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Probabilistic risk assessment method for prioritization of risk factors

Jay Tarakkumar Shah
Louisiana State University and Agricultural and Mechanical College, jshah1@paws.lsu.edu

PROBABILISTIC RISK ASSESSMENT METHOD FOR PRIORITIZATION OF RISK FACTORS

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ABSTRACT

Risk management involves assessing the risk sources and designing strategies and procedures to mitigate those risks to an acceptable level. Measurement of risk factors plays an important role in the assessment of risk. This research proposes to develop risk assessment frameworks and mathematical model (Probabilistic Risk Assessment model) identify the risk factors. Quantification and prioritization of risk factors will help to design controls, resource allocation policies and minimize the total cost using the Cost Minimization model. The proposed models are applied to a complex system that is representative of actual business situations.

CHAPTER 1. INTRODUCTION

In the past decade, control awareness in the risk management field has rapidly increased. Companies from small-scale manufacturers to large-scale industries have started to realize the value of risk management techniques. Significant research has been done in the field of risk management. However, none of this previous research has provided a concrete solution for the application of risk management to solve common industrial problems.

Risk management is the process of assessing risk and then designing strategies and procedures to mitigate the identified risk factors. Many factors have created an awareness of risk and its impact on industrial organizations including rapid technology evolutions, the global economy, and the changing role of engineering and business processes.

Different methodologies have been suggested to develop solutions for managing risk. The major two concepts evolving in risk management are the use of qualitative approaches and quantitative approaches.

Qualitative approaches require expert opinions or a knowledgeable person's views. An expert can be the one who has extensive knowledge about the field related to project or who has worked on similar projects in the past. The major disadvantages of using qualitative approaches are the amount of subjectivity during the project, variation in human judgments, and lack of standardized approach. There have been numerous approaches suggested by Chapman, R.J. (1998), like Delphi techniques and nominal group techniques to minimize the biasing, which exists, but still these approaches do not reduce the amount of subjectivity present in the process.

Quantitative approaches require a systematic framework or model that can quantify the likelihood of the risk. The major advantages of quantifying the risks are providing an adequate understanding of failure, consequences and events, which are difficult to explain by a qualitative approach. In addition, it is easy to understand the overall process, reach the appropriate decision, and allocate resources based on quantitative data rather than qualitative opinions.

Several strategies have been developed in quantitative and qualitative risk management, though they have been limited by one or more factors. The major focus of this research is to develop a generic flowchart and Probabilistic Risk Assessment (PRA) model for large and complex systems to identify the likelihood of the risk. The flowchart and formulation of a PRA model are vital elements to lead the foundation of the design of decision support systems for large-scale systems.

Risk management frameworks will lead to a step-by-step decomposition of the complex system under assessment into functionally or structurally defined segments. According to the division of each segment, the major risks and risk factors affecting these segments will be recognized, and the methods of assessing those risk factors are identified. The flowchart will provide a systematic framework to identify the possible risks affecting the system and select the appropriate method to quantify those risk factors.

After identifying risk factors through the flowchart approach, the next step is to quantify those risk factors through the PRA method. PRA method is a broad, structured, and logical approach aimed at identifying and quantifying risks in complex systems. The major purpose of the PRA method is to quantify the key risk factors identified by the flowchart approach so that controls will be designed according to the prioritization of risk factors to improve overall performance of the entire system. PRA supports management to improve the performance of the system as well as optimizes the decision-making. Well-formulated risk quantification methods are essential to support the decisions being made. Without a well-built risk model, important issues may go unidentified, and unimportant issues may receive more focus.

PRA works as a mathematical model to improvise the qualitative risk assessment approach while decreasing the subjectivity. PRA reduces the subjectivity but does not eliminate it. There must be a group of experts who are knowledgeable about the PRA who help management in making their decisions. PRA serves as a decision support tool.

In summary, the objective of this study is to develop the methods of managing risk through risk assessment frameworks, PRA model. The methods will apply to the real world application and help to prioritize the risks within the large business and engineering entity. Design of controls will be based on prioritization of risks, which will help to manage the risks within the entity to an acceptable level.

1.1 Literature Review

This section begins by outlining some related developments in the risk management field. The relevant literature mainly comprises phases in risk management approaches, qualitative approaches, and quantitative models that represent the likelihood of risks on large and complex systems.

1.1.1 Phases in Risk Management

Many past researchers have taken the approach of managing risk in large and complex systems or managing projects by phases, stages, and categories, which are broken down in many different ways. Some projects are related to the activities or tasks they perform, and others are related to the output produced. The breakdown of a particular system depends upon several factors such as the size of the system, complexity in the system, and changes affecting the system.

In the past, several models have been proposed for the project risk management process. Miller and Lessard (2001) developed an approach that sketches out the various components of risks, outlines strategies for coping with risks, and suggests a dynamic layering model for managing and shaping the risks in large engineering projects. These authors dissected risks into categories such as market related, completion, and institutional. After the categorization of risk, they suggested four main risk-management techniques: shape and mitigate, shift and allocate, influence and transform institutions, and diversify through portfolios. Furthermore, after tracing risk management in 60 large engineering projects, they identified six primary layers of mechanisms used by management for coping with the risks: assess/understand, transfer/hedge, diversify/pool, create options/flexibility, transform risk, and embrace residual risks.

Chapman (1979) suggests SCERT (Synergistic Contingency Evaluation and Response Techniques), which provides a systematic approach to the planning and financial evaluation of large engineering projects involving significant risks. SCERT is a four-phase approach, and the four phases include scope, structure, parameter, and manipulation and interpretation. All four phases are then divided into specific steps. “Scope” is divided into activity identification, primary risk identification, primary response identification, secondary risk identification, and secondary response identification. The structure phase is composed of minor and major risk identification, specific and general response identification, simple and complex decision rule identification, and risk/response diagramming. The parameter phase contains desired parameter identification, scenario identification, probability estimation, and manipulation. The interpretation phase contains risk computation, risk efficiency decision rule assessment, risk balance decision rule assessment, and budget contingency sum assessment steps.

Chapman and Ward (1997) have taken a nine-phase approach: define, focus, identify, structure, ownership, estimate, evaluate, plan, and manage to manage the risk in large and complicated projects. The nine phases are discussed in start-to-start precedence sequence. Once started, all phases proceed in parallel, with activities defined by an iterative model interlinking the phases. Each phase is associated with defined deliverables. Each deliverable is discussed in terms of its purpose and the tasks required producing it.

The Project Management Body of Knowledge (PMBOK) (1996) advocates a four-phase approach: identification, quantification, response development, and response control. Michaels (1996) has developed the Identification, quantification, and control approach. Even though all the methods suggest different phases or stages, the generic idea of all the methods includes the three basic phases of risk management: Risk Identification, Risk Assessment, Risk Control and Risk Mitigation. All four phases will be discussed in detail in Section 5.1 and Section 5.2 while discussing Risk Management Framework.

1.1.2 Qualitative Risk Management

As mentioned in the previous section the three basic phases of risk management are Risk Identification, Risk Assessment, Risk Control and Risk Mitigation. The first step in Qualitative Risk Management is to identify the risks. Identification of risks through Qualitative Risk Management is achieved through:

- Interviewing
- Brainstorming
- Expert opinions
- Analysis through trends, historic data or past experience
- Checklists

Once the risks are identified in key areas, the next steps are to associate the identified risks with the assessment process by risk categories, to determine the likelihood of each risk, to describe risk impacts or subjectively characterize each risk into high/low risk probabilities and impact on the projects. Qualitative techniques are comparatively economical and readily applied but are unable to provide numerical estimates or relative rankings for the risks identified

Semi-quantitative techniques allow some relative risk ranking, but these techniques are still unable to provide detailed assessments of large and complicated projects or systems. Similarly, neither can effectively be used in the prediction of low frequency/high consequence events. It is difficult to control or mitigate the risks solely using qualitative risk assessment. A combination of qualitative and quantitative risk assessment is beneficial to successfully identifying the risks associated with the process, while controlling the cost, time, and resources. Qualitative risk analysis helps with understanding the process, and it is highly recommended as an initiation of the risk management process irrespective of the fact that quantitative risk analysis is going to be done.

CHAPTER 2. QUANTITATIVE RISK MANAGEMENT

Quantitative Risk Assessment (QRA) tries to overcome the disadvantages of the qualitative risk assessment. Risk rankings, Risk Factors, Probabilistic Risk Assessment (PRA), and Hierarchical Holographic Modeling (HHM) are popular approaches that have been successfully implemented in the past by several authors. As mentioned above out of the three phases of risk management: Risk Identification, Risk Assessment, Risk Control and Mitigation, quantification of risk lies under the risk assessment phase. This section will review the past research that has been done in the field of quantitative risk management.

2.1 Hierarchical Holographic Modeling (HHM)

Haimes (1981) started the research in the field of HHM. HHM addresses the issues related to hierarchical institutional, managerial, organizational or functional decision-making structures. Kaplan et al. (2001) suggested that HHM has been regarded as a general method for identifying the set of risk scenarios. HHM is particularly useful in modeling large-scale, complex, and hierarchical systems. The HHM methodology recognizes that most organizational as well as technology-based systems are hierarchical in structure, and thus the risk management of such systems must be driven by and responsive to this hierarchical structure. The risks associated with each subsystem within the hierarchical structure contribute to and ultimately determines the risks of the overall system.

The major advantage of the HHM framework for risk assessment and management is its ability to identify risk scenarios that result from and propagate through the multiple overlapping hierarchies in real-life systems. In the planning, design, or operational modes, the ability to model and quantify the risks contributed by each subsystem facilitates understanding, quantifying, and evaluation the risks of the whole system. In particular, the ability to model the intricate relations among the various subsystems and the ability to account for all relevant and important elements of risk and uncertainty renders the modeling process more representative and encompassing.

Himes, et al. (2002) suggested that the nature and capability of HHM is to identify a comprehensive and large set of risk scenarios. To deal with this large set we need a systematic process that filters and ranks these identified scenarios is needed so that risk mitigation activities can be prioritized. In addition, Kaplan, et al. (2001) suggested that HHM could be viewed as one of the methods of Theory of Scenario Structuring (TSS), which is the part of QRA that is useful in identifying the set of risk scenario.

2.2 Risk Ranking

Risk ranking is the efficient way to set up risk priorities. Florig, et al. (2001) developed a method whereby risk experts categorize and define the risks to be ranked, identify the related risk attributes, and characterize the risk. The authors also suggested a five-step risk-ranking method, which is shown in Figure 1.

This five-step approach starts with the iterative process of defining and categorizing the risks to be ranked and the set of attributes that describe those risks. Based on risk attributes, the next step is to create the risk summarization sheets. Then, participants are selected and risk rankings are prepared based on the risk summarization sheets. Finally, a description of issues identified and the resulting rankings are prepared.

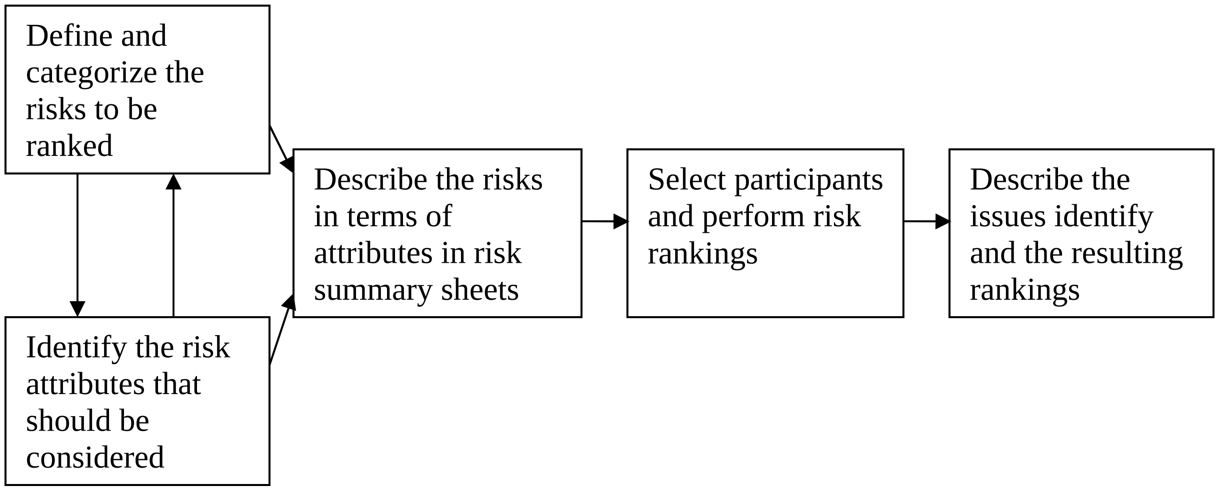


Figure 1: Steps in Risk-Ranking method

The authors also suggested that risk ranking should be viewed as only one input to the decision-making process and not for the final recommendations for management decision-making priorities. Also, based on higher to lower ranking management can assign the controls and resources to mitigate the risk. Several authors (Webler, et al., 1995 and Morgan, et al., 2000) have suggested different risk ranking methodologies according to their respective fields.

2.3 Risk Factors

Factorization of risk is a step-by-step approach toward quantifying the risk. Calculating Risk factors is the most economical and effective way to identify the risk priorities. Risk factorization is a method in which risk experts identify the risks, assign weights to those risks, and identify the total risk scores. Based on total risk scores, management sets their priorities to allocate the resources and design controls. The authors also suggested a seven-step risk factorization method.

Sumners, et al. (2003) suggested the following method for quantifying the risk method. The first step toward assessing the risk of a particular business, organization or department is to identify the risk universe. The risk universe will provide a macro level overview of the processes, activities, departments, functions etc. An in-depth knowledge about the business entity is an essential factor for identifying the risk universe.

The second step is to break down the risk universe into more micro-level classifications. To facilitate the process it is always advisable to breakdown processes into sub-processes and this continues until the end of the process. There are several constraints that increase the uncertainty of a single process, which ultimately increases the overall uncertainty. Time, technology change, complexity, size, cost, and competence of staff are the most common constrains that increase uncertainty of the overall project.

After breaking down the risk universe, the next step is to identify the risk factors. It is advisable to identify risk factors between three to eight. Possible disadvantages of this risk model are the inability to consider future events in the selection process. This disadvantage can be addressed by incorporating the future event into one of the risk factors.

The next step in the risk assessment methodology is to assign weights to the risk factors. In this method, the weights are normally allocated over 100%.

Allocation	**Risk Factor**
20%	Technology Change
20%	Complexity
25%	Size of unit

25%	Competence of staff
10%	Future change
100%	

After the weights are assigned, the above risk factors are scaled, using a scale of 1-5. The scale descriptions can be varied, according to the nature of the process. The most general description for the risk factors are

Score	**Description**
1	Adequate
2	Adequate but need improvement
3	Unknown
4	Risky
5	Very risky

The next step is to multiply the weights with the assigned scores. For example, assume that one department received a score of 4 and a weight of 20% on "Complexity". The risk weight would be computed as 0.8 (4 * .20). The priority weights for the unit are then totaled to provide the total risk score of the individual unit.

After computing the weights of all units, a plan is developed according to the highest to lowest risk scores. Based on the nature of each unit, decisions are made relevant to the scope, depth, and frequency of the plan.

The risk factorization methodology is a very powerful decision-making tool to identify and prioritize the risk factors according to their order from highest to lowest, but the major disadvantage of this system is the amount of subjectivity within the method.

2.4 Probabilistic Risk Assessment (PRA)

Due to the complexity in large systems, the risk management process involves uncertainty that should be addressed. Many factors increase the uncertainty in the risk management process including the changing role of engineering and business processes, rapid technology evolutions, and the global economy. The best way to address the uncertainty in the risk management process is through the study of probability concepts. This section presents strategies or formulation for risk management subject to probabilities and uncertainty. EP Curves, Monte Carlo Simulation, Bayesian approach, and specialized approaches that use the probability concepts are considered.

2.4.1 Simple Probabilistic Concept

Williams (1993) developed an approach using two important criteria to quantify the risk: (a) the probability, which is the possibility of an undesirable occurrence, and (b) the impact, which is degree of seriousness and the scale of the impact on other activities if any undesirable event occurs. Using a mathematical description, he described risk as

$R = P * I$, where

R = Degree of risk

P = Probability of risk occurring

I = Degree of impact of risk

2.4.2 Exceedance Probability (EP) Curves

Kunreuther (2002) included the approach of EP curve, Figure 2. The EP curve is the key element in evaluating a set of risk management tools. EP curves provide information on the degree of uncertainty associated with risk assessment. EP curves are graphical representations, which suggest an expert’s knowledge about a particular risk. The accuracy of the EP curve depends upon the ability of the scientific and engineering community as well as social scientists to estimate the impact of events of different probabilities and magnitudes, using different units of analysis. Estimates must consist of the frequency at which specific events occur and the extent of losses likely to be incurred. Such estimates can use historic data or scientific analyses of the future. An EP curve specifies the probabilities that a certain level of losses will be exceeded. The losses can be measured in terms of dollars of damage, fatalities, illness, or some other units of analysis.

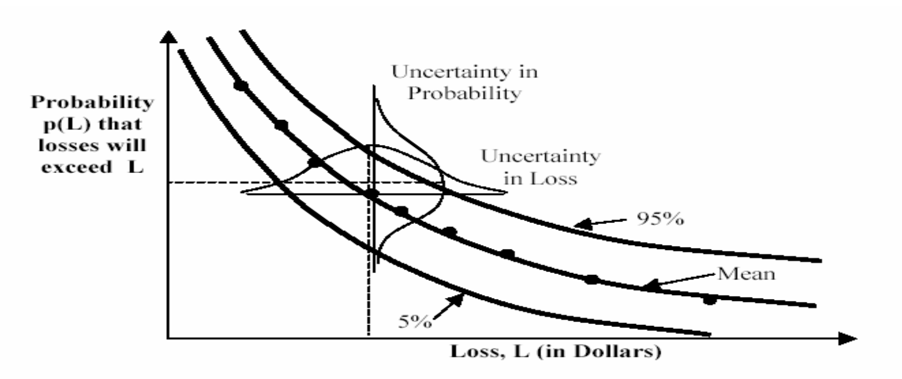


Figure 2 Exceedance Probability (EP) Curve

2.4.3 Monte Carlo Simulation

Monte Carlo simulation is a useful method for PRA. Monte Carlo simulation is designed to propagate the variability and uncertainty associated with each individual exposure input parameter in PRA. Monte Carlo simulation draws random variates from a probability distribution and includes the observed values in risk analysis. Combined with the PRA, it provides risk managers with sufficient data to choose from quantile of risk. Several authors (Eschenroeder, et al., 1988, Haas, 1997, and Binkowithz, et al., 2002) have suggested different Monte Carlo Simulation approaches within their respective fields.

2.4.4 Bayesian Model

The Bayesian model allows computation of the posterior probability of an event given its prior probability. Bayesian model use the old concept of conditional probability. The Bayesian model states that posterior probability is proportional to the prior probability and current data, which allows computation of posterior probability because it allocates values to prior probability information with new data. Pate-Cornell, et al., (1995) and Pate-Cornell (2002) have suggested Bayesian Model approaches. In addition, Greenland (2001) and Linville, et al. (2001) have combined the Bayesian model and Monte Carlo simulation in the decision analysis.

2.5 Specialized Approaches

Ben-David and Raz (2001) proposed a generic model that describes the risk abatement actions selection problem. The model opts to integrate the project work breakdown structure (WBS) with the risks generation and effects phenomena and to allocate risk abatement efforts in the planning stage of a project. Furthermore, the research advances in the development of a model that allows integrating a project's scope into the risk management process, and it emphasizes causes and effects of risks distributed among the project activities. Later, the same authors (2002) extended their work by developing a complete mathematical formulation of the model and of the actions selection problem, including extensions that allow for feasibility constraints among risk abatement actions for the design of decision-support systems for large-scale projects. In addition, they present optimal and heuristic algorithms for solving the risk abatement selection problem and report the results of an experiment that benchmark the performance of these algorithms.

In addition, there are popular specialized approaches like Boolean functions and Decision Tree Analysis, which are useful in decision making in the risk management field.

CHAPTER 3. TECHNICAL RISK ASSESSMENT METHODOLOGY (TRAM)

TRAM is a framework developed by Klein and Cork (1998) to assess the technical risks associated with a proposed system. The framework provides a systematic structure for selecting assessment methods and integrating results of the use of selected methods into a coherent overall assessment of the system.

The major principle on which TRAM relies is the principle of decomposition. Under the principle of decomposition, a system is not assessed as a whole during the entire assessment process, but for a substantial part of the process, it is decomposed into subsystems on which a detailed assessment is carried out.

3.1 TRAM Framework

TRAM can be characterized as consisting of seven phases. The seven-phase approach is a logical sequence, which is intended to be flexible and iterative, though the systematic nature of the approach should not be compromised. The seven-phase framework is shown in the Figure 3, and each phase is subsequently described.

3.1.1 Structure Phase

In the structure phase, the assessment is structured by successive decomposition of the system to be assessed into a hierarchically organized set of assessment areas. The whole system can be decomposed into areas, with as many lower levels that are required. Detailed assessment is organized by assessment area. Although structuring the assessment is logical, it can be elaborated or revised as required at any subsequent stage. The next five TRAM phases are generally organized in the bound assessment areas, and the final, seventh phase is concerned with integrating assessment results from separate areas.

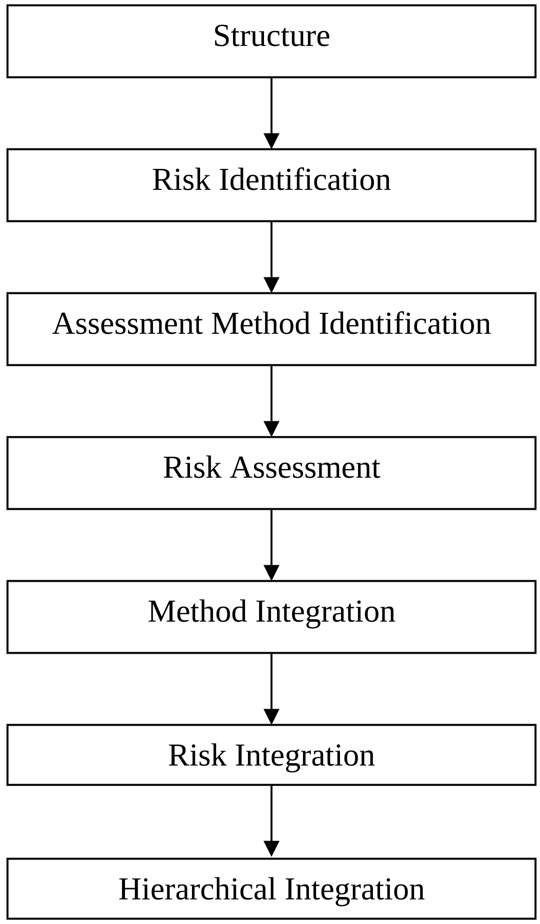


Figure 3: The logical structure of TRAM

3.1.2 Risk Identification, Assessment Method Identification, and Risk Assessment Phases

In the risk identification phase, the technical risks, which apply in the assessment area, are identified. The assessment method identification phase involves the identification, of the various assessment methods, which can be used for each of the risks. The risk assessment phase involves estimation of particular risks by using particular method.

3.1.3 Method Integration and Risk Integration Phases

The method integration phase combines the results of all one methods used, and to obtain an overall view of risk in the assessment area under consideration, assessments are combined as appropriate in the risk integration phase.

3.1.4 Hierarchical Integration Phase

The final phase identified in TRAM is the hierarchical integration phase in which assessments in all areas are systematically integrated from the bottom up into an overall assessment of the system.

CHAPTER 4. RESEARCH PROPOSAL

4.1 Proposal Introduction

The proposed research seeks to combine the qualitative and quantitative approaches to find risks associated with large complex systems. There are numerous factors that affect these systems and that increase uncertainty of the entire system.

The research combines risk management frameworks and PRA to find the risk factors of the systems. The combination of risk management frameworks and PRA reduces subjectivity associated with the system. Major research tasks associated with thesis are:

- Develop Risk Management Frameworks.
- Develop Probabilistic Risk Assessment Model.
- Validate and Verify the Proposed Method.
- Develop Cost Minimization Model

4,1.1 Develop Risk Management Frameworks

Risk management frameworks are a systematic framework for risk assessment. The frameworks will work on the principle of decomposition. Risk management frameworks will be an extension of the TRAM framework, which will combine the engineering and business application of large and complex systems.

Risk management frameworks will lead to systematic decomposition of the complex system under assessment into functionally or structurally defined assessed segments. According to the division of each segment, the major risks and risk factors affecting these segments will be recognized, and the methods of assessing those risk factors are identified. The flowchart will provide a systematic framework to identify the possible risks affecting the system and select the appropriate method to quantify those risk factors. The risk assessment frameworks will be a foundation of the mathematical model (PRA Model).

4.1.2 Develop Probabilistic Risk Assessment Model

After developing the risk management frameworks, the focus of the thesis is to develop a PRA model. The Probabilistic Risk Assessment (PRA) model is a modification of a mathematical approach developed by Sumners (2003) to quantify the risk factors. Models developed during this study will address uncertain situations to make decisions in highly large and complex systems and will reduce the subjectivity.

Probabilistic Risk Assessment (PRA) is a mathematical approach aimed to quantify risks in complex systems. After the risk management frameworks have identified risk factors, PRA model quantifies the risk factors based on past historical data in terms of probability. Prioritization will be determined based on the probability of risk factors, and according to the prioritization, resource allocation and controls will be designed by management to improve the overall performance of the entire system.

PRA serves as a decision support tool for management. PRA model helps management to design controls and allocate the resources to mitigate risks. On conclusion, PRA supports the management to improve the performance of the overall system and help to optimize the decision-making.

4.1.3 Validate and Verify Proposed Method

In this section, combination of risk management frameworks and PRA model will be applied to a large, complex system that reflects the real world situation.

4.1.4 Develop Cost Minimization Model

The cost minimization model is a mathematical approach to minimize the cost related to risks associated with the system under assessment. The costs associated with risk consist of two types: the costs incurred by resource allocation and designing of controls to mitigate the risks, and the costs of impacts caused by risks occurring with a certain probability. The objective of the model is to optimize resource allocation that minimizes the total risk related costs.

4.2 Proposed Schedule of Research Tasks

Research tasks are scheduled for timely completion of the proposed research. The major tasks associated with the thesis are development of risk management frameworks, development of the PRA model and validation and verification of proposed risk management frameworks and the PRA model approach. Risk management frameworks have already been developed. Currently, the focus is on development of the PRA model. The proposed models are applied to a complex system that is representative of actual business situations.

CHAPTER 5. RISK MANAGEMENT FRAMEWORKS

Risk is defined as probability and impact that threats can adversely affect organizations to achieve objectives. Organizations always face a challenge to manage risk in the business environment. Organizations can manage risk by properly design and implement internal controls.

Internal control weaknesses led to the downfall of once several profitable organizations and that has led to the introduction of significant new legislation, Sarbanes-Oxley act of 2002. Sarbanes-Oxley act makes upper management responsible for the transparency of the organization's internal control structure. Organizations require efficient risk management frameworks that not only address the control issues, but also perform engagement risk planning and allocate resources based on risk.

Risk management frameworks are representation of the risk identification phase. These frameworks will be used to identify the risk factors. The first risk management framework as shown in Figure 4 is a general risk management framework whereas the second framework as shown in Figure 5 is a micro level representation of risk management process.

5.1 General Risk Management Framework

The general risk management framework as shown in figure 4 is divided into four phases. The first phase starts with an objective, which is specific and measurable. The aim of the first phase is to define the organizations' goals and objectives. The second phase is a macro level assessment of departments, processes, sub-units or systems under evaluation, which provide the overview before starting the micro level assessment. The third phase is the micro level assessment that includes identification of risk threats, risk opportunities, and risk sources. The main purpose of this phase is to identify the risk factors. After the risk factors are identified the following steps are risk magnitudes calculations, risk prioritization, resource allocation and control procedures to mitigate risks. Final phase consist of residual risk which are the risks remaining in the system.

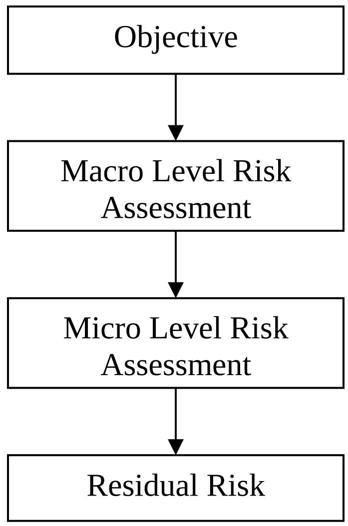


Figure 4: General Risk Management Framework

5.2 Risk Management Framework

The risk management framework mainly aims to identify the key risk factors affecting the systems, which will later be quantified through the PRA model. The framework shown in Figure 5 is a micro level representation of the general framework presented in Figure 4.

The risk management framework is a nine-phase approach beginning with the objective phase. The second phase is identification of the risk universe, which reflects macro level assessment of the identification of departments, processes, sub-units or systems, which are under risk assessment. Phase three to phase eight represent the micro level risk assessment phase of the general framework. Phase three begins with the identification of individual sources affecting the system, which can external or internal.

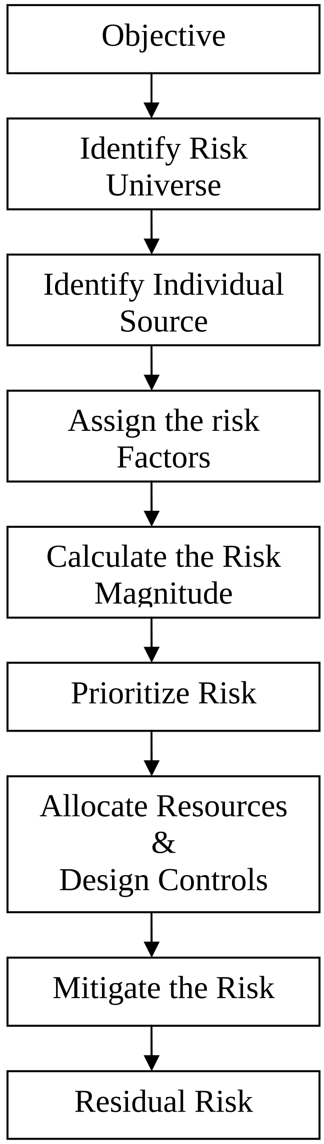


Figure 5: Risk Management Framework

After the identification of the risk sources, the next step is to decompose the system, department , department, process or sub-unit under review into risk segments, which are called risk factors. The next phase is to calculate risk magnitudes, which is mainly quantification of risk factors. Quantification of risk factors represents the probability or likelihood of risks occurring. Risk factors will be quantified using the PRA model. After risk factors are quantified in terms of probability, the next phase deals with the prioritization of risk based on higher to lower probability. Based on the prioritization of risk, resource allocation and controls will be designed by management to mitigate the risk using the cost minimization model, which represents the seventh and eighth phases of the framework. The final phase deals with the residual risks, which are the risks remaining in the system. Residual risks are accepted, transferred, or reinserted through the micro level risk assessment phase.

Organizations have to make a determination to accept, address and transfer risk and efficient risk management frameworks are effective way to identify and manage inherent risks in order to achieve their objectives.

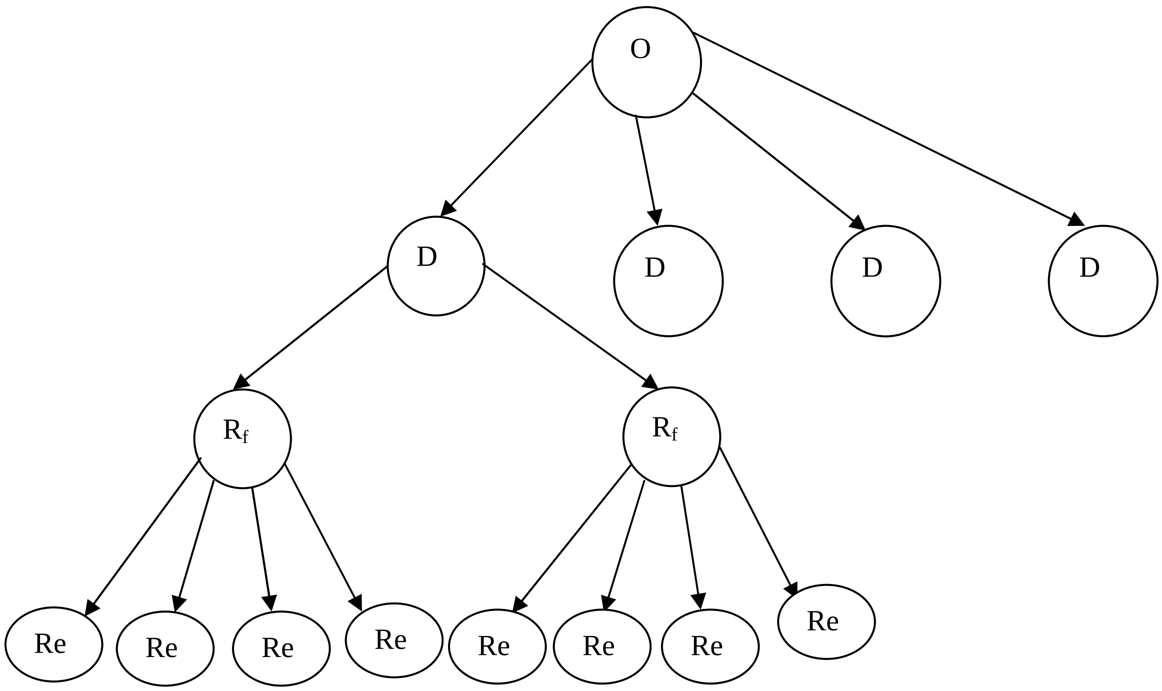
CHAPTER 6. PROBABILISTIC RISK ASSESSMENT MODEL

The Probabilistic Risk Assessment (PRA) model is a mathematical approach to quantify the risk factors. The developed model will address uncertain situations to make decisions in large and highly complex systems and will reduce the subjectivity. Probabilistic Risk Assessment (PRA) is a mathematical approach aimed to quantify risks in complex systems. The PRA model quantifies the risk factors based on past historical data in terms of probability. Prioritization will be determined based on the probability of risk factors, and according to the prioritization, resource allocation and controls will be designed using cost minimization model to improve the overall performance of the entire system.

The PRA model represents risk identification and risk assessment phase. The Risk Identification phase represents three elements of risk management framework: identify risk universe, identify individual risk source and assign risk factor.

The first step to assess the risk through the PRA model of a particular business, organization or department is to identify the risk universe. The Risk Universe will give the macro level overview about the processes, activities, departments, and functions. An in-depth knowledge about the business entity is an essential towards identifying the Risk Universe. The Risk Universe Breakdown Structure is shown in Figure 6

The second step is to decompose the risk universe into more micro level classifications, which are called as risk factors. Each risk factor can be exposed to an internal risk source, external risk source or combination of internal and external risk sources. Identification of risk source assists in defining risk factors.



O = Organization
D = Department, process or sub – unit under review
R_f = Risk Factor
Re = Risk Element

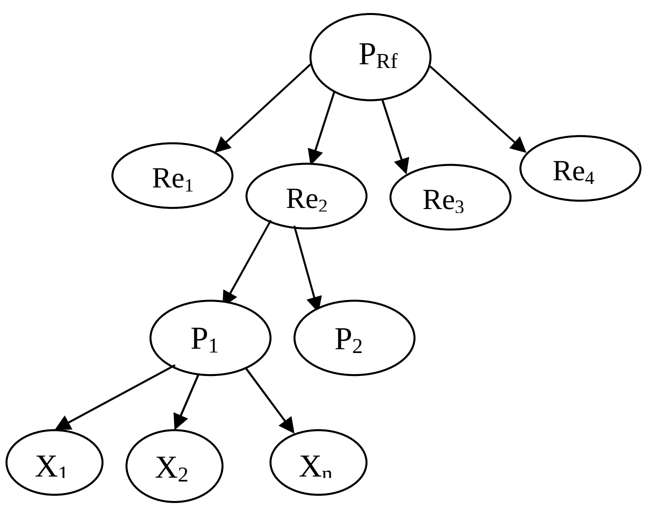
Figure 6: Risk Universe Breakdown Structure

After breaking down the risk universe into risk factors the next step is to identify the risk elements. The risk element represents risks affecting the individual risk factor. After the identification of risk factors the next step is to quantify the risk factors, which represent the risk assessment phase of risk management process. Quantification of risk will be approached using the mathematical formulation, which will be based on probability concepts and past historical data. The Risk Factor Breakdown Structure is shown in Figure 7.

6.1 Mathematical Model

The PRA model works on two basic principles: Principle of Decomposition and Baye's probabilistic principle.

- Principle of Decomposition: Under the principle of decomposition, a system is not assessed as a whole during the entire risk assessment process, but for a substantial part of the process, it is decomposed into subsystems on which a detailed risk assessment is carried out.
- Baye's probabilistic principle: Bayesian models use the old concept of conditional probability. The Bayesian model states that posterior probability is proportional to the prior probability and current data, which allows computation of posterior probability because it allocates values to prior probability information with new data.



P_{Rf} = Probabilistic Risk Factor
P = Parent Node
Re = Risk Element
X = End node

Figure 7: Risk Factor Breakdown Structure

PRA model has the following assumptions

- Each node should have at least one parent
- If a node has two parents it is consider mutually exclusive under both the parents
- Each node is mutually exclusive to each other.
- If the impact is not quantifiable in financial terms than weights will be assign subjectively according to end node.
- If there is no prior probability available in Baye's theorem than the prior distribution is uniform over the interval [0, 1] and prior probability is considered as 1.

Risk = Probability*Impact

R = P*I

The risk is calculated using multiplication of probability and impact. Probability is calculated using prior probability of the node and current probability of the node affecting to the respective node in upward direction. Impact is calculated by financial value of the node affecting to the total financial value of the respective node in upward direction.

6.1.1 Risk at End Node (X)

$$R\,(\textit{end node } X_k) = \frac{\text{Financial impact created by end node } \mathrm{X_k}}{\text{Total financial value of parent node } \mathrm{P_k}} * \mathrm{P}\,(X_k \mid P_k)$$

$$= \frac{I_{X_k}}{I_{P_k}} * \mathrm{P}\,(X_k \mid P_k) \qquad \text{Where, k = 1, 2, 3......n}$$

$$\mathrm{P}\,(X_k \mid P_k) = \frac{\mathrm{P\,(P_k \mid X_k) * P(X_k)}}{\mathrm{P\,(P}_k)}$$

$$\mathrm{P}\,(X_k \mid P_k) = \frac{\mathrm{P\,(P_k \mid X_k) * P(X_k)}}{\sum_{i=1}^{n} \mathrm{P\,(P_k \mid X_i) * P(X_i)}}$$

So,

$$R(X_k) = \frac{I_{X_k}}{I_{P_k}} * \frac{P(P_k \mid X_k) * P(X_k)}{\sum_{i=1}^{n} P(P_k \mid X_i) * P(X_i)} \qquad [6.1]$$

6.1.2 Risk at Parent Node (P)

$$R\,(\textit{parent node } P_k) = [\sum_{i=1}^{n} I_{x_i} * P(X_i \mid P_k)] * P(P_k \mid Re_k) \qquad \text{Where, } k = 1, 2, 3\ldots\ldots n$$

$$P(P_k \mid Re_k) = \frac{P(Re_k \mid P_k) * P(P_k)}{P(Re_k)}$$

$$P(P_k \mid Re_k) = \frac{P(Re_k \mid P_k) * P(P_k)}{\sum_{i=1}^{n} P(Re_k \mid P_k) * P(P_k)}$$

$$R(P_k) = [\sum_{i=1}^{n} I_{x_i} * P(X_i \mid P_k)] * \frac{P(Re_k \mid P_k) * P(P_k)}{\sum_{i=1}^{n} P(Re_k \mid P_k) * P(P_k)} \qquad [6.2]$$

The PRA model moves in the upward direction from bottom. As shown in Figure 7 after obtaining the risk for end node (X), the risk is being aggregated to parent and the end nodes are removed. Similarly, risk of parent (P) is aggregated to risk element (Re) and parents are removed. In the case of Figure 7, the process moves in the upward direction until the risk factor (R_f) is obtained. The final risk factor in the case of Figure 7 is the addition of all the risk elements.

$$R_f = Re_1 + Re_2 + Re_3 + Re_4 \qquad [6.3]$$

In general,

$$R_f = \sum_{k=1}^{n} Re_k \quad \text{where } k = 1, 2, 3\ldots\ldots n$$

The main purpose of the PRA model is to calculate a risk factor. The PRA model serves as a decision support and planning tool for management. Calculation of risk factors helps management to optimize resource allocation and minimize the total cost. The PRA model helps management to design controls and allocate the resources to mitigate risks. On conclusion, the PRA supports the management to improve the performance of the overall system and help to optimize the decision-making.

CHAPTER 7. COST MINIMIZATION MODEL

There are several constraints that increase the risk towards a single process, which ultimately increases the overall risk. If sub-component risks are minimized to an acceptable level, it will ultimately result in a reduction of overall risk. Time, technology change, complexity, size, cost, competence of staff etc. are most common constrains that increase uncertainty of overall project.

The cost minimization model represents risk control and risk mitigation phase of risk management process. Once the risk factors have been quantified and prioritized, the next step is to assign the resources or design strategies to minimize risks.

The major two costs associated in minimizing the risks are the costs incurred by resource allocation and the cost of impact. The costs incurred by resource allocation are the costs for designing controls, risk reduction techniques, and the cost for assigning the resources to minimize the risk factors. The Cost of impact is caused by risks occurring with a certain probability. Cost of impact can be affected, controlled or minimized by optimizing cost of resource allocation. The main objective of the cost minimization model is to optimize resource allocation that minimizes the total risk related cost.

TC = CR + IC

Where,

TC = Total cost

CR = Cost of resource allocation

IC = Cost of impact

Now,

$$IC = \sum_{i=1}^{n} P(R_{f\,\mathrm{i}}) * C(I) \qquad [7.1]$$

Where,

$P(R_f)$ = Probability of risk factor

C(I) = Cost Of Risk Impact respective to probabilistic risk factor

Equation [2] represents the cost of impact before any resource has been allocated, after the allocation the equation will be changed to

$$\text{Min (TC)} = CR + \sum_{i=1}^{n} P(R_{f\,\mathrm{i}}) * C(I) \qquad [7.2]$$

Constraints:

The objective function is subject to following constraints

$C(P_{rf}) \leq B$ where B = Budget constraint

$3 \leq n \leq 8$

CR and $C(I) \geq 0$

$P(Rf) \in (0, 1)$

Several variables and constraints are associated with a specific single process, when large and complex projects are decomposed into single processes. The cost minimization model focuses on problems in which a decision maker must choose among various options available. For purposes of resource allocation and many other kinds of decisions, the cost minimization model demonstrates a comprehensive approach is necessary to optimize the results while conforming to variables and constraints. The cost minimization model enables decision makers to optimize the resource allocation among the available options.

7.1 Risk Procedures

Risk Procedures are developed to obtain the solution among the available options. Risk Procedures are the combination of two procedures. First is the base procedure. The base procedure is the calculation of Total Cost from Min (TC) = CR + $\sum_{i=1}^{n} P(R_{f_i}) * C(I)$ without selecting any resource allocation. Second is the Probability-Impact Procedure. The Probability-Impact Procedure is the calculation of total cost from Min (TC) = CR + $\sum_{i=1}^{n} P(R_{f_i}) * C(I)$ with the selection of resource allocation. The Probability – Impact Procedure follows three different conditions in allocation of the resources.

- Allocation of resources according to highest impacts
- Allocation of resources according to highest probability
- Allocation of resources according to highest probability*impact value

The probabilistic risk factor and impact are calculated from PRA model developed in chapter 6.

7.1.1 Base Procedure

The Base Procedure is based on the concept of calculating Total Cost from Min (TC) = CR + $\sum_{i=1}^{n} P(R_{f_i}) * C(I)$ without allocating any resources. If any resources are not allocated in the calculation of TC than Min (TC) = CR + $\sum_{i=1}^{n} P(R_{f_i}) * C(I)$ will become

$$TC = \sum_{i=1}^{n} P(R_{f_i}) * C(I) \qquad [7.3]$$

Where,

TC = Total cost

$P(R_f)$ = Probabilistic risk factor

I = Risk Impact

Step 1

The set of resource allocation in calculating TC is zero

Step 2

Calculated the total cost from TC = $\sum_{i=1}^{n} P(R_{f\,i}) * C(I)$

7.1.2 Probability-Impact Procedure

The Probability-Impact Procedure is based on the concept of calculating TC from Min (TC) = CR + $\sum_{i=1}^{n} P(R_{f\,i}) * C(I)$ with allocating resources based on higher impacts, higher probability and higher impact*probability value conditions

Step 1

The set of resource are allocated to reduce the highest impact and probabilistic risk factor will be calculated from the PRA model developed in Chapter 6.

Step 2

Calculated the total cost from Min (TC) = CR + $\sum_{i=1}^{n} P(R_{f\,i}) * C(I)$

Step 3

The set of resource are allocated to reduce the highest probability and probabilistic risk factor will be calculated from the PRA model developed in Chapter 6.

Step 4

Calculated the total cost from Min (TC) = CR + $\sum_{i=1}^{n} P(R_{f\,i}) * C(I)$

Step 5

The set of resource are allocated to reduce the highest probability*impact and probabilistic risk factor will be calculated from the PRA model developed in section 6.

Step 6

Calculated the total cost from Min (TC) = CR + $\sum_{i=1}^{n}$ P (R $_{f\,\mathrm{i}}$) * C (I)

Step 7

Compare the results of step 2, step 4 and step 6 with total cost calculated in base procedure

CHAPTER 8. EXPERIMENTAL ANALYSIS

This section is developed for experimental analysis to evaluate mathematical model and risk procedures developed in Section 6 and Section 7. The experimentation will be performed on Online Payment System. Online Payment Service is a sub system under the Wireless Service provider organization's IT department.

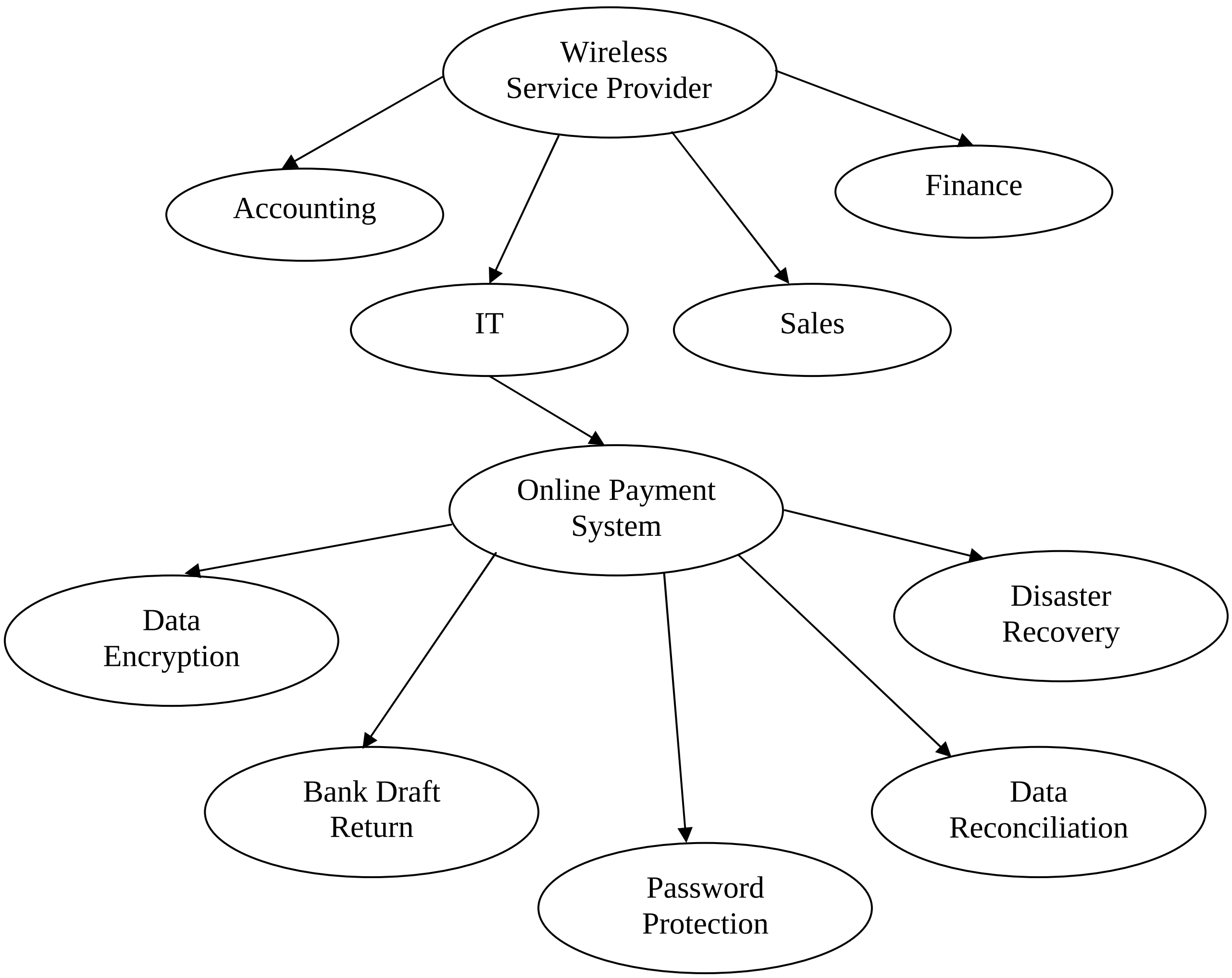


Figure 8: Online Payment System Risk Factorization

Online Payment System is a part of bill payment option provided by wireless service provider organization. It provides the facility to pay the bill from anytime and anywhere through internet, but developing secure Online Payment System is one of the biggest challenge to this organization. This section is developed to calculate the risk factor and mitigate the risks by assigning resource allocation based on highest risk factors related to Online Payment System.

The risk factors considered for the experimentation represents the characteristics of Online Payment System. Figure 8 shows the distribution of Online Payment System into five different risk factors. Furthermore, these risk factors will be decomposed until the end node.

8.1 Calculation of Risk Factors

As shown in Figure 8 Online Payment System is divided in five major risk factors as follows:

- Data Encryption
- Bank Draft Return
- Password Protection
- Data Reconciliation
- Disaster Recovery

This section is developed towards the calculation of risk factors. All the risk factors are calculated through PRA model developed in Chapter 6.

Data encryption is one of the major risk affecting Online Payment System's security. Organizations are very cautious about transferring inside or outside sensitive customer data information and to protect the customer confidentiality. To mitigate the risk of loosing data integrity organizations encrypt sensitive customer data information.

One of the major risks that affect the organization's revenue is bank draft return. There are many reasons for bank draft return for example invalid account number, Not Sufficient Funds (NSF) etc. To mitigate the risk of loosing revenue organizations are adapting the method of electronic re-presentment and design special software to overcome the bank draft return problem.

Password protection is one of the most important factors to maintain the data integrity. One of the major risks involving password loss is to loose confidential financial information. To protect password integrity organizations design the password policy, enforce the compulsory password change parameter after certain number of days.

Data reconciliation is one of the important monitoring methodologies. Organizations perform daily, weekly and monthly reconciliation to mitigate the risk of data inaccuracies.

Disaster recovery is one of the important factors in Online Payment System. Organizations cannot afford to lose of business due to system failure. It is very import to have a replica of online system installed geographically far from original system for business continuity.

Out of all the five risk factors one risk factor calculation is shown below for example. Figure 9 shows the decomposition of data encryption. The final aim is to calculate probabilistic risk factor of Data Encryption. As shown in Chapter 6 the calculation of risk factor starts from calculating risk factors at each end node using the following formula:

$$R(X_k) = \frac{I_{X_k}}{I_{P_k}} * \frac{P(P_k \mid X_k) * P(X_k)}{\sum_{i=1}^{n} P(P_k \mid X_i) * P(X_i)} \quad \text{where } k = 1, 2, 3\ldots\ldots n$$

Risk at end node not encrypted for Credit card transaction

R (X_1) = 0.36

Risk at end node partial encrypted (customer) for Credit card transaction

$R(X_2) = 0.01$

Risk at end node partial encrypted (company) for Credit card transaction

$R(X_3) = 0.03$

The calculation at the parent node is calculated using following formula:

$$R(P_k) = \left[\sum_{i=1}^{n} I_{x_i} * P(X_i \mid P_k)\right] * \frac{P(Re_k \mid P_k) * P(P_k)}{\sum_{i=1}^{n} P(Re_k \mid P_k) * P(P_k)} \text{ where } k = 1, 2, 3\ldots\ldots n$$

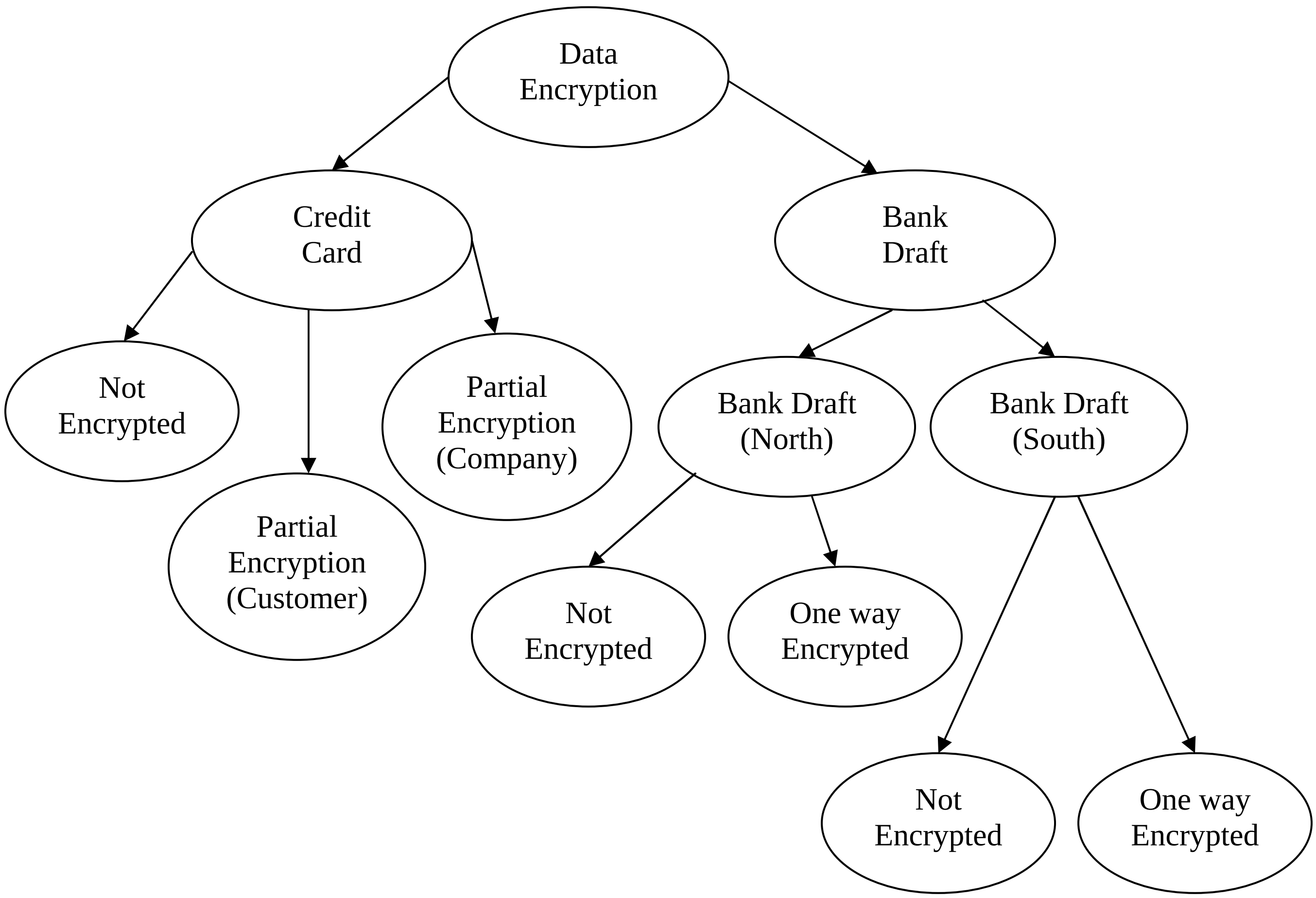


Figure 9: Data Encryption Breakdown Structure

Risk at parent node for Credit card transaction

$R(P_1) = [0.35 + 0.01 + 0.03]*0.80$

$= [0.39]*0.80$

$= 0.31$

Similarly, Risk at parent node for Bank Draft

$R(P_2) = 0.37$

Finally, the risk factor for data encryption is calculated

$R_{f1} = R(P_1) + R(P_2)$

$R_{f1} = 0.31 + 0.37$

R_{f1} (Data Encryption) = 0.68

Similar to Data Encryption the risk factors are calculated using PRA model for Bank Draft Return, Password Protection, Data Reconciliation and Disaster Recovery are as follows:

R_{f2} (Bank Draft Return) = 0.71

R_{f3} (Password Protection) = 0.42

R_{f4} (Data Reconciliation) = 0.52

R_{f5} (Disaster Recovery) = 0.27

8.2 Cost Minimization Model and Risk Procedure Calculation

The risk factors calculated using PRA model is the input of Cost Minimization model. The output will be obtained using Risk Procedures to the Cost Minimization model. The results gathered using PRA model, Cost Minimization model, Risk Procedures are going to be compared, and conclusion on the resource allocation will be made after statistical analysis of total cost.

As discussed in section 7, The Base Procedure is based on the concept of calculating TC without allocating any resources. The equation for total cost is as follows:

$$TC = \sum_{i=1}^{n} P(R_{f\,i}) * C(I)$$

The calculation of total cost based on Base Procedure is consists of major two factors, Probabilistic Risk factors and Cost of Impact.

Probabilistic Risk Factors are calculated using PRA model. The calculation of Probabilistic Risk Factors without allocating any resources is shown in section 8.1 and the values of all five Risk Factors are as follows:

R_{f1} (Data Encryption) = 0.68

R_{f2} (Bank Draft Return) = 0.71

R_{f3} (Password Protection) = 0.42

R_{f4} (Data Reconciliation) = 0.51

R_{f5} (Disaster Recovery) = 0.27

The Cost of Impact is determined in the ranges. Higher the Probabilistic Risk Factor higher the cost of impact. For this experimental analysis the cost of impact range is shown in the following table 1:

Table 1: Cost of Impact range

Probabilistic Risk Factor Range	**Cost of Impact**
0-.10	$10000
.10-.20	$20000
.20-.30	$30000
.30-.40	$45000
.40-.50	$60000
.50-.60	$75000
.60-.70	$90000
.70-.80	$110000
.80-.90	$135000
.90-1.00	$165000

From the above-mentioned values the Total Cost based on Base Procedures is

TC_1 = (0.68)*(90000) + (0.71)*(110000) + (0.42)*(60000) + (0.52)*(75000) + (0.27)*(30000)

TC_1 = $ 211914

In second portion of the Risk Procedures (Probability – Impact Procedure), the Probabilistic Risk Factors are calculated after the allocation of resources. The budget for allocation resources for this experimental analysis is fixed at $25,000. For this experimental analysis the higher resource and higher budget are assigned to higher probabilistic risk factor. The division of the budget in allocating resources is shown in Table 2

Table 2: Budget Allocation

Probabilistic Risk Factor Ranking	**% of budget ($25,000) assigned in resource allocation**
Highest Value of Risk Factor	40
2nd Highest Value of Risk Factor	30
3rd Highest Value of Risk Factor	15
4th Highest Value of Risk Factor	10
5th Highest Value of Risk Factor	5

The Probability – Impact Procedure follows three different conditions in allocation of the resources.

- Allocation of resources according to highest impacts
- Allocation of resources according to highest probability
- Allocation of resources according to highest probability*impact value

The calculation of Probabilistic Risk Factors using above-mentioned three conditions is shown in following table 3:

Table 3: Probabilistic Risk Factor Calculation according to Probability – Impact Procedure

	Allocation of resources according to highest impacts	**Allocation of resources according to highest probability**	**Allocation of resources according to highest probability*impact value**
R_{f1} (Data Encryption)	0.68	0.66	0.66
R_{f2} (Bank Draft Return)	0.70	0.67	0.65
R_{f3} (Password Protection)	0.39	0.40	0.39
R_{f4} (Data Reconciliation)	0.50	0.49	0.49
R_{f5} (Disaster Recovery)	0.27	0.26	0.25

After the calculations of Probabilistic Risk Factors using Probability-Risk Procedure's three condition in allocating resources, The equation for total cost is as follows:

$$TC = CR + \sum_{i=1}^{n} P(R_{f\,i}) * C(I)$$

Total Cost based on Allocation of resources according to highest impacts:

$TC_2 = 25000 + (0.50)*(60000)+ (0.27)*(30000) + (0.39)*(45000) + (0.70)*(90000) + (0.68)*(90000)$

$TC_2 = \$\ 204876$

Total Cost based on Allocation of resources according to highest probability:

$TC_3 = 25000 + (0.49)*(60000) + (0.26)*(30000) + (0.40)*(45000) + (0.67)*(90000) + (0.66)*(90000)$

$TC_3 = \$\ 200826$

Total Cost based on Allocation of resources according to highest probability*impact value:

$TC_4 = 25000 + (0.48)*(60000) + (0.25)*(30000) + (0.39)*(45000) + (0.65)*(90000) + (0.66)*(90000)$

TC_4 = $ 197733

Based on above calculations using Base Procedures and Probability – Impact analysis the Total Cost are summarized in following Table 4 and figure 10.

Table 4: Total Cost Comparison

Procedure Condition	**Total Cost**
Without resource allocation	$211,914
Allocation of resources according to highest impacts	$204,876
Allocation of resources according to highest probability	$200,826
Allocation of resources according to highest probability*impact value	$197,733

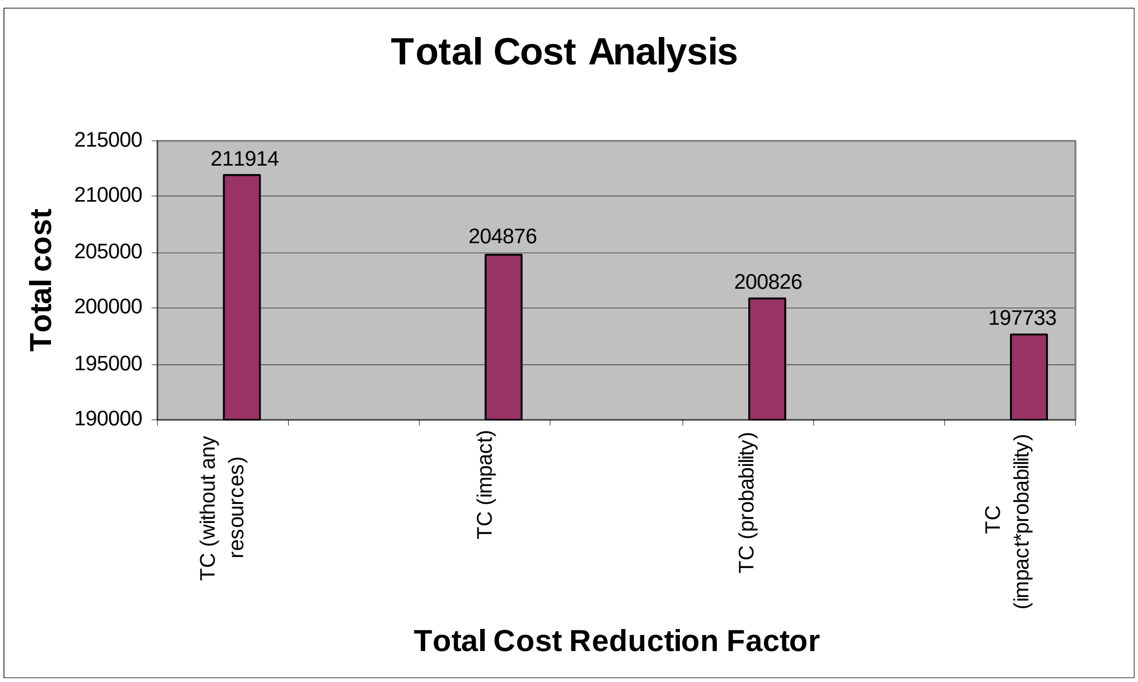


Figure 10: Total Cost Comparison

The Total Cost is minimum when the resource is allocated to reduce the Probability*Impact value in the PRA model.

CHPATER 9. SUMMARY AND CONCLUSIONS

This section highlights the summary of the present research followed by the conclusion and future research scope in the area of Probabilistic Risk Assessment for the Prioritization of Risk Factors.

9.1 Research Summary

In the past, many researchers have developed quantitative and qualitative methods in the field of risk management. This present research proposed risk management framework, Probabilistic Risk Assessment model and Cost minimization model to prioritize the risks and allocating the resources.

Risk management frameworks are generic frameworks, which help in systematic decomposition of the complex system under assessment into functionally or structurally defined segments and select the appropriate method to quantify those risk factors. The PRA model is a mathematical procedure to quantify the risk factors. Finally, the Cost Minimization model is and procedure to find the minimum total cost using the Risk Procedures and the PRA model Input. The proposed models have been applied to a complex system that is representative of actual business situations.

9.2 Conclusions

One of the key benefit of quantitative risk assessment is the improve understanding of the efficiency of the complex systems, effectiveness in the assigning resources and mitigate the risks.

This research is a combination of Risk Management Frameworks, the PRA model and the Cost minimization model to manage the risk. The research is a three-step procedure. First step is breakdown of the entire system to assess, identify and quantify risk factors. Second step is the PRA model, which is a mathematical procedure to quantify the risk factors. Third step is the Cost minimization model. The cost minimization model is an approach to minimize the cost using the Risk Procedures conditions. The Risk Procedures conditions provide the four different resource allocation criteria. Those four different criteria are resource allocation without any resources, Allocation of resources according to highest impacts, Allocation of resources according to highest probability and allocation of resources according to highest probability*impact value.

According to the experimental analysis, it is observed that the total cost is minimum if the resources are allocated according to highest probability*impact value to reduce the risk factors which ultimately suggest the overall reduction in the risk.

9.3 Future Research

The present research explains the Risk Management Frameworks, the PRA model and the Cost minimization model to manage the risk. The research can be extended as follows:

- In this research, it was assumed that each end node is mutually exclusive and should have only one parent, but the future research can be extended selecting dependency condition.
- The PRA model is developed on the simple probabilistic concept, but the concept of artificial intelligence and neural networks can be drafted in the PRA model for future research.
- Also, during this research the budget in the cost minimization model was selected fixed and the allocation of the budget is weighted according to highest risk factor, but

future work can be expanded the budget amount and the budget allocation can be solved using optimization concepts.

REFERENCES

Bedford, T., and Cooke, R., "Probabilistic Risk Analysis", *Cambridge University Press*, UK, 2001.

Ben – David, I., and Raz, T., "An integrated approach to risk response development in project planning", *Journal of the Operational Research Society,* 52(1), 14-25, 2001.

Ben – David, I., and Raz, T., "Economic Optimization of Project Risk Management Efforts", *working paper*.

Blinkowitz, B. S., and Wartenberg, D., "Disparity in Quantitative Risk Assessment: A Review of Input Distribution," *Risk Analysis*, Vol. 21, No. 1, 75-89, 2001.

Chapman, C. B., "Large Engineering project risk analysis", *IEEE Transactions on Engineering Management*, Vol. 26, No. 3, pp. 78-86, 1979.

Chapman, C. B., "A Risk Engineering Approach to Project Risk Management", *International Journal of Project Management*, Vol. 8, No. 1, pp. 5-16, 1990.

Chapman, C. B., and Ward, S.C., "Project Risk Management", John *Wiley & Sons*, 1997.

Chapman, R. J., "The Effectiveness of Working Group Risk Identification and Assessment Techniques", *International Journal of Project Management*, Vol. 16, No. 6, pp. 333-343, 1998.

Eschenreoeder, A. Q. and Faeder, E. J., "A Monte Carlo Analysis of Health Risks From PCB-Contaminated Mineral Oil Transformer Fires", *Risk Analysis*, Vol. 8, 291-297, 1988.

Florig, H. K., Morgan, M. G., Morgan, K. M., Jenni, K. E., Fischhoff, B., Fischbeck, P. S., and DeKay, M. L., "A Deliberative Method for Ranking Risks (I): Overview and Test Bed Development," *Risk Analysis*, Vol. 21, No. 5, 913-921, 2001.

Greenland, S., "Sensitivity Analysis, Monte Carlo Risk Analysis and Bayesian Uncertainty Assessment," *Risk Analysis*, Vol. 21, No. 4, 579-583, 2001.

Haimes, Y.Y., "Hierarchical Holographic Modeling", *IEEE Transaction on Systems, Man, and Cybernetics*, Vol. 11, 606-617, 1981.

Haimes, Y. Y., Kaplan, S., and Lambert, J H., "Risk Filtering, Ranking, and Management Framework Using Hierarchical Holographic Modeling (HHM)," *Risk Analysis*, Vol. 22, No. 2, 383-397, 2002.

Hass, C. N., "Importance of Distributional Form in Characterizing Inputs to Monte Carlo Risk Assessment," *Risk Analysis*, Vol. 17, 107-113, 1997.

Kaplan, S., and Garrick, B. J., "On the Quantitative Definition of Risk," *Risk Analysis*, Vol.1, 11-37, 1981.

Kaplan, S., Haimes, Y. Y., and Garrick, B. J., "Fitting Hierarchical Holographic Modeling (HHM) into the Theory of Scenario Structuring and Refinement to the Qunatititative Definition of Risk," *Risk Analysis*, Vol. 21, No. 5, 807-819, 2001.

Klein, J. H., and Cork, R. B., "An Approach to Technical Risk Assessment", *International Journal of Project Management*, Vol. 16, No. 6, pp 345-351, 1998.

Kunreuther, H., "Risk Analysis and Risk Management in Uncertain World", *Risk Analysis*, Vol. 22, No. 4, 655-664, 2002.

Largent, M. C., "A Probabilistic Risk Management Based Process for Planning and Management of Technology Development," *Ph.D. Thesis*, Georgia Institute of Technology, March 2003.

Law, A. M. and Ketlon, W. D., "Simulation Modeling and Analysis", *McGraw Hill*, 3rd Edition, New York, NY, 2000.

Linville, C. D., Hobbs, B. F., and Venkatesh, B. N., "Estimation of Error and Bias in Bayesian Monte Carlo Decision Analysis Using the Bootstrap", *Risk Analysis*, Vol. 21, No. 1, 63-74, 2001.

Michaels, J. V., "Technical Risk Management", *Upper Saddle River*, NJ, Prentice Hall, 1996.

Miller, R., and Lessard, D., "Understanding and Managing Risks in Large Engineering Projects," *International Journal of Project Management*, Vol. 19, No. 6, pp. 437-443, 2001.

Morgan, M. G., Florig, H. K., DeKay, M. L., and Fischbech, P., "Categorizing Risks for Risk Ranking", *Risk Analysis*, Vol. 20, No. 1, 49-58, 2000.

Pate-Cornell, E., "Fusion of Intelligence Information: A Bayesian Approach," *Risk Analysis*, Vol. 22, No. 3, 445-454, 2003.

Pate-Cornell, M., and Fischbeck, P. S., "Probabilistic Interpretation of Command and Control Signals: Bayesian Updating of the Probability of Nuclear Attack," *Reliability Engineering and System Safety*, Vol. 47, No. 1, 27-36, 1995.

Project Management Institute, "A Guide to Project Management Body of Knowledge (PMBOK)", *Project Management Institute*, 1996.

Sumners, G. E, Apostolou, B., and Lafleur, L. M., "How to Allocate Audit Efforts," *The Audit Report*, Vol. 12, No. 4, 11-13, 2003.

Webler, T., Rakel, H., Renn, O., and Johnson, B., “Eliciting and Classifying Concerns: A Methodology Critique,” *Risk Analysis*, Vol. 15, No. 3, 421-436, 1995.

Wharton, F., “Risk Management: Basic Concepts and General Principles in Risk Analysis, Assessment and Management”, *Eds J. Ansell and F. Wharton. Wiley*, Chichester, 1992.

Williams, T. M., “Risk Management Infrastructure”, *International Journal of Project Management*, Vol. 11, No. 1, pp 5-10, 1992.

VITA

Jay Tarakkumar Shah received his Bachelor of Engineering degree in mechanical engineering from L. D. College of Engineering, Gujarat University, India, in July 2002. He joined as a master's student in the Department of Industrial & Manufacturing Systems Engineering at Louisiana State University, Baton Rouge, Louisiana, in August 2002.