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Framework for Investment Decision-Making under Risk and Uncertainty for Infrastructure Asset Management

N. Piyatrapoomi
(Research Fellow, RMIT University, Melbourne, Australia)
A. Kumar
(Professor of Civil Engineering, RMIT University, Melbourne, Australia)
S. Setunge
(Senior Lecturer, RMIT University, Melbourne, Australia)

Summary

A study has been conducted to investigate current practices on 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 use scenarios for the investigation of the effects of risk and uncertainty of project investments. Different alternative scenarios are mostly considered during the engineering economic cost-benefit analysis stage. For instance, the World Bank requires an analysis of risks 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.

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 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 cost-benefit 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 included in decision-making frameworks, such as in a multi-criteria decision-making framework. But no suggestion has been made on how to incorporate risk into the investment decision-making process.

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 advanced technology deployment along with needed physical and communications infrastructure, 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, New South Wales: Total Asset Management 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, and 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, water shortage in New South Wales**,** Australia and the Northridge, California earthquake are good examples of risk related malfunction of infrastructure facilities. Also, the growing threat of terrorist activity in urban areas poses risks to physical, technological, and communications infrastructures of transportation systems. Under normal conditions, ITS may be quite effective in managing traffic and traffic-related incidents. However, if, for instance, communications are cut off due to an unforeseen event, then the capability of ITS technologies to function could be compromised. A traffic management center that relies on data from vehicle sensors may suddenly lose critical information needed to manage traffic and incidents (ironically, during major incidents and emergencies, the center's function is especially vital.)

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 term "risk" as comprising 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 involves devising regulatory measures based on risk assessment and on legal, political, social, economic, environmental and engineering considerations.

3. What is uncertainty?

Uncertainty is closely related to risk. The term "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 the randomness of events, along with 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 difference between observed and model values)

i) 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 complete historical data.

ii) 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 forecasting errors. There is a limit to our ability to reduce forecasting errors. *No matter how hard we try and how advanced our techniques, the future is unknowable*.

iii) 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 that involve the use of forecast traffic speeds and delays, fuel prices, national income and time valuation, and others**,** 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 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 (i.e., sensitivity assessment, probability-based assessment). The methodologies and findings are briefly discussed below.

i) 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 a scorecard for each scenario. Decision-making may be done based on the scenario that possesses the most benefit**,** is the most cost effective, with 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 calculate the probability of occurrence. Scenario analyses indicate what can happen from different given alternatives.

ii) Sensitivity Analyses

The objective of sensitivity analysis focuses on identifying the main source of uncertainty. Sensitivity analyses are conducted to identify whether some variables contribute greater uncertainty to the forecasts than others. Input variables with high susceptibility for future forecasts may need to be measured with more survey work 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 a 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 economic evaluation.

iii) Probability-based Assessment

This is a method for the assessment of risks by taking overall uncertainties into account. This is a pure statistical method. In this method, we first need to establish mathematical functions of related decision-making factors. Second, the uncertainties of input variables of the function are quantified and modeled by probability distribution and 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 a schematic chart of probability-based assessment. The probability-based assessment can also apply to different scenarios.

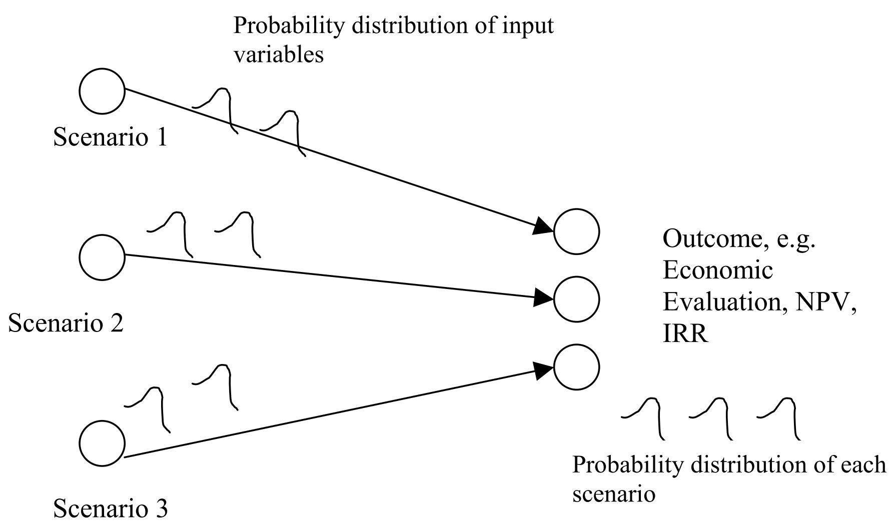

Figure 1 Schematic chart of probability-based uncertainty assessment

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 distributions of each input variable, including data errors, forecasting errors and model errors. The probability distributions were developed based on assumptions and derived from samplings.

A series of simulations were undertaken using the Monte Carlo simulation technique. These series of simulations were designed to cover the complete range of errors for each variable, and they generated a range of errors 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. However, for 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. Identification of social, environmental, political and other related risks for the decision-making

For infrastructure asset investment, political, social and environmental and other related risk issues may not be avoided in decision-making. The Australian Defense Organization (2002): Transport Infrastructure Industry Division has carried out an assessment to classify and prioritize 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 risk related issues. These include:

- 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 (Human Resources)
- Operational Risk (Training)
- Flexibility and Adaptability Risk

6. Risk Assessment Framework for Decision-Making Process

Quantitative as well as qualitative risks are important in decision-making. Recchia (2002) suggests 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. Figure 3 describes a step-by-step implementation of risk assessment.

Risk Analysis is a 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 a measure of public reactions to risk***.** 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 behavior data that reflect agreement or opposition to a project introduced.

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

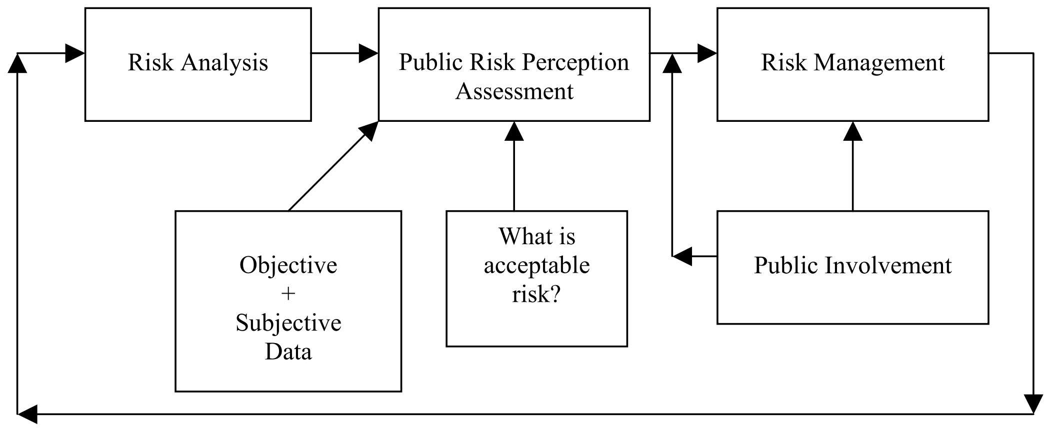

Figure 2 Framework for risk assessment

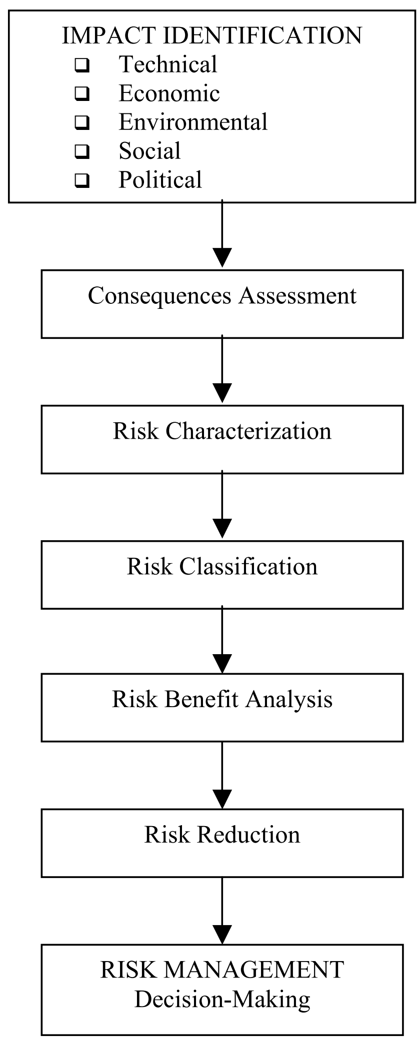

Figure 3 Step by step risk assessment

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

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

Consequences Assessment is the assessment of impacts and chance of exposure to the incident, severity and adverse effects to the public based on a particular decision.

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, cultural, and political factors as well as other uncertainties.

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

7. 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 and Rose 1999). Risk mapping is a tool to manage risk and adjust project allocations based on cost-benefit and risk. In 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 the Australian Defense Organization (2002) as discussed earlier. As an illustration, it can be seen from the figure that political and economic risks are unlikely to occur but the magnitude of 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 the magnitudes of consequences are major and moderate**,** respectively. Flexibility/adaptability and customer risks are likely, their consequence ratings are major and moderate**,** respectively. Risks of competitors, operational-training and substitutes are moderate and their consequences are also moderate. These risks fall into the intolerable region, and, therefore, their consequences need to be established and resolved.

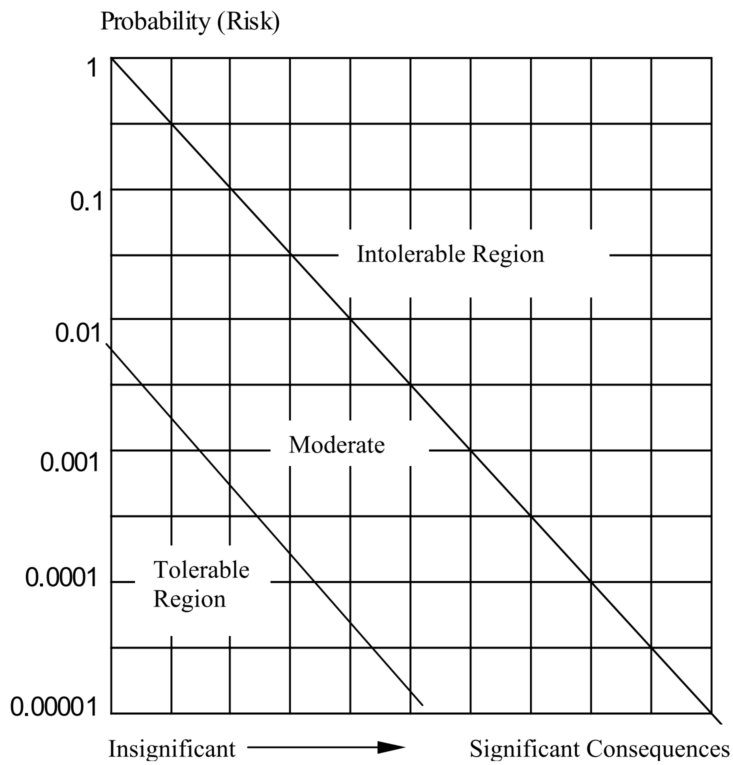

Figure 4 Risk Map (Modified after Harrington and Rose 1999)

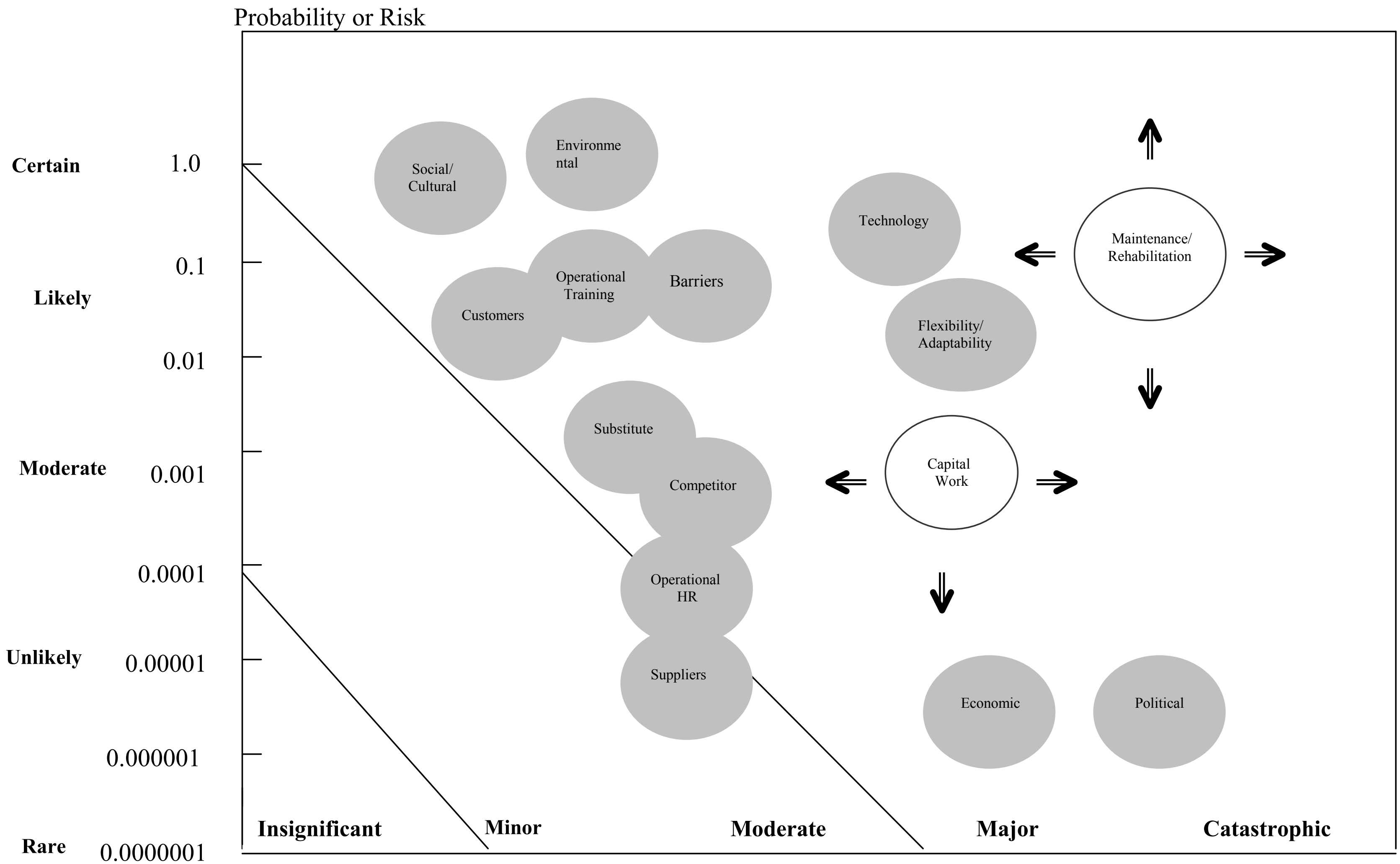

Figure 5 Plots of risk issues in the Risk Map (Modified after Harrington and Rose 1999 and Australian Defense Organization 2002)

8. Application of ITS for Risk (Reliability) and Uncertainty for Infrastructure Asset Management

ITS, which stands for Intelligent Transport Systems, is a broad-based term which is used to describe developments in communication and computing technologies applied to transport services in general. In infrastructure asset management, one of the issues of concern is manual data collection. Such form of data collection is time-consuming and high in cost. The application of communication and computing technologies has been developed for infrastructure asset management in the road sector. One such company (Barry, et. al. 2003) has developed digital video technology systems incorporating GPS and GIS to assist the management of over 6,000 kilometers of road network for the department of Main Roads in Western Australia. The images collected are linked with a Geographic Information System (GIS) and an asset management database. Using these technologies, an individual can conduct data collection for a road network of approximately 4,000 kilometers in less than a week. The system can effectively collect and store data which can be used for asset data capture, asset management, works management and risk management.

In the data collection technology developed by this company, raw data are captured on video using a capture vehicle fitted with a GPS receiver that uses OmniSTAR Satellite coverage to provide the required accuracy. The system consists of a standard vehicle fitted with two digital cameras to collect images every eight meters simultaneously both forward and rear directions, a GPS system and a mechanical distance meter attached to the front wheel. The entire data capture system is totally portable. The data capture system was installed in a Jackaroo 4-wheel drive and can be fitted to most vehicles without any modification to the vehicle.

Given the pavement types and pavement structures which are stored as part of the database, it is possible for the data to be exported and combined with condition data for analysis in pavement management packages such as HDM-4 (ISOHDM Technical Secretariat, 2001). HDM-4 is a software package for the analysis of road management and investment alternatives. As shown in Figure 5, probability-based risk assessments for maintenance/rehabilitation and capital works can be conducted by employing HDM-4 software package. Uncertainties associated with forecasting, model and data errors can be accounted for in the analysis by simulations.

The arrows in Figure 5 indicate that the decision-making on capital work or maintenance and rehabilitation can have significant impacts on social, cultural, environmental and other related issues. The government may affect changes to its policy through a reduction in the level of government funding, and may encourage investment in only commercially viable infrastructure projects. The likelihood of adopting such a policy by the government may be quite low, however the resultant consequences may have a significant impact. Implementing such government policies may result in reduced spending on maintenance and rehabilitation and may lead to reduced efficiency in road transportation. Alternative solutions need to be considered, such as the privatization of road transportation, i.e. charge users for increase use of private roads on a user-pay basis. An example of risks and consequences on environmental issues is that project development may encounter increased demands by society to reduce environmental damage. Road transport is seen to be a major cause of pollution via emissions. The risk that air and noise pollution adversely impact the environment is currently considered to be high, the resultant consequences of which are also significant. Road transport investment may be required to develop greener transport infrastructure solutions, such as the introduction of performance-based standards and road-friendly suspension for road vehicles to reduce wear and tear effects on road system. Noise regulations and curfews, particularly in residential areas and tougher penalties for vehicle traffic violations may need to be introduced. Greater costs for infrastructure projects may be incurred in order to satisfy environmental criteria and constraints. An example of culture change on transport users can be illustrated. Road transport growth may stimulate the preference of road transport mode, however this may be at the expense of other transport modes, such as reduction in rail utilization due to road transport growth. Technological risks may arise due to increased reliance on the use of IT and communications to design, operate and manage transport infrastructure; to maximize asset utilization and through technologically controlled infrastructure to monitor traffic flows, usage patterns and maintenance requirement. This interdependency may lead to greater vulnerability to any IT dysfunctions or interruption to services arising from malfunctions of technology. The utilization of these kinds of technologies require skilled personnel to manage IT, logistics and transport infrastructures. It may be difficult to secure skilled staff locally and therefore, necessary to recruit staff from overseas. The risk of malfunction of technologies may be considered to be high and consequences may have major impacts. Risk management procedures may need to be developed to cope with these kinds of problems. The risk of skill shortage developing may be low, however the consequence may have a moderate impact on transport operation. Training and development of skilled personnel in this area may need to be undertaken to combat future skill shortage.

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. The risk map given in Figure 5 provides a framework that can be used to analyse risks and their resultant consequences arising from investment decision-making. The framework points to the importance of evaluating overall risk-related issues and their consequences *prior* to the decision-making stage.

9. Findings

The terms “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, 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.
- The literature search indicated that the effects of uncertainty of data errors and model errors were trivial for the decision-making process. The dominant factor in output uncertainty fell into the forecasting category.
- For the 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.
- Data collection for infrastructure asset management can be assisted by communication and computing technologies.
- Probability-based risk (reliability) assessments for maintenance/rehabilitation and capital works can be conducted using HDM-4 software as a tool. Forecasting, data and model errors can be considered in the probability-based risk assessment by conducting simulation.

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