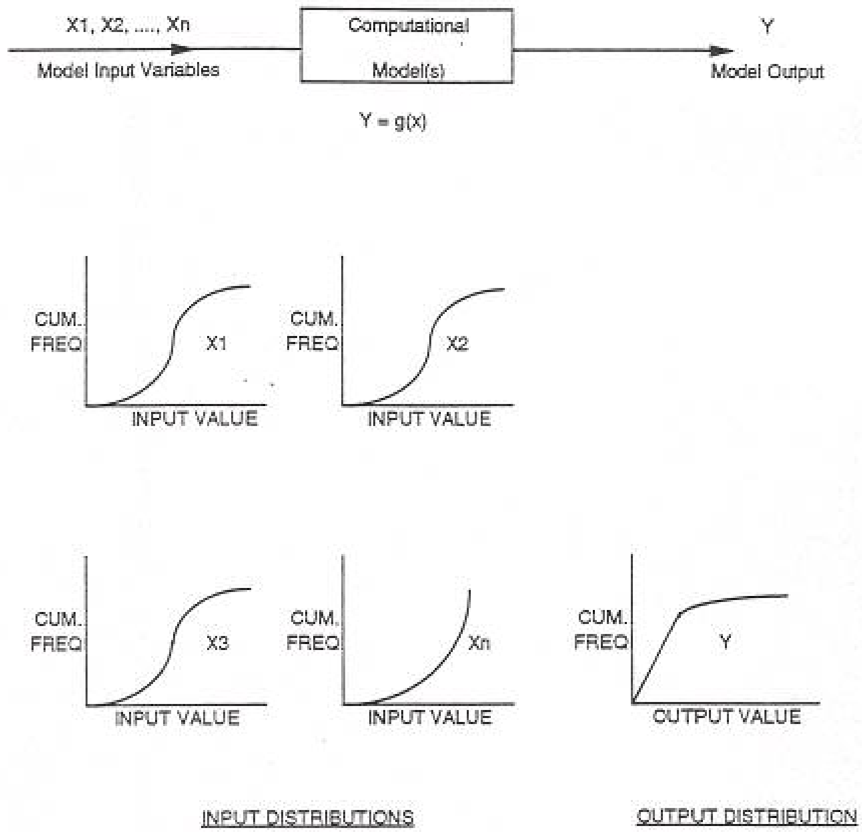

Figure 1. Schematic description of the Monte Carlo method for uncertainty analysis (*American Petroleum Institute, 1994*).

Defining the Statistical Distributions of Input Parameters

Defining the statistical distributions (pdfs) that will be used as input parameters for the model is perhaps the most difficult portion of a Monte Carlo analysis. The shape of the probability distribution can greatly affect the outcome of the Monte Carlo analysis and it is extremely important that a proper distribution be selected. To generate the pdf for a particular parameter a large amount of sample data has to be collected. Historical data from other studies, if valid, can also be used. The larger the sample size, the better the selection of a specific pdf can be supported as the uncertainty is reduced and the variability better characterized. Usually more than one distribution fit a given dataset. It is necessary to qualify the fit and to select the best distribution. There are many statistical techniques that can be used to help identify the type of pdf that may represent the data. Computer software, like "Best Fit" – Palisade Corporation distribution fitting tool (*Palisade.com, 2005*), can help in finding the right pdfs for input data. Additional information on the selection of input distributions for Monte Carlo analysis can be found in the "Report of the Workshop on Selecting Input Distributions for Probabilistic Assessment" (*EPA/630/R-98/004, 1999*).

It should be considered that not all input parameters have to be defined as probability distribution functions. It is acceptable to keep some parameters, for which there is no basis to assign pdf or for which variation and/or uncertainty is small, as fixed values. Actually, identifying pdfs for all input parameters could be very expensive and time consuming (*Hayse, 2000*).

The sensitivity analysis can be used to screen the input data. To do this, the values of all input parameters in the model, except one, are fixed, and the Monte Carlo analysis is run with the single parameter varying. This allows for estimating the effect of different values of the parameter on the outcome of the model. Information obtained from these simulations can be helpful when deciding about the need to collect additional project-specific information by focusing attention on reducing uncertainty for parameters that will most affect the outcome.

Model Simulations

Once the model is set up and the distributions for all input parameters are defined the simulations can be started. Computer software can be used to repeatedly run the model with input parameter values selected according to the probabilities identified in the pdfs. Computerized tool, like @RISK (*Palisade.com, 2005*) allows to specify the number of iterations (number of times the model is recalculated), what gives the control over the simulations. Typically, the model is run hundreds or thousands of times. Each time, entirely random numbers are sampled from the input functions and applied to the model. Every recalculation shows a possible combination of uncertain values or a "scenario" that could occur. At the end of the simulation we have a whole range of possible outcomes and the probabilities of their occurrence in the form of probability density function (*Palisade.com, 2005*).

In Monte Carlo analysis, samples are more likely to be drawn in areas of the distribution which have higher probabilities of occurrence. That means that the distribution is sampled more often around the expected value than at the low- and high-end values. With enough iterations, Monte Carlo sampling "recreates" the input distribution. However, a problem of clustering occurs when a small number of iteration is performed. Figure 2 illustrates that problem, where all five samples are drawn from the middle of the distribution. The values in the outer ranges of the distribution are not represented in the samples and, therefore, their impact on results is not incorporated in the simulations output (*Palisade Corporation, 2004*).

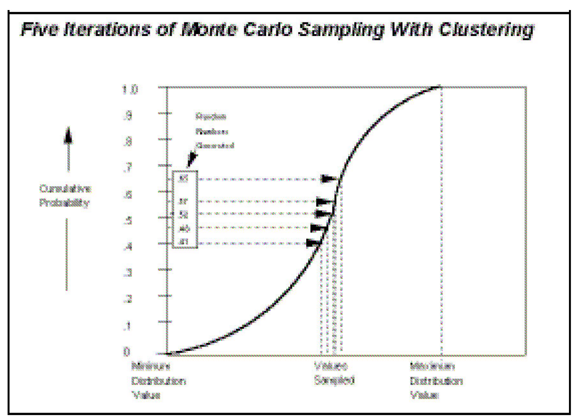

Figure 2. An example of Monte Carlo sampling with clustering (*Palisade Corporation, 2004*).

Clustering becomes a major problem when low probability outcomes have a great impact on the results. That is the case during the preliminary stage of project planning, when the range of possible outcomes is great and the uncertainty of the possible risks is significant. It is important to include the effects of these low probability risks in the simulation results. However, because their probability is low, Monte Carlo iterations may not sample sufficient quantities of these events to accurately represent their impact on the output (*Palisade Corporation, 2004*).

Analysis of the Results from the Monte Carlo Simulation

When the Monte Carlo simulations are completed, the output is usually examined in the graphical format, as a probability density function (pdf). Available commarcial computer programs for Monte Carlo analysis allow for displaying the results in form of probability density function. In this study, @RISK was used. An example of a hypothetical pdf of the modeling outputs is presented in Figure 3 which presents a distribution of risk index for cost overruns of a given project. An alternative illustration of the same results in the form of a cumulative distribution function can be seen in Figure 4. It presents a cumulative distribution function scaled from 0 to 10, which is typically used in Monte Carlo sampling. Both figures indicate that the mean value of the risk index is 2.97, and that there is a 5% chance that the risk index will be equal or less than 2.68, and 95% probability that the risk index will be equal or less 3.26. The difference between the low- and high-end (5th and 95th percentile) risk index values is 0.56, while 0.29 between the mean and high-end value. The results can be also evaluated to determine basic statistics such as, range, standard deviation, other percentile values, etc. Such information may be useful to the risk managers, especially when compared to the single value results that are obtained from environmental risk assessment matrices. With appropriate explanations, the results of a Monte Carlo analysis may also be used to help interested parties, such as the public or regulators, understand the basis for risk management decisions.

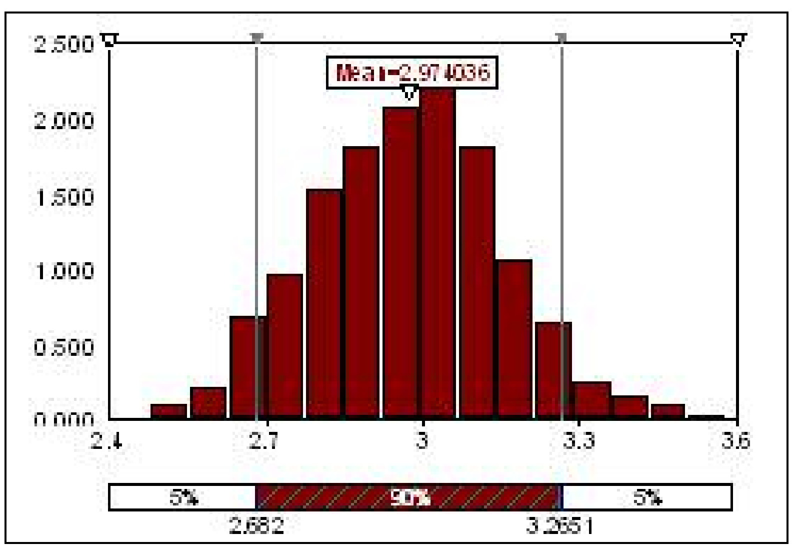

Figure 3. Hypothetical probability distribution function of output from a Monte Carlo simulation.

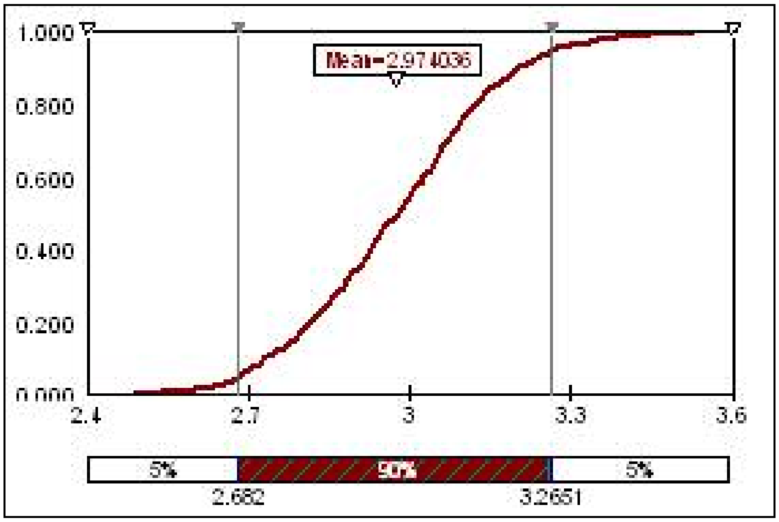

Figure 4. Hypothetical cumulative distribution function of output from a Monte Carlo simulation.

III. FUZZY SETS THEORY

Fuzzy sets allow for defining vague concepts in a mathematical sense. In a classical set theory, an element or object either belongs or does not belong to a set, whereas fuzzy set theory allows various degrees of membership for the elements of a given set. To clarify the differences between fuzzy and classical (crisp) sets, and for better understanding of the fuzzy sets theory, some basic definitions are introduced in this chapter.

Basic Definitions

A **crisp set** is defined as a group of elements $x \in X$. Each single element can either belong to or not belong to a set A, $A \subseteq X$. In the first case, the statement "x belongs to A" is true, while in the latter one it is false (*Zimmermann, 1985*).

There are three different ways in which crisp sets can be defined within a given universal set X (*Klir et al., 1995*):

- The elements that belong to the set can be enumerated or named (the list method). For example, let $a_1, a_2,...,a_n$ be members of a set A. Than, the given set A is written as:

$$A = [a_1, a_2, \ldots, a_n].$$

- A set can be described analytically by a property satisfied by its members (the rule method). We write:

  $$A = \{x | P(x)\},$$

  what means that A is a set of all elements of *X* for which the proposition *P(x)* is true. It is important to notice that for any given $x \in X$, the proposition *P(x)* is either true or false.
- The elements of *X* can be defined by a characteristic function μ_A, such, that $\mu_A(x) \in \{0,1\}$. The characteristic function declares which elements are members of a set A and which are not, as follows:

  $$\mu_A(x) = \begin{cases} 1 & for\ x \in A \\ 0 & for\ x \notin A \end{cases}$$

- For each $x \in X$, when $\mu_A(x) = 1$, x is a member of *A*; when $\mu_A(x) = 0$, *x* is a nonmember of *A*.

A **fuzzy set** is also defined by a characteristic function, called a membership function. The membership function takes its values in the interval [0, 1] instead of in the binary set {0, 1} as in crisp sets. The membership function allows various degrees of membership for the elements of a given set *X* (*Kaufmann and Gupta, 1991*).

Let *F* be a fuzzy set that belongs to *X*. Then fuzzy set *F* is defined by a membership function

$$\mu_F(x) \in [0,1]$$

which declares that the elements of *X* belong to *F* with a level located in [0, 1] (*Kaufmann and Gupta, 1991*).

A **fuzzy number** is a specific case of a fuzzy set defined upon the reals *R*. A fuzzy number *F* is a fuzzy set defined by a membership function

$$\mu_F : R \rightarrow [0,1],$$

that satisfies (*Cheng, 2004*):

1. *F* is normal, i.e., there exists a real number m, such that $\mu_F(m) = 1$.
2. *F* is fuzzy convex, i.e., for any pair *x, y*, belonging to support (*F*),

   $$\mu_F\left(\lambda x + (1-\lambda)y\right) \geq \min\{c, \mu_F(x)\}, \text{ for all } \lambda \in [0,1]$$

   where support (*F*) is the support of *F* and support $(F) = \{x \in R | \mu(x) > 0\}$.
3. *F* is upper semicontinuous, i.e., for each $\alpha \in (0,1)$, the *α*-level set

   $[F]_\alpha = \{x \in R | \mu(x) \geq \alpha\}$ [F]α = {x ε *R* | μ(x) ≥ α} is closed.

A fuzzy number can be defined with the following membership function (*Dubois and Prade, 1988*)

$$\mu_F(x) = \begin{cases} L\left(\dfrac{m-x}{e^L}\right), & x \leq m, \quad e^L \geq 0 \\ R\left(\dfrac{x-m}{e^R}\right), & x \geq m, \quad e^R \geq 0 \end{cases}$$

where: $x \in R$;

L(·), *R(·)* = left and right reference functions of the membership function, respectively;

m = mode, most likely values of the fuzzy number;

e^L, e^R = left and right spreads of the fuzzy number, respectively.

Fuzzy numbers defined in this form of equation are called L-R type fuzzy numbers. One particular case of semisymmetric L-R fuzzy number is a **triangular fuzzy number** (TFN), named for its shape (as shown in Figure 5).

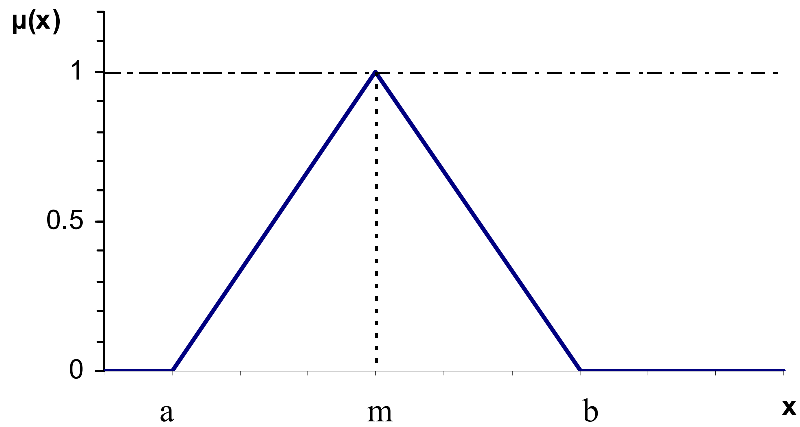

Figure 5. Membership function of a triangular fuzzy number (a, m, b).

A TFN is defined as

$$F(x;a,m,b)=\begin{cases}1-\dfrac{m-x}{m-a}, & a\le x\le m,\\ 1-\dfrac{x-m}{b-m}, & m\le x\le b,\\ 0, & elsewhere,\end{cases}$$

where, *m* is a mode and *a* and *b* are left and right endpoints, respectively.

A TFN can be also specified by a triplet such as

$$F=(a,m,b)$$

and this denotation will be used in this paper.

Fuzzy Arithmetic

One of the most practical principles in fuzzy set theory is the extension principle (*Kaufmann and Gupta, 1991*). It provides a general method for extending classical mathematical concepts to a fuzzy domain. Fuzzy arithmetic is crucial in the manipulation of fuzzy numbers. This study primarily involves addition and scalar multiplication of fuzzy numbers, and therefore these operations are discussed here.

Fuzzy Addition

If F_1 and F_2 are TFN's such that $F_1 = (a_1, m_1, b_1)$ and $F_2 = (a_2, m_2, b_2)$, then $F_1(+)F_2$ is also a TFN. The addition operation is given by

$$F_1 + F_2 = (a_1, m_1, b_1) + (a_2, m_2, b_2) = (a_1 + a_2, m_1 + m_2, b_1 + b_2).$$

Scalar Multiplication of a fuzzy number

If F is a TFN such that $F = (a, m, b)$, and k is a crisp number ($k \in R$), then their multiplication is given by

$$\begin{aligned} k \cdot F &= (ka, km, kb), && k > 0 \\ &= (kb, km, ka), && k < 0 \\ &= (0,0,0), && k = 0. \end{aligned}$$

It is important to notice that the result of this operation is also a TFN. Therefore, a resultant fuzzy number can be easily described by a triplet and not with a complicated membership function. It will be shown later that this is a crucial attribute for this study.

Ranking Fuzzy Numbers and Central Values

Since fuzzy numbers represent uncertain values, it is difficult to rank them according to their magnitude. Many methods for ranking fuzzy numbers have been proposed (*Lee-Kwang et al., 1999; Facchinetti et al., 2004; Chen et al., 2003*). Some are based on fuzzy relations while others represent fuzzy numbers with real values. The former are beyond the scope of this study and therefore will not be further discussed. The latter methods are called the defuzzification techniques. The defuzzying of a fuzzy number into a representative crisp value can be accomplished in many ways (*Mizumoto and Zimmermann, 1982*). Identifying central values such as means, medians, and modes of fuzzy numbers is a common defuzzying methodology.

In this study, the mean value of a fuzzy number named a center of gravity (COG) will be used. The COG "is defined as the value within the range of variable *v* for which the area under the graph of membership function μ_F is divided into two equal areas" (*Klir et al., 1995*).

The mathematical formula for this central value is given as follows:

$$COG = \frac{\int_a^b \mu_F(x)x\,dx}{\int_a^b \mu_F(x)\,dx}$$

For the TFN $F = (a, m, b)$ the center of gravity formula becomes a simple equation:

$$COG = \frac{a+m+b}{3}$$

This form of central value will be used later in this study to find the mean values of TFN's.

IV. MATERIALS AND METHODS

This chapter consists of two main parts, one is a background overview of a previous effort, and the other relates to the current research. The first part describes the research primarily done in the previous stage of this project, which focused on the development of the risk assessment matrices. These were modified slightly in the current effort. It is included in this paper to make the reader familiar with the background information and methodology that is further developed in this study.

In the second part, the current research is discussed. The main objective of this work was to find an optimal technique to introduce and evaluate the uncertainty to the previously developed risk assessment methodology. Two alternative techniques were considered: Monte Carlo analysis and fuzzy sets theory. Reportedly, they both supply equivalent results (*Quelch et al, 1994*). However, Monte Carlo analysis may require more detailed input information, which in case of pre-planning stage of the project is often unavailable (*Palisade Corporation, 2004*).

PREVIOUS EFFORT

In the previous research effort an environmental risk assessment protocol structured in the form of risk assessment matrices was developed to meet the objectives of the project. The risk matrices contain markers and descriptors of potential risk events. Each risk event was subjectively evaluated and subscribed an appropriate risk index from a scale from one to ten. This chapter provides background information on the process of matrices development and application.

Matrix Development

The study was done by the OTC research group in each of the seven areas of concern to determine if any risks existed which possessed the potential to affect a transportation project. These events were categorized as individual risk markers. Later, project specific descriptors were assigned to each individual risk marker. These descriptors subdivide the individual risk markers into management variables. The developed lists of risk markers and descriptors for each environmental area were reviewed by the group of experts from the FTA headquarters in Washington, D.C. and at Region 10 offices in Seattle, Washington.

In the next step of the research, a fully subjective approach was utilized to determine relative risks. The experts' opinion on the risk associated with each event was used to elicit the risk indices. This type of subjective methodology is commonly used in the risk assessment and modeling (*Tavana, 2004; Apeland et al., 2003; Wang, 1999; Gustafson et al., 2005*). The numerical risk index ratings were assigned to individual risk events and project descriptors. The appropriate risk indices were established by the OTC research group in cooperation with the FTA personnel through ranking of individual risk events considering their impact on the project.

The range of 0 to 10 of possible risk indices was applied. This range was divided into three categories according to the magnitude of risk ranging from low to high. A relative risk score of 7.5 to 10 placed the project marker in the category where a high likelihood of impact to either cost or schedule would result from this project configuration. A relative score of 3.5 to 7.49 presented a moderate risk while 0 to 3.49 represented a low risk estimate. Additionally, “0” is intended to indicate no risk to the project, and “10” is a “milestone” carrying a critical risk for the project completion. Table I describes the risk indices and their rating based on the assessment results.

TABLE I

RISK INDICES AND RATING BASED ON THE ASSESSMENT RESULTS

Risk Index	**Risk Rating**	**Color**	**Assessment Results**
7.5 - 10	High	Red	Represents an unacceptable level of risk requiring the inclusion of mitigation measures, provided the benefits outweigh the risk
3.5 – 7.49	Moderate	Blue	Represents an acceptable, moderate level of risk requiring the inclusion of mitigation measures within an acceptable time frame
0 – 3.49	Low	Green	Represents an acceptable, low level of risk requiring the inclusion of mitigation measures within an acceptable time frame

Finally, for each area, risk assessment matrices were developed through combination of the individual risk events and project descriptors, which were then coupled with relative risk index ratings. The risk templates were created in the previous phase of the research and can be found in the Phase 1 report for this effort (*McTernan et al., 2005*). However, during the further studies described in this paper, some minor changes to the original matrices were introduced. These modifications were done to make the matrices more efficient and generally involved combining individual markers. Additionally, some changes in values of risk indices were made. All modifications were made by the OTC research group in the agreement with the FTA.

All seven customized risk templates that are used in this study are presented here. In Figures 6 through 12, the risk templates for parklands, noise and vibration, property acquisition, historic resources, endangered species, environmental justice, and wetlands, respectively, are displayed. Each of these matrices consists of six columns. The first column contains a list of significant risk markers specific to a given area of environmental concern. In the second column, project descriptors inherent to given risk markers are listed. Finally, columns three through six consist of risk indices assigned to each project marker/descriptor. Four categories of risk to the project are recognized: cost risk with mitigation, cost risk without mitigation, schedule risk with mitigation, and schedule risk without mitigation.

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippages				
	Project Descriptors	Cost Risk with Mitigation	Cost Risk No Mitigation	Schedule Risk with Mitigation	Schedule Risk No Mitigation
1. Proximity of parkland to the alignment.	a. onsite	9	10	9	10
	b. adjacent	7	8	7	8
	c. far proximity	2	3	2	3
2. Proximity of parkland to the station.	a. onsite	9	10	9	10
	b. adjacent	6	7	6	7
	c. far proximity	3	4	3	4
3. Size of parkland	a. large; high probability for adverse effect on parkland	8	9	9	10
	b. medium; moderate probability for adverse effect on parkland	4	5	5	6
	c. small; low probability for adverse effect on parkland	2	3	2	3
4. Potential for adverse effect to mode selection	a. light rail	8	8	8	8
	b. heavy rail	6	6	6	6
	c. bus	2	2	2	2
	d. commuter rail (park & ride)	7	7	7	7
5. Potential for failing to obtain the Secretary of Transportation permit.	a. there are other higly feasible and prudent alternatives to the proposed project	9	10	9	10
	b. there are other moderately feasible and prudent alternatives to the proposed project	5	6	5	6
	c. there are other marginally feasible and prudent alternatives to the proposed project	2	3	2	3
6. Probability that the public will be opposed to the project.	a. highly politically active stake holders	9	10	9	10
	b. moderately politically active stake holders	5	6	6	7
	c. low politically active stake holders	2	3	2	3

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 6. Parklands risk template

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippages				
	Project Descriptors	**Cost Risk with Mitigation**	**Cost Risk No Mitigation**	**Schedule Risk with Mitigation**	**Schedule Risk No Mitigation**
1. Potential for noise sensitive areas/buildings in project corridor	a. high % category 1	7	8	9	10
	b. high % category 2	5	6	7	8
	c. high % category 3	3	4	2	3
2. Potential for noise sensitive areas/buildings in the area of station	a. high % category 1	8	9	9	10
	b. high % category 2	6	7	7	8
	c. high % category 3	3	4	4	5
3. Potential for noise pollution sensitive to alignment options	a. elevated rail	6	7	6	7
	b. land rail	5	6	5	6
	c. street	2	3	3	4
4. Potential for occurrence of noise sensitive receptors which recieve little or no improvement with mitigation	a. high occurrence	8	8	8	8
	b. moderate occurrence	5	5	5	5
	c. low occurrence	2	2	2	2
5. Potential for vibration sensitive areas/buildings in project corridor	a. high % category 1*	8	9	8	9
	b. high % category 2*	5	6	5	6
	c. high % category 3*	2	3	2	3
6. Potential for vibration sensitive areas/buildings in the area of station	a. high % category 1*	9	10	9	10
	b. high % category 2*	5	6	5	6
	c. high % category 3*	2	3	2	3
7. Potential of vibration production sensitive to mode selection	a. light rail	8	8	8	9
	b. heavy rail	10	10	10	10
	c. bus	0	0	0	0
	d. commuter rail (park & ride)	7	7	7	7
8. Potential for receptors sensitive to electro-magnetic interference	a. high number of receptors	9	10	9	10
	b. moderate number of receptors	5	6	5	6
	c. low number of receptors	3	4	3	4
9. Probability that the public will be opposed to the project.	a. highly politically active stake holders	9	10	9	10
	b. moderately politically active stake holders	5	6	5	6
	c. low politically active stake holders	2	3	2	3

* Indicates vibration categories

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 7. Noise and vibration risk template

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippages				
	Project Descriptors	Cost Risk with Mitigation	Cost Risk No Mitigation	Schedule Risk with Mitigation	Schedule Risk No Mitigation
1. Number of overlapping jurisdictional areas involved in project.	a. single government entity beyond FTA present	3	4	3	4
	b. multiple governmental entitys present	8	9	8	9
2. Potential for parcels w/o clear record titles.	a. majority of parcels w/well recorded ownership	1	2	2	3
	b. majority of parcels w/poorly recorded ownership	6	7	7	8
3. Potential for unanticipated joint-use agreement or Rail-road ROW in project corridor.	a. rail-road entities in the project area	7	8	9	10
	b. public entities in the project area	3	4	3	4
	c. quasi-public entities in the project area	4	5	4	5
4. Potential for unforeseen action required including: relocation assistance,encroachments, or functional replacement; parcel improvements; and utility relocation.	a. well documented history and current land use of project area and adjoining properties	3	4	3	4
	b.poorly documented history and current land use of project area and adjoining properties	7	8	7	8
5. Potential for inverse condemnation.	a. high potential for adverse effect on adjoining land	8	9	8	9
	b. moderate potential for adverse effect on adjoining land	5	6	5	6
	c. low potential for adverse effect on adjoining land	3	4	3	4
6. Potential for mode specific adverse effects.	a. light railway	8	8	8	8
	b. heavy rail	5	5	5	5
	c. buses	0	1	0	1
	d. commuter rail (park & ride)	6	6	6	6
7. Probability that the public will be opposed to the project.	a. highly politically active stake holders	9	10	9	10
	b. moderately politically active stake holders	5	6	5	6
	c. low politically active stake holders	2	3	2	3

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 8. Property acquisition risk template

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippage.				
	Project descriptors	Cost Risk with Mitigation	Cost Risk No Mitigation	Schedule Risk with Mitigation	Schedule Risk No Mitigation
1. Proximity of property either on or eligible for inclusion in Historic Register to station.	a. close proximity	8	9	9	10
	b. moderate proximity	5	6	6	7
	c. far proximity	2	3	2	3
2. Proximity of property either on or eligible for inclusion in Historic Register to project corridor.	a. close proximity	8	9	9	10
	b. moderate proximity	5	6	6	7
	c. far proximity	1	2	2	3
3. Sensitivity of Historic property to mode selection.	a.light rail	8	8	8	8
	b. heavy rail	5	5	5	5
	c. bus	1	1	1	1
	d. commuter rail (park & ride)	7	7	7	7
4. Potential that the public will be opposed to the project.	a. highly politically active stake holders	7	7	7	7
	b. moderately politically active stake holders	5	5	5	5
	c. low politically active stake holders	1	1	1	1
5. Potential for previously unidentified historic or archeological resource.	a. proximity to know arch., native or hist. sites.	8	9	8	9
	b. arch. native or historic sites in vicinity	6	7	6	7
	c. no known native, hist. or arch. sites in area.	2	3	2	3

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 9. Historic resources risk template

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippages				
	Project Descriptors	Cost Risk with Mitigation	Cost Risk No Mitigation	Schedule Risk with Mitigation	Schedule Risk No Mitigation
1. Proximity of critical habitat to the alignment.	a. onsite	9	10	9	10
	b. immediately offsite	5	6	6	7
	c. far proximity	1	1	2	3
2. Proximity of critical habitat to the station.	a. onsite	9	10	9	10
	b. immediately offsite	5	6	6	7
	c. far proximity	1	2	1	2
3. Potential for critical habitat designation in the area affected by project.	a. highly environmentally exceptional areas.	7	8	8	9
	b. moderately environmentally exceptional areas.	4	5	5	6
	c. low environmentally exceptional areas.	1	2	1	2
4. Proximity of endangered species to the alignment.	a. onsite	7	8	7	8
	b. immediately offsite	3	4	3	4
	c. way offsite	2	2	2	3
5. Proximity of endangered species to the station.	a. onsite	7	8	7	8
	b. immediately offsite	4	5	4	5
	c. way offsite	1	2	1	2
6. Potential for previously unidentified endangered species.	a. high - lots of undeveloped lands in the project area	7	8	7	8
	b. moderate - a few undeveloped lands in the project area	5	6	5	6
	c. low - no undeveloped lands in the project area	0	1	0	1
7. Sensitivity of CH/endangered species to mode selection.	a. light rail	8	8	8	8
	b. heavy rail	5	5	5	5
	c. bus	1	1	1	1
	d. commuter rail (park & ride)	6	6	6	6
8. Potential for regulatory adverse effect determination.	a. severe impact of the project on CH/endangered species habitat with potential for Jeopardy Decision	9	10	8	9
	b. moderate impact of the project on CH/endangered species habitat	5	6	5	6
	c. low impact of the project on CH/endangered species habitat	0	1	0	1
9. Proximity of project corridor to Essential Fish Habitat (EFH)	a. close proximity	9	9	9	9
	b. moderate proximity	5	5	5	5
	c. far proximity	0	0	0	0
10. Probability that the public will be opposed to the project.	a. highly politically active stake holders	9	9	9	9
	b. moderately politically active stake holders	5	5	5	5
	c. low politically active stake holders	2	2	2	2

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 10. Endangered species risk template

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippages				
	Project Descriptors	Cost Risk with Mitigation	Cost Risk No Mitigation	Schedule Risk with Mitigation	Schedule Risk No Mitigation
1. Potential for unforeseen, localized, disproportionately high adverse effects.	a. highly centralized project activities	8	9	8	9
	a. moderately centralized project activities	4	5	3	4
	c. dispersed project activities	0	1	2	3
2. Potential for unforeseen minority population in the project corridor.	a. well defined social profile of the area	3	4	4	5
	b. not well defined social profile of the area	7	8	9	10
3. Potential for unforeseen low-income populations or minority business owners/property in the project corridor.	a. area with well defined neighborhood and community boundries	1	2	2	3
	b. area with not well defined neighborhood and community boundries	5	6	6	7
4. Potential for mode specific adverse effects.	a. light railway	9	9	9	9
	b. heavy rail	5	5	5	5
	c. buses	1	1	1	1
	d. commuter rail (park & ride)	7	7	7	7
5. Probability that the public will be opposed to the project.	a. highly politically active stake holders	8	9	8	9
	b. moderately politically active stake holders	5	6	5	6
	c. low politically active stake holders	1	2	1	2

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 11. Environmental justice risk template

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippages				
	Project Descriptors	Cost Risk with Mitigation	Cost Risk No Mitigation	Schedule Risk with Mitigation	Schedule Risk No Mitigation
1. Proximity of significant wetland to the alignment.	a. onsite	9	10	9	10
	b. immediately offsite	6	7	6	7
	c. far proximity	0	1	0	1
2. Proximity of significant wetland to the station.	a. onsite	9	10	9	10
	b. immediately offsite	6	7	6	7
	c. far proximity	1	2	0	1
3. Sensitivity of wetland mitigation to mode selection	a. light rail	3	3	3	3
	b. heavy rail	8	8	8	8
	c. bus	1	1	1	1
	d. commuter rail (park & ride)	2	2	2	2
4. Potential for findings within wetland requiring additional permits, nomination for protection, or inaccurate estimate of buffer zone.	a. high ecosystem knowledge	0	1	1	2
	b. moderate ecosystem knowledge	3	4	5	6
	c. low ecosystem knowledge	7	8	9	10
5. Probability of EPA to veto COE permit	a. high functional capacity	7	8	9	10
	b. inadequate COE performance	4	5	4	5
	c.adequate COE performance	0	1	0	1
6. Sensitivity of wetland for relocation.	a. high functional capacity	7	8	9	10
	b. moderate functional capacity	4	5	6	7
	c. low functional capacity	2	3	1	2
7. Probability that the public will be opposed to the project.	a. highly politically active stake holders	10	10	10	10
	b. moderately politically active stake holders	5	6	5	6
	c. low politically active stake holders	2	3	2	3

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 12. Wetlands risk template

The RAM's were developed specifically for the use in the preplanning stage of a project. Their universal design allows the user to employ them for a range of different transportation projects not just a particular one. That is due to the structure of the matrices, where the user is given a range of descriptors for each risk marker (event). By choosing appropriate descriptors, one customizes a risk assessment to a specific project.

The next step is calculating the magnitude of the risk associated with the project. When the descriptors for each marker that describe best our project are selected, the risk indices associated with them are automatically indicated. These risk indices are cumulated and the average risk index for each matrix, and therefore for each area of concern, is calculated. Finally, in the same manner, the cumulative average risk index of the project is determined. The highest individual markers will also be identified since a single event risk could be smoothed out by averaging.

The methodology of averaging the risk indices was employed for the consistency of risk description used in the study. Thus, the values of input and output risk indices and their rating are based on the same scale. That is to assure that the final risk assessment tool is straightforward and user-friendly. For more detailed information on the development and utilization of matrices, please refer to Phase 1 report for this effort (*McTernan et al., 2005*).

CURRENT RESEARCH

In the previous section, the development and utilization of matrices was described. The outcome of a risk matrix is a single value describing the risk associated with a specific event (project). Single value results allow for comparing different alternatives, however, do not describe the uncertainty associated with the project risk. This information is of great importance for effective decision-making. Therefore, an effort to include and evaluate the uncertainty in the preliminary project risk assessment process was undertaken in the current research. Two alternative methods were considered for this purpose and are discussed in detail in this chapter: Monte Carlo analysis and fuzzy numbers.

Monte Carlo Analysis

Monte Carlo is a common tool for conducting probabilistic uncertainty analysis. There are several commercially available Monte Carlo Simulation software packages which can be used in conjunction with standard spreadsheet software to perform probabilistic risk computations. Utilization of the computer software allows for time efficient performance of Monte Carlo analysis. In this study, @Risk by Palisade (*Palisade.com, 2005*) was used to conduct all simulations.

Development of MC Risk Indices

A simple approach was taken to create input MC risk indices where triangular pdf's were used to describe the variability and uncertainty inherent to each risk index. Triangular distributions were selected as they did not require detailed input information. Supplying most likely, minimum and maximum values was sufficient to define distributions of risk indices. Moreover, triangular distributions emphasize the most likely risks and propagate that information to the results of simulations.

The single value risk indices that were previously elicited from the experts' opinions were used to create these triangular pdf's. The formerly determined values were considered to be the most likely risks, and used as peaks of the triangular pdf's. Subsequently, the spread of each pdf was subjectively determined. The minimum and maximum values were assigned to each of them accordingly with the level of uncertainty inherent to a given descriptor. The levels of uncertainty were expressed as ranges of possible outcomes on a scale of from 0 to ±3 of the most likely value. The levels of uncertainty associated with the descriptors were assigned by OTC research group.

It was decided that all risk indices previously defined as "moderate" or "medium" are highly uncertain and therefore were assigned the range of ±3. The uncertainty comes from the range of possible outcomes. When one deals with the "moderate" situation there is a probability that the level of impact will be lowered or elevated, depending on the circumstances. Moreover, the uncertainty related to expert's judgment is of great importance here. It is natural for the expert to choose a middle value when he is less confident about the choice.

The "high" and "low" risk indices carry a medium level of uncertainty and were assigned a ±2 range. That is based on a hypothesis that a higher confidence is expected in high and low risk situations that in "moderate" cases. However, even the uncertainty from the range of possible outcomes is lower, the uncertainty associated with the experts' judgment has to be taken into account. Therefore, a ±2 level of uncertainty was assigned to the "low" and "high" risk indices.

In specific cases, single values were left to describe descriptors which impact levels were certain. These are the “0” (no) impact risk index, and “10” (critical) impact risk index. Table II summarizes information on the uncertainty levels applied to each group of risk indices.

TABLE II

UNCERTAINTY LEVELS APPLIED TO ALL CRISP RISK INDICES

Crisp risk indices (Most likely values)	**Uncertainty levels** (spread of triangles)
0	0
1 - 3	±2
4 – 7	±3
8 - 9	±2
10	±0

Not all triangular pdf’s (indices) are in a form of isosceles triangle. Uneven spreads of triangles result from disproportionate uncertainty levels. That is a consequence of a possible range of risk indices of 1-10 (“0” risk index was excluded in creating fuzzy numbers as an event that has some impact cannot be stretched into the “no impact” range). For example, a low risk index “2” with a possible range of ±2. The most likely value is “2”, the maximum value is 2 + 2 = “4” , and the minimum value is “1”. The minimum value is not equal to 2 – 2 = ”0” because, as stated before, we cannot assign “0”, but “1” as the lowest possible impact.

All Monte Carlo risk indices were created in this process using the Palisade @RISK software and, later, applied to the risk matrices. The suitable probability distribution functions employed for all MC risk indices are presented in Figures 13 and 14. MC risk indices from 1 to 9 are defined with triangular distributions while risk indices 0 and 10 are described with single values.

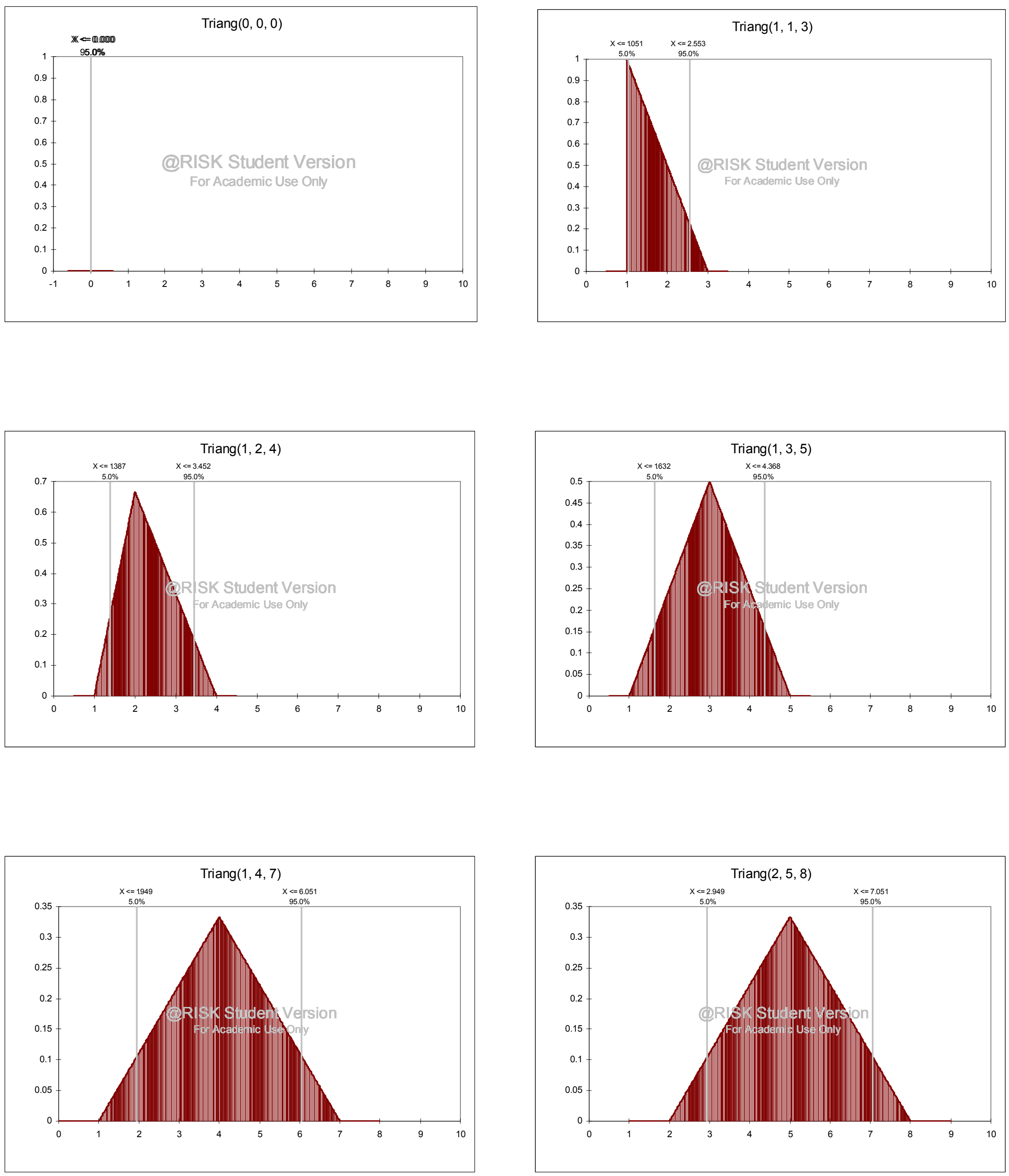

Figure 13. The pdf’s for the MC risk indices from 0 to 5.

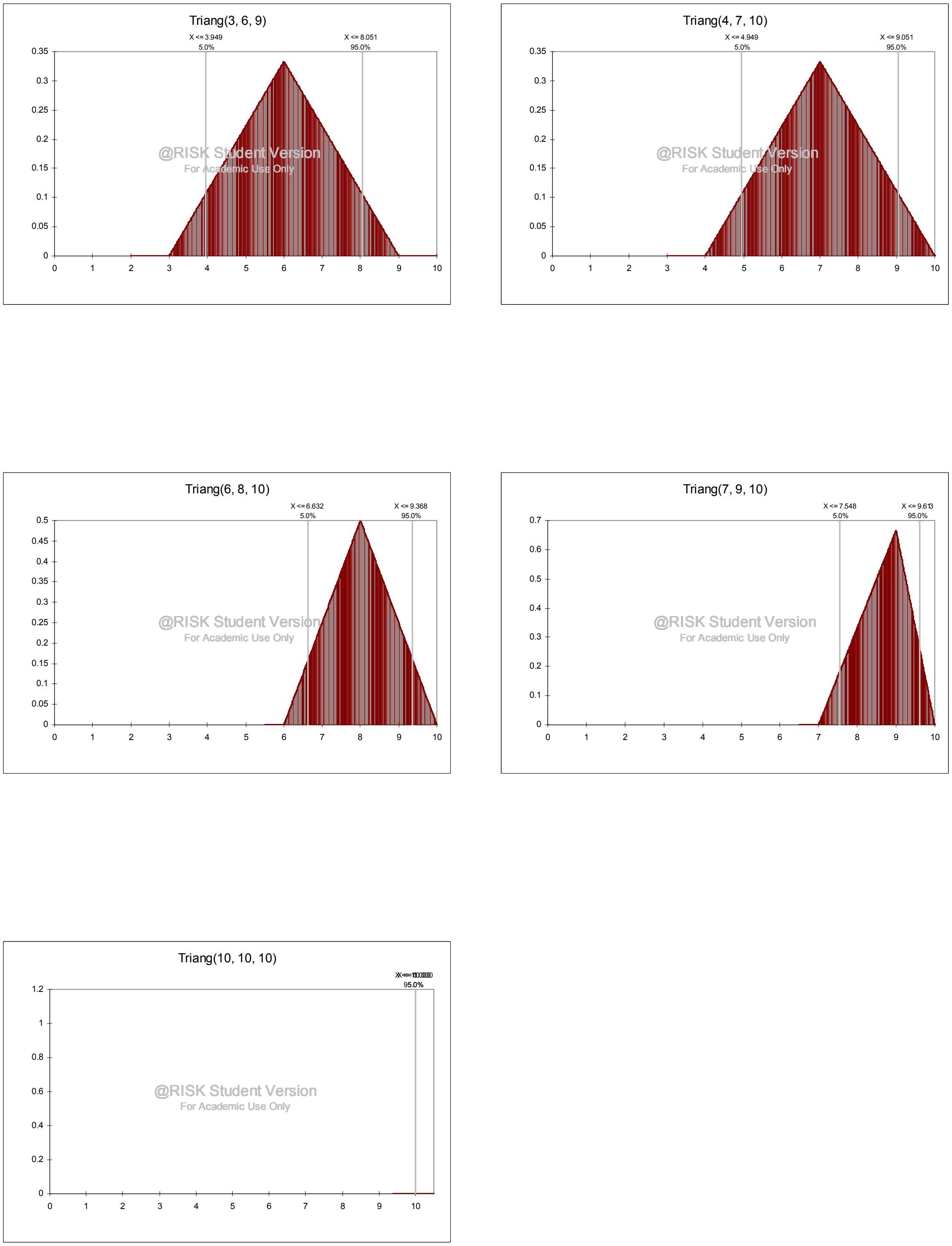

Figure 14. The pdf's for the MC risk indices from 6 to 10.

Monte Carlo Risk Matrix

All MC risk indices were applied to the risk matrices. Created this way MC risk matrices not only allow for comparison of different alternatives but also, through incorporation of uncertainty, supply an informative tool for decision-makers. However, computations of the risk using MC risk indices are complicated and tedious as it requires running a Monte Carlo simulation to obtain the result.

In case of single value risk indices the result is just a simple arithmetical average. These calculations can be conducted in an easy and fast manner. To calculate the average of MC risk indices, however, each result has to be simulated separately. All these simulations have to be conducted prior to the software creation. That means that all possible results have to be generated using @RISK and the created database included in the software. Because of the enormous amount of possible combinations of the risk events, this is a very time consuming process. Specifically, in this research, 443,268 simulations would have to be run in order to meet the objectives of the project. The number of simulations was determined from combinations of descriptors within each matrix and indicates a cumulative amount of all possible results from seven matrices. Each of these simulations would require about 1000 or more iterations to prevent clustering and achieve convergence.

The following example is included to show the difference between the "regular" and "MC" risk matrices, and to explain how the MC simulations are conducted. The example problem presented in Table III for the historic resources risk template, cost risk with mitigation was considered. The result for the "regular" matrix is simply obtained by calculating an average value of appropriate “single” risk indices as shown in Table III. To obtain the result from the MC matrix, a Monte Carlo simulation had to be performed.

TABLE III
AN EXAMPLE OF SINGLE VALUE RISK OUTPUTS FROM HISTORIC RESOURCES MATRIX

Significant Risk Markers	**Project descriptors**	**Single value risk index**
1. Proximity of property either on or eligible for inclusion in Historic Register to station.	b. moderate proximity	5
2. Proximity of property either on or eligible for inclusion in Historic Register to project corridor.	a. close proximity	8
3. Sensitivity of Historic property to mode selection.	b. heavy rail	5
4. Potential that the public will be opposed to the project.	b. moderately politically active stake holders	5
5. Potential for previously unidentified historic or archeological resource.	c. no known native, hist. or arch. sites in area.	2
Total Score from the Matrix		5

The Monte Carlo analysis was conducted using the @RISK and the Microsoft Excel spreadsheet. The suitable risk indices were selected as the input pdf’s to the Monte Carlo simulation. The model was created as the average of the input variables to obtain the resultant risk. Six hundred iterations, satisfactory to achieve convergence, of the model were performed to obtain the simulation output. The pdf of the output average risk is presented in the Figure 15. It should be noted that the input pdf's are triangular pdf's but the output pdf is a non-triangular function, a Weibull distribution in this case.

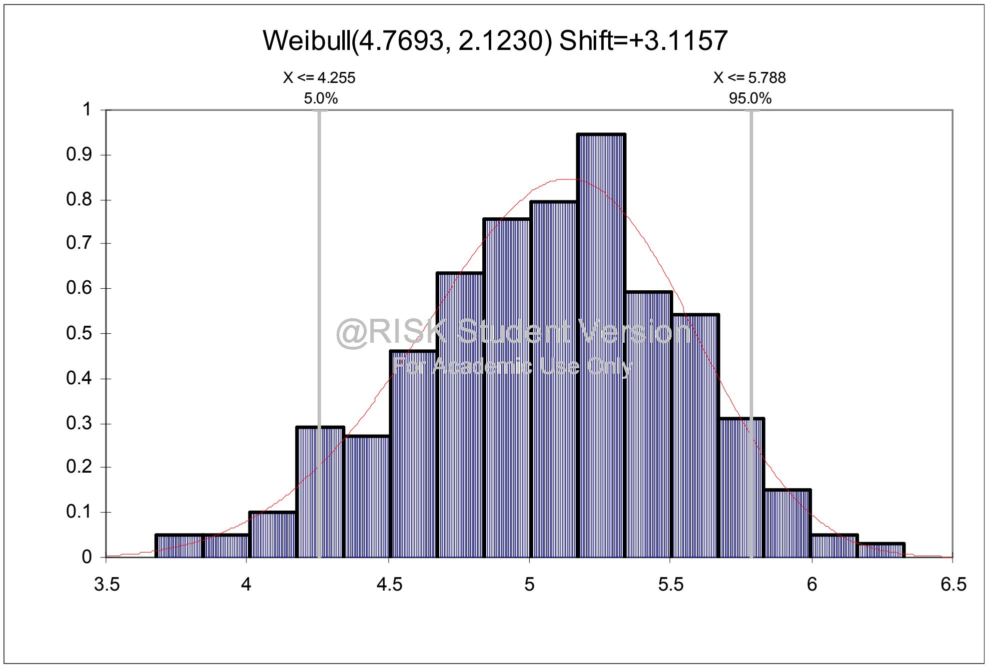

Figure 15. The pdf of the output risk index for the example problem.

@RISK also calculates statistics of the output risk index, which are of great importance in this study. Table IV contains a summary statistics generated for the example output risk in @RISK.

The summary statistics (Table IV) show that the Monte Carlo simulations generated the mean of the possible outputs 5.06 which is almost equal to the single value risk assessment result of 5.0 (see Table III). That indicates the agreement of the Monte Carlo analysis results with those from a single value risk assessment matrix. Moreover, MC simulation supplied a variety of statistics, such as: mode, maximum and minimum values, standard deviation, etc. that characterize the variability and uncertainty of the result. These data are of great importance to the decision-maker as they provide information not only about the most likely scenario but also about the range of possible impacts to the project.

TABLE IV

SUMMARY STATISTICS FOR THE OUTPUT RISK INDEX FOR THE EXAMPLE PROBLEM

Summary Statistics

Statistic	Value	%tile	Value
Minimum	3.679504395	5%	4.248592377
Maximum	6.329553127	10%	4.422477245
Mean	5.059637125	15%	4.58206892
Std Dev	0.465724471	20%	4.664730072
Variance	0.216899283	25%	4.751857758
Skewness	-0.235806965	30%	4.826215744
Kurtosis	2.889716619	35%	4.908153057
Median	5.078125477	40%	4.977769852
Mode	4.813633601	45%	5.024754524
Left X	4.248592377	50%	5.078125477
Left P	5%	55%	5.143288136
Right X	5.785140514	60%	5.204366684
Right P	95%	65%	5.246684551
Diff X	1.536548138	70%	5.306468964
Diff P	90%	75%	5.372958183
#Errors	0	80%	5.459642887
Filter Min		85%	5.563242435
Filter Max		90%	5.637922764
#Filtered	0	95%	5.785140514

Monte Carlo simulations generate detailed information about the risk to the project such as the distribution of possible results and the output statistics. Such in depth analysis is, however, beyond the quality of the input data available at the pre-planning stage of a project. Furthermore, all Monte Carlo simulations have to be performed prior to the final deliverable software creation. Therefore, the MC risk assessment matrix is not a flexible tool as it does not allow the user to supply alternative input information.

Discussions between OTC and FTA have centered upon eventually developing an interactive user option where FTA personnel and their contractors could change the default values for both the most likely risk level identified in the original RAM's as well as the uncertainty levels introduced in table II. In this way future users can modify the tool to their respective requirements without any additional programming. For instance, as a project comes closer to completion, uncertainty levels should decrease. User supplied parameter ranges can address the worth of these new data while still producing compatible risk assessment outputs. If the interactive user options were to be included, the extensive simulations of new factors would have to be done. Therefore, an alternative option for uncertainty evaluation was considered – fuzzy set theory.

Fuzzy Numbers

The previous chapter provided a condensed introduction to fuzzy sets theory necessary to understand the mathematical computations presented here. The following subchapter describes the effort to introduce the uncertainty to the risk assessment matrices and evaluate it using the fuzzy sets theory.

Development of Fuzzy Risk Indices

In this approach the risk indices were defined in the form of fuzzy numbers with similar statistical inputs as were described for the Monte Carlo simulations. Here, the triangular fuzzy numbers were used to describe the variability and uncertainty inherent to each risk index.

Correspondingly to the MC approach, each risk index was described with the most likely, minimum and maximum values, where the most likely value is the peak of the triangle, and the minimum and maximum values indicate the spread of the triangle. The same methodology in assigning the spread (range of possible risks) that was previously adapted to create the triangular pdfs was used for fuzzy membership functions. For example, for a crisp risk value of “4” a triangular pdf with the most likely values of “4” and the minimum and maximum of “1” and “7”, respectively. As a result a set of fuzzy risk indices, corresponding to MC risk indices, was developed.

All fuzzy indices that were created in this process and applied to the risk matrices are defined as triplets and listed in Table V. The appropriate membership functions for all fuzzy risk indices are presented in Figures 16 and 17. One important difference between fuzzy triangular membership function and triangular pdf is that the area below the pdf is equal to unity whereas the fuzzy one is normalized.

TABLE V

A LIST OF FUZZY RISK INDICES DEFINED AS TRIPLETS ASSIGNED TO ALL CRISP INDICES

Crisp risk index	**Fuzzy risk index**
0	$F_0 = (0,0,0)$
1	$F_1 = (1,1,3)$
2	$F_2 = (1,2,4)$
3	$F_3 = (1,3,5)$
4	$F_4 = (1,4,7)$
5	$F_5 = (2,5,8)$
6	$F_6 = (3,6,9)$
7	$F_7 = (4,7,10)$
8	$F_8 = (6,8,10)$
9	$F_9 = (7,9,10)$
10	$F_{10} = (10,10,10)$

where $F_0, F_1 \ldots F_{10}$ are fuzzy risk indices “0”, “1”…”10”, respectively.

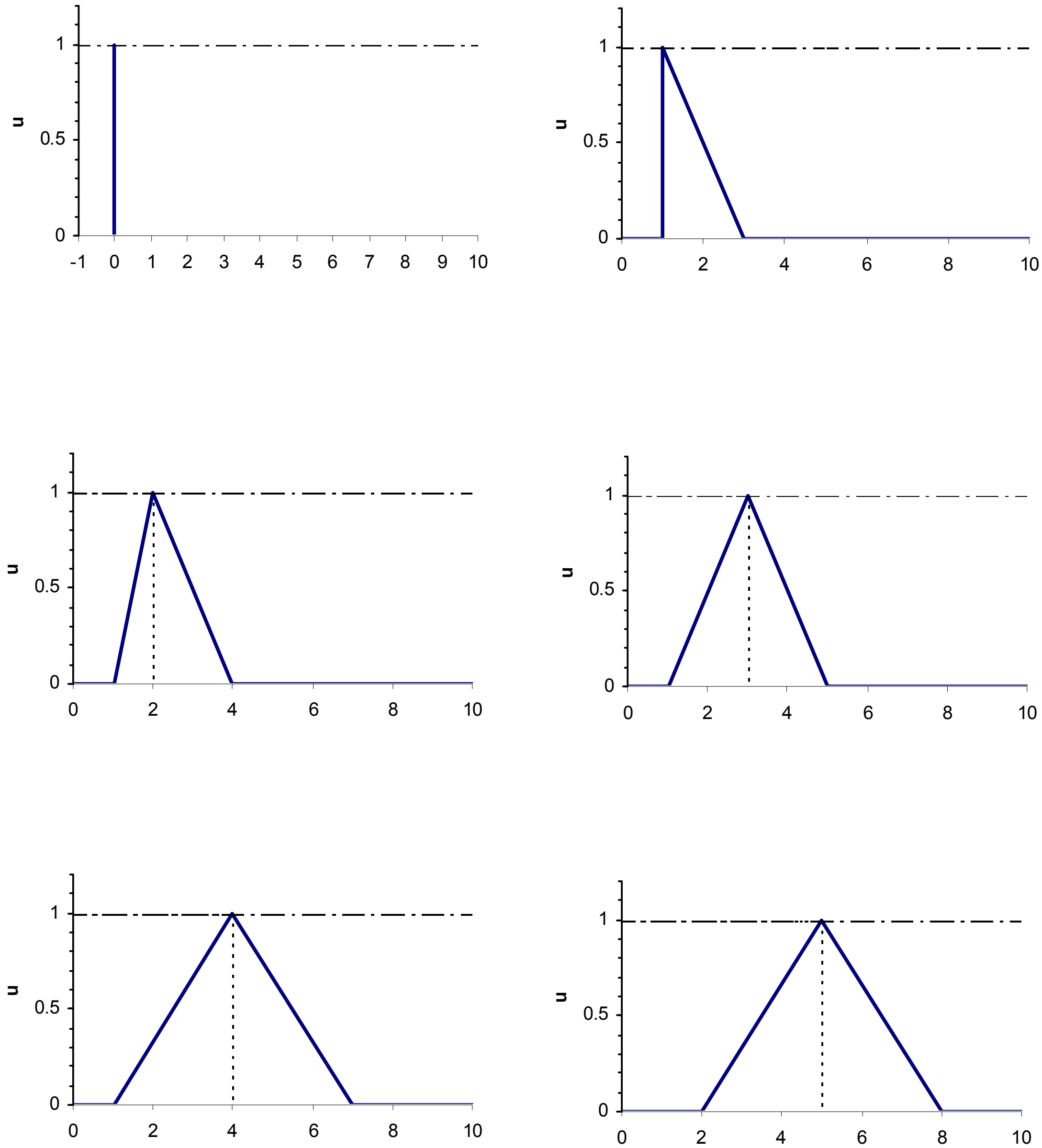

Figure 16. Crisp membership function for risk index “0” and fuzzy membership functions for fuzzy risk indices “1” –“5“.

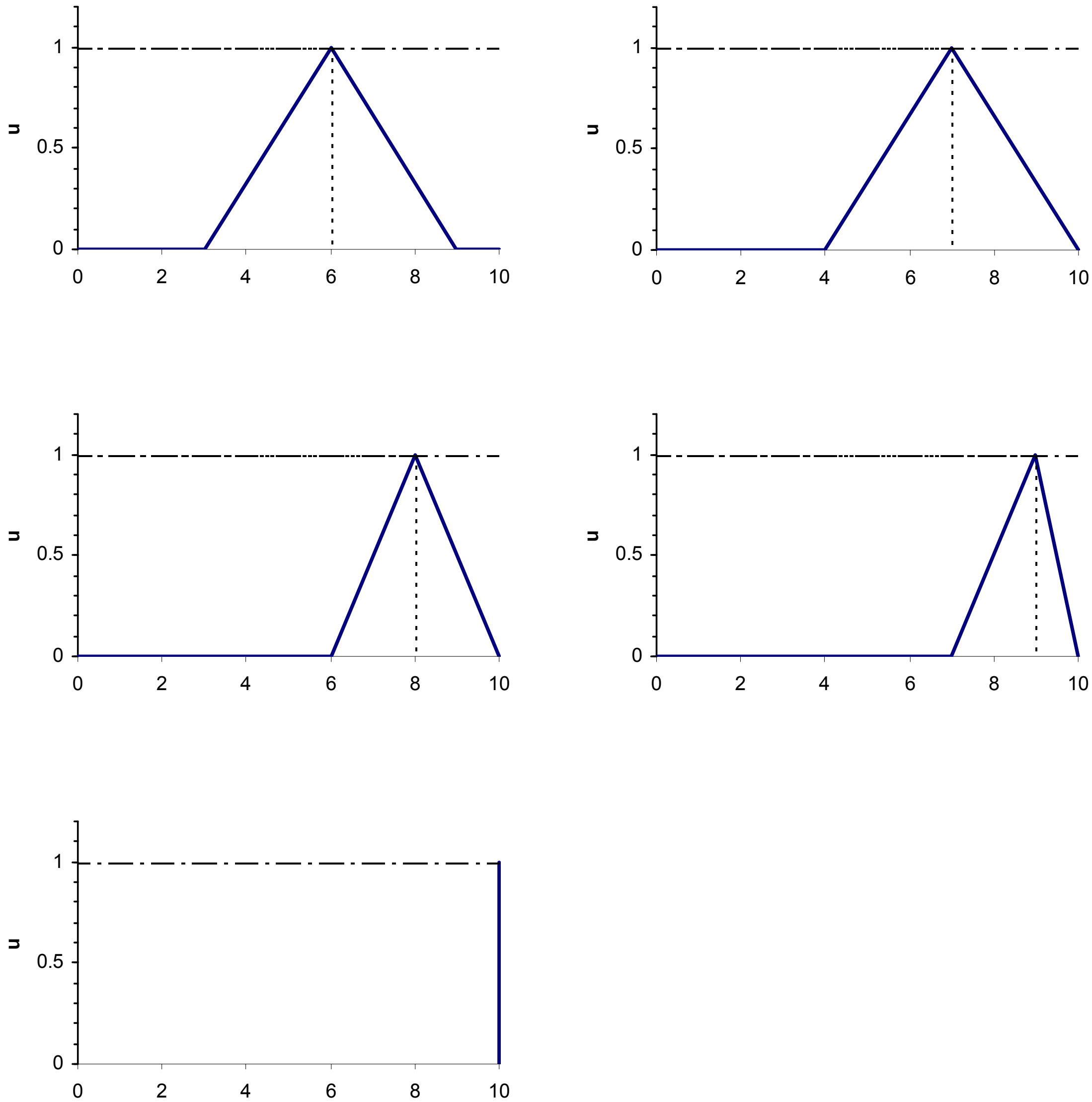

Figure 17. Fuzzy membership functions for fuzzy risk indices “6” –“9“ and crisp membership function for risk index “10”.

Fuzzy Risk Matrix

The fuzzy risk indices were applied to the risk matrices. The created fuzzy risk matrices, similar to MC risk matrices, not only allow for comparison of different alternatives but also, through incorporation of uncertainty, supply an informative tool for decision-makers.

To show the difference between the "regular" and "fuzzy" risk matrices, and to explain how the fuzzy calculations are conducted, the same example that was previously used while discussing MC risk matrices of the historic resources risk template cost risk with mitigation was considered as presented in Table VI .The result for the "regular" matrix is obtained by calculating an average value of appropriate "single" risk indices. In the case of fuzzy matrix, each triangular fuzzy risk index is described as a triplet of minimum, most likely and maximum values. From the fuzzy arithmetic, we know that we can calculate a mean TFN by taking averages of appropriate triplet values (e.g. mean of minimum, mean of most likely and mean of maximum values) , as follows:

$$F_{mean} = \frac{(F_1+F_2+F_3+F_4+F_5)}{5} = \left[\frac{(2,5,8)+(6,8,10)+(2,5,8)+(2,5,8)+(1,2,4)}{5}\right] =$$

$$= \left[\left(\frac{2+6+2+2+1}{5}\right),\left(\frac{5+8+5+5+2}{5}\right),\left(\frac{8+10+8+8+4}{5}\right)\right] =$$

$$= (2.6,5,7.6)$$

where F1, F2, …F5 are fuzzy risk indices describing marker/descriptor 1, 2…5 in Table VI.

TABLE VI

A COMPARISON OF EXAMPLE CRISP AND FUZZY OUTPUTS FROM HISTORICAL RESOURCES RISK MATRIX

Significant Risk Markers	**Project descriptors**	**Crisp risk index**	**Fuzzy risk index**		
			Minimum	Most likely	Maximum
1. Proximity of property either on or eligible for inclusion in Historic Register to station.	b. moderate proximity	5	2	5	8
2. Proximity of property either on or eligible for inclusion in Historic Register to project corridor.	a. close proximity	8	6	8	10
3. Sensitivity of Historic property to mode selection.	b. heavy rail	5	2	5	8
4. Potential that the public will be opposed to the project.	b. moderately politically active stake holders	5	2	5	8
5. Potential for previously unidentified historic or archeological resource.	c. no known native, hist. or arch. sites in area.	2	1	2	4
Total Score from the Matrix		5	2.6	5	7.6

Obtained this way triplet of mean values describes a mean TFN of the TFN's used in calculations. This mean TFN is a fuzzy result from the matrix. The fuzzy result gives more information to the decision maker than a crisp result. Instead of a single value output we get a whole range of possible results. Moreover, from the fuzzy arithmetic, we can also calculate a mean value (center of gravity) of the result. For our example problem:

$$COG = \frac{2.6 + 5 + 7.6}{3} = 5.07$$

Fuzzy Screening Tool

A screening tool was created based on the risk matrices with fuzzy risk indices. This tool is a preliminary version and is intended to serve as a foundation for development of final software that will be delivered to the FTA at the end of the project.

The screening tool is programmed in Microsoft Excel and allows for calculating results from all matrices separately as well as providing an estimate of the total impact of the project. It consists of fifteen interrelated spreadsheets. The first seven of them contain the fundamental environmental risk templates with fuzzy risk indices previously developed, which serve as an input to the software. The next seven spreadsheets contain risk matrices in a questionnaire form, and are intended for a user to choose the information specific to a project. Finally, the last spreadsheet presents results describing each area of environmental concern separately and a total impact of the project. The result tables indicate the following values: minimum, most likely, maximum, and mean of cost risk and schedule risk both with and without mitigation. The results are presented in form of numerical values ranging from 0 to 10, and verbal descriptors (low, medium, and high), in a way consistent with the description of input variables. Table VII presents the summary information about all spreadsheet included in the tool, their contents and application.

TABLE VII

SUMMARY INFORMATION ABOUT THE FUZZY SCREENING TOOL

Spreadsheet	Contents	Comments
1-7	Questionnaires addressing all seven matrices	Allow the user to chose information/descriptors specific to the project
8	Results	Separate results for each area of concern and a cumulative results for the project in the numerical (minimum, maximum, mean and most likely values) and verbal (high, medium, low) form
9	Graph of results	• Graphical representation of cumulative results for the project • Membership functions for cost and schedule risk with and without mitigation
10-16	Risk templates of seven areas of environmental concern	• Input data to the simulations • Can be interactively accessed and changed by the user

The computations of the screening tool are based on the fuzzy arithmetic previously discussed. Simple Microsoft® Excel functions, mathematical and logical, are employed to automate the process of calculations and allow to obtain results for all possible combinations of project descriptors. The mathematical functions used in the screening tool included: sum and average. Sample logical functions used in the tool are presented in Table VIII in the Excel format. These functions were taken from the wetlands questionnaire sheet.

TABLE VIII

SAMPLE EXCEL FUNCTIONS USED IN THE SCREENING TOOL

Code String	Comments
Cell D9=IF($C9="a",'Wetlands-template'!C9,IF($C9="b",'Wetlands-template'!C10,IF($C9="c",'Wetlands-template'!C11,$C9)))	This logical function is used to assign the most likely value (m) of the fuzzy risk index depending on the descriptor choice and using the risk template as a source of information
Cell D10 =IF(D9=0,0,IF(D9<=4,1,IF(D9<8,D9-3,IF(D9<10,D9-2,10))))	This logical function assigns the left spread (a) of the risk index based on the risk rating (most likely value)
Cell D11=IF(D9=0, 0, IF(D9>=7, 10, IF(D9>3, D9+3, D9+2)))	This logical function assigns the right spread (b) of the risk index based on the risk rating(most likely value)
Cell R15=IF(R9<3.5, "LOW", IF(R9<7.5, "MEDIUM", "HIGH"))	This logical function assigns the verbal description to the results

The layout of the screening tool is presented in Figures 18 through 25. Only the questionnaire and results sheets are presented as the risk templates were already discussed in this chapter. In Figures 18 to 24 the risk matrices in questionnaire form are shown, while Figure 25 illustrates the spreadsheet with results. The utilization of the fuzzy screening tool is discussed on the example of historic resources template that is given in Figure 21.

At the top of the spreadsheet, the user is asked to indicate if there are any historic resources/site in/close to the project corridor. If there are none, there is no reason to answer the questionnaire and all the results from this matrix are automatically set equal to “0”. There are only two such templates in this program for which the whole questionnaire can be skipped, historic resources (Figure 21) and wetlands (Figure 24), in case of their absence in the project corridor. In all other cases, the user has to complete the entire questionnaire.

Are there any PARKLANDS in the project corridor? (Y/N) — Answer: y

If "YES" then answer the following questionaire. If "NO" then go to the next template.

Significant Risk Markers	**Project Descriptors**	Choose one answer
1. Proximity of parkland to the alignment.	a. onsite b. adjecent c. far proximity	c
2. Proximity of parkland to the station.	a. onsite b. adjecent c. far proximity	c
3. Size of parkland	a. large; high probability for adverse effect on parkland b. medium; moderate probability for adverse effect on parkland c. small; low probability for adverse effect on parkland	c
4. Potential for adverse effect to mode selection	a. light rail b. heavy rail c. bus d. commuter rail (park & ride)	a
5. Potential for failing to obtain the Secretary of Transportation permit.	a. there are other highly feasible and prudent alternatives to the proposed project b. there are other moderately feasible and prudent alternatives to the proposed project c. there are other marginally feasible and prudent alternatives to the proposed project	c
6. Probability that the public will be opposed to the project.	a. highly politically active stake holders b. moderately politically active stake holders c. low politically active stake holders	a

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.83	4.33	6.17	4.44
Cost Risk without Mitigation	3.33	5.17	7.00	5.17
Schedule Risk with Mitigation	2.83	4.33	6.17	4.44
Schedule Risk without Mitigation	3.33	5.17	7.00	5.17

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

Figure 18. Parklands questionnaire and results.

Please answer the following questionaire.

Significant Risk Markers	Project Descriptors	Choose one answer
1. Potential for noise sensitive areas/buildings in project corridor	a. high % category 1 b. high % category 2 c. high % category 3	c
2. Potential for noise sensitive areas/buildings in the area of station	a. high % category 1 b. high % category 2 c. high % category 3	c
3. Potential for noise pollution sensitive to alignment options	a. elevated rail b. land rail c. street	c
4. Potential for occurrence of noise sensitive receptors which recieve little or no improvement with mitigation	a. high occurrence b. moderate occurrence c. low occurrence	c
5. Potential for vibration sensitive areas/buildings in project corridor	a. high % category 1* b. high % category 2* c. high % category 3*	c
6. Potential for vibration sensitive areas/buildings in the area of station	a. high % category 1* b. high % category 2* c. high % category 3*	c
7. Potential of vibration production sensitive to mode selection	a. light rail b. heavy rail c. bus d. commuter rail (park & ride)	a
8. Potential for receptors sensitive to electro-magnetic interference	a. high number of receptors b. moderate number of receptors c. low number of receptors	c
9. Probability that the public will be opposed to the project.	a. highly politically active stake holders b. moderately politically active stake holders c. low politically active stake holders	a

* Indicates vibration categories

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.22	3.78	5.67	3.89
Cost Risk without Mitigation	2.56	4.56	6.67	4.59
Schedule Risk with Mitigation	2.22	3.89	5.89	4.00
Schedule Risk without Mitigation	2.78	4.78	6.78	4.78

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

Figure 19. Noise and vibration questionnaire and results.

Please answer the following questionaire.

Significant Risk Markers	**Project Descriptors**	Choose one answer
1. Number of overlapping jurisdictional areas involved in project.	a. single government entity beyond FTA present b. multiple governmental entitys present	a
2. Potential for parcels w/o clear record titles.	a. majority of parcels w/well recorded ownership b. majority of parcels w/poorly recorded ownership	a
3. Potential for unanticipated joint-use agreement or Rail-road ROW in project corridor.	a. rail-road entities in the project area b. public entities in the project area c. quasi-public entities in the project area	b
4. Potential for unforeseen action required including: relocation assistance,encroachments, or functional replacement; parcel improvements; and utility relocation.	a. well documented history and current land use of project area and adjoining properties b.poorly documented history and current land use of project area and adjoining properties	a
5. Potential for inverse condemnation.	a. high potential for adverse effect on adjoining land b. moderate potential for adverse effect on adjoining land c. low potential for adverse effect on adjoining land	c
6. Potential for mode specific adverse effects.	a. light railway b. heavy rail c. buses d. commuter rail (park & ride)	a
7. Probability that the public will be opposed to the project.	a. highly politically active stake holders b. moderately politically active stake holders c. low politically active stake holders	a

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.57	4.29	6.14	4.33
Cost Risk without Mitigation	3.00	5.14	7.43	5.19
Schedule Risk with Mitigation	2.57	4.43	6.29	4.43
Schedule Risk without Mitigation	3.00	5.29	7.57	5.29

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	HIGH	MEDIUM

Figure 20. Property acquisition questionnaire and results.

	Answer
Are there any HISTORIC RESOURCES/SITES in/close to the project corridor? (Y/N)	y

If "YES" then answer the following questionaire. If "NO" then go to the next template.

Significant Risk Markers	**Project descriptors**	Choose one answer
1. Proximity of property either on or eligible for inclusion in Historic Register to station.	a. close proximity b. moderate proximity c. far proximity	c
2. Proximity of property either on or eligible for inclusion in Historic Register to project corridor.	a. close proximity b. moderate proximity c. far proximity	c
3. Sensitivity of Historic property to mode selection.	a.light rail b. heavy rail c. bus d. commuter rail (park & ride)	a
4. Potential that the public will be opposed to the project.	a. highly politically active stake holders b. moderately politically active stake holders c. low politically active stake holders	a
5. Potential for previously unidentified historic or archeological resource.	a. proximity to know arch., native or hist. sites. b. arch. native or historic sites in vicinity c. no known native, hist. or arch. sites in area.	c

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.60	4.00	6.20	4.27
Cost Risk without Mitigation	2.60	4.60	6.80	4.67
Schedule Risk with Mitigation	2.40	3.80	5.60	3.93
Schedule Risk without Mitigation	2.60	4.80	7.00	4.80

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

Figure 21. Historic resources questionnaire and results.

Please answer the following questionaire.

Significant Risk Markers	**Project Descriptors**	Choose one answer
1. Proximity of critical habitat to the alignment.	a. onsite b. immediately offsite c. far proximity	c
2. Proximity of critical habitat to the station.	a. onsite b. immediately offsite c. far proximity	c
3. Potential for critical habitat designation in the area affected by project.	a. highly environmentally exceptional areas. b. moderately environmentally exceptional areas. c. low environmentally exceptional areas.	c
4. Proximity of endangered species to the alignment.	a. onsite b. immediately offsite c. way offsite	c
5. Proximity of endangered species to the station.	a. onsite b. immediately offsite c. way offsite	c
6. Potential for previously unidentified endangered species.	a. high - lots of undeveloped lands in the project area b. moderate - a few undeveloped lands in the project area c. low - no undeveloped lands in the project area	c
7. Sensitivity of CH/endangered species to mode selection.	a. light rail b. heavy rail c. bus d. commuter rail (park & ride)	a
8. Potential for regulatory adverse effect determination.	a. severe impact of the project on CH/endangered species habitat with potential for Jeopardy Decision b. moderate impact of the project on CH/endangered species habitat c. low impact of the project on CH/endangered species habitat	c
9. Proximity of project corridor to Essential Fish Habitat (EFH)	a. close proximity b. moderate proximity c. far proximity	c
10. Probability that the public will be opposed to the project.	a. highly politically active stake holders b. moderately politically active stake holders c. low politically active stake holders	a

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	1.80	2.30	3.60	2.57
Cost Risk without Mitigation	2.00	2.80	4.50	3.10
Schedule Risk with Mitigation	1.80	2.40	3.70	2.63
Schedule Risk without Mitigation	2.00	3.10	4.80	3.30

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Cost Risk without Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk without Mitigation	LOW	LOW	MEDIUM	LOW

Figure 22. Endangered species questionnaire and results.

Please answer the following questionaire.

Significant Risk Markers	**Project Descriptors**	Choose one answer
1. Potential for unforeseen, localized, disproportionately high adverse effects.	a. highly centralized project activities a. moderately centralized project activities c. dispersed project activities	c
2. Potential for unforeseen minority population in the project corridor.	a. well defined social profile of the area b. not well defined social profile of the area	a
3. Potential for unforeseen low-income populations or minority business owners/property in the project corridor.	a. area with well defined neighborhood and community boundries b. area with not well defined neighborhood and community boundries	a
4. Potential for mode specific adverse effects.	a. light railway b. heavy rail c. buses d. commuter rail (park & ride)	a
5. Probability that the public will be opposed to the project.	a. highly politically active stake holders b. moderately politically active stake holders c. low politically active stake holders	a

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	3.00	4.20	5.60	4.27
Cost Risk without Mitigation	3.40	5.00	6.80	5.07
Cost Risk without Mitigation	3.20	5.00	7.00	5.07
Schedule Risk without Mitigation	3.60	5.80	7.60	5.67

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM

Figure 23. Environmental justice questionnaire and results.

	Answer
Are there any WETLANDS in the project corridor? (Y/N)	y

If "YES" then answer the following questionaire. If "NO" then go to the next template.

Significant Risk Markers	**Project Descriptors**	Choose one answer
1. Proximity of significant wetland to the alignment.	a. onsite b. immediately offsite c. far proximity	c
2. Proximity of significant wetland to the station.	a. onsite b. immediately offsite c. far proximity	c
3. Sensitivity of wetland mitigation to mode selection	a. light rail b. heavy rail c. bus d. commuter rail (park & ride)	a
4. Potential for findings within wetland requiring additional permits, nomination for protection, or inaccurate estimate of buffer zone.	a. high ecosystem knowledge b. moderate ecosystem knowledge c. low ecosystem knowledge	a
5. Probability of EPA to veto COE permit	a. high functional capacity b. inadequate COE performance c.adequate COE performance	c
6. Sensitivity of wetland for relocation.	a. high functional capacity b. moderate functional capacity c. low functional capacity	c
7. Probability that the public will be opposed to the project.	a. highly politically active stake holders b. moderately politically active stake holders c. low politically active stake holders	a

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	1.86	2.29	3.14	2.43
Cost Risk without Mitigation	2.29	3.00	4.71	3.33
Schedule Risk with Mitigation	1.86	2.14	3.00	2.33
Schedule Risk without Mitigation	2.29	2.86	4.57	3.24

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	MEDIUM	LOW

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 24. Wetlands questionnaire and results.

WETLANDS

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	1.86	2.29	3.14	2.43
Cost Risk without Mitigation	2.29	3.00	4.71	3.33
Schedule Risk with Mitigation	1.86	2.14	3.00	2.33
Schedule Risk without Mitigation	2.29	2.86	4.57	3.24

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	MEDIUM	LOW

ENVIRONMENTAL JUSTICE

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	3.00	4.20	5.60	4.27
Cost Risk without Mitigation	3.40	5.00	6.80	5.07
Cost Risk without Mitigation	3.20	5.00	7.00	5.07
Schedule Risk without Mitigation	3.60	5.80	7.60	5.67

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM

ENDANGERED SPECIES

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	1.80	2.30	3.60	2.57
Cost Risk without Mitigation	2.00	2.80	4.50	3.10
Schedule Risk with Mitigation	1.80	2.40	3.70	2.63
Schedule Risk without Mitigation	2.00	3.10	4.80	3.30

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Cost Risk without Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk without Mitigation	LOW	LOW	MEDIUM	LOW

HISTORIC RESOURCES

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.60	4.00	6.20	4.27
Cost Risk without Mitigation	2.60	4.60	6.80	4.67
Schedule Risk with Mitigation	2.40	3.80	5.60	3.93
Schedule Risk without Mitigation	2.60	4.80	7.00	4.80

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

PROPERTY ACQUSITION

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.57	4.29	6.14	4.33
Cost Risk without Mitigation	3.00	5.14	7.43	5.19
Schedule Risk with Mitigation	2.57	4.43	6.29	4.43
Schedule Risk without Mitigation	3.00	5.29	7.57	5.29

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	HIGH	MEDIUM

NOISE & VIBRATION

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.22	3.78	5.67	3.89
Cost Risk without Mitigation	2.56	4.56	6.67	4.59
Schedule Risk with Mitigation	2.22	3.89	5.89	4.00
Schedule Risk without Mitigation	2.78	4.78	6.78	4.78

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

PARKLANDS

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.83	4.33	6.17	4.44
Cost Risk without Mitigation	3.33	5.17	7.00	5.17
Schedule Risk with Mitigation	2.83	4.33	6.17	4.44
Schedule Risk without Mitigation	3.33	5.17	7.00	5.17

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

TOTAL PROJECT RISK

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.41	3.60	5.22	3.74
Cost Risk without Mitigation	2.74	4.32	6.27	4.45
Schedule Risk with Mitigation	2.41	3.71	5.38	3.83
Schedule Risk without Mitigation	2.80	4.54	6.47	4.60

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

Figure 25. Results from simulations for all matrices and total project risk.

In the historic resources example, the user selects the appropriate descriptors for each significant risk marker. Answers a, b, c, or d (note that in other then historical resources cases, a "0" can be chosen indicating that a marker does not apply) identify the most likely risk level for that marker to be used in future calculations. Later, the spreadsheet creates fuzzy indices by assigning the left and right spread (minimum and maximum values, respectively) to each most likely value, according to the rules discussed before. These triplets are then used to find the mean fuzzy results, which are presented as minimum, most likely and maximum results. The fuzzy results are subsequently defuzzyfied, and the mean values of outputs are found. Obtained this way results from each risk matrix are imported to the RESULT sheet, where they are compiled and the final total impact of the project is calculated.

It should be noted that, because the input most likely values are taken from the input risk templates and are not defined in internal functions, the user can define his own input variables if in his judgment they are different from the defaults. This adds an extra flexibility to the tool and allows the decision-maker to fit the risk analysis best to a specific project.

V. RESULTS

The results presented in this chapter address findings in the following areas:

- Modifications made to the Phase 1 indices to promote more efficient use and subsequent simulations.
- Comparison of results from Monte Carlo simulations with those generated with the fuzzy approach.
- Presentation of representative results from all of the fuzzy simulations.
- Application of fuzzy risk assessment to BART San Francisco Airport Extension project.

MATRIX MODIFICATIONS

Figures 26 through 32 present the modified matrices for the seven areas of environmental concerns. Modifications to these matrices were done to make them more efficient when applied to FTA projects and generally involved combining individual markers. Additionally, some changes to the risk indices values were made. Table IX presents all these modifications. These modifications represented a relatively small component of the subject research but are included here to complete the record of all activities undertaken in this area.

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippages				
	Project Descriptors	Cost Risk with Mitigation	Cost Risk No Mitigation	Schedule Risk with Mitigation	Schedule Risk No Mitigation
1. Proximity of parkland to the alignment.	a. onsite	9	10	9	10
	b. adjacent	7	8	7	8
	c. far proximity	2	3	2	3
2. Proximity of parkland to the station.	a. onsite	9	10	9	10
	b. adjecent	6	7	6	7
	c. far proximity	3	4	3	4
3. Size of parkland	a. large; high probability for adverse effect on parkland	8	9	9	10
	b. medium; moderate probability for adverse effect on parkland	4	5	5	6
	c. small; low probability for adverse effect on parkland	2	3	2	3
4. Potential for adverse effect to mode selection	a. light rail	8	8	8	8
	b. heavy rail	6	6	6	6
	c. bus	2	2	2	2
	d. commuter rail (park & ride)	7	7	7	7
5. Potential for failing to obtain the Secretary of Transportation permit.	a. there are other higly feasible and prudent alternatives to the proposed project	9	10	9	10
	b. there are other moderately feasible and prudent alternatives to the proposed project	5	6	5	6
	c. there are other marginally feasible and prudent alternatives to the proposed project	2	3	2	3
6. Probability that the public will be opposed to the project.	a. highly politically active stake holders	9	10	9	10
	b. moderately politically active stake holders	5	6	6	7
	c. low politically active stake holders	2	3	2	3

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 26. Parklands risk template

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippages				
	Project Descriptors	**Cost Risk with Mitigation**	**Cost Risk No Mitigation**	**Schedule Risk with Mitigation**	**Schedule Risk No Mitigation**
1. Potential for noise sensitive areas/buildings in project corridor	a. high % category 1	7	8	9	10
	b. high % category 2	5	6	7	8
	c. high % category 3	3	4	2	3
2. Potential for noise sensitive areas/buildings in the area of station	a. high % category 1	8	9	9	10
	b. high % category 2	6	7	7	8
	c. high % category 3	3	4	4	5
3. Potential for noise pollution sensitive to alignment options	a. elevated rail	6	7	6	7
	b. land rail	5	6	5	6
	c. street	2	3	3	4
4. Potential for occurrence of noise sensitive receptors which recieve little or no improvement with mitigation	a. high occurrence	8	8	8	8
	b. moderate occurrence	5	5	5	5
	c. low occurrence	2	2	2	2
5. Potential for vibration sensitive areas/buildings in project corridor	a. high % category 1*	8	9	8	9
	b. high % category 2*	5	6	5	6
	c. high % category 3*	2	3	2	3
6. Potential for vibration sensitive areas/buildings in the area of station	a. high % category 1*	9	10	9	10
	b. high % category 2*	5	6	5	6
	c. high % category 3*	2	3	2	3
7. Potential of vibration production sensitive to mode selection	a. light rail	8	8	8	9
	b. heavy rail	10	10	10	10
	c. bus	0	0	0	0
	d. commuter rail (park & ride)	7	7	7	7
8. Potential for receptors sensitive to electro-magnetic interference	a. high number of receptors	9	10	9	10
	b. moderate number of receptors	5	6	5	6
	c. low number of receptors	3	4	3	4
9. Probability that the public will be opposed to the project.	a. highly politically active stake holders	9	10	9	10
	b. moderately politically active stake holders	5	6	5	6
	c. low politically active stake holders	2	3	2	3

* Indicates vibration categories

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 27. Noise and vibration risk template

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippages				
	Project Descriptors	Cost Risk with Mitigation	Cost Risk No Mitigation	Schedule Risk with Mitigation	Schedule Risk No Mitigation
1. Number of overlapping jurisdictional areas involved in project.	a. single government entity beyond FTA present	3	4	3	4
	b. multiple governmental entitys present	8	9	8	9
2. Potential for parcels w/o clear record titles.	a. majority of parcels w/well recorded ownership	1	2	2	3
	b. majority of parcels w/poorly recorded ownership	6	7	7	8
3. Potential for unanticipated joint-use agreement or Rail-road ROW in project corridor.	a. rail-road entities in the project area	7	8	9	10
	b. public entities in the project area	3	4	3	4
	c. quasi-public entities in the project area	4	5	4	5
4. Potential for unforeseen action required including: relocation assistance,encroachments, or functional replacement; parcel improvements; and utility relocation.	a. well documented history and current land use of project area and adjoining properties	3	4	3	4
	b.poorly documented history and current land use of project area and adjoining properties	7	8	7	8
5. Potential for inverse condemnation.	a. high potential for adverse effect on adjoining land	8	9	8	9
	b. moderate potential for adverse effect on adjoining land	5	6	5	6
	c. low potential for adverse effect on adjoining land	3	4	3	4
6. Potential for mode specific adverse effects.	a. light railway	8	8	8	8
	b. heavy rail	5	5	5	5
	c. buses	0	1	0	1
	d. commuter rail (park & ride)	6	6	6	6
7. Probability that the public will be opposed to the project.	a. highly politically active stake holders	9	10	9	10
	b. moderately politically active stake holders	5	6	5	6
	c. low politically active stake holders	2	3	2	3

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 28. Property acquisition risk template

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippage.				
	Project descriptors	Cost Risk with Mitigation	Cost Risk No Mitigation	Schedule Risk with Mitigation	Schedule Risk No Mitigation
1. Proximity of property either on or eligible for inclusion in Historic Register to station.	a. close proximity	8	9	9	10
	b. moderate proximity	5	6	6	7
	c. far proximity	2	3	2	3
2. Proximity of property either on or eligible for inclusion in Historic Register to project corridor.	a. close proximity	8	9	9	10
	b. moderate proximity	5	6	6	7
	c. far proximity	1	2	2	3
3. Sensitivity of Historic property to mode selection.	a.light rail	8	8	8	8
	b. heavy rail	5	5	5	5
	c. bus	1	1	1	1
	d. commuter rail (park & ride)	7	7	7	7
4. Potential that the public will be opposed to the project.	a. highly politically active stake holders	7	7	7	7
	b. moderately politically active stake holders	5	5	5	5
	c. low politically active stake holders	1	1	1	1
5. Potential for previously unidentified historic or archeological resource.	a. proximity to know arch., native or hist. sites.	8	9	8	9
	b. arch. native or historic sites in vicinity	6	7	6	7
	c. no known native, hist. or arch. sites in area.	2	3	2	3

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 29. Historic resources risk template

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippages				
	Project Descriptors	Cost Risk with Mitigation	Cost Risk No Mitigation	Schedule Risk with Mitigation	Schedule Risk No Mitigation
1. Proximity of critical habitat to the alignment.	a. onsite	9	10	9	10
	b. immediately offsite	5	6	6	7
	c. far proximity	1	1	2	3
2. Proximity of critical habitat to the station.	a. onsite	9	10	9	10
	b. immediately offsite	5	6	6	7
	c. far proximity	1	2	1	2
3. Potential for critical habitat designation in the area affected by project.	a. highly environmentally exceptional areas.	7	8	8	9
	b. moderately environmentally exceptional areas.	4	5	5	6
	c. low environmentally exceptional areas.	1	2	1	2
4. Proximity of endangered species to the alignment.	a. onsite	7	8	7	8
	b. immediately offsite	3	4	3	4
	c. way offsite	2	2	2	3
5. Proximity of endangered species to the station.	a. onsite	7	8	7	8
	b. immediately offsite	4	5	4	5
	c. way offsite	1	2	1	2
6. Potential for previously unidentified endangered species.	a. high - lots of undeveloped lands in the project area	7	8	7	8
	b. moderate - a few undeveloped lands in the project area	5	6	5	6
	c. low - no undeveloped lands in the project area	0	1	0	1
7. Sensitivity of CH/endangered species to mode selection.	a. light rail	8	8	8	8
	b. heavy rail	5	5	5	5
	c. bus	1	1	1	1
	d. commuter rail (park & ride)	6	6	6	6
8. Potential for regulatory adverse effect determination.	a. severe impact of the project on CH/endangered species habitat with potential for Jeopardy Decision	9	10	8	9
	b. moderate impact of the project on CH/endangered species habitat	5	6	5	6
	c. low impact of the project on CH/endangered species habitat	0	1	0	1
9. Proximity of project corridor to Essential Fish Habitat (EFH)	a. close proximity	9	9	9	9
	b. moderate proximity	5	5	5	5
	c. far proximity	0	0	0	0
10. Probability that the public will be opposed to the project.	a. highly politically active stake holders	9	9	9	9
	b. moderately politically active stake holders	5	5	5	5
	c. low politically active stake holders	2	2	2	2

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 30. Endangered species risk template

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippages				
	Project Descriptors	Cost Risk with Mitigation	Cost Risk No Mitigation	Schedule Risk with Mitigation	Schedule Risk No Mitigation
1. Potential for unforeseen, localized, disproportionately high adverse effects.	a. highly centralized project activities	8	9	8	9
	a. moderately centralized project activities	4	5	3	4
	c. dispersed project activities	0	1	2	3
2. Potential for unforeseen minority population in the project corridor.	a. well defined social profile of the area	3	4	4	5
	b. not well defined social profile of the area	7	8	9	10
3. Potential for unforeseen low-income populations or minority business owners/property in the project corridor.	a. area with well defined neighborhood and community boundries	1	2	2	3
	b. area with not well defined neighborhood and community boundries	5	6	6	7
4. Potential for mode specific adverse effects.	a. light railway	9	9	9	9
	b. heavy rail	5	5	5	5
	c. buses	1	1	1	1
	d. commuter rail (park & ride)	7	7	7	7
5. Probability that the public will be opposed to the project.	a. highly politically active stake holders	8	9	8	9
	b. moderately politically active stake holders	5	6	5	6
	c. low politically active stake holders	1	2	1	2

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 31. Environmental justice risk template

Significant Risk Markers	Risk Evaluation: the relative potential for either cost-overruns or schedule slippages				
	Project Descriptors	Cost Risk with Mitigation	Cost Risk No Mitigation	Schedule Risk with Mitigation	Schedule Risk No Mitigation
1. Proximity of significant wetland to the alignment.	a. onsite	9	10	9	10
	b. immediately offsite	6	7	6	7
	c. far proximity	0	1	0	1
2. Proximity of significant wetland to the station.	a. onsite	9	10	9	10
	b. immediately offsite	6	7	6	7
	c. far proximity	1	2	0	1
3. Sensitivity of wetland mitigation to mode selection	a. light rail	3	3	3	3
	b. heavy rail	8	8	8	8
	c. bus	1	1	1	1
	d. commuter rail (park & ride)	2	2	2	2
4. Potential for findings within wetland requiring additional permits, nomination for protection, or inaccurate estimate of buffer zone.	a. high ecosystem knowledge	0	1	1	2
	b. moderate ecosystem knowledge	3	4	5	6
	c. low ecosystem knowledge	7	8	9	10
5. Probability of EPA to veto COE permit	a. high functional capacity	7	8	9	10
	b. inadequate COE performance	4	5	4	5
	c.adequate COE performance	0	1	0	1
6. Sensitivity of wetland for relocation.	a. high functional capacity	7	8	9	10
	b. moderate functional capacity	4	5	6	7
	c. low functional capacity	2	3	1	2
7. Probability that the public will be opposed to the project.	a. highly politically active stake holders	10	10	10	10
	b. moderately politically active stake holders	5	6	5	6
	c. low politically active stake holders	2	3	2	3

Green=low impact=0 - 3.49
Blue = moderate impact=3.5 - 7.49
Red = high impact = 7.5 - 10

Figure 32. Wetlands risk template

TABLE IX

SUMMARY OF MODIFICATIONS TO THE MATRICES

Matrix	Modifications	Comments
Parklands	Changed values of risk indices	Increased value of risk indices for markers/descriptors: 1/a,b; 4/a,b,c,d
Wetlands	Reduced number of markers from 8 to 7	Removed marker 5 due to not significant risk
	Changed values of risk indices	Increased value of risk indices for markers/descriptors: 1/a,b; 2/a,b; 3/a,b,c; and decreased value of risk indices for markers/descriptors: 1/c; 3/c
Environmental Justice	Changed values of risk indices	Increased value of risk indices for markers/descriptors: 1/a; 5/a
Endangered Species	Reduced number of markers from 11 to 10	Markers 8 and 9 combined together to create a modified marker 8
	Reduced number of descriptors	Reduced number of descriptors from 4 to 3 in markers 4 and 5 (removed “transient”)
	Increased number of descriptors	Added descriptor “low” in marker 6
	Changed values of risk indices	Increased value of risk indices for markers/descriptors: 1/a,b; 2/a,b; 8/a; 9/c and decreased value of risk indices for markers/descriptors: 6/b
Historic Properties	Changed values of risk indices	Increased value of risk indices for markers/descriptors: 2/a,b; 4/c; 5/b and decreased value of risk indices for markers/descriptors: 3/c
Property Acquisition	Reduced number of markers from 11 to 7	Markers 4, 5, 6 and 7, defined with the same descriptors and similar risk level, combined together to create a modified marker 4 Marker 8 removed as overlapping with marker 11 on public reaction
	Changed values of risk indices	Increased value of risk indices for markers/descriptors: 1/a,b; 2/b; 5/a,b,c; 6/c
Noise and Vibration	Reduced number of markers from 11 to 9	Markers 7 and 8 removed as overlapping with markers 1, 2, 3, and 4 on potential for noise/vibration sensitive areas/buildings in the project area
	Changed values of risk indices	Increased value of risk indices for markers/descriptors: 3/a,b; 7/b,c and decreased value of risk indices for markers/descriptors: 7/a

MONTE CARLO SIMULATIONS VERSUS FUZZY APPROACH

The following example problem compared the results from Monte Carlo and fuzzy simulations. For simplicity, it was assumed that all markers describing “physical” impact (i.e. proximity, amount, etc.) posed a low risk to the project. Accordingly, the lowest risk descriptors were chosen for these markers. However, the public was considered to be highly concerned about the project in all environmental areas and, therefore, bringing high risk to the project. Only one mode was selected for these sample simulations: light railway. The detailed discussion of the problem is not applicable here as it serves only for the example purposes. The vital fact is that the same input information was used for both simulation techniques to make the results comparable.

Figures 33 – 37 present the results from the Monte Carlo simulations conducted using @RISK. In Figure 33, a summary of results is presented for all conditions considered, i.e. cost and schedule risk with and without mitigation. The following statistics of the results are presented: minimum, maximum, most likely and mean values. The minimum and maximum values define the range of possible results, whereas, the mean and most likely are the central values indicating the average of all possible results and the most likely to occur result, respectively. Here, all values are in the range of medium risk level, except for one, minimum cost risk with mitigation, which shows low level of risk.

TOTAL PROJECT RISK

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	3.42	3.78	4.04	3.74
Cost Risk without Mitigation	4.08	4.50	4.78	4.44
Schedule Risk with Mitigation	5.55	3.92	4.21	3.90
Schedule Risk without Mitigation	4.24	4.57	5.03	4.62

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	MEDIUM	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	MEDIUM	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	MEDIUM	MEDIUM

Figure 33. Summary statistics of results from Monte Carlo simulations.

Figures 35 – 37 present the graphical results from the Monte Carlo analysis. On separate figures the cost and schedule with and without mitigation results generated in @RISK are shown. The results are in form of histograms and probability density functions. The appropriate shapes of probability distribution functions were defined in @RISK using the BestFit function.

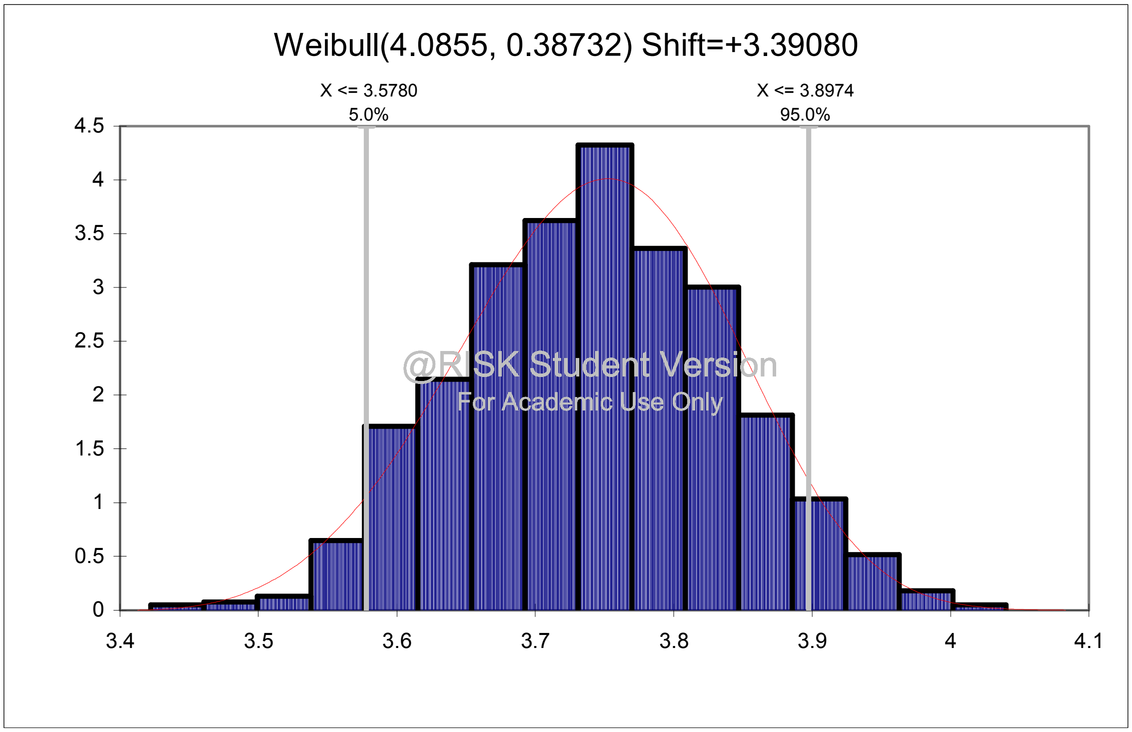

Figure 34. Histogram and pdf of cost risk with mitigation from Monte Carlo analysis.

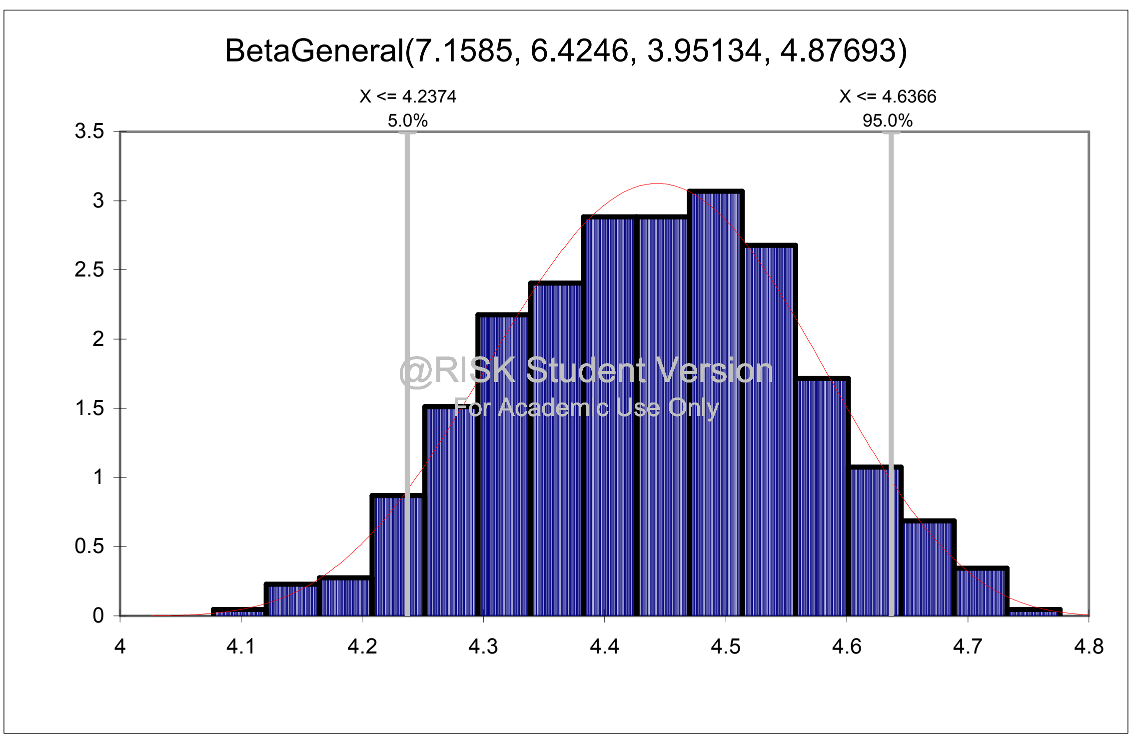

Figure 35. Histogram and pdf of cost risk without mitigation from Monte Carlo analysis.

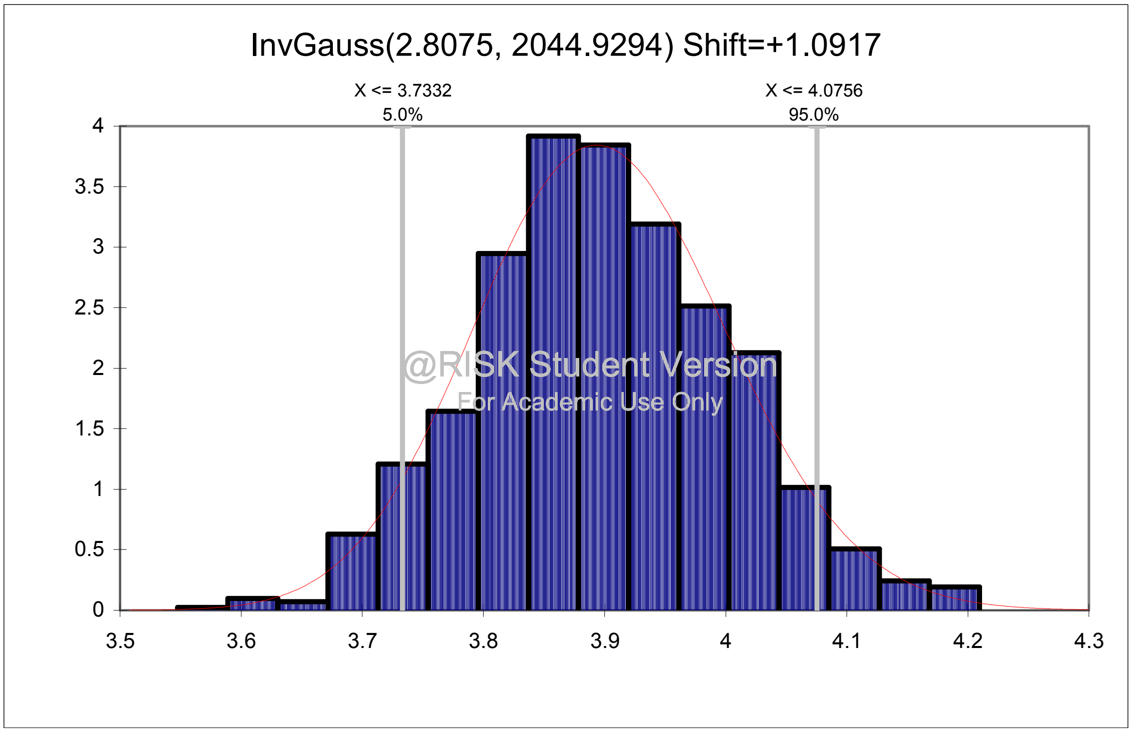

Figure 36. Histogram and pdf of schedule risk with mitigation from Monte Carlo analysis.

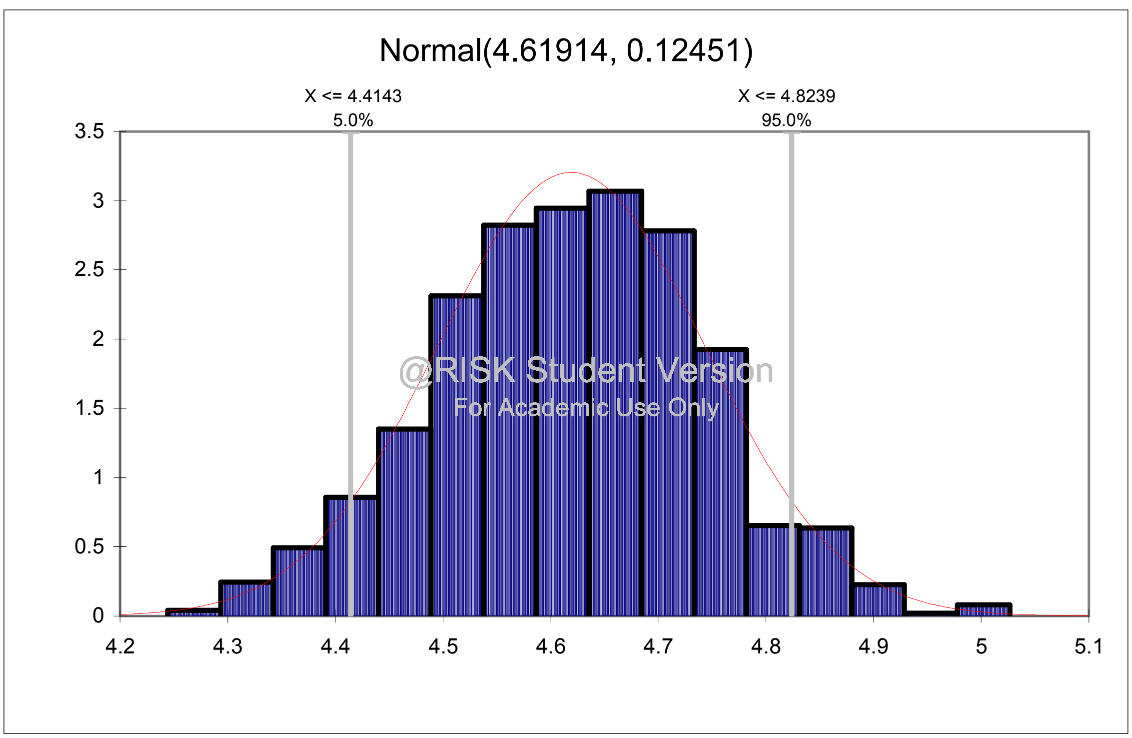

Figure 37. Histogram and pdf of schedule risk without mitigation from Monte Carlo analysis.

The following Figures 38 and 39 present the results from fuzzy analysis. Calculations using the fuzzy approach were performed in Excel spreadsheets utilizing mathematical and logical functions. To make it easy for the reader to follow, the results are presented in a similar fashion as the Monte Carlo analysis. In Figure 38, a summary of results is presented for all conditions considered, i.e. cost and schedule risk with and without mitigation. The subsequent statistics of the results are presented: minimum, maximum, most likely and mean values. All values are in the range of medium risk level, except for the minimum risk values, which are located in the range of low impact level.

TOTAL PROJECT RISK

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.41	3.60	5.22	3.74
Cost Risk without Mitigation	2.74	4.32	6.27	4.45
Schedule Risk with Mitigation	2.41	3.71	5.38	3.83
Schedule Risk without Mitigation	2.80	4.54	6.47	4.60

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

Figure 38. Summary statistics of results from fuzzy simulations.

Figure 39 presents the fuzzy membership functions of the results from fuzzy analysis. This figure shows the graphical results generated in Microsoft® Excel for the total project cost and schedule with and without mitigation.

TOTAL PROJECT RISK

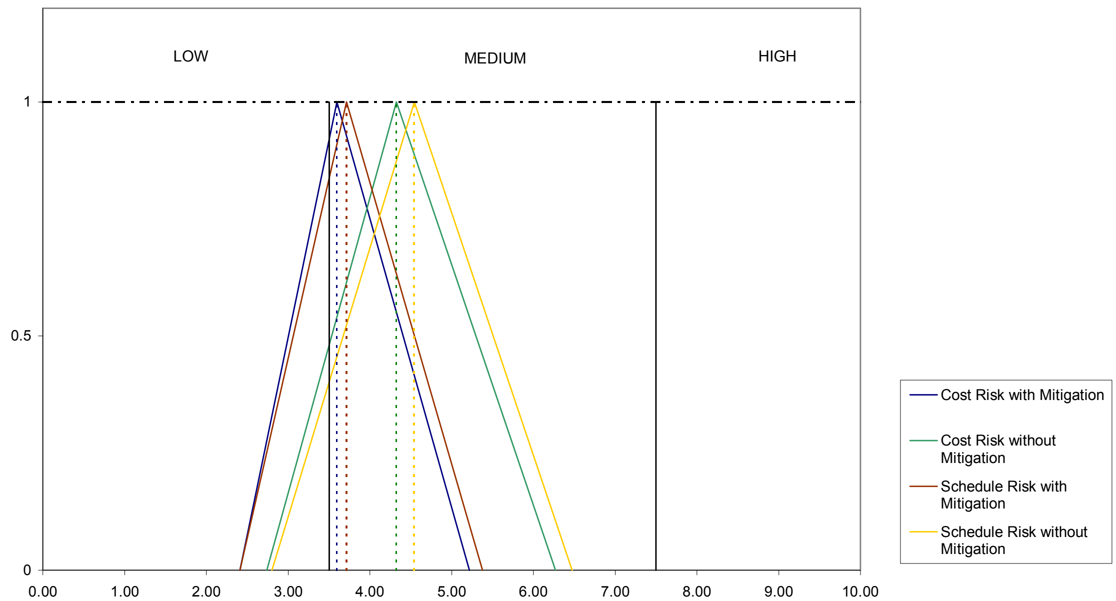

Figure 39. Fuzzy membership functions of the total project risk from fuzzy analysis.

The data presented in these figures and tables directly illustrates that the fuzzy approach employed in this effort produces corresponding results to those generated by Monte Carlo simulation. When factors such as ease of use and adaptability to changing conditions are included in the evaluation, the fuzzy approach was considered to be far better for this project.

RESULTS FROM ALL FUZZY SIMULATIONS

A total of 443,268 fuzzy simulations for all matrices were generated in this effort. All combinations of potential conditions that could result from full applications of the seven matrices were evaluated. All analyses were completed in Microsoft® Excel spreadsheets utilizing mathematical and logical functions. Figure 40 presents representative results from the simulations for historic resources matrix. A fraction of 30 simulations out of 324 possible, performed for cost risk with mitigation in historic resources matrix is presented. The first column enumerates the simulations consecutively. The next five columns refer to the five markers inherent to historic resources and the specific combinations of descriptors yielding the result of a given simulation. The subsequent columns: “m”, “a” and “b” refer to the triplets of triangular fuzzy risk indices of given descriptors taken to the simulations, and present the most likely, minimum and maximum values, respectively. Finally, the last four columns present the results from the calculations. Fundamental statistics of the outputs are included such as, most likely and mean values, and the range of possible outcomes.

The simulations for other matrices were performed in a similar fashion. The results generated in these simulations were written on two CDs and are available from the Oklahoma Transportation Center at Oklahoma State University upon request.

The 443,268 simulations performed in this effort relate only to the number of possible outcomes from each matrix separately. The total project results are simulated through subsequent combinations of these results. Since the number of the possible final outcomes is significantly bigger than the number of results within the matrices, it was not feasible to perform all these simulations. The resultant database, if created, would be enormous in size and, therefore, difficult to utilize for the purposes of the future software that is an intended final product of this project. For that reason, a Fuzzy Screening Tool, introduced in chapter 2, was created. This tool is programmed in Excel spreadsheets and can be interactively accessed to calculate the risk of a given project. It delivers evaluation of risks from each separate matrix as well as the total impact of the project.

Simulation	Marker/Descriptor					Cost Risk with Mitigation m					Cost Risk with Mitigation a					Cost Risk with Mitigation b					Results			
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	Most likely	Min	Max	Mean
1	a	a	a	a	a	8.00	8.00	8.00	7.00	8.00	6.00	6.00	6.00	4.00	6.00	10.00	10.00	10.00	10.00	10.00	7.80	5.60	10.00	7.80
2	a	a	a	a	b	8.00	8.00	8.00	7.00	6.00	6.00	6.00	6.00	4.00	3.00	10.00	10.00	10.00	10.00	9.00	7.40	5.00	9.80	7.40
3	a	a	a	a	c	8.00	8.00	8.00	7.00	2.00	6.00	6.00	6.00	4.00	1.00	10.00	10.00	10.00	10.00	4.00	6.60	4.60	8.80	6.67
4	a	a	a	b	a	8.00	8.00	8.00	5.00	8.00	6.00	6.00	6.00	2.00	6.00	10.00	10.00	10.00	8.00	10.00	7.40	5.20	9.60	7.40
5	a	a	a	b	b	8.00	8.00	8.00	5.00	6.00	6.00	6.00	6.00	2.00	3.00	10.00	10.00	10.00	8.00	9.00	7.00	4.60	9.40	7.00
6	a	a	a	b	c	8.00	8.00	8.00	5.00	2.00	6.00	6.00	6.00	2.00	1.00	10.00	10.00	10.00	8.00	4.00	6.20	4.20	8.40	6.27
7	a	a	a	c	a	8.00	8.00	8.00	1.00	8.00	6.00	6.00	6.00	1.00	6.00	10.00	10.00	10.00	3.00	10.00	6.60	5.00	8.60	6.73
8	a	a	a	c	b	8.00	8.00	8.00	1.00	6.00	6.00	6.00	6.00	1.00	3.00	10.00	10.00	10.00	3.00	9.00	6.20	4.40	8.40	6.33
9	a	a	a	c	c	8.00	8.00	8.00	1.00	2.00	6.00	6.00	6.00	1.00	1.00	10.00	10.00	10.00	3.00	4.00	5.40	4.00	7.40	5.60
10	a	a	b	a	a	8.00	8.00	5.00	7.00	8.00	6.00	6.00	2.00	4.00	6.00	10.00	10.00	8.00	10.00	10.00	7.20	4.80	9.60	7.20
11	a	a	b	a	b	8.00	8.00	5.00	7.00	6.00	6.00	6.00	2.00	4.00	3.00	10.00	10.00	8.00	10.00	9.00	6.80	4.20	9.40	6.80
12	a	a	b	a	c	8.00	8.00	5.00	7.00	2.00	6.00	6.00	2.00	4.00	1.00	10.00	10.00	8.00	10.00	4.00	6.00	3.80	8.40	6.07
13	a	a	b	b	a	8.00	8.00	5.00	5.00	8.00	6.00	6.00	2.00	2.00	6.00	10.00	10.00	8.00	8.00	10.00	6.80	4.40	9.20	6.80
14	a	a	b	b	b	8.00	8.00	5.00	5.00	6.00	6.00	6.00	2.00	2.00	3.00	10.00	10.00	8.00	8.00	9.00	6.40	3.80	9.00	6.40
15	a	a	b	b	c	8.00	8.00	5.00	5.00	2.00	6.00	6.00	2.00	2.00	1.00	10.00	10.00	8.00	8.00	4.00	5.60	3.40	8.00	5.67
16	a	a	b	c	a	8.00	8.00	5.00	1.00	8.00	6.00	6.00	2.00	1.00	6.00	10.00	10.00	8.00	3.00	10.00	6.00	4.20	8.20	6.13
17	a	a	b	c	b	8.00	8.00	5.00	1.00	6.00	6.00	6.00	2.00	1.00	3.00	10.00	10.00	8.00	3.00	9.00	5.60	3.60	8.00	5.73
18	a	a	b	c	c	8.00	8.00	5.00	1.00	2.00	6.00	6.00	2.00	1.00	1.00	10.00	10.00	8.00	3.00	4.00	4.80	3.20	7.00	5.00
19	a	a	c	a	a	8.00	8.00	1.00	7.00	8.00	6.00	6.00	1.00	4.00	6.00	10.00	10.00	3.00	10.00	10.00	6.40	4.60	8.60	6.53
20	a	a	c	a	b	8.00	8.00	1.00	7.00	6.00	6.00	6.00	1.00	4.00	3.00	10.00	10.00	3.00	10.00	9.00	6.00	4.00	8.40	6.13
21	a	a	c	a	c	8.00	8.00	1.00	7.00	2.00	6.00	6.00	1.00	4.00	1.00	10.00	10.00	3.00	10.00	4.00	5.20	3.60	7.40	5.40
22	a	a	c	b	a	8.00	8.00	1.00	5.00	8.00	6.00	6.00	1.00	2.00	6.00	10.00	10.00	3.00	8.00	10.00	6.00	4.20	8.20	6.13
23	a	a	c	b	b	8.00	8.00	1.00	5.00	6.00	6.00	6.00	1.00	2.00	3.00	10.00	10.00	3.00	8.00	9.00	5.60	3.60	8.00	5.73
24	a	a	c	b	c	8.00	8.00	1.00	5.00	2.00	6.00	6.00	1.00	2.00	1.00	10.00	10.00	3.00	8.00	4.00	4.80	3.20	7.00	5.00
25	a	a	c	c	a	8.00	8.00	1.00	1.00	8.00	6.00	6.00	1.00	1.00	6.00	10.00	10.00	3.00	3.00	10.00	5.20	4.00	7.20	5.47
26	a	a	c	c	b	8.00	8.00	1.00	1.00	6.00	6.00	6.00	1.00	1.00	3.00	10.00	10.00	3.00	3.00	9.00	4.80	3.40	7.00	5.07
27	a	a	c	c	c	8.00	8.00	1.00	1.00	2.00	6.00	6.00	1.00	1.00	1.00	10.00	10.00	3.00	3.00	4.00	4.00	3.00	6.00	4.33
28	a	a	d	a	a	8.00	8.00	7.00	7.00	8.00	6.00	6.00	4.00	4.00	6.00	10.00	10.00	10.00	10.00	10.00	7.60	5.20	10.00	7.60
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
323	c	c	d	c	b	2.00	1.00	7.00	1.00	6.00	1.00	1.00	4.00	1.00	3.00	4.00	3.00	10.00	3.00	9.00	3.40	2.00	5.80	3.73
324	c	c	d	c	c	2.00	1.00	7.00	1.00	2.00	1.00	1.00	4.00	1.00	1.00	4.00	3.00	10.00	3.00	4.00	2.60	1.60	4.80	3.00

Figure 40. Representative results from the fuzzy simulations on the example of historic resources

The Fuzzy Tool automates the risk assessment process allowing the simulations to be conducted by a future user.

APPLICATION TO BART SAN FRANCISCO AIRPORT EXTENSION PROJECT

In the previous stage of this research the risk templates were tested on a real world transit project. The June 1996 EIS from the Bay Area Rapid Transit (BART)-San Francisco Airport Extension (*Federal Transit Administration, 1996*) was used to obtain the necessary information. Two of five alternatives were chosen for analyses and were viewed as separate projects to determine the effectiveness of the risk templates. These were Colma, California, and South San Francisco, California areas. The selection was made based on the distinctive variations in these alternatives that highlight different aspects of matrix usage. These include mode number variation and entire matrix omission due to the absence of certain areas of concern. The pre-existing environmental conditions were used to determine the presence of risk markers by identifying the specific project descriptor that described conditions. Each alignment and the determination of risks present are discussed in detail in the Phase 1 Report for this effort (*McTernan et al., 2005*).

In this study, the BART San Francisco Airport Extension project was used to test the application of fuzzy risk matrices. The same markers and descriptors were used as in the Phase 1 Report. The developed fuzzy screening tool was employed to perform the simulations.

Risk analysis included all areas of environmental concern. Cost and schedule risk with and without mitigation was calculated for each individual matrix, as well as for the entire project. Transportation modes considered for each alternative were as follows:

- Town of Colma, California: commuter rail
- City of South San Francisco: commuter rail, light railway and bus service.

Figures 42 through 44 summarize the results from fuzzy simulations performed for the proposed transit project identified for the Town of Colma. Figure 41 and 42 show the results of fuzzy simulations for the individual matrices and figure 43 presents a summary of a total project risk estimate. The estimated risks from this project range from low to medium with a maximum value of 4.65. However, the risks in several individual matrices, such as environmental justice, historic resources, noise and vibration, and property acquisition, tend to be higher. Special attention should be paid to the property acquisition where the schedule risk without mitigation can possibly yield high risk to the project with the risk index of 7.57.

WETLANDS

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	1.43	2.14	3.14	2.24
Cost Risk without Mitigation	2.14	2.86	4.29	3.10
Schedule Risk with Mitigation	1.57	2.14	3.43	2.38
Schedule Risk without Mitigation	2.14	2.86	4.29	3.10

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	MEDIUM	LOW

ENVIRONMENTAL JUSTICE

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.20	4.00	6.60	4.27
Cost Risk without Mitigation	2.80	4.80	7.20	4.93
Cost Risk without Mitigation	2.80	4.40	6.40	4.53
Schedule Risk without Mitigation	3.40	5.20	7.20	5.27

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

ENDANGERED SPECIES

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	0.00	0.00	0.00	0.00
Cost Risk without Mitigation	0.00	0.00	0.00	0.00
Schedule Risk with Mitigation	0.00	0.00	0.00	0.00
Schedule Risk without Mitigation	0.00	0.00	0.00	0.00

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	LOW	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	LOW	LOW

HISTORIC RESOURCES

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	3.40	4.80	6.60	4.93
Cost Risk without Mitigation	3.80	5.20	6.60	5.20
Schedule Risk with Mitigation	3.60	5.00	6.60	5.07
Schedule Risk without Mitigation	4.40	5.40	6.60	5.47

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	MEDIUM	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	MEDIUM	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	MEDIUM	MEDIUM

Figure 41. Results of fuzzy simulations for the Town of Colma. Results from individual matrices: wetlands, environmental justice, endangered species, and historic resources.

PROPERTY ACQUSITION

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.43	4.29	6.57	4.43
Cost Risk without Mitigation	2.86	5.14	7.43	5.14
Schedule Risk with Mitigation	2.86	4.71	6.71	4.76
Schedule Risk without Mitigation	3.43	5.57	7.57	5.52

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	HIGH	MEDIUM

NOISE & VIBRATION

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.33	4.33	6.44	4.37
Cost Risk without Mitigation	2.89	4.89	6.89	4.89
Schedule Risk with Mitigation	2.67	4.56	6.44	4.56
Schedule Risk without Mitigation	3.33	5.11	6.89	5.11

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

PARKLANDS

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	0.00	0.00	0.00	0.00
Cost Risk without Mitigation	0.00	0.00	0.00	0.00
Schedule Risk with Mitigation	0.00	0.00	0.00	0.00
Schedule Risk without Mitigation	0.00	0.00	0.00	0.00

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	LOW	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	LOW	LOW

Figure 42. Results of fuzzy simulations for the Town of Colma. Results from individual matrices: property acquisition, noise and vibration, and parklands.

TOTAL PROJECT RISK

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	1.68	2.79	4.19	2.89
Cost Risk without Mitigation	2.07	3.27	4.63	3.32
Schedule Risk with Mitigation	1.93	2.97	4.23	3.04
Schedule Risk without Mitigation	2.39	3.45	4.65	3.49

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Cost Risk without Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk without Mitigation	LOW	LOW	MEDIUM	LOW

Figure 43. Results of fuzzy simulations for the Town of Colma. Total project impact.

Similar analysis using fuzzy risk matrices was done for the City of South San Francisco option. Here, three alternative mode selections were considered: light railway, commuter rail, and bus service. Figures 44 through 50 summarize the results from fuzzy simulations performed for the proposed transit project in the City of South San Francisco. Figure 44 through 49 show the results of fuzzy simulations for the individual matrices for all three modes; Figures 44 – 45 present results for light railway, Figures 46 – 47 for commuter rail, and Figures 48 – 49 for buses. Analysis of individual areas of concern is very important as the risk among different matrices varies greatly. Some matrices show the lowest relative risk of 0 as they were omitted in simulations (i.e. no wetlands or endangered species in the project corridor). Others, however, are associated with a very high risk of up to 9 (i.e. noise and vibration cost and schedule risk without mitigation for light railway and commuter rail modes).

In Figure 50, a summary of a total project risks for these modes is presented. The range of possible total project risk is from low to medium. The lowest possible total project risk of 1.88 was for cost risk with mitigation for the bus service alternative. The highest risk of 4.81 was observed for schedule risk without mitigation for the light railway alternative.

WETLANDS

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	0.00	0.00	0.00	0.00
Cost Risk without Mitigation	0.00	0.00	0.00	0.00
Schedule Risk with Mitigation	0.00	0.00	0.00	0.00
Schedule Risk without Mitigation	0.00	0.00	0.00	0.00

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	LOW	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	LOW	LOW

ENVIRONMENTAL JUSTICE

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.80	4.40	6.60	4.60
Cost Risk without Mitigation	3.40	5.20	7.20	5.27
Cost Risk without Mitigation	3.40	4.80	6.40	4.87
Schedule Risk without Mitigation	4.00	5.60	7.20	5.60

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	MEDIUM	MEDIUM

ENDANGERED SPECIES

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	0.00	0.00	0.00	0.00
Cost Risk without Mitigation	0.00	0.00	0.00	0.00
Schedule Risk with Mitigation	0.00	0.00	0.00	0.00
Schedule Risk without Mitigation	0.00	0.00	0.00	0.00

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	LOW	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	LOW	LOW

HISTORIC RESOURCES

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	4.20	6.00	8.20	6.13
Cost Risk without Mitigation	4.80	6.60	8.40	6.60
Schedule Risk with Mitigation	4.60	6.40	8.40	6.47
Schedule Risk without Mitigation	5.60	7.00	8.60	7.07

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Cost Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk with Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM

Figure 44. Results of fuzzy simulations for the City of South San Francisco, light railway mode. Results from individual matrices: wetlands, environmental justice, endangered species, and historic resources.

PROPERTY ACQUSITION

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	4.14	6.14	8.29	6.19
Cost Risk without Mitigation	5.29	7.00	8.71	7.00
Schedule Risk with Mitigation	4.57	6.57	8.43	6.52
Schedule Risk without Mitigation	5.86	7.43	8.86	7.38

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Cost Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk with Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM

NOISE & VIBRATION

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	3.44	5.89	8.44	5.93
Cost Risk without Mitigation	4.22	6.67	9.00	6.63
Schedule Risk with Mitigation	3.89	6.22	8.44	6.19
Schedule Risk without Mitigation	5.11	7.11	9.00	7.07

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	HIGH	MEDIUM
Cost Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk with Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM

PARKLANDS

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	0.00	0.00	0.00	0.00
Cost Risk without Mitigation	0.00	0.00	0.00	0.00
Schedule Risk with Mitigation	0.00	0.00	0.00	0.00
Schedule Risk without Mitigation	0.00	0.00	0.00	0.00

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	LOW	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	LOW	LOW

Figure 45. Results of fuzzy simulations for the City of South San Francisco, light railway mode. Results from individual matrices: property acquisition, noise and vibration, and parklands.

WETLANDS

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	0.00	0.00	0.00	0.00
Cost Risk without Mitigation	0.00	0.00	0.00	0.00
Schedule Risk with Mitigation	0.00	0.00	0.00	0.00
Schedule Risk without Mitigation	0.00	0.00	0.00	0.00

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	LOW	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	LOW	LOW

ENVIRONMENTAL JUSTICE

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.20	4.00	6.60	4.27
Cost Risk without Mitigation	2.80	4.80	7.20	4.93
Cost Risk without Mitigation	2.80	4.40	6.40	4.53
Schedule Risk without Mitigation	3.40	5.20	7.20	5.27

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

ENDANGERED SPECIES

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	0.00	0.00	0.00	0.00
Cost Risk without Mitigation	0.00	0.00	0.00	0.00
Schedule Risk with Mitigation	0.00	0.00	0.00	0.00
Schedule Risk without Mitigation	0.00	0.00	0.00	0.00

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	LOW	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	LOW	LOW

HISTORIC RESOURCES

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	3.80	5.80	8.20	5.93
Cost Risk without Mitigation	4.40	6.40	8.40	6.40
Schedule Risk with Mitigation	4.20	6.20	8.40	6.27
Schedule Risk without Mitigation	5.20	6.80	8.60	6.87

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Cost Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk with Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM

Figure 46. Results of fuzzy simulations for the City of South San Francisco, commuter rail mode. Results from individual matrices: wetlands, environmental justice, endangered species, and historic resources.

PROPERTY ACQUSITION

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	3.71	5.86	8.14	5.90
Cost Risk without Mitigation	4.86	6.71	8.57	6.71
Schedule Risk with Mitigation	4.14	6.29	8.29	6.24
Schedule Risk without Mitigation	5.43	7.14	8.71	7.10

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Cost Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk with Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM

NOISE & VIBRATION

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	3.22	5.78	8.44	5.81
Cost Risk without Mitigation	4.00	6.56	9.00	6.52
Schedule Risk with Mitigation	3.67	6.11	8.44	6.07
Schedule Risk without Mitigation	4.78	6.89	9.00	6.89

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	HIGH	MEDIUM
Cost Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk with Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM

PARKLANDS

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	0.00	0.00	0.00	0.00
Cost Risk without Mitigation	0.00	0.00	0.00	0.00
Schedule Risk with Mitigation	0.00	0.00	0.00	0.00
Schedule Risk without Mitigation	0.00	0.00	0.00	0.00

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	LOW	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	LOW	LOW

Figure 47. Results of fuzzy simulations for the City of South San Francisco, commuter rail mode. Results from individual matrices: property acquisition, noise and vibration, and parklands.

WETLANDS

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	0.00	0.00	0.00	0.00
Cost Risk without Mitigation	0.00	0.00	0.00	0.00
Schedule Risk with Mitigation	0.00	0.00	0.00	0.00
Schedule Risk without Mitigation	0.00	0.00	0.00	0.00

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	LOW	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	LOW	LOW

ENVIRONMENTAL JUSTICE

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	1.60	2.80	5.20	3.20
Cost Risk without Mitigation	2.20	3.60	5.80	3.87
Cost Risk without Mitigation	2.20	3.20	5.00	3.47
Schedule Risk without Mitigation	2.80	4.00	5.80	4.20

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

ENDANGERED SPECIES

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	0.00	0.00	0.00	0.00
Cost Risk without Mitigation	0.00	0.00	0.00	0.00
Schedule Risk with Mitigation	0.00	0.00	0.00	0.00
Schedule Risk without Mitigation	0.00	0.00	0.00	0.00

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	LOW	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	LOW	LOW

HISTORIC RESOURCES

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	3.20	4.60	6.80	4.87
Cost Risk without Mitigation	3.80	5.20	7.00	5.33
Schedule Risk with Mitigation	3.60	5.00	7.00	5.20
Schedule Risk without Mitigation	4.60	5.60	7.20	5.80

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	MEDIUM	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	MEDIUM	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	MEDIUM	MEDIUM

Figure 48. Results of fuzzy simulations for the City of South San Francisco, bus service. Results from individual matrices: wetlands, environmental justice, endangered species, and historic resources.

PROPERTY ACQUSITION

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	3.29	5.00	6.86	5.05
Cost Risk without Mitigation	4.57	6.00	7.71	6.10
Schedule Risk with Mitigation	3.71	5.43	7.00	5.38
Schedule Risk without Mitigation	5.14	6.43	7.86	6.48

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk with Mitigation	MEDIUM	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM

NOISE & VIBRATION

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.78	5.00	7.33	5.04
Cost Risk without Mitigation	3.56	5.78	7.89	5.74
Schedule Risk with Mitigation	3.22	5.33	7.33	5.30
Schedule Risk without Mitigation	4.33	6.11	7.89	6.11

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Cost Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM
Schedule Risk with Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk without Mitigation	MEDIUM	MEDIUM	HIGH	MEDIUM

PARKLANDS

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	0.00	0.00	0.00	0.00
Cost Risk without Mitigation	0.00	0.00	0.00	0.00
Schedule Risk with Mitigation	0.00	0.00	0.00	0.00
Schedule Risk without Mitigation	0.00	0.00	0.00	0.00

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	LOW	LOW
Cost Risk without Mitigation	LOW	LOW	LOW	LOW
Schedule Risk with Mitigation	LOW	LOW	LOW	LOW
Schedule Risk without Mitigation	LOW	LOW	LOW	LOW

Figure 49. Results of fuzzy simulations for the City of South San Francisco, bus service. Results from individual matrices: property acquisition, noise and vibration, and parklands.

LIGHT RAILWAY - TOTAL PROJECT RISK

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	2.08	3.20	4.50	3.26
Cost Risk without Mitigation	2.53	3.64	4.76	3.64
Schedule Risk with Mitigation	2.35	3.43	4.52	3.43
Schedule Risk without Mitigation	2.94	3.88	4.81	3.87

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Cost Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

COMMUTER RAIL - TOTAL PROJECT RISK

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	1.85	3.06	4.48	3.13
Cost Risk without Mitigation	2.29	3.50	4.74	3.51
Schedule Risk with Mitigation	2.12	3.29	4.50	3.30
Schedule Risk without Mitigation	2.69	3.72	4.79	3.73

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Cost Risk without Mitigation	LOW	LOW	MEDIUM	MEDIUM
Schedule Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk without Mitigation	LOW	MEDIUM	MEDIUM	MEDIUM

BUS - TOTAL PROJECT RISK

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	1.55	2.49	3.74	2.59
Cost Risk without Mitigation	2.02	2.94	4.06	3.01
Schedule Risk with Mitigation	1.82	2.71	3.76	2.76
Schedule Risk without Mitigation	2.41	3.16	4.11	3.23

	MIN	MOST LIKELY	MAX	MEAN
Cost Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Cost Risk without Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk with Mitigation	LOW	LOW	MEDIUM	LOW
Schedule Risk without Mitigation	LOW	LOW	MEDIUM	LOW

Figure 50. A comparison of total project impact of alternatives for the City of South San Francisco.

VI. DISCUSSION

The purpose of this study was to find the most favorable technique to introduce and evaluate the uncertainty in environmental risk assessment during an early stage of a project. Two alternative methodologies were considered: Monte Carlo analysis and fuzzy approach.

Monte Carlo simulation is a commonly used technique in probabilistic risk assessment. It enables a complete characterization of uncertainty and variability in the analysis inherent to the range of potential scenarios. Monte Carlo analysis supplies a decision-maker with valuable information on possible results and their probability of occurrence. However, Monte Carlo analysis requires a considerably large amount of data to adequately define the probability distribution functions for all input parameters. Only then, the accurate quantitative characterization of variability and uncertainty can be achieved. The detailed information necessary for accurate characterization of input parameter is, however, generally not available in the early stage of the project. Moreover, a complete quantitative characterization of variability and uncertainty may not be required at this level of planning. Therefore, an alternative method was considered here for uncertainty evaluation.

The fuzzy sets theory has been recently widely used for representation and propagation of uncertainty in quantified risk assessment. It is intended for development of concepts and techniques for dealing with sources of uncertainty or imprecision, as it allows a definition of vague concepts in a mathematical sense. For example, statements such as “about 8”, or “somewhere between 2 and 5 with the most likely to be 4”can be described by fuzzy sets without omitting any of the information given in the vague statement. Therefore, to define the input parameters detailed information like in the Monte Carlo analysis is not required. The operations on fuzzy sets do not supply as thorough statistical characterization of the outcomes as Monte Carlo analysis, however, they do provide comparable results.

In chapter 3 the results from the simulations for an example problem using both Monte Carlo and fuzzy techniques were presented. Using these outcomes the evaluation of both methods was done. In Figures 51 through 54 the comparison graphs of relative results from Monte Carlo and fuzzy analysis are presented. Figures 51 and 52 show the results of total project cost risk with and without mitigation, respectively, while the results of total project schedule risk with and without mitigation are presented in figures 53 and 54, respectively.

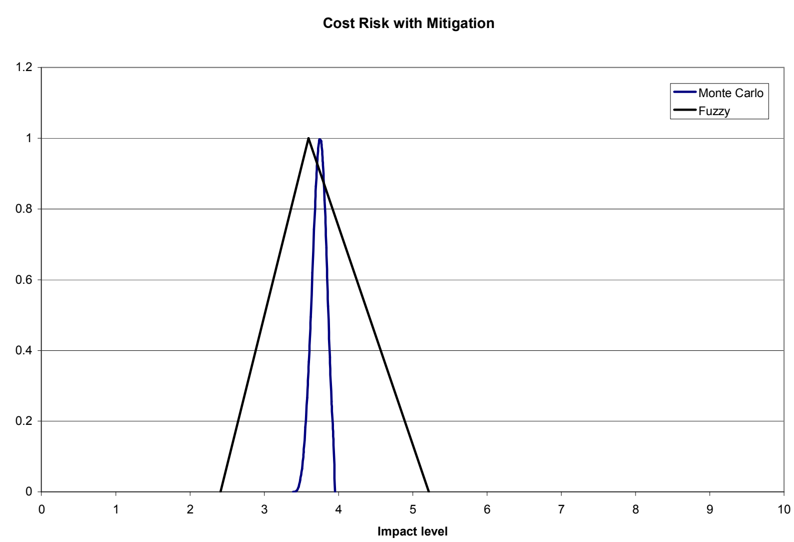

Figure 51. Comparison of Monte Carlo and fuzzy results for total project cost risk with mitigation.

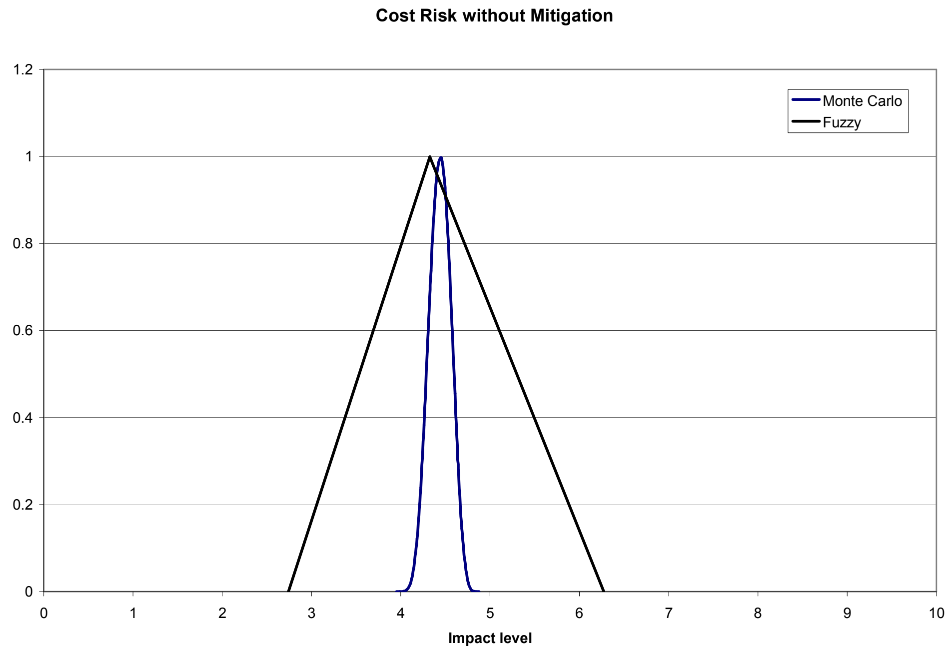

Figure 52. Comparison of Monte Carlo and fuzzy results for total project cost risk without mitigation.

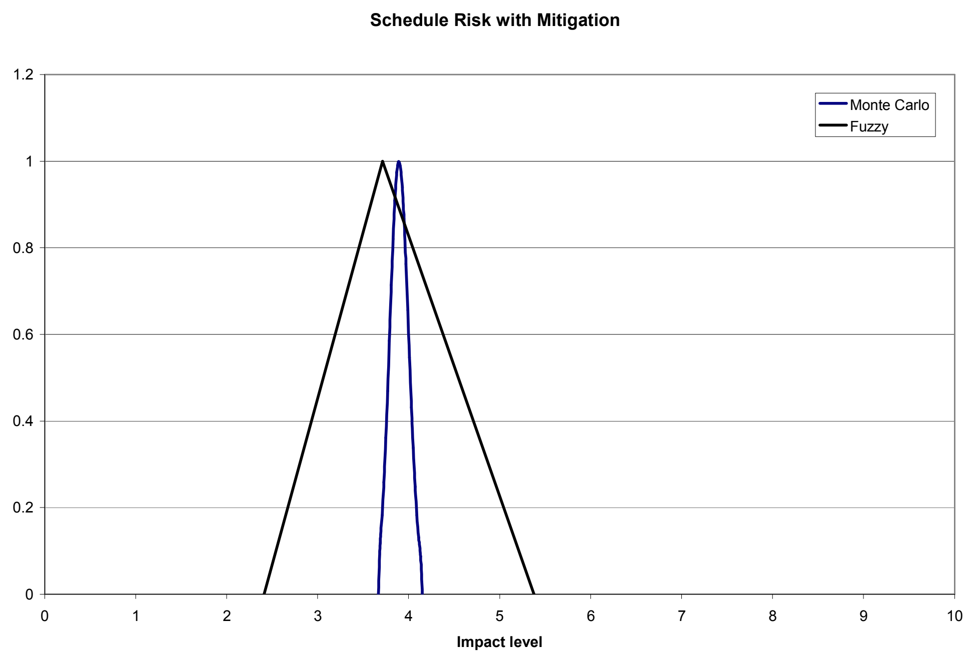

Figure 53. Comparison of Monte Carlo and fuzzy results for total project schedule risk with mitigation.

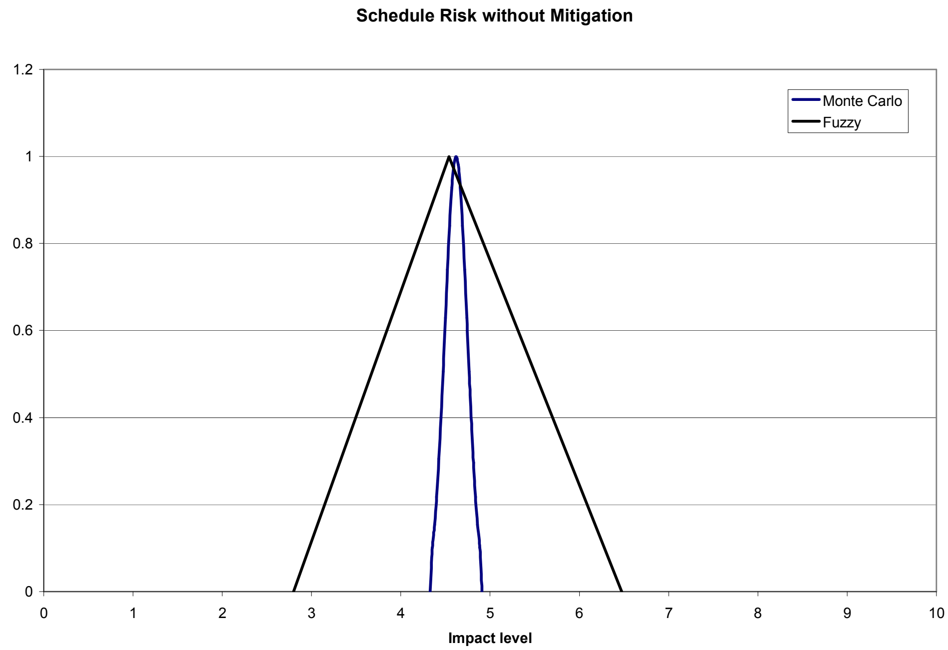

Figure 54. Comparison of Monte Carlo and fuzzy results for total project schedule risk without mitigation.

In all cases, both techniques provide comparable results. The mean values from Monte Carlo and fuzzy simulations are similar as it was presented in Figures 33 and 38 in previous chapter. The peaks of the output functions are not aligned perfectly but that is not a general rule. The shifting of the Monte Carlo outputs to the left or to the right of the fuzzy functions results from the unequal spreads of input triangular functions and differences in calculations of most likely values. If the triangles were isosceles the peaks of these functions would be identical.

The key difference is in the range of possible outcomes. Monte Carlo analysis tends to sample the pdfs of input parameters around the expected value, while the extremes are neglected. That results in the sharp peaks and narrow ranges of outcome distributions. The fuzzy mathematical operations, on the other hand, consider the most likely values to be of the same importance as the extreme ones. Therefore, the fuzzy membership functions of results have wider spreads relative to the wide ranges of possible values of input parameters.

The wider spreads of fuzzy results are a desired feature in this study. The risk of a project in the pre-planning stage is characterized with a great variation. Therefore, the information about the wide range of possible risks supplied by fuzzy indices is of great value for a decision-maker. Eventually FTA personnel and their contractors will be able to modify these default estimation ranges within the fuzzy simulator. It is anticipated that this could be done as more data become available later in the project planning cycle.

Monte Carlo simulation had limited appeal due to the excessive number of individual evaluations needed to complete this project. Of greater importance, however, was the fact that these same limitations apply to future users of the software that will result from subsequent efforts. This limitation meant that future users would be limited to only the default simulations rather than having the flexibility to configure a simulation to their own individual project conditions. This restraint would be felt most keenly as the individual project progresses through sequential planning levels which implicitly equates to lowered levels of uncertainty. The prospective user needs to be able to modify the assessment tool to be reflective of these changing conditions. Simulations based upon fuzzy sets theory are more readily applied to changing situations and were proven to yield comparable results to Monte Carlo method.

The efficiency and applicability of fuzzy approach was tested on a real world transit project. The fuzzy risk matrices were applied to the BART San Francisco Airport Extension project (*Federal Transit Administration, 1996*). The simulations were performed in an easy and time efficient manner. The results obtained from these simulations not only allow users to distinguish between the alternatives considered but also characterize the uncertainty associated with the risk assessment.

To illustrate the importance of including and evaluating uncertainty in the risk assessment process a comparison with the previous risk assessment presented in the Phase 1 Report (*McTernan et al., 2005*) was done. The highest relevance risk factor observed for the Town of Colma was 5.20, for environmental justice impact on schedule risk without mitigation. While the uncertainty analysis using fuzzy risk indices indicates the range of 3.40 to 7.20 of possible risks for the same case. The highest risk factor observed for the City of South San Francisco was 6.82 for noise and vibration impact on schedule risk without mitigation. Again, the uncertainty analysis provides a range of possible risks from 5.11 to 9.00 for the same consideration.

The results of fuzzy risk assessment employed in this research to the BART San Francisco Airport Extension project proved the utility of performing uncertainty analysis. Specifically, the results for the noise and vibration pollution impacts on cost risk with mitigation (Figures 45 and 47) illustrate a great variation in the range of possible impacts to the project. These risks could be from low to high for both light railway and commuter rail alternatives. The estimated impacts ranged from 3.44 to 8.44 with the most likely value of 5.89, and from 3.22 to 8.44 with the most likely value of 5.78, for light railway and commute rail, respectively.

The uncertainty analysis provided important information about the range of possible impacts of the project. It plays a significant role in risk management supplying a basis for decision-making.

VII. CONCLUSIONS

The purpose of this study was to find the most advantageous technique to introduce and evaluate the uncertainty in environmental risk assessment during an early stage of a transit project. Specifically, uncertainty associated with estimation was to be introduced to the matrix risk assessment protocol developed in a previous research effort. Two alternative methodologies were considered in this study: Monte Carlo analysis and fuzzy sets theory. The results from simulations using both techniques were analyzed for comparability. Also the ease of simulation performance and the effort versus usefulness of outcomes were evaluated. Finally, application of the fuzzy risk assessment was studied on a real world transit project.

The following conclusions were made:

- The results generated using a fuzzy approach are comparable to these from the Monte Carlo simulations
- The fuzzy results worked better in depicting a variation of uncertainty inherent to an early stage of a project
- Monte Carlo analysis provided a better statistical characterization of the results, however such detailed information is not necessary at the pre-planning stage
- The Monte Carlo method requires more input data, which are generally not available at this point of the project

- With the Monte Carlo method a future user would be limited to only the default simulations, rather than having the flexibility ensured by fuzzy approach to configure a simulation accordingly to project conditions
- The Fuzzy approach, applied to the BART San Francisco Airport Extension project was found to be a suitable and efficient technique for risk assessment in the early stage of project. It supplied valuable information on the uncertainty associated with the project risk in an easy and time effective manner.

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Scope and Method of Study: The purpose of this study was to find and apply the most favorable technique to introduce and evaluate the uncertainty of risk that environmental factors have on transit projects during the preliminary phase of planning. Specifically, methods to introduce estimation uncertainty into a risk matrix assessment protocol were developed in the subject research effort. Two alternative methodologies were considered: Monte Carlo analysis and fuzzy approach. Monte Carlo simulations were performed using @RISK, while the fuzzy computations were done in Excel spreadsheets. The results from simulations using both techniques were analyzed for comparability. Also the ease of simulation performance and the effort versus usefulness of outcomes were evaluated. Once this was done, the developed tool was applied to the real transit projects to determine its applicability.

Findings and Conclusions: The fuzzy approach was shown in this research application to deliver comparable results as the Monte Carlo simulations. The fuzzy results are more efficient in depicting variation of uncertainty inherent to an early stage of a project. Monte Carlo analysis provided a better statistical characterization of the results, however, such detailed information is not necessary at the pre-planning stage. It also requires more input data, which are usually not available at this point of the project. Moreover, Monte Carlo analysis includes time consuming performance of simulations. An uncertainty analysis based upon Monte Carlo simulation would limit a future user to only the default simulation, rather than having the flexibility ensured by fuzzy approach to configure a simulation accordingly to project conditions. The fuzzy approach, applied to the BART San Francisco Airport Extension project, was found to be a suitable and efficient technique for risk assessment in the early stage of project. It supplied valuable information on the uncertainty associated with the project risk in an easy and time effective manner.

ADVISER'S APPROVAL: William F. McTernan