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Investment Decision-Making under Risk (Reliability) and Uncertainty for Infrastructure Asset Management

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PREFACE

A Study has been conducted to investigate current practices in decision-making under risk and uncertainty for infrastructure project investments. It was found that many European countries such as the UK, France, Germany including Australia used scenarios for the investigation of the effects of risk and uncertainty on project investments. Different alternative scenarios were mostly considered during the engineering economic benefit cost analysis stage. For instance, the World Bank required an analysis of risks in all project appraisals. Consequently, risk in economic evaluation needs to be addressed by calculating the degree of sensitivity of the rate of return for a number of events.

Risks and uncertainties of project developments arise from various sources of errors including data, model and forecasting errors. It was found that the most influential factors affecting risk and uncertainty resulted from forecasting errors. Data errors and model errors were found to have trivial effects. It was argued by many analysts that scenarios do not forecast what will happen but scenarios indicate only what can happen from given alternatives. It was suggested that the probability distributions of end products of the project appraisal such as benefit cost ratios that take forecasting errors into account are feasible decision tools for economic evaluation. Political, social, environmental as well as economic and other related risk issues have been addressed and suggestions have been made for these issues to be included in decision-making frameworks, such as in the multi-criteria decision-making framework. But no suggestion has been made on how to incorporate risk into the investment decision-making process.

Risks and the impact of consequences on social, cultural, environmental and other issues in investment decision-making need to be thoroughly assessed and taken into account. This report presents a study on decision-making under risk and uncertainty. The report begins by providing definitions of risk and uncertainty, which are explained in Sections 2 and 3, respectively. Section 4 explains current methods used in assessing risk and uncertainty. Section 5 summarises decision-making tools for risk and uncertainty assessment at national and international levels. Section 6 provides a summary of risks to which the transport infrastructure sector is exposed. Sector 7 formulates a risk assessment framework for decision-making process. Section 8 introduces risk mapping as a tool for decision-making. Section 8 summarises findings from the present study. The framework points to the importance of evaluating overall risk-related issues and their consequences *prior* to the decision-making stage.

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EXECUTIVE SUMMARY

Risks and uncertainties are inevitable in engineering projects and infrastructure investments. Decisions about investment in infrastructure such as for maintenance, rehabilitation and construction works can pose risks, and may generate significant impacts on social, cultural, environmental and other related issues.

This report presents the results of a literature review of current practice in identifying, quantifying and managing risks and predicting impacts as part of the planning and assessment process for infrastructure investment proposals.

In assessing proposals for investment in infrastructure, it is necessary to consider social, cultural and environmental risks and impacts to the overall community, as well as financial risks to the investor.

The report defines and explains the concept of risk and uncertainty, and describes the three main methodology approaches to the analysis of risk and uncertainty in investment planning for infrastructure, viz examining a range of scenarios or options, sensitivity analysis, and a statistical probability approach, listed here in order of increasing merit and complexity.

Forecasts of costs, benefits and community impacts of infrastructure are recognised as central aspects of developing and assessing investment proposals. Increasingly complex modelling techniques are being used for investment evaluation. The literature review identified forecasting errors as the major cause of risk.

The report contains a summary of the broad nature of decision-making tools used by governments and other organisations in Australia, New Zealand, Europe and North America, and shows their overall approach to risk assessment in assessing public infrastructure proposals.

While there are established techniques to quantify financial and economic risks, quantification is far less developed for political, social and environmental risks and impacts.

For risks that cannot be readily quantified, assessment techniques commonly include classification or rating systems for likelihood and consequence. The report outlines the system used by the Australian Defence Organisation and in the Australian Standard on risk management.

After each risk is identified and quantified or rated, consideration can be given to reducing the risk, and managing any remaining risk as part of the scope of the project. The literature review identified use of risk mapping techniques by a North American chemical company and by the Australian Defence Organisation.

This literature review has enabled a risk assessment strategy to be developed, and will underpin an examination of the feasibility of developing a risk assessment capability using a probability approach.

1. Introduction

A review of the literature revealed that there is a gap of empirical studies on decision-making procedures for infrastructure asset management. Very few studies offered solutions that can assist transport infrastructure planners in making decisions on maintenance, rehabilitation and capital works. The available technical reports and manuals on asset management stressed the inclusion of risk assessment in the investment decision-making framework (Government of South Australia 1999, Asset Strategy-NSW 2001, Queensland Government Public Works 2002, Byrne 2001). However, only an overview of the importance of risk assessment has been given, but no suggestion has been made on how to incorporate risk into the investment decision-making process. Economic, political, social and other related risk issues have been recognized as crucial criteria for investment decision-making. Many countries have preliminarily developed frameworks that can incorporate these risk factors in the investment decision consideration (Goodwin 1999, Mihai, et. al. 2000, Duchene 2000). The aim of this paper is to explore the application of risk assessment so that it would be a tool for decision-makers to confront risk and uncertainty with greater confidence. It can be systematically incorporated in an integrated decision-making framework such as multi-criteria decision-making framework.

This paper begins with the presentation of terminology of risk and uncertainty and how current practices incorporate risk and uncertainty in decision-making processes. The identification of economic, social, environmental and other related risk issues for transport infrastructure is presented. A formulation of risk assessment is also described.

2. What is Risk?

Risks have always been a part of life. The recent power failure in Auckland New Zealand, gas failure in Victoria and water shortage in New South Wales Australia were good examples of risk related malfunction of infrastructure facilities. *The objective of risk assessment is to conduct an assessment to foresee negative effects or risks so that adverse consequences can be minimized.* Most literature on this subject defines the word “risk” as comprising of two elements: First is the probability (or likelihood) of occurrence of a negative event during the lifetime of operation of a facility: Second is the resultant consequence when a negative event has taken place (Rackwitz 2001, Bedica 2000, Recchia 2002). The first term involves risk assessment, whilst the second term is risk management. Risk assessment is mainly a scientific task, while risk management is the subject of devising regulatory measures based on risk assessment and considerations of a legal, political, social, economic, environmental and engineering natures.

3. What is Uncertainty?

Uncertainty is closely related with risk. The word “uncertainty” emphasizes that the choice of decision-making must be made on the basis of incomplete knowledge about projects that do not yet physically exist (Walker 2000). Uncertainties arise from three sources of errors, namely (The World Road Congress Committee on Economic and Finance 1983):

- Data errors (uncertainties about past events)
- Forecasting errors (uncertainties about future events)
- Model errors (residual errors, i.e. the different between observed and model values)

3.1 Data Errors

Data errors are technical problems. Data errors stem from measurement errors, sampling errors and simple human errors. Their uncertainties can be measured using statistical techniques. We can reduce data errors by collecting more past data.

3.2 Forecasting Errors

The nature of forecasting errors is the uncertainty about "future events". An economic evaluation of the future is questionable or unquantifiable. An economic analysis in a conventional form (e.g. net present value or internal rate or return) is subjected to forecast errors. There is a limit to our ability to reduce forecasting errors. *No matter how hard we try and how advanced our techniques are, the reason is the future is unknowable*.

3.3 Model Errors

Model errors contain residual errors, i.e. the difference between observed and model values. Model errors arise due to the impossibility of perfectly representing the real world in a mathematical model. Quantifications of economic benefits involves the use of forecast traffic speeds and delays, fuel prices, national income and time valuation, and etc. contain model errors.

4. Assessment Of Uncertainty And Risk

The analyses of risk and uncertainty include scenario investigation, sensitivity assessment and probability-based assessment. Current practices for the assessment of risk and uncertainty emphasize on scenario analyses (Walker 2000, Austroads 1996, Gwillian 2000). The World Road Congress Committee on Economic and Finance (1983) explored the application of the other two methods. The methodologies and findings are briefly discussed below.

4.1 Scenario Analyses

Currently, scenario assessment is a basic tool used to assess risk and uncertainty about future forecasts (Walker 2000). Since the future is uncertain and has risk involved, one way to deal with this uncertainty and assess risks is to construct possible scenarios and look for options that perform reasonably well with minimum risk. Scenarios can begin with defining alternative scenarios, criteria, impacts and risks. Assessment impacts and risks may involve creating scorecard for each scenario. Decision-making may be done based on the scenario that possess the most benefit cost effective, minimum risks and impacts. Basically, scenarios assess the influence of different alternatives on a project development. Scenario assessments do not forecast what will happen or probability of occurrence they indicate what can happen from different given alternatives.

4.2 Sensitivity Analyses

The objective of sensitivity analysis focuses on identifying the main source of uncertainty. The sensitivity analyses are conducted to identify whether some variables contribute greater uncertainty to the forecasts than other. Input variables with high susceptibility for future forecasts may need to be measured with more survey works or more analyses and only uncertainties of highly susceptible factors may be considered in decision-making.

The World Road Congress Committee on Economic and Finance (1983) explored the sensitivity analysis methodology. The main objective of the analysis was to identify fully the main effects and interaction effects of input variables. The uncertainties of data errors and forecasting errors were considered in the sensitivity analysis. Seventeen input variables were identified as potential sources of error in the traffic model and these were classified as susceptible to random testing. The range of possible values was established by variety of means: research observations, calibration data from traffic models and Delphi.

The committee found that uncertainty is dominated by forecasting errors rather than data errors or model errors. Among forecasting errors, the most influential factors are the economic forecast of GDP growth and fuel price movements. These have multiplicative effects, firstly through the traffic model and secondly through the economic evaluation.

4.3 Probability-based Assessment

This is the method for the assessment of risks by taking overall uncertainties into account. This is a pure statistical method. In this method, firstly we need to establish mathematical functions of related decision-making factors. Secondly, the uncertainties of input variables of the function are quantified and modelled by probability distribution and its statistical parameters (i.e. mean and coefficient of variation). The probability distributions of output parameters will be the outcome from the analysis. Figure 1 shows schematic chart of probability-based assessment. The probability-based assessment can also apply to different scenarios.

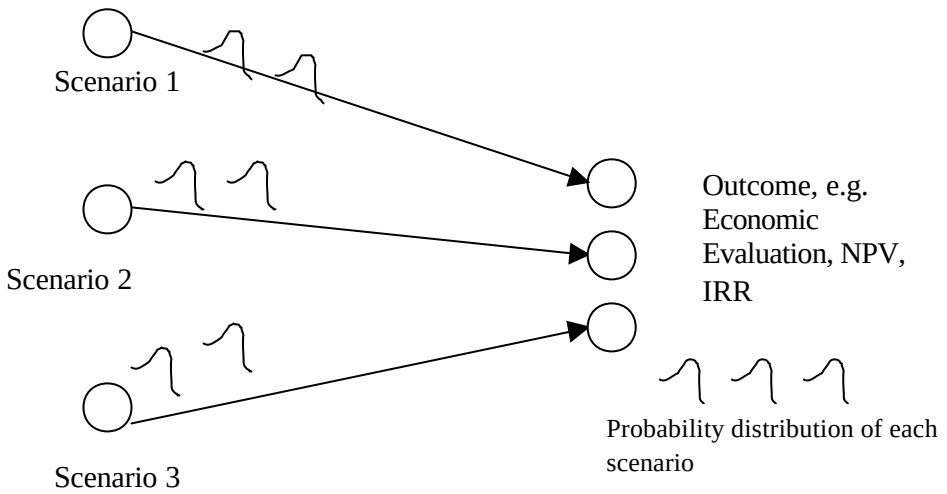

Figure 1 Schematic chart of probability-based uncertainty assessment

The World Road Congress Committee on Economic and Finance (1983) explored a full assessment of this method. The research programme was based on a real investment proposal, and the first stage sought to estimate the accuracy of traffic forecasting at the level of the individual highway investment and to explore the uses of these forecasts. The outputs were expected to be the probability distribution of traffic flows and the probability distribution of economic benefits.

The process began with the identification of probability distribution of each input variable, including data errors, forecasting errors and model errors. The probability distributions were developed based on assumption and derived from samplings. Input data include:

1. Probability distribution of sample from National Income Growth
2. Expected growth in the economic parameters
3. Forecast planning data

4. Base year trip matrix
5. Do something and do nothing
6. Probability distribution of sample from Study Area Employment
7. Probability distribution of sample from Fuel Cost Growth
8. Probability distribution of sample from Local Income Variation
9. Probability distribution of sample from Zonal Planning Data
10. Probability distribution of sample from Income and Fuel Cost Elasticity
11. Probability distribution of sample from Base Year Matrix
12. Probability distribution of sample for Route Parameter Elasticity
13. Probability distribution of sample from Base Year Route Parameter
14. Probability distribution of sample from Road Link Speed

A series of simulation were undertaken using Monte Carlo simulation technique. This series of simulation was designed to cover the complete range of errors for each variable, and it generated a range of error for each of the model outputs (i.e. the probability distributions of traffic flow and economic benefits).

From the analysis, it was concluded that it was not practicable to pursue the objective of full probability-based decision-making. This was due to the computational burden of the Monte Carlo simulation, even though the probability distributions of the outcomes were useful for decision-making. For the decision-making purposes, the probability distributions of end products of the project appraisal, such as NPVs, that take into account only forecasting errors are a feasible decision tool for economic evaluation.

5. Risk (Reliability) And Uncertainty Assessment At National And International Level

Table 1 provides a summary of current decision-making tools at national and international levels. All countries adopted benefit cost analysis as a basic tool for decision-making. Risk and uncertainty assessments are considered using alternative scenarios.

In France, Germany, the Netherlands and the UK different scenarios are studied based on appropriate combinations of national income growth, fuel prices, vehicle fuel efficiency, etc. Economic evaluations are carried out for both scenarios using economic parameters appropriate to each value such as values of time, vehicle operating costs and accident rates (Directorate General-Germany 2000, Duchene 2000, Gwillian 2000, Kauf 2000).

The U.S. Federal Highway Administration (FHWA) has incorporated risk assessment into some of its economic analysis tools. The FHWA's Surface Transportation Efficiency Analysis Module (STEAM 2.0) was developed to provide an analytical tool for estimating impacts of multi-modal transportation alternatives in a system planning context. The model incorporates risk analysis.

World Bank requires an analysis of risk in all project appraisals. Risk in economic evaluation needs to be addressed by calculating sensitivity of the rate of return for a number of events. These may include among others, changes in assumptions about costs, construction period, traffic growth rate and so forth. The World Bank's main focus is on economic evaluation. The full economic justification, including that of the selection between alternatives, has to be fully worked out. A positive net present value would normally be required on the basis of a nationally accepted discount rate (usually 12% is adopted), and an internal rate of return of 12% or more would normally be required. Economic benefits usually follows generally accepted procedures of estimation of flows and link performances, vehicle operating cost savings, critical level of traffic, time, pain and grief costs of accidents or loss of life, time saving, labour costs, road maintenance and rehabilitation (Gwillian 2000).

In the ACT Government, risks are normally assessed during procurement planning stages. If a project is considered to be of high risk to the Government, it is necessary to get Government Procurement Board's approval. Hence, the investment decision in terms of risk would be based on the overall benefits to, and commitments from, the Government. Projects of high risk would have the risks transferred to a higher level of the organisation. Irrespective of these, investment decision would have to go through all the basic project management stages, including project initiation, implementation, commissioning and closing. Project Initiation includes benefit cost analysis, whole of life costing of infrastructures and road user cost. In the project initiation stage, it is also necessary to carry out initial and detail planning on the asset creation and its acquisition. This involves financial management, operation cost and maintenance cost, together with rehabilitation/renewal, and replacement and disposal. Salvage cost is also included and it sometimes gives a negative value. At any one of these stages, risks can be identified and investment decision relies on management decision. It is often difficult to quantify risks in realistic monetary terms without the influence of subjective personal judgment.

6. Identification Of Social, Environmental, Political And Other Related Risks For The Decision-Making

For an investment for infrastructure asset investment, political, social and environmental and other related risk issues may not be avoided in decision-making. Australian Defense Organization (2002) in a study on the Transport Infrastructure Industry has carried out an assessment to classify and prioritise the risks to which the transport infrastructure sector is exposed. Risk levels were based on five different risk scales namely; rare, unlikely, moderate, likely and almost certain. Consequences are classified into five categories namely; insignificant, minor, moderate, major and catastrophic. The Australian Defense Organization (2002) has identified and classified the following risk related issues. Details of these risks are given in Table 2.

- Political Risk
- Economic Risk
- Social Risk
- Cultural Risk
- Environmental Risk
- Technology Risk
- Supplier Risk
- Customer Risk
- Risk of Substitutes
- Competitor Risk
- Barriers to Entry Risk
- Operational Risk (HR)
- Operational Risk (Training)
- Flexibility and Adaptability Risk

Table 1: Investment Decision-Making Procedure for Transport Infrastructure.

Countries/ Organisation	Engineering Economic Benefit Cost Analysis	Scenario Assessment	Sensitivity Assessment	Multi-Criteria on cost-benefit/economic/env./social/health Other non costs factors for final decision-making	Probability-based uncertainty assessment	Risk and Reliability	Risk Identification and Risk Management Strategy
France (2000)	✓	✓					
UK (1999)	✓	✓		Proposed for the consideration of social, political and environmental issues			
Netherlands (2001)	✓	✓		Preliminary stage	Collecting data		
Germany (2000)	✓	✓		Preliminary stage			
World Bank (2000)	✓	✓					
The World Road Congress Finance/Economic Committee, (1983)	✓	✓	Conducted a study to explore the concept		Conducted a study to explore the concept		
European Investment Bank (2001)	✓			Proposed to consider			
International Road federation (2000)	✓			Proposed to consider			
Organisation of Economic Cooperation and Development (2000)	✓			Preliminary stage			

Table 1 / Continued

Countries/ Organization	Benefit Cost Analysis	Scenario Assessment	Sensitivity Assessment	Multi-Criteria on cost-benefit/economic/env./social/health Other non costs factors for final decision-making	Probability-based uncertainty assessment	Risk and Reliability	Risk Identification and Risk Management Strategy
US Federal Highway Administration (2002)	✓						
New Zealand (2000)	✓			Preliminary stage			
Twenty-two states in the US (2000)	✓						
Australian Defense Organization (2002)							Conducted a study on risks
Western Australia (2000)	✓			Adopt multi-criteria framework			Stated in AM-Framework
DMR Queensland (2002) ❑ Department Level	✓		(GAM)	Goal Achievement Metric (GAM)			
Victoria (1995)	✓			Stated in AM-Framework			Stated in AM-Framework
South Australia (1999)	✓			Stated in AM-Framework			Stated in AM-Framework
New South Wales (2001)	✓			Stated in AM-Framework			Stated in AM-framework
Business/Finance Sectors (2002)	✓	✓	✓		✓	✓	✓

Note: AM-Framework is Asset Management Framework.

Table 2: Classifications of risks and consequences ratings (Australian Defense Organization 2002)

Risk Category	Causes	Consequences	Consequence Rating	Likelihood Rating	Risk Rating
Political Risk	Government policy changes, i.e. Taxation, privatisation and competition	Reduced spending on maintenance and trend toward development of only commercially viable infrastructure projects	Major	Unlikely	Significant
Economic Risk	Reduced access to government funds, providing transport infrastructure in key locations, rationalization of industry players as escalating fixed costs lead to smaller margins and intense competition	Reduction in maintenance / development of infrastructure, increased usage charges, reduced efficiency of infrastructure and greater of total funds invested on maintenance rather than new development	Major	Unlikely	Significant
Social/Environmental / Cultural Risk	Increased demands by society to reduce environmental damage, increase public awareness of life, civil rights issues, expectation of fast service	Greater costs for infrastructure projects may be incurred in order to satisfy environmental, social criteria and constraints	Minor	Almost Certain	Significant
Technology Risk	Increasing reliance on the use to IT and communications to design, operate and manage transport infrastructure and collect revenue	Interdependency results in greater vulnerability to any IT interruption of services	Major	Almost Certain	High

Table 2 / Continued

Customer Risk	Increased levels of customer sophistication demands, e.g. faster service, efficient transfer between transport modes.	Pressures for transport modes to be concurrently planned to enable greatest efficiency.	Moderate	Likely	Significant
Risk of Substitutes	Perception of unreliability in comparison with other transport mode, e.g. rail versus road	Loss of business due to restriction in product handling methods	Moderate	Moderate	Significant
Flexibility and adaptability	Road infrastructure is a large, long-term capital investment	Infrastructures are fixed in the medium term, limited options to adapt to new technologies in the short run	Major	Likely	High

7. Risk Assessment Framework For Decision-Making Process

In section 4, the methodologies for the quantitative assessment of uncertainty and risk were described. In section 6.6, political, economic, social and other related risks are studied and quantified qualitatively. Quantitative as well as qualitative risks are important in decision-making. Recchia (2002) and AS4360 suggest a framework for a complete risk assessment and risk management. This framework incorporates both quantitative and qualitative risks in the assessment and is shown in Figure 2.

Risk analysis is the quantitative technical assessment and can be estimated by the probability (P) of an event of occurrence over a specified period of time and its related consequences. Risk is a function of the probability of occurrence and the magnitude of consequences (M), R=f(P,M).

Public Risk Perception is the measure of public reactions to risk and. Public risk perception can be quantified qualitatively and quantitatively. A perception may be defined as a judgement of the degree to which one likes or dislikes some objects, concepts, projects or persons. The term risk perception describes people's feelings about risk.

Objective and Subjective Data is the behaviour data that reflect agreement or opposition to a project introduced.

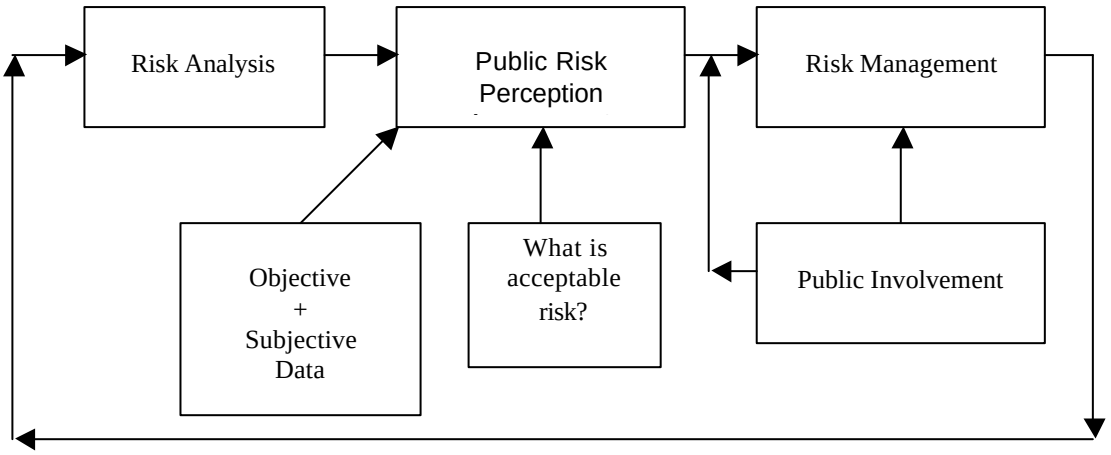

Figure 2 Framework for risk assessment

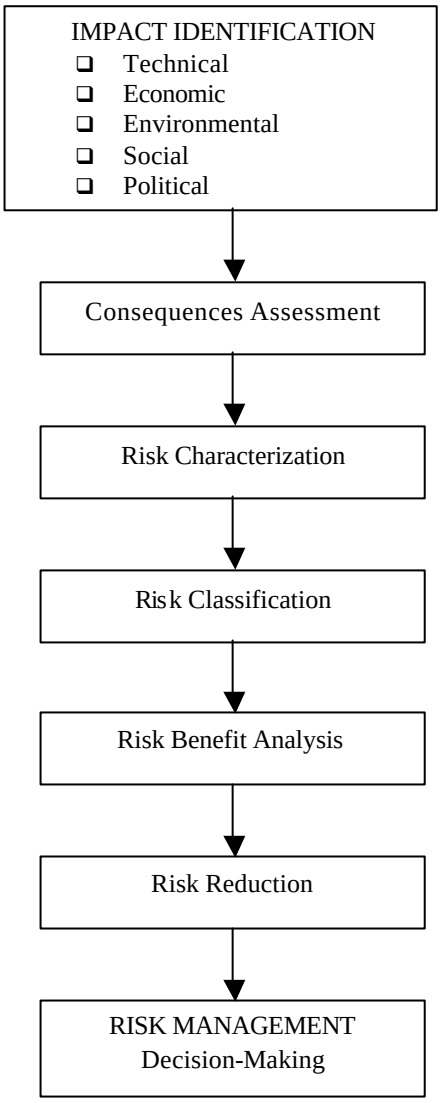

Figure 3 Step by step risk assessment

Acceptable risk is the degree of risk to be accepted. In many instances, the public determines which levels of potential risks are acceptable.

Risk Management is the final process to be implemented to ensure that risks are kept at minimum and do not have adverse effects to the public. It is a part of a decision-making process that entails consideration of political, social, economic, engineering information and cost-benefit with risk related information to develop, analyse and compare and make a decision on appropriate solutions.

Figure 3 describes step-by-step implementation of risk assessment. Details of each step are given below:

Impact Identification is the identification of adverse effects on economic, environment, social, political and technology resulting from a project development.

Consequences Assessment is the assessment of impacts and exposure chance of the incidence, severity and adverse effects resulting from a decision-making on the public.

Risk Characterization is the estimation of the incidence and severity likely to occur in a human population or environmental components due to actual or predicted exposure to the adverse effects resulting from a decision-making.

Risk Classification is the evaluation of risks in order to decide if risk reduction is required.

Risk Benefit Analysis is the assessment whether taking into account certain risks gains benefits. It is a task that decision-makers have to consider not only the risk assessment but also other aspects such as technical feasibility, costs-benefits, social and cultural, political factors as well as uncertainties.

Risk Reduction is the process to protect man and/or environment from the risks identified.

8. Risk Mapping For Decision-Making

Once the risks have been assessed a major difficulty still remains: synthesizing the diverse impacts of risks. Risk mapping can be incorporated in the multi-criteria decision-making framework to present the results in a way that facilitate the comparison and accounting for risks in the final decision-making process. Risk mapping technique has been used by a major US Chemical engineering company to identify key strategic environmental, health and safety issues (Harrington, 1999). Risk mapping is a tool to manage risk and adjust project allocations based on cost-benefit and risk. In the risk mapping, the levels of risk can be quantified qualitatively or quantitatively. Figure 4 shows a risk map.

The X-axis is the magnitude of the resultant consequences, which may range from being insignificant to highly significant.

Intolerable region is the region where risks are high and the impact of the consequences is significant. Risks and the resultant consequences that fall within this region need to be immediately addressed and resolved.

Tolerable region is the region where risks are low and the impact of the resultant consequences is low. An event that falls within this region may be considered to be trivial and may be ignored at the stage of decision-making.

Moderate region is the region where risks and the impact of the consequences are at moderate levels. Events falling within this region need to be taken into account before a final decision can be made.

Figure 5 shows the mapping of risks from risk assessment studied by Australian Defense Organization (2002) as described above. For illustration, it can be seen from the figure that political and economic risks are unlikely to occur but the consequences are significant. On

the contrary social, environment, cultural risks are almost certain however the consequences are minor. These risks need to be addressed and their consequences should be resolved immediately. Technological and barriers risks are almost certain and their consequences are major and moderate respectively. Flexibility/adaptability and customer risks are likely, their consequence ratings are major and moderate respectively. Risks of competitor, operational-training and substitutes are moderate and their consequences are also moderate. These risks fall into intolerable region, their consequences need to be established and resolved.

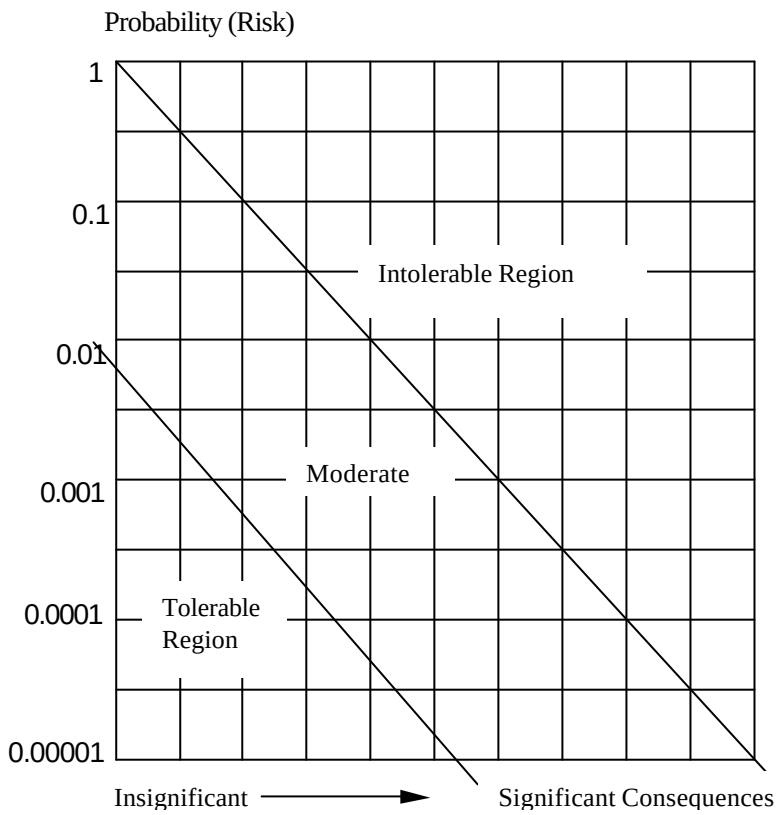

Figure 4 Risk Map (Modified after Harrington and Rose 1999)

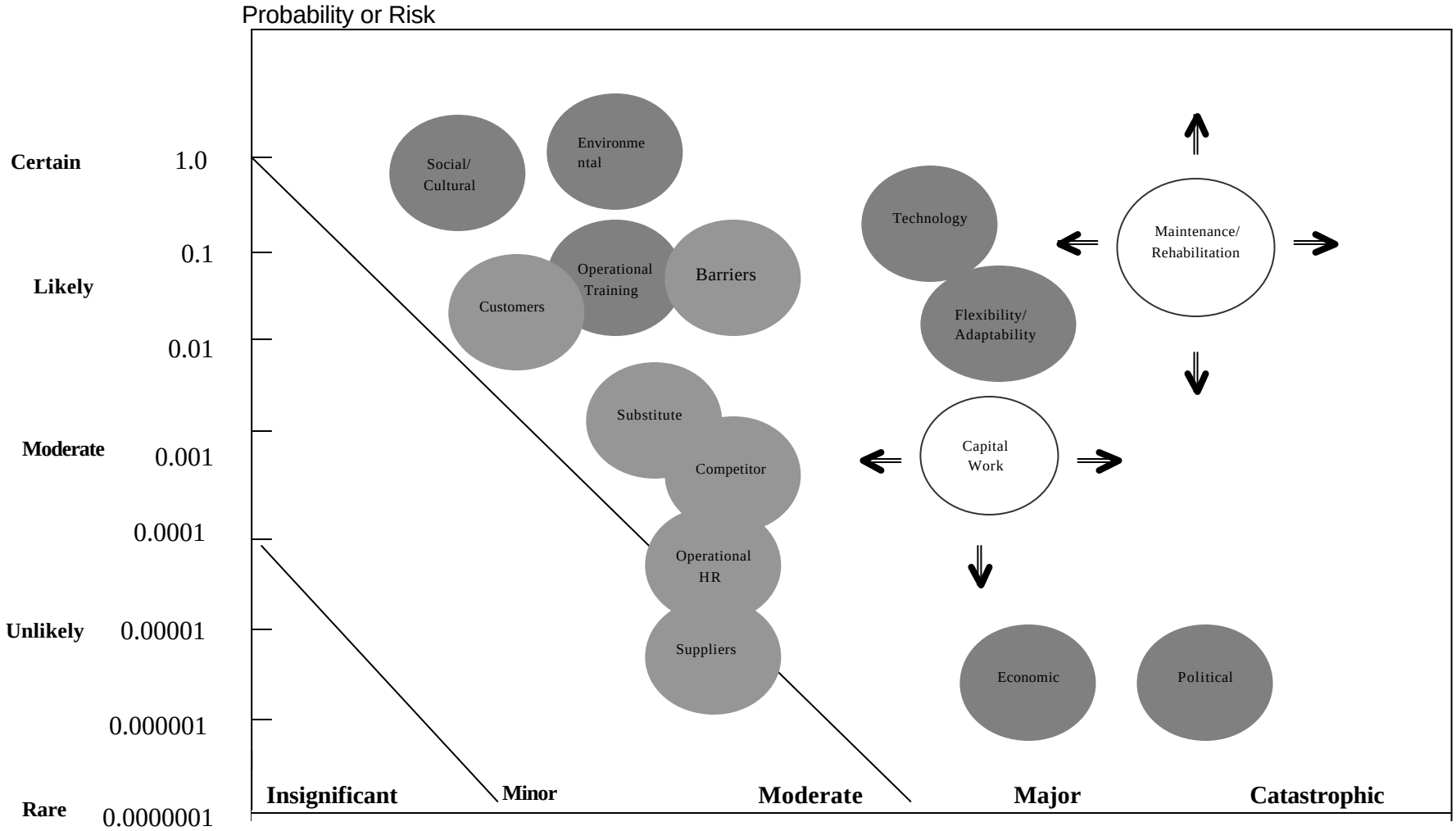

Figure 5 Plots of risks related issues in the Risk Map (Modified after Harrington and Rose 1999 and Australian Defense Organization 2002)

9. Findings

The words “risk” and “uncertainty” emphasize that the decision-making must be made on the basis of incomplete information such as political changes, uncertainty in budget allocation, economic performance, and etc. The key findings are summarized below;

- Most countries including Australia adopt scenarios for the assessment of risk and uncertainty for a project development.
- Uncertainties arise from data, model and forecasting errors.
- Among the overall uncertainties, the World Road Congress Committee on Economic and Finance 1983, found that dominant factors in output uncertainty fell into the forecasting category. The effects of uncertainty of data errors and model errors were trivial for the decision-making process.
- For decision-making process, the probability distributions of end-products of the project appraisal process, such as NPVs, that take into account only forecasting errors are a feasible decision tool for economic evaluation.
- The risks to which the transport infrastructure is exposed include political, social, environmental and other related risk issues that need to be addressed and assessed.
- A risk management framework needs to be formulated to minimize or eliminate adverse consequences that may arise.

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