School of Marketing

Supply Chain Risk Management of Liquefied Natural Gas (LNG) in Australia

Abida Sultana Ankhi

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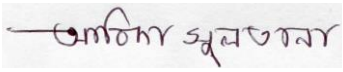
DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

To the best of my knowledge and belief, this thesis contains no material previously published by another person except where due acknowledgement has been made.



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ABSTRACT

Liquefied natural gas (LNG) is a new product in the international energy market. Advances in technology have made it possible for LNG to reach distant markets, thus overcoming geopolitical challenges. LNG supply chain is complex as it is affected by: long-term investment; cross-regional and international ventures; involvement of national and international law; government policies; geopolitical issues; roles of other forms of energy; and advances in technology. In an ever-changing world, global supply chains, such as the LNG supply chain, are experiencing many risks emerging from local (e.g. community concerns), regional (e.g. energy security) or international phenomena (e.g. Global Financial Crisis [GFC]), or from natural disasters (e.g. the Fukushima disaster). Hence it is imperative that global supply chain practice appropriates supply chain risk management (SCRM) which includes the identification of risk, assessment of risk, adoption of risk management strategies and allocation of resources to risk management.

With significant gas reserves, political stability and proximity to the Asia-Pacific market, Australia is in a good position to exploit the global LNG market. However, the Australian LNG supply chain is facing multiple challenges such as: high labour costs; remoteness of projects; strong local currency; competition from other forms of energy; competition from other exporters; the shale gas revolution; etc. to name a few. These challenges expose the LNG supply chain to risks which need to be managed for the long-term success of the LNG industry in Australia.

Supply chain risk management (SCRM) is an emerging area of research with its theory and methods only recently evolving. In the absence of well-established methods for SCRM, this doctoral thesis has developed a method for SCRM and has applied the method to LNG SCRM in Australia.

The methods for this research were developed following the “mixed-methods” approach and comprised (i) qualitative and (ii) quantitative analyses. Identifying supply chain risks (SCRs) and risk mitigation strategies (RMSs) through a review of the literature belonged to qualitative analysis, while the assessment of SCRs and

RMSs and the allocation of resources fell into quantitative analysis. The quantitative analysis method was developed based on a widely used risk formula, "*risk = probability x impact"*, with this followed by utilization of the quality function deployment (QFD) method to assign and prioritize RMSs as well as the allocation of resources. An optimization model was then developed to find the optimal set of RMSs for the mitigation of SCRs for different cost scenarios. To generalize the findings from the optimization model, a simulation model was developed. Based on the findings from the optimization and simulation models, a decision tool was developed.

In the qualitative analysis with the study undertaking a comprehensive review of the literature, the SCRs of the Australian LNG supply chain were identified, followed by identification of RMSs for their mitigation. The SCRs and RMSs were reviewed by an LNG industry expert to ensure that the list of SCRs and RMSs was comprehensive and relevant to the Australian LNG industry. For the quantitative analysis, data were collected from six LNG experts from around the world through a survey following a structured questionnaire. Risks and RMSs were prioritized, with the cost of implementing RMSs estimated based on data collected from the experts. The optimization model was then developed and applied to solving different cost scenarios to find optimal sets of RMSs for those scenarios. Some new concepts (namely, the risk flexibility index [RFI] and the assessment of the "effectiveness of strategies") were introduced to enhance the understanding of SCR and RMS assessment. To generalize the optimization model's findings, a simulation model was developed and, using a model run of 50 simulations, was applied to possible solutions.

The findings from this research have both theoretical and practical implications. Firstly, the research develops a method for SCRM which enriches the limited methods currently available in the literature. Many SCRM studies end with the prioritization of SCRs identified as a need. In the current research, SCRs were prioritized, RMSs were assigned and prioritized, the costs of RMS implementation were estimated, an optimization model was developed and solved for the optimal set of RMSs for different cost scenarios, with this followed by the development of a simulation model. A decision tool was then developed to find the optimal level of risk mitigation that could be achieved for a cost scenario. Therefore, the study's method for SCRM was comprehensive in its nature. Another key advantage of this method was its ability to be generalized to SCRM in any other relevant industry. Secondly, the findings from this research could be beneficial to the Australian LNG industry in which 33 SCRs and 30 RMSs were identified and prioritized. The effectiveness of these RMSs was measured which these results able to be used for the management of supply chain risks (SCRs).The optimal set of RMSs presented for different cost scenarios was based on data collected from the LNG experts and could be beneficial to risk managers in a limited resources scenarios. The simulation model captured the uncertainties around the research process and provided a possible range of solutions to find the level of risk mitigation achievable for a certain cost scenario. Therefore, the findings of this research are expected to equip risk managers with insight into LNG SCRM in Australia. In the current state with limited research available on LNG SCRM, this research enriches the body of knowledge both in terms of methods and practice.

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LIST OF ABBREVIATIONS

ABARES-BRS	Australian Bureau of Agricultural and Resource Economics and Sciences – Bureau of Rural Sciences
ABC	Australian Broadcasting Corporation
ABS	Australian Bureau of Statistics
AHP	analytic hierarchy process
AI	absolute importance
ALP	Australian Labor Party
ANN	artificial neural network
ANP	analytical network process (model)
APPEA	Australian Petroleum Production and Exploration Association
APS	advanced planning and scheduling (system)
ASI	American Supplier Institute
ATC	Australian Trade Commission
BBC	British Broadcasting Corporation
BCA	Business Council of Australia
bcm	billion cubic metres
BoM	Bureau of Meteorology
BOT	build, operate and transfer (projects)
BP	British Petroleum
BREE	Bureau of Resources and Energy Economics (Australia)
BSC	balanced scorecard
C	Celsius
C/SRM	customer and supplier relationship management
CM	consensus mean
CO_2	carbon dioxide
COCOMO	constructive cost model
CPFR	collaborative planning, forecasting and replenishment (system)
CR	customer requirement
CRM	customer relationship management
CSG	coal seam gas
CSR	corporate social responsibility
CSSUE	Safety and Health Committee of Spanish Universities
DR	design attribute/requirement

EDI	electronic data interchange
EIA	Energy Information Administration (US)
EISC	Economics and Industry Standing Committee
EM	ensemble mean
ERM	enterprise risk management
ERP	enterprise resource planning
ES	effectiveness of a strategy
ETS	emissions trading scheme
EU ETS	European Union Emissions Trading System
FIFO	fly-in fly-out
FR	*Financial Review (The)*
f(x)	objective function
GHG	greenhouse gases
GLL	Global LNG Limited
GOAL/QPC	Growth Opportunity Alliance of Lawrence, Massachusetts/ Quality Productivity Center
HoQ	House of Quality
HRM	human resources management
IEA	International Energy Agency
IETA	International Emissions Trading Association
IGU	International Gas Union
IHS	Information Handling Services
IPA	Independent Project Analysis
IS	information system/systems
JCC	Japan Customs-cleared (crude oil)
KPI	key performance indicator
LHS	left-hand side
LNG	liquefied natural gas
LP	linear programming
MILP	mixed integer linear programming (model)
MIT	Massachusetts Institute of Technology
mmBTU	one million British thermal units
MS	Microsoft
MTPA	million tonnes/annum
NBI	normal boundary intersection

OECD	Organisation for Economic Co-operation and Development
PA	Parliament of Australia
PI	probability impact
PJ	petajoule
PLS	partial least squares
PNG	Papua New Guinea
PSO	particle swarm optimization
PTR	product technical requirement
QFD	quality function deployment
R&D	research and development
RAI	relative absolute importance
RAND()	RAND function: a built-in function in MS Excel, categorized as a Math/Trig Function, and returns a new random number each time the spreadsheet recalculates
Rank (AI)	ranking of RMSs based on AI
Rank (E)	ranking of RMSs based on effectiveness
R (WA)	rank based on weighted average
RBA	Reserve Bank of Australia
RC	relative cost
RD	robust design (methodology)
RE	relative effectiveness
RFI	risk flexibility index
RHS	right-hand side
R_{ij}	relationship score between SCR_i and RMS_j
RIN/risk ID No.	risk identification number
RMS	risk mitigation strategy
SC	supply chain
SCM	supply chain management
SCP	supply chain performance
SCPR	streamlined consensus priority ranking (method)
SCR	supply chain risk
SCRM	supply chain risk management
SEM	structural equation modelling
S_{ij}	cost savings for simultaneous implementation of RMS_i and RMS_j
SIM	Simulation

SIN	strategy identification number
SME	small and medium-sized enterprise
SMH	*Sydney Morning Herald (The)*
Tcf	trillion cubic feet
Tcm	trillion cubic metres
toe	tonnes of oil equivalent
TOPSIS	technique for order performance by similarity to ideal solution
TQM	total quality management
UAE	United Arab Emirates
UK	United Kingdom
UN	United Nations
UNEP	United Nations Environment Programme
US/USA	United States/United States of America
VAS	visual analogue scale
W	weightage
WA	weighted average
WA	Western Australia/n
WESP	World Economic Situation and Prospects

CHAPTER 1

INTRODUCTION

1.1 Chapter Introduction

Supply chain risk management (SCRM) is an emerging area of research with increasing interest from industry and academics in recent times. Through citing others (Narasimhan and Talluri, 2009; Gurnani et al., 2011; Tang et al., 2012), Giannakis and Papadopoulos (2016) stated that risk management in the supply chain has emerged as one of the primary research topics in the supply chain management (SCM) literature. Sodhi et al. (2012) reported that to date the boundaries of the SCRM research area have been unclear, with research fields greatly diversified in terms of the SCRM scope. In the absence of consensus on a definition, or the scope, of supply chain risk, Sodhi et al. (2012) reviewed the recent SCRM literature. They found that aspects of risk, such as sources, identification, categorization, measurement or assessment, vary widely among the studies. Giannakis and Papadopoulos (2016) delineated that interest in the risk management of complex global supply chains has gained more ground with the continuing uncertainty of the world economy, business trends (such as increased outsourcing and offshoring) and advances in technology. Loss of supply, production or market share (and thus of revenue) from supply chain disruption are well reported in many studies in the literature (e.g. Sheffi and Rice, 2005; Chopra and Sodhi, 2004). Therefore, the adoption of SCRM has been increasing in recent times as part of overall management practice.

Based on findings from a review and analysis of the SCRM literature, Sodhi et al. (2012) reported that, in SCRM, a great variety of research tools are used, with these depending on the domains of expertise of the research studies and selected to suit the scope of the study and industry needs. These authors also outlined that research methods in SCRM are not well developed. The research methods (such as quantitative, qualitative or mixed), research process and steps, research framework, etc. vary widely among researchers depending on the background of the researcher, research topic, objectives of the study, level of complexity of the investigation, etc. Hence, to study SCRM, it is essential to develop a systematic approach.

Liquefied natural gas (LNG) is a form of natural gas which, through advances in technology, has emerged as a new product in the international energy market. Although some studies have been conducted on price dynamics and transportation costs (Maxwell and Zhu, 2011), energy security (Cabalu, 2010), investment decision making (Furlonge, 2011) and other issues related to LNG, few, if any, studies have been carried out on risk management of the LNG supply chain.

This study on LNG SCRM in Australia is carried out following a positivist research paradigm. The LNG SCRM process involves: (a) identification of potential risk areas; (b) identification of LNG supply chain risks; (c) assessment or measurement of the risks; (d) prioritization of risks to be mitigated; (e) identifying risk mitigation strategies for mitigating LNG supply chain risks; (f) measuring the importance or effectiveness of risk mitigation strategies in risk mitigation; (g) formulation of an optimization problem for the allocation of limited resources for mitigation; (h) selection of a recommended set of strategies for different cost scenarios; and (i) development of a simulation model for generating a range of risk mitigation scenarios. The study concludes with a decision model for LNG SCRM for Australia.

1.2 Research Problem

Liquefied natural gas (LNG), a form of fossil fuel (primarily methane), is now widely recognized as a clean, safe and conventional form of energy which can be readily supplied to distant markets (Australian Government, 2008). Starting from 1964 and through to the last decade, LNG was an expensive, regionally traded fuel; however, with advances in technology, it has become a globally traded source of energy (Rüster and Neumann, 2008). The LNG supply chain is complex (Shively and Ferrare, 2005) and, due to these complexities, global LNG supply chain risks are generally seen as unavoidable; therefore, they have received little attention until recently (Burr, 2005). Australia has a substantial amount of natural gas reserves, estimated at 153 trillion cubic feet (Tcf) (Australian Government, 2008). In their report, Jensen Associates (2007) projected the world trade of LNG to 2020, with this showing considerable growth of LNG demand in the North-east Asia market in the Pacific Basin by 2020. This increased demand is projected to be met mostly from increased supply from Australia with relatively no growth from other suppliers in the region. With a stable political environment, significant gas reserves and an attractive geographical location, Australia is well placed to secure and competitively supply LNG to the Asia-Pacific market, in comparison to its competitors (Malaysia, Algeria, Qatar, Trinidad and Tobago, Nigeria, Brunei, Oman and the United Arab Emirates [UAE]) (Cabalu and Manuhutu, 2009). Australia is not far away from the Asia-Pacific market. Also, the navigation route from Australia to the gas importing countries in the Asia-Pacific market is relatively safe form any geo-political conflict. This makes Australia an attractive geographical location. However, success in capitalizing on this strategic position in the world gas market will largely depend on how Australia addresses the LNG supply chain risks in the future. Every risk in the LNG supply chain poses a potential risk to disrupt the supply chain if it is not addressed with appropriate risk mitigation strategies. For example, natural gas plays an important role in power generation along with coal, oil and renewable sources in energy mix of Australia. However, debate on increasing use natural gas in power generation is continuing to replace coal based power stations mostly to reduce carbon emission and ensure reliability of supply. Increased demand of natural gas in power generation may force the Australian government to impose restriction on LNG export which may impact the LNG industry for attracting investment for new projects.

The ultimate success of a traditional LNG project, which can be described as a "supply chain", is at risk due to the possible failure of its weakest links (Jensen, 2003). The important features of an LNG project which contribute to multidimensional risks are: large gas requirement; large capital requirement; international venture; delay in capital recovery; front-end-loaded investment; operations covering large geographical areas; complex technology involvement; national and international policy change (fiscal, environmental, social, etc.); involvement of different stakeholders in the supply chain; and long-term agreement (Jensen, 2003). Other factors which make the LNG supply chain complex and expose it to risks are: capacity of infrastructure; natural disasters; national and international demand for clean energy; threat from terrorism; competition from other form of energy; and competition among exporting countries in the absence of an international regulatory organization (Moniz et al., 2011; Leather et al., 2013; Cabalu, 2010). The collapse of global financial markets since mid-2007 (Simshauser, 2010) and the emergence of the short-term LNG market (Furlonge, 2011) have added new dimensions of risk in the supply chain in terms of securing upstream investment in a fluctuating market. Australia is a major exporter of LNG in the Asia-Pacific market with significant gas reserves (Australian Government, 2008) but is acutely dependent on the international debt market for investment (Simshauser, 2010).

Liquefied natural gas (LNG) has some inherent advantages over gas supply by pipeline as it can be transported to distant markets in tankers and can avoid geopolitics between rival countries as it does not need overland infrastructure (such as pipelines). Thus, with its growing market share, LNG has attracted the attention of researchers in recent times. For example, Jensen (2003) examined the barriers of complex cross-border trade and the likely future of the LNG industry. Pil et al. (2008) assessed the reliability of re-liquefaction systems on LNG carriers. Maxwell and Zhu (2011) investigated the dynamics of natural gas prices, LNG transport costs and LNG imports through an empirical study. Cabalu (2010) evaluated the security of the natural gas supply (including LNG) in Asia through a number of gas supply security indicators. Furlonge (2011) proposed an integrated modelling approach to optimize economic returns from LNG by considering uncertainty in various key input parameters as part of an investment decision-making process. Reporting on the accelerated integration of previously segmented markets in North America, Europe and Asia from the increase in the liquefied natural gas trade, Neumann (2009) provided evidence on the integration of the transatlantic natural gas market. However, none of these studies focused on risk management of the LNG supply chain.

Three principal research problems have shaped the research focus of this study. Firstly, supply chain risk management (SCRM) has emerged as a new area of research (Giannakis and Papadopoulos, 2016); secondly, the research methods of SCRM are not well established due to diverse perception of risk and approaching this research area from different domain (Sodhi et al., 2012); and, thirdly, few, if any, studies have been carried out on managing the risks of the LNG supply chain in Australia. Therefore, this research focuses on supply chain risk mitigation of the LNG industry in Australia through the development of a risk management framework (with appropriate methods and process) starting from supply chain risk identification through allocation of risk mitigation strategies leading to the development of optimization and simulation models.

1.3 Research Questions

Based on the above discussion, the two fundamental research questions of this study are as follows:

1. What are the supply chain risks (SCRs) for the LNG supply chain in Australia that may influence LNG exports to global markets?
2. What are the risk mitigation strategies (RMSs) that can be adopted to mitigate the LNG SCRs to secure investment and greater market share through exports?

1.4 Research Objectives

The main objective of this research is mitigation of the supply chain risks of the LNG industry in Australia. Mitigation of supply chain risks involves key tasks such as: (i) identification of risks; (ii) identification of risk mitigation strategies; (iii) prioritization of risks; (iv) prioritization of risk mitigation strategies; (iv) estimating the cost of implementing risk mitigation strategies; and (v) determining the optimal set of risk mitigation strategies for different cost scenarios. The specific objectives of this research are as follows:

1. To identify SCRs and RMSs for the LNG supply chain in Australia.
2. To develop a method for SCRM and apply the method for LNG SCRM to the LNG industry in Australia.
3. To prioritize SCRs and RMSs including investigation of the relationship between SCRs and RMSs of the LNG supply chain in Australia.
4. To develop an optimization model for SCRM to determine optimal sets of RMSs to achieve the maximum level of risk mitigation with limited resources.
5. To develop a simulation model for SCRM to assess the reliability of the optimization model for SCRM and generalize the results of the optimization.

1.5 Research Significance

Considering the three primary aspects of this research: (i) the supply chain as an emerging area of research; (ii) LNG as a relatively new industry; and (iii) lack of well-established methods for SCRM, this research has developed its focus to overcome these limitations. In the current study, a research framework has been developed for supply chain risk management (SCRM). The method is applied to mitigate SCRs of the LNG industry in Australia. The method can be treated as a generic method for SCRM: in addition, its application to mitigate SCRs of the LNG supply chain in Australia can be considered as a comprehensive study of LNG supply chain risk mitigation. The specific importance of this research can be grouped into two broad categories: (i) contribution to theory; and (ii) contribution to practice. Firstly, in the absence of a well-developed method for SCRM, this research has proposed a comprehensive method which covers the process from risk identification through to the development and solution of a simulation model. Secondly, the application of the method has demonstrated its usefulness and capabilities to mitigate the risks of a supply chain. The contributions of this research to theory and practice are explained below:

Contributions to theory: Until recently, risks to the LNG supply chain were generally seen as unavoidable and thus received little attention (Burr, 2005). As a relatively new field of research, SCRM is currently chaotic and, to some extent, disorganized due to several different classifications of risks and methods; also, frequent focus on event based risk management rather than continuous changes in the chain (Trkman and McCormack, 2009). With regard to the LNG supply chain, to date very limited work has been carried out. Thus, the research methods for LNG SCRM are not well developed (Sodhi et al., 2012). The current study utilizes a research framework consisting of a widely used risk prioritization approach (Cox, 2012), the quality function deployment (QFD) method (Park and Kim, 1998) for assigning and prioritizing RMSs, and, to address the domain variability of SCRs and RMSs, QFD-based optimization (Park and Kim, 1998) and the development of a simulation model. The method for LNG SCRM involves: risk identification; risk prioritization; risk mitigation strategy identification; finding relationships between risk and risk mitigation strategies; prioritizing risk mitigation strategies; estimating the cost of implementing risk mitigation strategies; finding effective risk mitigation strategies; prioritizing risk mitigation strategies; developing and solving an optimization problem to find an optimal set of risk mitigation strategies for a cost scenario; and developing and solving a simulation model to address uncertainties of supply chain risk mitigation. The research framework has been developed based on the positivist paradigm. The methods and algorithm used in the framework are: (i) a widely used formula for risk prioritization, *risk = probability x impact* (Cox, 2012); (ii) the relationship matrix of the quality function deployment (QFD) method; (iii) the QFD method's conventional approach for risk mitigation strategy (RMS) prioritization (Park and Kim, 1998); and (iv) an optimization algorithm for developing and solving the optimization model (Park and Kim, 1998) and the simulation model. Therefore, this research has outlined a comprehensive SCRM method. Although the method has been explained focusing on supply chain risk mitigation of the LNG industry, it can be adopted and applied for supply chain risk mitigation of any industry or at least of most industries.

Contributions to practice: The issue of energy security is of immense importance for Australia for its development and sustainability. Australia has limited crude oil with relatively greater reserves of natural gas and coal (Australian Government, 2008). With advances in technology, LNG has emerged as a global commodity (Rüster and Neumann, 2008) with greater flexibility in its transportation, both by container and by pipeline. This has created a lucrative opportunity for Australian natural gas to be exported as LNG to the Asia-Pacific energy market where demand for energy is growing, with this expected to continue in the future (Jensen Associates, 2007; Cabalu and Manuhutu, 2009). However, recent figures from the Australian Bureau of Agricultural and Resource Economics and Sciences – Bureau of Rural Sciences (ABARES-BRS, 2010) indicate that Australia is exporting more LNG for less value. In addition, as LNG is a form of natural gas, it is a relatively clean form of energy (Australian Government, 2008), for example, carbon emission to generate electricity from LNG or natural gas is relatively less compare to other fuel such as coal. Local and global debate on carbon tax as well as demand for clean energy both in the domestic and international markets has increased the importance of LNG as a key energy mix component in the energy market of the Asia-Pacific region (Leather et al., 2013). Thus, Australia needs the best value for its LNG exports. Moreover, Australia will face more competition from other LNG exporting countries (such as Qatar, Malaysia and Indonesia) in the region with regard to price, investment, technology, operational challenges (e.g. cost, labour), policy change, etc. To capitalize on the opportunity of the growing energy market in the Asia-Pacific region, Australia needs to secure upstream investment in the LNG supply chain. The current research focuses on developing strategies for SCRM of the LNG industry in Australia to secure upstream investment and to minimize supply chain risks. Therefore, findings from this research are expected to be beneficial to risk managers in mitigating SCRs of the LNG industry in Australia.

1.6 Definition of the Terms

LNG: “LNG is natural gas, primarily methane, which has been cooled to its liquid state at minus 161°C. Liquefying natural gas reduces the volume it occupies by more than 600 times, making it a practical size for storage and transportation in specifically designed and built tankers” (Australian Government, 2008).

Supply chain risk management (SCRM): “[T]he management of supply chain risks through coordination or collaboration among the supply chain partners so as to ensure profitability and continuity” (Tang, 2006).

Vulnerability: “Vulnerability is a concept that may be used to characterize a supply chain system's lack of robustness or resilience with respect to various threats that originate both within and outside its system boundaries” (Asbjørnslett, 2009).

Sustainability: Sustainability is a concept developed from an understanding that each human activity has environmental, economic and social impacts (May and Brennan, 2006) which need to be managed effectively.

Risk: Risk is a subjective term and has many definitions depending on the discipline, nature of the study, objective of the study, etc. The Oxford Dictionary definitions of risk include: (i) a situation involving exposure to danger; (ii) a person or thing regarded as a threat or likely source of danger; (iii) a possibility of harm or damage against which something is insured; (iv) a person or thing regarded as likely to turn out well or badly in a particular context or respect; or (v) the possibility of financial loss. In this study, risk has been defined as a multifaceted issue or event which, if it occurs, would have a negative consequence and which is measured as *risk = probability x impact* (Cox, 2012) where *impact* is the negative effects or consequence if the issue or event occurs and *probability* is the likelihood of the occurrence of an event or issue.

Probability scale: It is important to note that statistically probability is measured in a scale of 0-1. However, in this research, to measure SCR attributes (probability and impact), a numeric visual analogue scales (VAS) (Van Laerhoven et al., 2004) ranging from 0–9 was used as presented in Appendix C. The values of 9, 5 and 0 represent probabilities of 1, 0.5 and 0 respectively.

Supply chain: The term "supply chain" has many definitions. The definition for supply chain presented in the Oxford Dictionary is "the sequence of processes involved in the production and distribution of a commodity". This is the definition principally followed in this research.

LNG supply chain: The LNG supply chain is the end-to-end process from start (extraction) to end (end-user) of liquefied natural gas (LNG). The LNG supply chain can broadly be divided into three stages: upstream, midstream and downstream (details presented in a later chapter). The upstream link contains elements such as extraction (exploration and production) and, in some cases, pipeline to the coast, liquefaction and storage. The midstream link mainly deals with shipping (tanker transportation) to distant markets while the downstream link includes re-gasification in terminal facilities, storage and distribution to markets (end-users).

LNG supply chain risk: A risk which poses threats to the LNG supply chain and makes the chain vulnerable. If any of these risks occur, negative consequences (economic, social, political, environmental, health, etc. or a combination) affect the LNG supply chain.

Risk mitigation strategy (RMS): A risk mitigation strategy is an action plan for companies to implement after making a thorough evaluation of the possible risks such as financial, operational, strategic, hazard, geopolitical and environmental (Sheffi, 2005). The purpose of mitigation strategies is to lessen the impact before any damage or calamity takes place. If any of the strategies are implemented, this helps to reduce either the probability or consequence of a risk and contributes to making the supply chain functional.

LNG supply chain risk mitigation strategy: A risk mitigation strategy may reduce the risk (if the strategy is implemented) to the LNG supply chain.

1.7 Organization of the Thesis

This thesis consists of 10 chapters. The organization of this thesis is outlined in Figure 1.1 and demonstrates each chapter's primary content and key outcome.

Chapter 1: An overview of the research is provided in the introduction chapter. Here, the research objectives and research questions are identified. The significance of this research is explained, some key terminologies are defined, with this followed by an outline of this thesis.

Chapter 2: An in-depth review of the literature is presented in Chapter 2. The literature review includes: an overview of the LNG industry, supply chain risks (SCRs), supply chain risk management (SCRM), the LNG supply chain, LNG supply chain risks and risk mitigation strategies (RMSs).

Chapters	Primary content	Key outcome
Chapter 1	Research overview; research problem; research objectives; research questions; and organization of thesis	Development of the research problem
Chapter 2	Review of literature on industry background; supply chain risk; risk mitigation strategies; and methods of supply chain risk management	Setting the scene of this research
Chapter 3	LNG vulnerability map; LNG supply chain risks (SCRs) and risk mitigation strategies (RMSs); description of SCRs and RMSs	LNG SCRs and RMSs are identified and explained
Chapter 4	Development of a research framework for SCRM with QFD-based optimization and simulation; application of the method for LNG SCRM	A method for SCRM with application to LNG SCRM
Chapter 5	Prioritization of RMSs of the LNG industry in Australia; exploration of different aspects of prioritization and need for optimization model	LNG SCRs prioritized and need for optimization defined
Chapter 6	Prioritization of RMSs for mitigating LNG supply chain risks in Australia and exploring different aspects of RMSs' prioritization	LNG RMSs prioritized and different aspects explored
Chapter 7	Development and solution of an optimization model for LNG SCRM and need for a simulation model are explored	Optimal set of RMSs are identified for cost scenarios
Chapter 8	Development and solution of simulation model for LNG SCRM and results are compared with optimization	Results of optimization are verified and generalized
Chapter 9	Overall findings are explained and research questions are answered based on findings; reliability and validity of models are checked	Key research questions are answered
Chapter 10	Summary of this research is presented; limitations and future research directions are outlined	Research summary; limitations; future directions

Figure 1.1: Organization of this thesis on LNG supply chain risk management

Chapter 3: In Chapter 3, supply chain risks (SCRs) relevant to the LNG supply chain in Australia are identified through a comprehensive review of the literature. Through identifying the SCRs, a vulnerability map with key terminologies associated with SCRs is prepared. Then, SCRs are described based on the existing literature. Risk mitigation strategies (RMSs) to mitigate the SCRs are identified through the review of the literature relevant to supply chain risk management. To explain the RMSs, short descriptions are provided.

Chapter 4: The research methods developed and applied in this study are delineated in Chapter 4. The key elements of this chapter are: (i) the research paradigm; (ii) research methods; (iii) the research framework; and (iv) the research process for this LNG SCRM study. The research process has three major parts in which each element has its own steps: (i) Part 1: development of the quality function deployment (QFD) framework for SCRM; (ii) Part 2: development of the optimization model for LNG SCRM; and (iii) Part 3: development of a simulation model for LNG supply chain risk management (SCRM).

Chapter 5: The prioritization of LNG SCRs is illustrated in Chapter 5. Important components of this chapter include the importance of LNG supply chain risk prioritization, data collection for this research, development of a weighted scale to capture consensus among the experts, and demonstration of the SCRs' domain variability. The domain variability of LNG SCRs establishes the basis for extending the application of risk parameters to develop the optimization and simulation models.

Chapter 6: This chapter presents another important part of this research, LNG supply chain risk mitigation for Australia. Here, the contextualization of the proposed method of LNG supply chain risk mitigation is presented. In Chapter 6, relationships between SCRs and RMSs are demonstrated using the QFD method's relationship matrix. The LNG supply chain RMSs are prioritized following the proposed method, with different aspects of their prioritization explained. The chapter introduces the concept of the risk flexibility index (RFI). Mitigation of individual SCRs as well as a holistic approach to risk mitigation is discussed. In addition, the basis of the simulation model for LNG SCRM is described. Dependencies between the RMSs are outlined, with these possibly resulting in cost savings from the simultaneous implementation of those that are interrelated.

Chapter 7: This chapter outlines details of the development and solution of the optimization model for LNG supply chain risk management (SCRM). The conceptual framework of the optimization model is delineated. Cost savings from simultaneous implementation of RMSs are itemized and cost constraints are defined. Nine cost scenarios are developed in this chapter with the optimization model used in their solution while taking into consideration cost constraints. The results from the optimization model are provided and discussed in detail. Sensitivity analysis of the optimization model is carried out. The chapter explores different approaches to developing and solving the optimization model based on primary data with the results compared. A better approach of developing and solving optimization model for LNG SCRM based on primary data is recommended. Close examination of the optimization results reveals the need of developing and solving a simulation model for LNG SCRM.

Chapter 8: Details of the development and solution of the simulation model for LNG SCRM are presented in Chapter 8. The conceptual basis and conceptual framework of the simulation model are described showing the essential features of the model. Steps are laid out for developing and solving the simulation model. Results from the simulation model are discussed and compared with the optimization model's results. The application and advantages of the results from the simulation model are explained.

Chapter 9: The implications and findings of this research are encapsulated and discussed in Chapter 9. A synopsis of the rankings of SCRs and RMSs is provided, with this showing effective RMSs for SCRs of high probability and high impact for LNG SCRM in Australia. Optimal sets of RMSs for different cost scenarios are discussed. The reliability and validity of the optimization model are examined. An evaluation of this research work is accomplished through delineating the findings against each research question (as previously outlined in Chapter 1, Section 1.3).

Chapter 10: This research concludes with Chapter 10. The current research work is recapitulated at the start of this chapter followed by presentation of the study's contributions to theory and practice. A decision model is presented for LNG SCRM in Australia. The implications of the study's findings for the LNG industry in Australia are expounded. The limitations of this research and future directions for research are also outlined.

1.8 Chapter Summary

This chapter introduced the current study on LNG supply chain risk management (SCRM) in Australia. Chapter 1 began with an overview of the research problem followed by specific research questions and research objectives. These established the research's rationale, with this further extended through revealing its importance in the discussion under research significance. Some key terminologies used in this research were defined. The section on the organization of the thesis outlined the primary content and key outcome of each chapter of the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Introduction

This chapter provides a comprehensive review of the literature relevant to this study of LNG supply chain risk management (SCRM) in Australia. The background of the LNG industry and recent work in supply chain risk management (SCRM) are explained. The LNG supply chain and the nature of supply chain risks (SCRs) and risk mitigation strategies (RMSs) are outlined. The background and historical development of the quality function deployment (QFD) method are summarized. In addition, the conceptual development of QFD is explored to assess its suitability as a method for supply chain risk management (SCRM). To understand its applicability for LNG SCRM, applications of QFD in SCRM in different areas are reviewed. Furthermore, recent work on QFD-based optimization is reviewed to understand the feasibility of extending the QFD method to develop an optimization model for LNG supply chain risk management (SCRM).

2.2 Industry Background

In 1964, Algeria delivered LNG to the United Kingdom (UK) and established the world's first LNG market. Figure A2.1 (Appendix A) shows the LNG production statistics by country since 1964. Historically, the LNG markets have been classified into three regions: Atlantic Basin, European and Asia-Pacific regions (Sakmar and Kendall, 2009). The Atlantic Basin region has imported less LNG in the past decade but is predicted to be the major source of demand growth for LNG in the near future (Sakmar and Kendall, 2009). The Asia-Pacific region has been the largest market for LNG because Japan, the world's largest LNG importer, is in the Asia-Pacific region. Japan, South Korea and Taiwan have little gas and mostly rely on imported LNG for their energy supply. China and India have recently emerged as LNG importers. Australia, Indonesia, Malaysia and Brunei are the exporters in the LNG supply chain in the Asia-Pacific region. Figure A2.2 (Appendix A) presents countries' market share of the LNG trade in 2007: (a) Asia-Pacific market and (b) global market. The "revolution" in LNG started shortly after the North-West Shelf project in Western Australia in 1989, followed, seven years later, by the greenfield LNG project start-up by Qatargas in Qatar (Jensen, 2003). In the mid-1990s, the importation of LNG by the United States (US) was significantly reanimated with a rise in natural gas prices and increased energy demand.

International trade in natural gas is driven by the imbalance between supply and demand (Cabalu, 2010). Since the 1990s, although investment in the LNG supply chain has increased rapidly throughout the world, the demand for natural gas has grown more, notably leading to substantial economies of scale throughout the value chain. To meet the energy demand for distant markets, LNG is proving to be a significant contributor (Furlonge, 2011). Today, LNG is essential to the energy supply of coastal nations such as the USA, the UK, Spain, South Korea, India, Japan and China. Table A2.2 (Appendix A) shows LNG trade in the Asia-Pacific market during 2007 and 2010. Northeast Asian countries, such as Japan, Korea, Taiwan and China, have only 1% of world reserves but consume almost 8% of the total LNG trade. On the other hand, the Middle East, particularly Iran and Qatar, and Russia hold two-thirds of world reserves while, in 2008, their consumption contributed to only one-quarter of world demand, as reported by British Petroleum (BP) (2009). Australia has significant natural gas reserves which, at the current rate of extraction, can provide supply for around the next 100 years (Australian Government, 2008). Strong demand for LNG is expected in the Asia-Pacific region (China, Korea, Taiwan, India, west coast of the USA and Mexico) in coming decades (Australian Government, 2008). In the US Energy Information Administration (EIA) scenario, coal is predicted to become more attractive for power generation due to the high price of natural gas. However, with the introduction of a price for carbon dioxide (CO_2) emission, the relative price of coal in the USA is likely to increase (Rüster and Neumann, 2008): hence, LNG will play an important role in power generation and industrial development in the Asia-Pacific region over the coming decades (Australian Government, 2008). Jensen Associates (2007) have projected the global LNG supply and demand for different regions for 2020 for three different scenarios: base case, high case and low case (Figure A2.3 [Appendix A]). The projection indicates that most of the increased demand would be met by increased supply from Australia with relatively little or no growth from other competitors in the region. It is therefore of utmost importance that Australian LNG supply chain risks (SCRs) are studied in depth to manage the supply chain effectively, which is the primary objective of this research.

Referring to the International Energy Agency (IEA) (2005), Jacobs (2011) reported that investments in LNG production are largely dominated by multinational oil and gas companies, in some cases along with state-controlled bodies. The overall investment climate in Australia is relatively favourable due to political stability, vast access to LNG technology and proximity to Asia (Jacobs, 2011). Australia is the fourth largest exporter in the global market and is expecting to be the second largest exporter in the next few years if the projects under way proceed as planned (BP, 2011). However, Australia needs to achieve best value for its LNG exports. An analysis of LNG export volume and revenue earned based on data from the Australian Bureau of Agricultural and Resource Economics and Sciences – Bureau of Rural Sciences (ABARES-BRS, 2010) reveals that Australia is exporting more LNG for less value (Figure A2.4, Appendix A). Thus, adoption of appropriate RMSs such as increase storage facilities, securing long term contract likely to assist to secure best value of LNG export. Therefore, to achieve the best value for its LNG exports, Australia needs to effectively manage the supply chain risks (SCRs) of the LNG industry.

2.3 Concept of Risk in Supply Chain Risk Management

The supply chain literature has many definitions of risk. The common theme of most definitions of risk is its likelihood of occurrence and consequences (Ritchie and Brindley, 2007). According to Tang and Musa (2011), two important dimensions of risk are the outcome of risk impact and the expectation of risk sources. With regard to the first dimension, most of the literature describes risk as being associated with negative consequences (Christopher and Lee, 2004; Paulsson, 2005; Spekman and Davis, 2004; Wagner and Bode, 2006). However, for the second dimension of risk, the expectancy of an event and its measures (probability or frequency of occurrence) still remain a well-debated issue (Tang and Musa, 2011). For example, can risk be treated as an expected event (such as quality deficiencies) (Wagner and Bode, 2006) or as an unexpected event (such as terrorist attacks, wars, natural disasters, etc.) (Christopher and Lee, 2004; Kleindorfer and Saad, 2005; Quinn, 2006)? It is also noted that all supply chains carry a combination of expected and unexpected dimensions of risk. A summary of various definition of risk in context of SCRM is presented in Table A2.1A (Appendix A) incorporating the two dimensions (likelihood and impact) as defined by the scholars.

Tang (2006) defined supply chain risk management (SCRM) as the management of SC risk with co-ordination or collaboration among supply chain (SC) partners for ensuring profitability and continuity. In theory, SCRM is a proactive relationship integrating various stakeholders from different tiers in the chain (Trkman et al., 2007). In practice, due to increased dependency among the companies, they are more exposed to risk (Hallikas et al., 2004). As a result, SCs are fragile, with this mostly due to environmental disruptions (such as power failure, fire, flood etc.) which are beyond their control (Zsidisin et al., 2005). As SCRM is a broad topic, different researchers have classified risk based on various aspects (Trkman and McCormack, 2009) and some have mostly focused on risk associated with logistics (Spekman and Davis, 2004). Tang (2006) suggested that risk could be grouped into operational and disruption risk. Hallikas et al. (2004) grouped risk based on the probability of occurrence and the associated impact and, similarly, Hunter et al. (2004) classified risk based on probability and importance. Ritchie and Brindley (2007) favoured a complementary division of risk into strategic, tactical and operational risk. Many of these classifications of risk are a subset of risk in the supply chain (SC). A subset of risk in the supply chain (SC) can also be further classified from the entity perspective (such as the customer, supplier, technology, etc.) (Li and Lin, 2006; Chen and Paulraj, 2004). Zeng et al. (2005) grouped risk depending on its origin, technology compatibility, supply disruption, currency fluctuation and disasters. As the LNG supply chain is relatively complex, to identify LNG SCRs in this research, a holistic approach has been taken.

2.4 The LNG Supply Chain

The LNG supply chain can broadly be divided into three stages: upstream, midstream and downstream (Figure 2.5). The upstream link contains elements such as extraction (exploration and production) and, in some cases, pipeline to the coast, liquefaction and storage. The risks associated with the upstream link and a mitigation strategy for these risks in the Australian context is the major focus of this research. The midstream link mainly deals with shipping (tanker transportation) to distant markets and the downstream link includes re-gasification in terminal facilities, and storage and distribution to the market (end-users). Due to the presence of two expensive activities (liquefaction and transport) in the LNG supply chain, until the last decade, LNG remained a less competitive form of energy. In recent times, developments in technology have led to a dramatic reduction in gas liquefaction and transportation costs, making LNG competitive with traditional pipeline gas (Cabalu, 2010). Development in technical include both in the process and in equipment scaling, manufacturing, and metallurgy. For example, advances tanker facilities, LNG receiving terminals and re-gasification plants is expected to facilitate expansion of spot market (Furlonge, 2011) which likely to reduce LNG prices. Also, large scale production with large gas reserve such as production from Qatar (Cabalu, 2010 and Leather et al., 2013) is likely to reduce cost of LNG. The LNG market is also responding positively due to reductions in the gas price rather than to shipping costs which tend to affect LNG trade gradually (Maxwell and Zhu, 2011). In the current decade, the increased size of LNG ships has been a growing trend responding to the need to decrease transport costs and to meet the increasing LNG demand (Pil et al., 2008). Thus, LNG is becoming a global commodity with rapid growth in the market and greater flexibility in its use. In the LNG supply chain, risks are involved at different stages, with these risks able to be minimized through the optimization of technology and the adoption of a risk management strategy. The LNG supply chain needs a large amount of capital investment for the entire chain and is also dependent on various infrastructure requirements, the distance to market and technology.

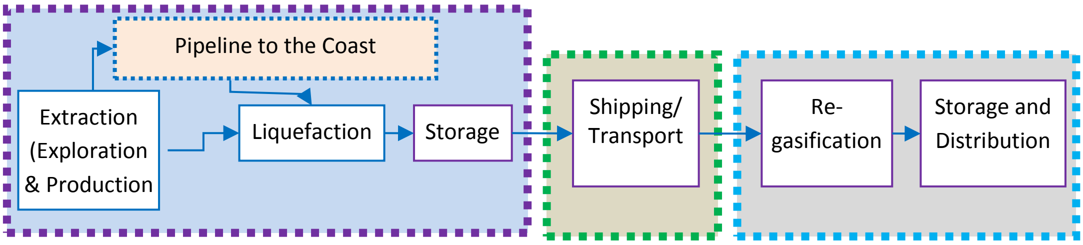


Figure 2.5: Major streams of LNG supply chain
Source: Rüster and Neumann (2009)

2.5 Nature of Supply Chain Risks of the LNG Industry

In general, the LNG supply chain is capital-intensive requiring mostly front-end-loaded investment (with most of the investment requiring earlier stage of the project) and needing international ventures (hence, collaboration) and large gas reserves. As LNG projects are long term (as well as large) investment, it takes a long time for a return on investment, with operations covering a large geographical area and involving high technology. Thus, the LNG supply chain is exposed to multidimensional risks, such as capital recovery risk due to delay and breakdown in any part of the chain, and risks arising from changes to laws and regulations as parts of the chain are subject to different countries' laws and regulations (Jensen, 2003). The risks involved during production and liquefaction include being subject to the laws and regulations of the producing country, transportation that is governed under international laws, and the re-gasification and distribution that are related to the importing country's regulations (Jensen, 2003). In addition, other factors that may influence the LNG supply chain are the adequacy of infrastructure; natural disasters; environmental regulations; demand for clean energy; threats from terrorism; competition from other countries and other forms of energy; economic recession, etc. Due to changes in the market structure (e.g. the emergence of the short-term market) and the development of infrastructure (e.g. LNG tanker facilities, LNG receiving terminals and re-gasification plants), LNG traders are now keen to capitalize on inter-regional price dynamics (Furlonge, 2011).

The three broad stages of the LNG supply chain (Figure 2.5) increase the vulnerability of the LNG infrastructure. In an interdisciplinary study by Massachusetts Institute of Technology

(MIT), it was reported that extraction and production, liquefaction, storage, shipping, re-gasification, storage and distribution have become increasingly vulnerable to both malevolent attacks and natural disasters (Moniz et al., 2011). The study (Moniz et al., 2011) stated that LNG processing facilities, pipelines, terminals and tankers can be easy targets to locate and destroy as they are usually undefended and thus vulnerable to attacks, including cyber-attacks. The global market dynamics of LNG are changing from the traditional form (state-controlled infrastructure, inflexible bilateral long-term supply agreements) to new flexible trading patterns (more privately-owned infrastructure, short-term agreements, emerging spot market) (Rüster, 2010). Without being sold, LNG projects are moving forward, with buyer and seller increasingly integrating vertically along the entire LNG supply chain (Rüster, 2010). The way in which investment in the LNG industry is happening now (more privately-owned infrastructure, short-term agreements, emerging spot market) is in contrast compared to the traditional form (state-controlled infrastructure, inflexible bilateral long-term supply agreements). Some companies are investing to cover the entire supply chain to capitalize on flexible trading and regional price differences, while other companies are investing in infrastructure, such as LNG terminals as tolling facilities, to gain the benefits of short-term trading (Rüster, 2010). Rüster and Neumann (2009) conducted an empirical study of the LNG supply chain with an emphasis on different strategic investment approaches. In two separate studies, Foss (2007, 2011) explored fundamental changes to LNG price dynamics and observed price convergence. Cabalu (2010) carried out a study focusing on the security of the natural gas supply to the countries in Asia. In another study, Cabalu and Manuhutu (2009), using market risk indicators, examined the relative vulnerability of eight gas-importing countries in Asia for 2006. Cook (2005) suggested that, along with gas reserves, winners need to develop upstream gas and liquefaction capacity which requires capital in order to reach the potential market, and also require a portfolio of global skills comprising all the technical skills, experience, a strong safety track record, shipping expertise, project management, marketing and project financing. In their study, Cabalu and Manuhutu (2009) indicated that Australia faces strong competition from other existing and potential LNG-producing countries. To take up the opportunity of greater demand from the Asia-Pacific market, Australia needs an effective LNG supply chain to attract more upstream investment, develop infrastructure, recruit skilled manpower, adopt technology, etc. The existing literature lacks such a study on the Australian LNG supply chain.

Although LNG SCRs are discussed in some studies (as presented above), none of these studies has focused solely on SCRs in a holistic way from the supply chain viewpoint. Each study has focused on specific aspects of LNG such as project management, energy security, market dynamics, etc. In other cases, the studies have only addressed the LNG supply chain partially, studying one component, such as upstream, downstream or midstream. In some instances, the studies were highly technical and focused on a technical aspect of risk in the LNG industry (such as challenges with an LNG tanker). Therefore, the evident research gap is identification of SCRs of the LNG supply chain covering upstream, midstream and downstream, with a particular focus on the Australian LNG industry.

2.6 Nature of Risk Mitigation Strategies for the LNG Industry

Risk mitigation strategies (RMSs) are action plans for companies for implementation after making a thorough evaluation of the possible risks, such as financial, operational, strategic, hazard, geopolitical and environmental (Sheffi, 2005). The purpose of these mitigation strategies is to lessen the impact before any damage or calamity takes place. Simchi-Levi (2010) reported that it is necessary to gain an understanding through analysis of different sources of risk and assessment of the impact of these risks on business operations before developing various mitigation measures. Chopra and Sodhi (2004) observed that no silver bullet strategy exists that will protect organizational supply chains. In this type of situation, the company needs capabilities to select which mitigation strategy works best against an arising risk. To address effectiveness in its supply chain, the company should create a shared, organization-wide understanding of supply chain risk and should then determine how to adapt risk mitigation strategies (RMSs) to its circumstances. Furlonge (2011) reported that the three stages of the LNG business's supply chain may give rise to different types of risk. The current research lacks specific risk identification and risk management in LNG SCRM in the Australian environment. Therefore, the evident research gap is the identification of RMSs for the LNG industry in Australia which will help to achieve positive outcomes, such as effective LNG supply chain risk management (SCRM) and competitive upstream investment.

2.7 Methods of Supply Chain Risk Management (SCRM)

Supply chain risk management (SCRM) is a process which involves some logically sequenced steps or elements. In general, the basic steps in a SCRM process should include: (i) assessing potential risk sources; (ii) identifying potential risks; (iii) measuring and prioritizing risk impact; and (iv) risk mitigation and response with the available resources. The literature suggests (Sodhi et al., 2012) that the steps of SCRM vary widely among SCRM studies depending on the scope of the study, nature of the industry, expertise of researchers and other factors (such as accessibility of risk information, availability of funding, needs of the industry, etc.). For example, in developing a conceptual framework for analysing risk in supply networks, Keow Cheng and Hon Kam (2008) described the SCRM stages of a supply network as: (i) define structure of the network; (ii) analyse the dynamics of risk; and (iii) assess the impact of risk. Kleindorfer and Saad (2005) developed a framework for managing the risks of disruption in the supply chain based on four main premises: (i) specifying the nature of underlying hazards leading to risk; (ii) risk assessment through quantification; (iii) approach for managing risk; and (iv) appropriate management policies and actions aligned with the supply chain. According to these authors, the four premises comprise three main tasks which are: (i) specifying sources of risk and vulnerability; (ii) assessment; and (iii) mitigation. Sodhi et al. (2012) grouped the SCRM process into four elements: (i) risk identification; (ii) risk assessment; (iii) risk mitigation; and (iv) responsiveness to risk incidents. These authors then reviewed the existing SCRM literature and identified the SCRM process that had been followed in those research articles. While the scope of SCRM research varies greatly as do the steps or elements of the process, each element involves method(s), such as methods for risk identification, methods for risk measurement, etc. Yu and Li (2011) reviewed supply chain risks and risk management methods focusing on risk identification, risk measures and risk management. The methods mentioned for risk identification are comprehensive analysis, classification and analysis of judgment (Haiyan, 2007); risk mapping technology (Souter, 2000); the statistical probability model and supply chain model (Zolkos, 2003); and the data mining method (Zhang and Huang, 2004). The risk measurement methods that were found in Yu and Li's (2011) review are conditional value at risk (Wu and Wang, 2004); the supply chain operations model (Lin, 2005); a two-level programming model with expected loss (Wang et al., 2008); and the back propagation neural network model (Wang, 2010). The review of risk measurement methods is obviously not very comprehensive as it does not include some widely used methods of risk measurement and risk prioritization, such as the probability impact matrix; operational loss distribution; key performance indicators (KPIs); qualitative and quantitative data (primary and secondary); and expert opinion. Yu and Li (2011) grouped the risk management methods of the reviewed literature under five theoretical domains: (i) theory of operation; (ii) theory of cost; (iii) theory of elasticity; (iv) theory of options; and (v) the information coordination and theory mechanism. In terms of risk management methods, Sodhi et al. (2012) categorized SCRM articles into three groups: (i) conceptual; (ii) quantitative empirical (statistical analysis of empirical data); and (iii) qualitative empirical (case studies). These authors found that the empirical work on SCRM was not extensive, although the existing work was useful in considering SCRM as an emerging area of research. The methods of SCRM as identified by various scholars are summarized in Table A2.1B (Appendix A).

2.8 Overview of Quality Function Deployment (QFD) Method

The quality function deployment (QFD) method was introduced as an approach during the late 1960s to incorporate customer choices (i.e. the voice of the customer) in the product design process. Over time, its areas of application have widened to cover a wide range of disciplines such as marketing, governance, management, education, the food industry, medicine, the supply chain and many more. The QFD method's analytical platform, described as the House of Quality (HoQ), brings different stakeholders together to contribute, negotiate and trade-off, and prioritize issues to achieve better results and outcomes. One advantage of the HoQ is that, although it brings different stakeholders together around a table or on a platform to contribute, the decision or outcome is no individual's responsibility which, in reality, helps stakeholders to share ideas, knowledge and information. The decisions or outcomes are results of a systematic process of the analytic platform's mathematical computation which provides the best possible outcome for all concerned. Therefore, the applications of QFD are ever increasing in number, covering wider disciplinary areas, with this expected to continue in the future.

To meet the needs of different users from multiple disciplines, QFD has been evolving since its development in 1972. The QFD process consists of a series of matrices, occasionally defined as a "house", which links the inputs and outputs of the different developmental steps (Han et al., 2001) through articulation of the relationship between input and output. It is evident that the number of "houses" depends on the level of detail; organizational structure; nature of the industry; objective and nature of the study (new product development, product improvement, service development, etc.); availability of data; and other factors. In a presented example, four "houses" were used in a QFD process for product development of a manufacturing process to present data at the different steps (Griffin and Hauser, 1993; Hauser and Clausing, 1988) with input and output linked in those steps. These four linked houses carried the voice of the customer through to manufacturing (Hauser and Clausing, 1988), resulting in improved or new products and services. The first house in the process is the House of Quality (HoQ) which links "customer needs to engineering characteristics or design attributes" (Griffin and Hauser, 1993; Hauser and Clausing, 1988). The fundamental principle behind the HoQ is the effort undertaken to establish a clear relationship between customer need and manufacturing functions where it is difficult to visualize the achievement of customer satisfaction (Hauser and Clausing, 1988). Griffin and Hauser (1993) described design attributes as engineering measures of product performance. The customer attributes tell "what" to do and the design attributes note "how" to meet customer attributes, thus creating a relationship matrix of "how" and "what" representing customer attributes and design attributes. In the second house of QFD, the design attributes of the HoQ are linked to the *actions* that the organization or firm can take (Griffin and Hauser, 1993). Here, the "how" of the HoQ becomes the "what" of the second house, and actions for addressing the "what" (design attribute) are treated as the "how" for the second house. In a truly inter-functional team, the "how" from one house forms the "what" for the next house and links the houses in quality function deployment (QFD). Actions are linked to *implementation* decisions (e.g. manufacturing process operations) in the third house of QFD (Griffin and Hauser, 1993). The third house has been shown as "process planning" where parts' characteristics represent the "what" and key process operations represent the "how". The final house of QFD links implementation decisions to *production planning* (Griffin and Hauser, 1993). Although the QFD process involves a series of "houses", in practice, most applications of the process conclude with completion of the first matrix (Cohen, 1995; Hauser and Clausing, 1988). Hauser and Clausing (1988) noted that the principal benefit of the HoQ is that it presents quality in the house which makes people think together and think in the right direction: for most US companies, this alone is a quiet revolution. In addition, many companies, such as Volvo, have reported that quite a large benefit can be achieved through completion of the first matrix (Han et al., 2001) with around 95% of companies ending up with completion of the first matrix (Cox, 1992).

2.9 Quality Function Deployment (QFD) Method for Supply Chain Risk Mitigation

With globalization and the free market economy, companies are competing to achieve greater market share for their product and, therefore, the quality of products has become a critical imperative strategy in today's market (Park and Kim, 1998). In achieving better quality, greater productivity and greater customer satisfaction, firms have adopted total quality management (TQM) as an important means to achieve their business goals, and have implemented TQM methods, such as quality function deployment (QFD), design for manufacturability and statistical process control (Park and Kim, 1998). Quality function deployment (QFD) translates customer needs and wants into technical design requirements through integrating the different functions of an organization, such as marketing, design engineering, manufacturing and other relevant functions (Akao, 1990; Ansari and Modarress, 1994). In other words, QFD is a tool to translate customer needs into the final product through the product design process. It is a communication and planning tool which forms the product development cycle in a structured way (Cohen, 1995). Along with incorporating technological innovation, its primary focus is to accommodate customers' needs and desires into a product (Bossert, 1991). Quality function deployment (QFD) is an important management tool with a structured approach to seek customer needs and to incorporate their needs in the planning and design process of products and services in order to deliver improved or new products and services (Han et al., 2001). In a QFD series, customer needs and wants are addressed in the design process through different design requirements which, in turn, also satisfy the production requirements and, ultimately, meet customer requirements. Thus, QFD is a management tool to meet customer requirements with improved or new products and services.

Many studies in the established research literature on the management of technology have acknowledged and reported that communication and cooperation between different functions (e.g. research and development [R&D], marketing, engineering, manufacturing, process planning, production planning, etc.) in an organization or firm help greater new product success with increased profits and lower costs (Griffin and Hauser, 1993). As a management tool, QFD improves communication and cooperation between the functions in an organization through visual presentation of a variety of data by linking customer needs (i.e. the voice of the customer) to the decisions of the functions (Griffin and Hauser, 1993). The visual presentation of data helps to promote communication and understanding between the functions in an organization and the organizational functions find it easy to use. Griffin and Hauser (1993) noted that, as a management tool, in many ways, QFD is similar to the new product or service development process in marketing (Urban and Hauser, 1992; Pessemier, 1986; Wind, 1982; Shocker and Srinivasan, 1979); the process for the improvement of existing products and services; the lens model (Brunswik, 1952; Tybout and Hauser, 1981); and the benefit of market structure analysis (Myers, 1976). These marketing processes use customer perception as a requirement in designing new products to achieve greater customer satisfaction which, ultimately, promotes sales, resulting in greater profits. As in the lens model and market structure analysis, QFD uses the perception of customer needs as the means by which to understand the relationship between product characteristics or a service's policies and customer preferences and level of satisfaction.

2.9.1 Historical development of QFD

Yoji Akao first introduced the concept of QFD as an approach for designing products in Japan in 1966, with this later becoming much clearer with the introduction of the quality chart by Nishimura and Takayanagi in 1972 (Akao, 1972, 1988 1990). Thus, the innovation of QFD is more than five decades old; however, during this time, it has gone through significant adaptation, modification, customization and extension. Although the concept was introduced in the late 1960s, QFD did not appear as a method until 1972 when it was applied at the Kobe shipyards of Mitsubishi Heavy Industries in Japan (Hales et al., 1990; Taguchi, 1987). Toyota and its suppliers then developed it further to carry out a rust prevention study (Hauser and Clausing, 1988; Wasserman, 1993). The Toyota auto body plant applied QFD from 1977–1984. During that seven-year period, the use of QFD was claimed to have reduced manufacturing start-up and pre-production cost by 60% and, with the improvement of quality, the product development cycle was reduced by 33% (Wilson and Greaves, 1990).

In the USA, the first recorded case studies in QFD were in 1986 (King, 1989), and magnificent work was undertaken in publicizing QFD by the American Supplier Institute (ASI) and GOAL/QPC (Growth Opportunity Alliance of Lawrence, Massachusetts/Quality Productivity Center). The US companies which have used QFD include: Ford, General Motors, Chrysler, AT&T, Procter and Gamble, Hewlett-Packard, Digital Equipment, ITT and Baxter Healthcare (Prasad, 1998; Park and Kim, 1998). Historically, QFD has passed through four different phases of development: inspection, process control, quality assurance and strategic quality management (Sivaloganathan and Evbuomwan, 1997).

2.9.2 Conceptual development of QFD

As a conceptual approach for designing products, QFD was first introduced by Yoji Akao in Japan in 1966, with the first book on QFD titled, *Quality Function Deployment,* published in Japan in 1978. Since then, numerous case studies have been published covering a wide range of disciplines. The best way of learning QFD is to learn through practice and experience, following its practical applications and not the theory, and also not taking a “play it by the book” approach (Akao, 1988). As every company is unique, QFD should be applied in an imaginative way that is appropriate and suitable to the company’s conditions (Akao, 1988). The House of Quality (HoQ) is a form of conceptual map that provides the means for inter-functional planning and communications by bringing together people with different problems and responsibilities to design priorities through putting patterns of evidence on the house's grid (Hauser and Clausing, 1988). The foundation and underlying belief of the HoQ are that customers' desires and tastes should be reflected in product design and, in order to do so, different segments within an organization (marketing, engineering, manufacturing, etc.) must work together from the initial conception of the product (Hauser and Clausing, 1988).

The number of components of the HoQ varies depending on users' needs and the objective of the study (or application). Different users name different components with slightly different names to suit the industry and the purpose. For example, Han et al. (2001) proposed a six-stage hierarchical framework in the HoQ as a basis for systematic group decision making to improve planning in the development process, with this representing a complex problem-solving process with a sequential multistage structure. The sequential stages are: (i) the voice of the customer; (ii) competitive analysis; (iii) the voice of the organization; (iv) design targets; (v) the relationship matrix; and (vi) the correlation matrix. Hauser and Clausing (1988) presented the HoQ with components (not in sequence) as: (i) customer attributes; (ii) relative importance; (iii), customer perceptions; (iv) engineering characteristics; (v) the relationship matrix; (vi) objective measure (to evaluate competitive products); (vii) the roof matrix and extending the analysis to measure technical difficulty, imputed importance, estimated cost and targets. Park and Kim (1998) have simplified the HoQ with the components: (i) customer requirements; (ii) degree of importance of customer requirements; (iii) design requirements; (iv) the relationship matrix; (v) correlation between design requirements; and (vi) absolute and relative importance of design requirements. They modified the HoQ to develop an integrative decision model to select an optimal set of design requirements through solving the optimization problem. Griffin and Hauser (1993) explained the HoQ as the voice of the customer with components: (i) customer needs; (ii) importance; (iii) design attributes; (iv) relationship between customer needs and design attributes; (v) customer perceptions; (vi) cost and feasibility; (vii) engineering measures; and (viii) roof matrix. For the purpose of explaining the different components that more commonly appear in the HoQ for new product development or the improvement of a product in manufacturing, Figure 2.6 presents a schematic diagram of the HoQ showing the different components.

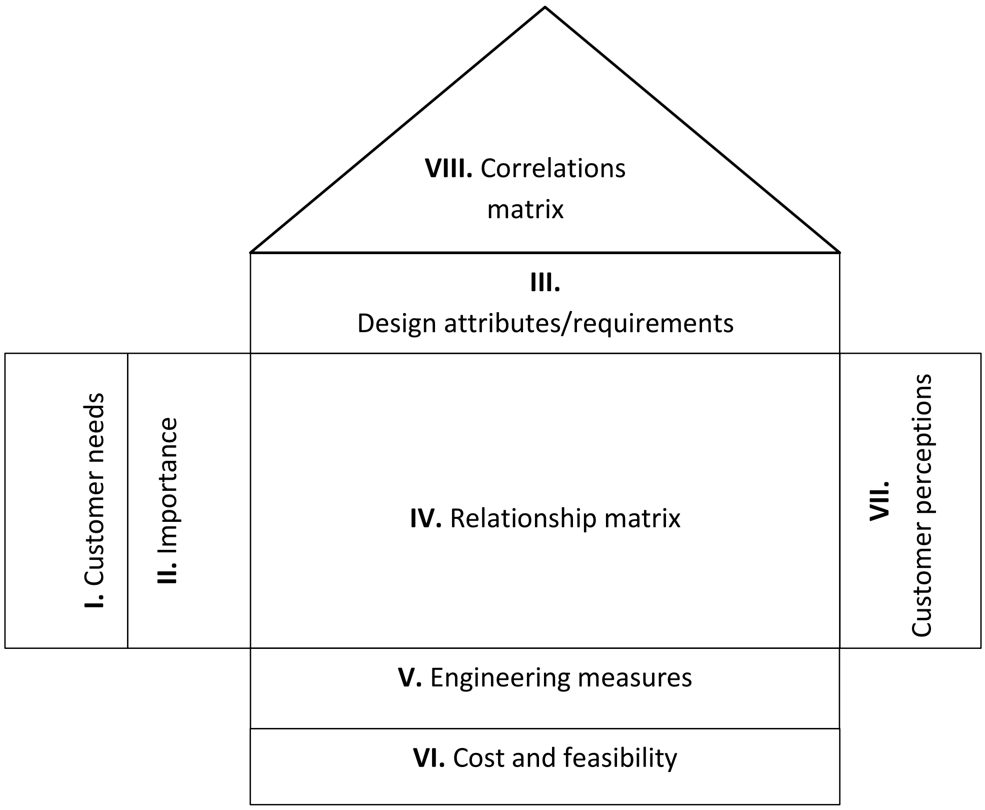


Figure 2.6: Schematic diagram of House of Quality (HoQ)
Sources: modified from Griffin and Hauser (1993) and Han et al. (2001)

A HoQ starts with customer needs (denoted as I) as shown in Figure 2.6 (at the left side of the house). A customer need is a description, in the customer's own words, of the quality, product or service required or wanted by the customer. In other words, it is the customer's description of the product and the product characteristics. Customer needs are customer-provided information about qualities that systematically need to be analysed for product development.

Several formal and informal ways are used to collect the information that expresses customer needs. For example, some Japanese companies put their product into a public place for potential customers to examine and make comments while design team members listen to them and write down potential customers' comments (Hauser and Clausing, 1988). In most cases, formal market research is adopted through customer surveys, in-depth qualitative interviews, focus group discussions, workshops, etc. The collection of customer information about quality must be systematically analysed to construct customer needs or customer attributes.

All needs articulated and organized under customer needs are not equally important to customers; instead, some needs have priority over other needs. The prioritization of customer needs (denoted as II) as shown in Figure 2.6 is useful to the product team as it enables the team to focus on meeting the important needs of customers from among their many needs as all needs cannot be met or might not be feasible to meet either technologically or economically. Therefore, prioritization of customer needs is an important aspect in developing the HoQ, with the relative importance of customer needs measured to prioritize the needs. Hauser and Clausing (1988) reported several techniques for measuring the relative importance of customer needs such as: (i) weightings provided by team members with direct experience with customers or on surveys; (ii) collecting customer preferences through statistical techniques comparing existing and new products; and (iii) "revealed preference techniques" to judge customer tastes through their actions and words. Armacost et al. (1994) and Lu et al. (1994) have applied the analytic hierarchy process (AHP) (Saaty, 1980; Saaty and Kearns, 1985) to prioritize customer requirements. This process is regarded as a commonly used proven and effective technique for prioritizing customer needs (Han et al., 2001; Wang and Hong, 2007). Park and Kim (1998) used Expert Choice computer software (Forman et al., 1985) which utilizes the eigenvector method (which is part of the AHP) to prioritize customer requirements. Based on the method used to determine the relative importance of customer needs, either a weighted or an importance value is assigned against each customer need as it appears in the House of Quality (HoQ). To suit further analysis of the HoQ, the relative importance score could be expressed either as a value or as a percentage.

Design attributes/requirements (DRs) (denoted as III) as shown in Figure 2.6 respond to each "what" (customer requirement [CR]) to find a solution, that is, "how" this can be met. In the HoQ, along the top of the house, the design team lists DRs to meet each of the CRs which may address one or more customer requirements (CRs). Design attributes/requirements (DRs) are the language of engineers or the design team and describe the product in the language of engineers or designers. Design attributes (DRs) should be clearly defined without any ambiguity and must be measurable. A DR could be positive or negative with positive meaning maximization of a particular DR whereas minimization of a DR is negative. Similar to CRs, a hierarchical structure (such as primary, secondary and tertiary) applies where the primary level could be strategic DRs, the secondary level could be tactical DRs and the tertiary level could be operational DRs. An example of constructing DRs is demonstrated by Hauser and Clausing (1988).

The relationship matrix (denoted as IV) as shown in Figure 2.6 displays the relationships between customer needs (CRs) and design attributes (DRs), through defining which CRs affect which DRs and to what extent. Using consensus, the inter-functional team of the organization completes this matrix based on design and market experience, customer response, tabulated data from statistical analysis or control experiments (Hauser and Clausing, 1988). In completing the matrix, the team could use any set of symbols or numbers that suits them and fits with the analysis and purpose of the study or experiment. Objective measures, such as the effectiveness or importance of each design attribute (DR) in designing or improving a product, can be measured through adding the score for the relationship between customer need/requirement (CR) and design attribute (DR) and the relative importance of customer need. This reflects the influence of a design attribute (DR) in meeting customer needs in designing new products or improving existing products.

As shown in Figure 2.6, the engineering measures (denoted as V) can be calculated based on importance (denoted as II) in relation to customer needs and the score from the relationship matrix (denoted as IV). Depending on the objective measures and the scale used, the design attributes can thus be evaluated based on their importance. Following the engineering measures (denoted as V) and cost estimate to implement a design attribute (denoted as III), the cost and feasibility (denoted as VI) of a design attribute can be measured. This is expected to provide the cost effectiveness of a design measure compared to other design measures. Customer perceptions (denoted as VII) can be measured from the importance of customer needs and the relationship matrix which is likely to provide the relative combined importance of the implementation of a customer need taking into consideration the design attributes.

Some of the engineering characteristics or design attributes could be linked, thus affecting each other. With the correlation matrix (denoted as VIII in Figure 2.6) of the HoQ, the designers define the relationships between the design attributes that need to be implemented together. The correlation matrix contains critical information for the design team regarding design attributes which facilitate necessary design trade-offs. In some cases, one design attribute could be linked with many other design attributes: due to difficulty in measuring trade-offs, the design team may decide to leave a particular design attribute alone (Hauser and Clausing, 1988).

2.10 Applications of QFD in Areas of Risk Management

Since the late 1980s, QFD has gained wide acceptance across the world covering a wide range of disciplines. Since then, many firms have used QFD as a TQM method to improve their market share through improved products and services. Chan and Wu (2002) and Sharma et al. (2008) carried out a review of QFD-based literature which included about 800 publications to 2006. Applications of QFD in risk management and supply chain risk management (SCRM) are presented in the following sections.

2.10.1 QFD in risk management

Few studies investigated the application of QFD in risk management before 2010. The literature suggests that, even since 2010, only a limited number of studies have been carried out on the application of QFD in risk management. For example, Gento et al. (2001) applied QFD in a service environment as a new approach to risk management in emergencies in a university centre using data from the Safety and Health Committee of Spanish Universities (CSSUE) and the experience of the university's prevention service. The study was centred on self-protection against emergencies in a building of the University of Valladolid (Spain). The study sought to find the key areas where more emphasis must be given to receive the highest satisfaction from limited resources through defining the House of Quality (HoQ) and the process for developing the information about the "whats", "hows", relationships, correlations, etc. (Gento et al., 2001).

Faisal (2010) developed a structured QFD process through modification of the House of Quality (HoQ) and used it to understand the relationships between various supply chain risks and risk mitigation variables. The process also undertook the subsequent prioritization of various risks with an understanding of the current status and identification of deficient areas in regard to the risk mitigation capabilities of the supply chain. The developed QFD process provides supply chain managers with a conceptual map which enables them to improve planning and the control of various risks that might disrupt the supply chain (Faisal, 2010). However, the study did not extend to the allocation of resources or optimization.

Congcong et al. (2010) adopted QFD for transforming organizational performance measures into project performance measures in developing a systematic procedure for risk identification, assessment, response planning, and control as part of a new risk management framework. The objectives were to align project risk management to corporate strategy and the performance measurement system in order to increase the success rates of R&D projects in accomplishing corporate strategic goals. This risk management framework integrates the balanced scorecard (BSC) (Kaplan and Norton, 1992) and QFD following the risk management process widely used by industry and allows an R&D project to focus on achieving corporate goals, as well as facilitating an effective way of identifying, assessing, analysing and monitoring R&D risks in a project cycle.

Yong-zhong and Jun-wen (2010) used QFD in an R&D project risk management framework which unifies QFD with risk management: this followed a design evaluation experiment which enabled the participants to positively appraise the risk management framework through the appraisal of subjective feelings and experiences. In the framework, the risks are de-composed using the QFD relationship matrix through the analysis of customer competitiveness, technical competitiveness, expert participation and group cooperation. These authors noted one important benefit of using QFD was that it breaks down barriers between functional departments and promotes exchange and cooperation between departments, with this being beneficial in realizing the R&D "parallel" design process and reducing or eliminating adverse consequences.

Francisque et al. (2011) applied the QFD approach in identifying and prioritizing factors for reconciling the "actual" risk with the "perceived" risk from the consumer viewpoint of the drinking water in a water distribution network. Customer requirements were prioritized using the analytic hierarchy process (AHP) with factors affecting water quality prioritized using QFD followed by sensitivity analysis to check the robustness of the approach. The proposed approach was applied through a case study in a water distribution network in Quebec City (Canada) to find the water quality factors that affected customer requirements.

Roghanian and Bazleh (2011) proposed a method using fuzzy QFD and the "technique for order performance by similarity to [the] ideal solution" (TOPSIS) to select build, operate and transfer (BOT) projects taking into consideration the risk factors and their impact on four important aspects in projects. They used fuzzy QFD to calculate the weight of each risk factor and ranked BOT projects that called for massive development of infrastructure and assets using the fuzzy TOPSIS algorithm.

The quality function deployment (QFD) method was applied by Costantino et al. (2012) to identify risks associated with warranty programs with the increasing interest in warranty management issues resulting from growing customer expectations for both products and services. They used QFD to identify the riskiest aspects of warranty activities through prioritizing these activities in accordance with customer perspectives, with these subsequently deeply analysed with either qualitative and/or quantitative risk analysis techniques. These authors tested the applicability of the method conducting a case study on agricultural and gardening equipment. They found that a better knowledge of warranty risks provides better opportunity to reduce the gap between customer expectations and the service offered.

Faisal (2013) reported that the most difficult parts in supply chain risk management (SCRM) are prioritizing the risks and understanding the relationships between the risks and risk mitigation variables. He proposed a modified House of Quality (HoQ) based on the standard framework to understand the relationships between different supply chain risks and risk mitigation variables. This would help in prioritizing different risks, understanding the current condition of the supply chain and identifying deficient areas in regard to risk mitigation potential for small and medium-sized enterprises (SMEs). Therefore, the proposed QFD process would give supply chain managers a conceptual map which would help in the planning and control of different supply chain risks.

Bolar et al. (2014) implemented the QFD approach to achieve quality and customer satisfaction for infrastructure maintenance with two separate applications on bridges as examples: (i) inspection prioritization and (ii) decision making for replacement or rehabilitation. Consumer demands ("whats") are translated into engineering or inspection requirements ("hows") through preparation of an inspection House of Quality (HoQ) for both cases followed by prioritization of the inspection or engineering requirements ("hows"). Hypothetical survey data were used for inspection prioritization while case study data were used for the decision-making scenarios.

Wang et al. (2014) reported that the research literature indicates employee turnover to be a complicated system which involves multiple aspects and that they considered QFD as an appropriate method for their study as QFD enables interactions between the components of a system in a holistic way (Bas, 2014).

Supply chain risk management (SCRM) is the process of risk mitigation in supply chains achieved through collaboration, coordination and application of risk management tools between the partners, to ensure continuity coupled with long-term profitability of the supply chain. Supply chain risks emanate from multiple sources and, similarly, risk mitigation in supply chains is dependent on several variables. The literature suggests that most applications of QFD to risk management to date are focused on the identification and prioritization of risk in different service industries. Some studies extend to defining relationships between risk and management strategies but, in many cases, these studies are either based on secondary data or hypothetical data. Therefore, they are of little value compared to similar studies carried out with primary data. It is difficult to collect primary data to carry out QFD-based risk assessment as data collection could be tedious and expertise may be lacking in defining relationships between risk and management strategies. Therefore, a research gap is evident in carrying out QFD-based risk assessment with primary data. In addition, few, if any, studies have extended further, apart from prioritization of the risks or assigning management strategies against the risks. Therefore, a research gap also exists in relation to extending the QFD-based risk analysis to prioritizing risk management strategies; estimating the cost of implementing risk management strategies; allocating resources; determining the optimal set of strategies for limited budget scenarios; and, ultimately, leading to the development of optimization and simulation models.

2.10.2 Application of QFD in supply chain management (SCM)

Recent applications of QFD are expanding into many disciplines including some areas of supply chain management (SCM). Some earlier applications of QFD in areas of SCM include the supplier role in product development (Holmen and Kristensen, 1998; Ansari and Modarress, 1994); evaluation of potential suppliers (Rich, 1995); and improving task partitioning (Von Hippel, 1990). During the early 2000s, some applications of QFD and its modified forms (e.g. fuzzy QFD) in the areas of SCM included as the tool and method for manufacturing supply chain decisions (Li et al., 2001); reliability consideration for SCM (Sohn and Choi, 2001); developing supply chain strategies (Kuei et al., 2002); and supplier involvement in a parts design scheme for product development (Tang et al., 2005). Since the 2000s, the application areas of QFD have widened into areas of SCM and have diversified into different industries. To suit the particular study’s objectives, the research studies have modified, extended (e.g. fuzzy QFD, extended QFD, dynamic QFD, etc.) or applied the basic QFD method as appropriate and, in some cases, QFD has been applied with other tools, for example, for optimization and prioritization. The applications of QFD in supplier selection and supplier assessment have continued to increase in recent times as popular areas for its utilization in SCM (Bevilacqua et al., 2006; Bhattacharya et al., 2010; Raut et al., 2010; Vinodh et al., 2011; Kumar et al., 2011; Osorio et al., 2011; Dey et al., 2012; Dai and Blackhurst, 2012; Haldar et al., 2012; Tidwell and Sutterfield, 2012; Abbasi et al., 2013; Rajesh and Malliga, 2013; Alinezad et al., 2013; Dursun and Karsak, 2013; Karsak and Dursun, 2013). Other application areas of QFD in SCM during the late 2000s and early 2010s have been: as a new decision tool for outsourcing in the supply chain (Daozhi et al., 2005); an approach or method for the supplier selection approach to SCM optimization (Gunasekaran et al., 2006); an approach for strategic management for logistics services (Bottani and Rizzi, 2006); an approach for effective marketing for a closed-loop supply chain network (Nukala and Gupta, 2006); a supply chain information matrix for an agile enterprise (Baramichai et al., 2007); achieving a consumer focus in supply chains (Zokaei and Hines, 2007); optimization of logistics services capacity (Shushan et al., 2008); designing supply chain management (SCM) for an academic curriculum (Gonzalez et al., 2008); as metrics for performance measurement of a closed-loop supply chain (Pochampally et al., 2009); enhancing the competitiveness of companies through agility (Bottani, 2009); as a process integration evaluation method for fourth party logistics (Leina et al., 2010); strategic sourcing in manufacturing (Ho et al., 2011); and as a customer relationship management (CRM) framework assessment in agile manufacturing (Zandi and Tavana, 2011). More recently, since early 2010, the application areas of QFD have expanded to SCM strategies (Ayağ et al., 2013); supply chain leanness (Zarei et al., 2011); aligning competitive strategy with supply chain strategy (Prasad et al., 2012); and supply chain design through optimization (Prasad et al., 2014) and sustainability. For example, some recent applications of QFD in sustainability of the supply chain are sustainability analysis of a supply chain structure with incomplete preferences (Büyüközkan and Çifçi, 2010); designing a sustainable supply chain (Büyüközkan and Berkol, 2011); developing an integrated framework for a sustainable supply chain (Büyüközkan and Çifçi, 2013); and an approach to supplier assessment from a sustainability perspective (Dai and Blackhurst, 2012).

In recent times, although QFD has been used in various areas of supply chain management (SCM), few studies have been found that have directly applied QFD to SCRM and, in particular, no studies were found that related to the LNG industry. In line with the approach of Park and Kim (1998), the QFD method, together with the analytic hierarchy process (AHP), was applied by Dewan (2014) to model the blended value of the banking industry. He found that, based on QFD, management strategies can be prioritized and optimized for different cost scenarios. However, he used the partial least squares (PLS)-based structural equation modelling (SEM) technique (Chin 1998) to confirm the findings from QFD-based optimization. Thus, this method cannot be considered as a general approach to SCRM solely based on quality function deployment (QFD). In another study, Chowdhury and Quaddus (2015) applied QFD-based optimization for assessing vulnerability and prioritizing the management strategies of the garment industry using three case studies for three different companies. They found that companies faced similar vulnerabilities with some differences in the quantitative results. However, extending the optimization model to a simulation model could explain the variability of the optimization results. Therefore, the optimization model based on QFD needs to extend to a simulation model to explain the variability and uncertainty of results which could appear due to biases in data or limited data. Hence, a generic approach for applying QFD in SCRM is needed which extends to a simulation model.

2.10.3 Basis of applicability of QFD in supply chain management (SCM)

Since 1966, QFD has been applied across many countries and covering a wide range of industries. Some of the world's largest and most successful companies which have widely used QFD include: Ford, General Motors, IBM, Procter and Gamble, Kodak, Xerox and Toyota (Griffin and Hauser, 1993). Chan and Wu (2002) conducted a review of the QFD literature with a reference bank of 650 QFD publications. The review covered a categorical analysis of QFD applications explaining why and where QFD has been applied. The review referred to only a few applications of QFD in supply chain planning (Li et al., 2001) and supply chain management (SCM) (Samuel and Hines, 1999; Sohn and Choi, 2001) in the planning and management categories. The review noted that no definite boundaries were apparent for the potential application of QFD (Chan and Wu, 2002), with a similar view acknowledged in other studies in the literature. For example, as cited by McElroy (1989), according to Norman Morrell, Corporate Manager of Quality–Product Reliability at Budd, "QFD can be applied to whatever process you have control over: new product design, business plans, engineering proposal systems, even reducing die transition time". Mazur (1993, 1997) proposed comprehensive service QFD, and Dubé et al. (1999) later extended this for service transactions through substitution of the quality-parts-process-production links of the traditional QFD approach with quality-function-process-task links that were suited to a service (Wang and Hong, 2007). Wang and Hong (2007) applied QFD to develop an integrated service strategy for a telecom company with the objectives of achieving win–win strategies through trade-offs between customer requirements and business requirements; maximizing utilization of resources; sustaining a stable and profitable consumer base; and exploiting resources. Some applications of QFD have extended to the optimization problem where they have been used for selecting an optimal set of design requirements with the objectives of cost savings, resources' constraints or profit maximization. For example, Park and Kim (1998) used a new integrative HoQ model for determining an optimal set of design requirements through maximizing customer satisfaction and cost minimization for two cost constraints. For the optimization problem, the integer programming model was adopted with the problem solved with the Solver function of MS Excel Solver. In a study of blended value-based modelling for e-business sustainability of the banking industry, Dewan (2014) applied the QFD method. Chowdhury and Quaddus (2015) assessed supply chain vulnerabilities of the garment industry of Bangladesh using the QFD approach. Therefore, the QFD method can be applied for LNG SCRM and for SCRM in general.

2.11 QFD-based Optimization

In an early work on QFD-based optimization, Wasserman (1993) reported that, due to the complexity of the decision process, the design team often relies on ad hoc procedures to assist in this process and that such procedures are sub-optimal. Therefore, formal approaches are needed to provide an objective basis for the evaluation of cost trade-offs for competing design requirements. Gavoor and Wasserman (1989) showed that a mathematical programming framework could be useful for capturing details of the decision process. Wasserman (1993) proposed a planning model using the information content of the QFD method’s product planning matrix to assist the designer in the selection of product features in the decision process. This represented a refinement of a previous model that did not properly consider the effect of dependencies among the engineering design requirements (Bordley and Paryani, 1990; Gavoor and Wasserman, 1989). The proposed model was formulated considering the QFD planning process as a linear programming model for selecting a set of engineering requirements under the constraint of a given target cost, with the objective of achieving the highest level of customer satisfaction. The objective function was formulated considering the linear weighting of the technical importance measures for the normalized relationship matrix and the decision variables to fulfil customer requirements and solving the objective function for a proposed linear cost constraint.

Park and Kim (1998) used QFD to translate customer requirements into design requirements to increase customer satisfaction through determination of an optimal set of design requirements. They utilized the QFD method’s House of Quality (HoQ): as a matrix, the HoQ was drawn as a conceptual map for the design process as a means to understand customer requirements (CRs), with these met by determining the priorities of design attributes/requirements (DRs). Following the prioritization of DRs, these authors used an integer programming model to maximize customer satisfaction through the selection of appropriate design attributes/requirements (DRs). Maximizing the total absolute importance of the selected DRs was the objective function of this model which ultimately would represent the level of customer satisfaction. This is an extension of traditional QFD to count the trade-offs between the level of customer satisfaction attained from a selected set of DRs that considered organizational resources, such as cost.

Each of the four different stages of the QFD method's product development process prioritizes elements for that stage, with the stages linked together in this process. Based on the current study's review of the literature, Table A2.2 (Appendix A) presents a summary of the study objective, the objective function and the variables used by some researchers in QFD-based optimization from 1993–2006. More recently, Piedras et al. (2006) noted that all the optimization approaches that utilized QFD (Kim, 1997; Dawson and Askin, 1999; Wasserman, 1993; Zhou, 1998; Lin, 2003; Karsak, 2004a,b ; Chen et al., 2004; Kwong and Bai, 2003; Wang et al., 2005) were not intended for simultaneous optimization of the four phases of the product development process and added the claim that constructing the stages of product development in QFD sequentially may lead to sub-optimal solutions. These authors introduced a mathematical formulation for simultaneous optimization of the QFD method's product development process with the objective being to cover the whole product development process: the intention was to develop greater confidence in this process addressing customer specifications along with the adoption of low-cost production techniques (Piedras et al., 2006). The proposed mathematical programming technique for optimizing the product development process uses a concurrent engineering approach which maps the stages in this process, with the decision variables of all stages determined simultaneously (Piedras et al., 2006). While the QFD approach is based on a qualitative sequential approach, the proposed approach is intended to concurrently conduct product–process optimization and the approach is applied to the first two stages of the product development process: (i) the optimization of customer satisfaction and (ii) the optimization of the product's design (Piedras et al., 2006).

Kovach and Cho (2008) demonstrated a new approach through combining aspects of QFD with traditional robust design (RD) methodology to develop a method where QFD could be used for solving multi-response optimization problems. The proposed approach has two stages: (i) the QFD process and (ii) robust design methodology. In the first stage, QFD is used to determine the factors and responses of interest based on customers' needs, with these then used to establish absolute and relative priorities of the individual quality characteristics

(Kovach and Cho, 2008). The priorities of the quality characteristics determined using QFD are then incorporated into the optimization model which uses goal programming techniques (Hillier and Lieberman, 2001), creating a unique optimization strategy to solve a multi-response robust design (RD) problem (Kovach and Cho, 2008).

Noting that technical parameters are the usual attributes of preference considered by customers in selecting a product from a product family, Luo et al. (2008) proposed an optimization method for the selection of components based on the QFD method to minimize the difference between customers' expectations and the selected product. They developed a mathematical model for components' selection based on QFD with the objective being to achieve the most satisfying solution when taking into consideration customer requirements. For finding an efficient solution, the model has been converted to an equivalent linear integer programming model that can be solved using a variety of traditional algorithms (such as branch-and-bound, cutting planes, implicit enumeration, etc.) (Luo et al., 2008). The approach was illustrated using the practical product of air compressor equipment cooperation in southern China. They found that the model reasonably mapped the relationships between customer requirements, technical attributes and component attributes and that the optimization results also reasonably represented customer requirements (Luo et al., 2008).

Shushan et al. (2008) established a dynamic neural network for QFD, combining it with a linear programming model to evaluate an automotive logistics enterprise, with this evaluation based on the demand experienced by its logistics services. Reporting that the services process included design, implementation and improvement as a continuous and dynamic process, Shushan et al. (2008) recommended the need for circular feedback of customer demand information. As a remedy for the imperfections of traditional QFD, they proposed dynamic QFD based on a neural network. The customer satisfaction survey was used to construct traditional QFD as a basis for dynamic quality function deployment (QFD). In dynamic QFD, customer demand information is transformed into the relevant logistics services' indices using an information feedback loop. This loop, which keeps feeding back customer demand-weighted data to the services' process through judgment of the need for the services' elements to be adjusted, is calculated with the output of the new weights to capitalize on market opportunities (Shushan et al., 2008).

Xinggang et al. (2008) extended QFD through the development of an optimization model using standard linear programming for optimization of a scalable product platform. Sener and Karsak (2010) used a non-linear programming-based fuzzy regression approach in modelling functional relationships between customer requirements and engineering characteristics in product planning. They developed a fuzzy mathematical programming model as a decision model for determining target levels of engineering characteristics on the basis of functional relationships developed from fuzzy regression.

Xinggang et al. (2011) later developed a QFD-based optimization model for a multi-segment market to maximize overall customer satisfaction, with the weights of market segments and development costs expressed as triangular fuzzy numbers to describe the imprecision from subjective human judgment. With their approach among the many approaches used to solve this type of optimization problem (e.g. Luhandjula, 1987; Rommelfanger, 1989; Lai and Hwang, 1992), they followed Lai and Hwang's (1992) approach which was claimed to be easy to implement. Jain et al. (2011) developed a QFD-based optimization approach for aligning competitive strategy and supply chain strategy though computing a supply chain performance index for the different sets of supply chain design objectives. In this approach, supply chain performance was defined using information collected from the QFD method's House of Quality (HoQ) and the utility functions. Kashyap and Misra (2013) identified that the production of quality software with timely design and within proper cost estimates was a major challenge for many software firms. In response, they integrated a cost estimation model with the QFD method to facilitate decision making in software design and development processes to improve quality in a timely manner and within cost estimates. Their cost estimation model was developed on the basis of multi-objective particle swarm optimization (PSO) (Eberhart and Shi, 2001) to adjust the parameters of the constructive cost model (COCOMO) (Boehm et al., 2000).

Optimization of the product development process needs different product variant information at different stages of product development and, at the early design stage, sufficient product information is lacking (Kutschenreiter-Praszkiewicz, 2013). The artificial neural network (ANN) was adopted by Kutschenreiter-Praszkiewicz (2013) as an intelligent estimation method to provide the measurable engineering information needed for the QFD method and for different stages of product development such as: (i) goal setting; (ii) data acquisition; (iii) configuration of ANN architecture; and (iv) completion of the QFD matrix. They found the intelligent estimation method to be useful, with the approach illustrated by the example of the procedure for engineering characteristic estimation of a toothed gearbox.

Prasad et al. (2014) developed an approach for designing a supply chain for a product with the alignment of competitive strategies and supply chain strategies by adopting a QFD-based optimization method. The optimal weights of the supply chain design objectives were determined using the normal boundary intersection (NBI) method, and multi-objective optimization was carried out through developing a weighted additive model (Prasad et al., 2014). Supply chain performance (SCP) was defined using information from the QFD method's House of Quality (HoQ) and from the utility-based attribute functions, with the latter structuring the relationships between the elements of the competitive strategies and those of the supply chain (Prasad et al., 2014). The supply chain activities were planned on the basis of the SCP index which was calculated from the set of supply chain design objectives acquired through solving the weighted additive model (Prasad et al., 2014).

With an optimization problem, most QFD-based optimizations are extensions of the QFD method's House of Quality (HoQ). To suit the needs of the optimization, the HoQ has been modified. The optimization problem has been formulated and solved mostly on the basis of integer programming, linear programming or goal programming. In a few cases, fuzzy QFD and the fuzzy optimization concept have been used to address the issues of uncertainty and human biases in defining the relationships between customer requirements and design attributes/requirements. However, QFD-based optimization is a fairly new area of research and few studies have covered the discrete areas of this body of knowledge and discipline. Therefore, no general method of optimization covers a particular discipline. The selection of the objective function and the constraints under consideration vary based on the discipline, the researcher's priorities, the availability of data, the needs of the industry and many other factors. Hence, QFD-based optimization appears as a complex area for future research. No studies on QFD-based optimization for LNG SCRM were found in the literature, with none of the existing optimization work able to be considered as a general approach to optimization for supply chain risk management (SCRM). In addition, few, if any, studies were found that explained the variability or uncertainty in the results of QFD-based optimization by further extension of existing studies. An extension of such a study could be the development of a simulation model which, it is expected, would explain the variability or uncertainty in the results.

2.12 Chapter Summary

This chapter has identified the prior literature relevant to LNG SCRM in Australia and provides the background for this study. In this chapter, different aspects of LNG supply chain risks (SCRs), risk mitigation strategies (RMSs) and recent work on the development of the QFD method, including optimization, were explained. The study's literature review reported in this chapter has set the scene of this study of LNG SCRM in Australia. The LNG SCRs and RMSs are discussed in Chapter 3.

CHAPTER 3

LNG SUPPLY CHAIN RISKS AND RISK MITIGATION STRATEGIES

3.1 Chapter Introduction

In this chapter, LNG supply chain risks (SCRs) and risk mitigation strategies (RMSs) are identified. Some SCRs and RMSs are interrelated and it is difficult to define or study them independently. Firstly, through the review of the literature, a vulnerability map associated with LNG SCRs was developed along with relevant key risk terminology as presented in studies in the literature. Based on the vulnerability map, 33 LNG SCRs were identified and compiled into a comprehensive list of LNG SCRs in Australia. A short description of each SCR is presented based on the current literature. These SCRs are one of the key elements of this analysis, in response to which RMSs are identified and described based on the available literature. The chapter concludes with a summary.

3.2 LNG Vulnerability Map

Liquefied natural gas (LNG) is a relatively new product in the international energy market, with its usage expected to grow rapidly in the future but this growth could be vulnerable for many reasons. British Petroleum, in its *Energy Outlook 2035* (BP, 2015), forecast significant growth in LNG trade (demand and supply) for a period up to 2035 with most of the demand growth in the Asia-Pacific market and a significant increase in supply from Australia. The global LNG supply is influenced by factors ranging from technology and innovation through to responses to a country's local or domestic policy changes. Example of such factors include change in energy policy, change in fiscal policy, lack of skilled human resources, competition from other form of energy, remote gas reserves, natural disaster, political instability, community concern etc. Therefore, the LNG supply chain in Australia depends on these factors, some of which could be determinants of LNG exports from Australia in the future. These factors bring changes to the LNG supply chain which can be either positive or negative (creating opportunity or, alternatively, threat or risk). To capitalize on any changes in a positive way, the supply chain needs to be agile or flexible and, therefore, needs to have a management mechanism in place. Hence, any change to these factors exposes the LNG supply chain to potential vulnerability. Asbjørnslett (2009) used the concept of vulnerability to characterize a supply chain system's lack of robustness or resilience. Adopting as an approach of analysing vulnerability in a supply chain system, risk can be reduced, to improve the system's resilience (Asbjørnslett, 2009). The analysis of vulnerability establishes the relationship between relevant risks and the potential scenarios (as well as consequences) (Asbjørnslett, 2009). In the study of LNG SCRM, the concept of vulnerability is used to map the SCRs. A vulnerability map (Figure A3.1, Appendix B) for the LNG supply chain in Australia was prepared through the review of the literature and incorporating possible factors which may affect the supply chain in the future. The types of literature reviewed were journals, conference papers, newspaper articles, company brochures, magazines, websites, etc. The vulnerability map is a preliminary work to identify LNG SCRs in Australia. Based on the vulnerability map, SCRs were identified with these presented in the following section accompanied by citations of the relevant references.

3.3 Identification of LNG Supply Chain Risks

Following the development of the LNG vulnerability map (Figure A3.1), a total of 33 SCRs were identified for the LNG supply chain in Australia with these summarized in Table 3.1.

Table 3.1: LNG supply chain risks for Australia

SCR Code	LNG Supply Chain Risks	References
SCR1	Downgrade of investment attractiveness for new plants	(ATC, 2015, 2016)
SCR2	Occurrences of policy differences from state to state	(EISC, 2014)
SCR3	Increasing international pipeline gas supply	(Jacobs, 2011; BP, 2015; Leidos, 2014)
SCR4	Higher cost of skilled human resources than paid by competitors	(BCA, 2012, 2013; Cann and Giles, 2015)
SCR5	Lower productivity for LNG production	(Cann and Giles, 2015)
SCR6	Strong A$ (local currency)	(BCA, 2013)
SCR7	Different types of reception terminal and storage facilities	(Leather et al., 2013; Bramoulle et al., 2004)
SCR8	Cost of energy mix for securing energy security	(ABS, 2013; EIA, 2015a)
SCR9	Introduction of a carbon tax	(Leather et al., 2013; IETA, 2014)
SCR10	Adoption of new emissions trading scheme	(PA, 2010; Sopher and Mansell, 2014)
SCR11	Strong community concerns regarding non-conventional gas exploration	(Ferguson, 2015; Shearman, 2012; Leather et al., 2013)
SCR12	Plant start-up delays	(Macdonald-Smith, 2015a)
SCR13	Supply of gas in domestic market at lower cost hence reduced LNG exports	(IGU, 2015; Chambers, 2014; Leather et al.,2013)
SCR14	Competition from other exporters in global LNG market	(Diss, 2015)
SCR15	Emergence of new exporters in global LNG market	(Cassidy and Kosev, 2015; GLL, 2015)
SCR16	Discovery of new reserves, for example, East Africa	(IEA, 2014)
SCR17	Emergence of US shale gas revolution	(EIA, 2015b)
SCR18	Extraction of natural gas from methane hydrate in Japan	(BBC, 2013; Beaudoin et al., 2014)
SCR19	Multiple regulatory risks	(BCA 2013; EISC, 2014)
SCR20	Emergence of LNG spot market and short-term contracts	(Kwok, 2012; Cassidy and Kosev, 2015; IEA, 2013)
SCR21	High cost due to remoteness of projects	(BCA, 2013)
SCR22	Increase in competition from other fuels	(Macdonald-Smith, 2015b; BP, 2015, Krauss, 2015)
SCR23	Flexible capability of technology adaptation	(Leather et al., 2013)
SCR24	Customer demand priority shifts to another energy mix	(BP, 2015)
SCR25	Over-proposed LNG projects	(Macdonald-Smith, 2015b; Leather et al., 2013)
SCR26	Unstable fiscal stability and fiscal credibility	(Leather et al., 2013; Shell Companies in Australia, 2009; APPEA, 2014)
SCR27	Lack of skilled staff in LNG projects	(BCA, 2013; Grudnoff, 2012; Briggs, 2010)
SCR28	Slowed recovery from global economic slowdown	(Ryan, 2015; UN, 2015)

SCR29	Long-term supply contract revision	(Leather at al., 2013; Cassidy and Kosev, 2015) (Macdonald-Smith, 2015c; Hartley, 2013)
SCR30	Fluctuation of LNG price due to oil production	(Jacobs, 2011; Cassidy and Kosev, 2015)
SCR31	Severe weather causing low productivity	(BCA, 2013)
SCR32	Emergency shutdown of the plant due to floods	(BoM, 2015)
SCR33	Emergency shutdown of the plant due to tropical cyclones	(BoM, 2015; Leather et al., 2013; Woodside, 2015)

Notes: ABS=Australian Bureau of Statistics; APPEA=Australian Petroleum Production and Exploration Association; ATC=Australian Trade Commission; BBC=British Broadcasting Corporation; BCA=Business Council of Australia; BoM=Bureau of Meteorology; BP=British Petroleum; EIA=Energy Information Administration; EISC=Economics and Industry Standing Committee; FR=*The Financial Review*; GLL=Global LNG Limited; IEA=International Energy Agency; IETA=International Emissions Trading Association; IGU=International Gas Union; PA=Parliament of Australia; UN=United Nations.

3.4 Short Descriptions of LNG Supply Chain Risks

Short descriptions of SCRs are presented below. Some risks are interrelated, thus making it difficult to study them independently. Here, efforts have been made to define them independently which is how they are presented in this study of LNG supply chain risk mitigation in Australia.

SCR1: Downgrade of investment attractiveness for new plants

The Australian Trade Commission (ATC) in its benchmark reports (2015, 2016) reported that Australia is an attractive investment destination for reasons including: (i) its record of 25 years of uninterrupted growth; (ii) provision of a safe, low-risk environment for doing business; (iii) an innovative economy which supports world-class research and development (R&D) opportunities; (iv) a talented workforce which is among the most skilled and diverse in the world; (v) its connection to Asia both economically and culturally; and (v) one of the easiest places for doing business in the world (ATC, 2015, 2016). However, in a dynamic world, things are changing at an ever-increasing pace both domestically and internationally. In the context of investment in the LNG sector, in recent times and particularly in the last four years, some signs of domestic changes in Australia in comparison to the past include: (i) lower level of political stability, for example, Australia has had five prime ministers since November 2007 to October 2016 (Henderson, 2016); (ii) relatively more changes in policy with changes in government, for example, proposed introduction of carbon tax from 1 July 2012 by the Labor government (Leather et al., 2013) and subsequent repeal legislation by the Coalition controlled House of representatives (IETA, 2014); (iii) budget deficit and financial instability, for example contentious negotiation by the Labor and the Coalition of the resources super profit tax leading to lack of trust in the government by the business community (Leather et al., 2013); (iv) slowing resources sector and fall in commodity prices, for example fall of price of iron ore international market; (v) relatively high unemployment rate; and (vi) loss of AAA credit rating by some state governments. With these changes in the local political and economic arenas as well as the global changes, the investment attractiveness of Australia is at risk with a possible downgrade of investment attractiveness. This may result in challenges in attracting investment for new LNG plants.

SCR2: Occurrences of policy differences from state to state

Australia is a large country with a great diversity of geological, environmental, social and political settings, and diverse economic activities across the country. It has one federal government and seven state or territory governments responsible for governing the country. It is a challenging task to keep all federal and state or territory laws and legislation consistent over time to meet the needs of people and business. As is usual, some inconsistencies exist between the policies for different states or territories which pose a risk for the LNG industry in operating across the nation. The findings from the report, *The Economic Impact of Floating LNG on Western Australia* (Economics and Industry Standing Committee [EISC], 2014), suggest many inconsistencies and disputes and a lack of clarity among policies between federal (Commonwealth) and state (Western Australian [WA]) policies. For example, Finding 12 of the report states that "[u]nilateral Commonwealth decisions relating to petroleum Retention Leases potentially have a major negative impact on the Western Australian economy". Another example is Finding 10 which states "[t]he Commonwealth Government's 2013 approval of variations to the Commonwealth Browse gas field Retention Leases does not amend the leases for State titles". An example of lack of clarity is Finding 16 which states "[i]t is not clear what criteria the Department of State Development applies in its assessment of whether a resource project should be developed through a State Agreement".

SCR3: Increasing international pipeline gas supply

The two main ways of transporting and trading natural gas are: (i) transporting gas through a pipeline under high pressure (the more conventional way); and (ii) transporting gas as LNG in specialized tankers where gas is cooled to a liquid form with its volume reduced (Jacobs, 2011). As shown in Figure 3.2(a), in 2010, the international LNG trade was around half the size of the pipeline gas trade. Since 2010, the pipeline gas trade has remained steady with an increase in the LNG trade (Figure 3.2[b]). However, the market share of the LNG trade is projected to increase in the future (BP, 2015). A working paper prepared by Leidos, Inc. for the US Energy Information Administration (EIA) in August 2014 reported that the evolution of the pipeline gas supply in growing economies will impact upon the course of the LNG trade including natural gas supply and consumption (Leidos, 2014). In addition, the paper reported on some pipeline projects that were at different stages (conceptual, proposed and under development), for example: (i) the Trans-Alaska pipeline; (ii) the Pacific Trail pipeline to potential LNG export terminals; (iii) the Iran–Pakistan–India pipeline; (iv) the Sakhalin–Japan pipeline; etc. Moreover, the two major proposed pipeline developments (in terms of proposed size and potential market influence) were: (i) the Russia–China pipeline and (ii) the Southeast Asian pipelines. The paper remarked that, due to pipeline competition, stranded markets, such as China, South Korea and Japan, may behave more like the European market. These countries (China, South Korea and Japan) are major importers of LNG from Australia. Thus, LNG from Australia may face significant challenges in these markets with an increasing pipeline supply of natural gas in coming years. Therefore, an increasing pipeline supply of natural gas is considered as a risk to the LNG supply chain in Australia.

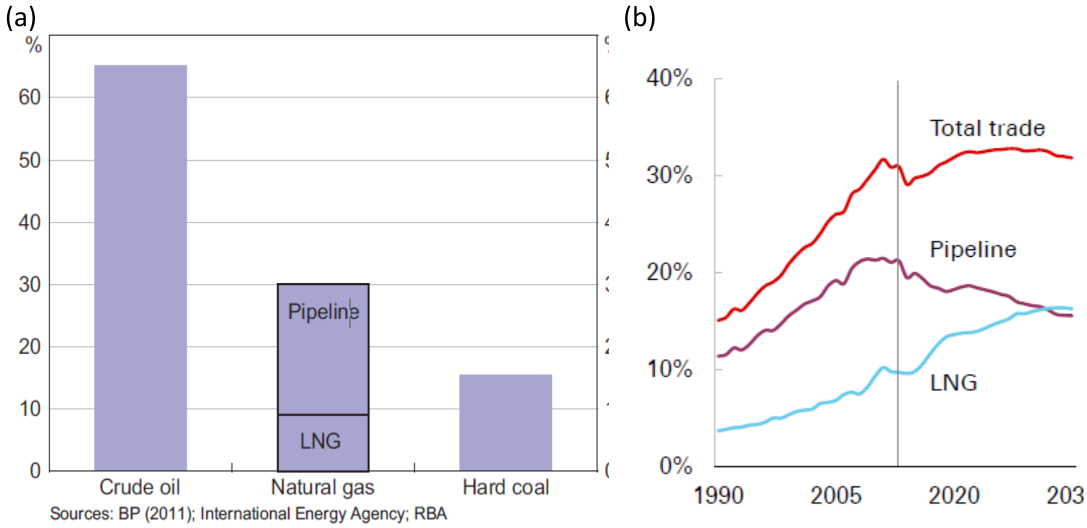


Figure 3.2: (a) International trade in energy commodities as percentage of production in 2010; and (b) share of global gas consumption

Sources for Figure 3.2(a): BP (2011); International Energy Agency (IEA) and Reserve Bank of Australia (RBA), cited in Jacobs (2011): source for Figure 3.2(b): *Energy Outlook 2035* (BP, 2015)

SCR4: Higher cost of skilled human resources than paid by other competitors

The Business Council of Australia (BCA) in a study released in June 2012, titled *Pipeline or Pipe Dream? Securing Australia's Investment Future* warned that Australia was becoming a high-cost environment in delivering major projects including LNG projects (BCA, 2012). Citing research, the report mentioned that resources projects in Australia are 40% costlier than comparable projects in the US Gulf Coast. A task force formed by the BCA in September 2012 following the report findings confirmed that project costs in Australia were higher compared to those in other developed countries (BCA, 2013, p.3). In news analysis of Australia's gas industry published in *Gas Today* on 29 April 2015, the high cost of labour was reported to be one of the biggest challenges for Australia's LNG industry (Cann and Giles, 2015). Citing several independent studies, the analysis highlighted that the unit labour cost in the Australian gas sector was higher compared to its global competitors: more specifically, wages in the Australian gas industry were 35% higher than in the USA and on par with Norway (the highest in the world) (Cann and Giles, 2015). The high labour cost is a potential risk to the LNG supply chain in Australia as the cost is relatively high compared to other parts of the world, especially African countries. The high cost of labour could work as a barrier to attracting investment to proposed or new LNG projects in Australia.

SCR5: Lower productivity for LNG production

Lower productivity in the LNG industry in Australia has been well reported in newspapers, such as *The Australian*, over the last two years. News analysis of Australia’s gas industry published in *Gas Today* on 29 April 2015 reported that low productivity is one of the biggest challenges for the LNG industry in Australia (Cann and Giles, 2015). In addition, the analysis reported that workers in Australia achieved only 65–70% of the productivity achieved by equivalent workers on the US Gulf Coast. Citing the Australian Bureau of Statistics (ABS), the analysis added that Australia's productivity performance grew strongly until 2003–04; however, in many of the years since then, negative growth has been recorded. Lower productivity contributes to increases in project cost and delays in project delivery. These factors ultimately negatively influence the ability to attract competitive investment; therefore, lower productivity appears as a risk to the LNG supply chain in Australia.

SCR6: Strong A$ (local currency)

The Independent Project Analysis (IPA) undertakes assessment of overall project construction productivity at various locations around the world through its series of “twinning studies”. The study compares the total construction hours on groups of projects of similar scope at various locations around the world, with all cost benchmarks prepared through adjusting to US Gulf Coast conditions in 2003 (BCA, 2013, p.14). Citing findings from the IPA's paper, the BCA (2013) reported that project cost in Australia has been impacted by increases in the foreign exchange rate in recent times, and particularly since 2003. The high exchange rate of Australian currency negatively influences the ability to attract competitive investment for LNG projects. Therefore, a strong local currency is considered as a risk to the LNG supply chain in Australia.

SCR7: Different types of reception terminal and storage facilities

As previously mentioned, LNG has some competitive advantages (e.g. being cheaper to supply to distant markets and avoidance of geopolitical risk) over the pipeline supply of natural gas. However, the gas composition of importing countries or regions varies considerably due to their distinct reservoir conditions (Leather et al., 2013). The quality specifications of LNG unloaded at a reception terminal are determined by the terminal's limitations which usually reflect the constraints of the gas transport and distribution network of a particular region in the downstream of the supply chain (Leather et al., 2013). These quality specifications vary to a great extent from one country to another and even for different networks within a country where several companies operate the gas distribution network (Leather et al., 2013). Official regulations or the gas distribution network operators usually set these specifications (Bramoulle et al., 2004). Therefore, Leather et al. (2013) cited that "there is no such a thing as a go anywhere LNG product". Thus, downstream facilities, such as the reception terminal, storage facilities and distribution network, play an important part in the export of liquefied natural gas (LNG). Hence, the different types of reception terminal and storage facilities are regarded as a risk to the LNG supply chain in Australia.

SCR8: Cost of energy mix for securing energy security

An important part of a country's energy policies is the energy mix with the reasons for its importance including: (i) enhancing energy security; (ii) controlling emissions; (iii) providing economic benefits and well-being; and (iv) determining the source of supply or availability. For example, in Australia, the total domestic primary energy supply was 6100 petajoules (PJ) in 2010–11 with the majority (96%) from non-renewable sources (Australian Bureau of Statistics [ABS], 2013). In recent times, the use of gas has been increasing while the proportion of coal is in decline (Figure 3.3). Both major political parties in Australia are willing to increase the share of renewable energy in the future as it helps to reduce carbon emissions to meet the obligation set out in the Kyoto Protocol and is a source of sustainable energy for the future. The increased use of gas also helps Australia to reduce its carbon emissions and to become more self-reliant on its own sources of energy as natural gas is abundant in Australia, thus meeting the demand for the future enhancement of energy security.

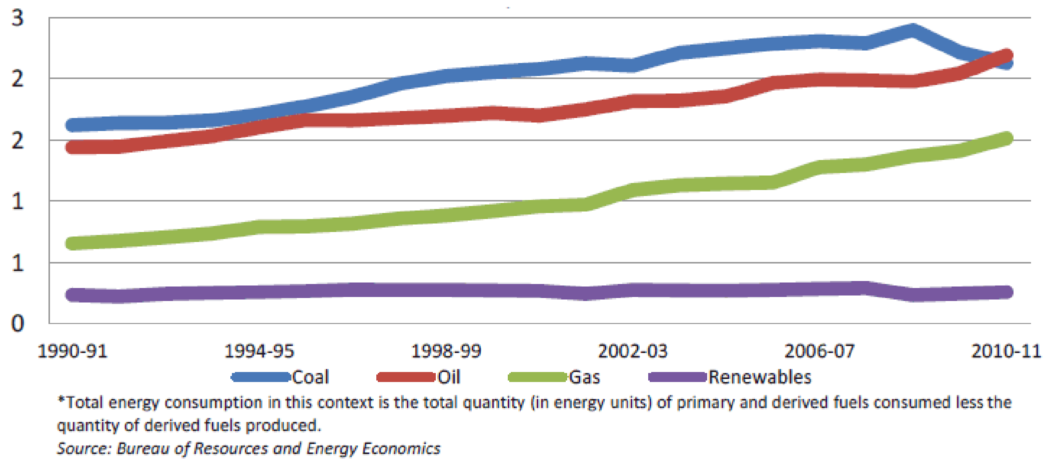


Figure 3.3: Total energy consumption in Australia (petajoules [PJ], 000) by fossil fuels and renewable sources for period 1990–91 to 2010–11

Source: ABS (2013)

In 2012, most energy in China was supplied by coal, with oil and hydroelectric power the next largest sources (Figure 3.4). The US Energy Information Administration (EIA, 2015a) has reported that the Chinese government is currently increasing the consumption of natural gas (reducing the use of coal) and has set a target of increasing the use of non-fossil fuel to 15% and 20% of the energy mix by 2020 and 2030, respectively.

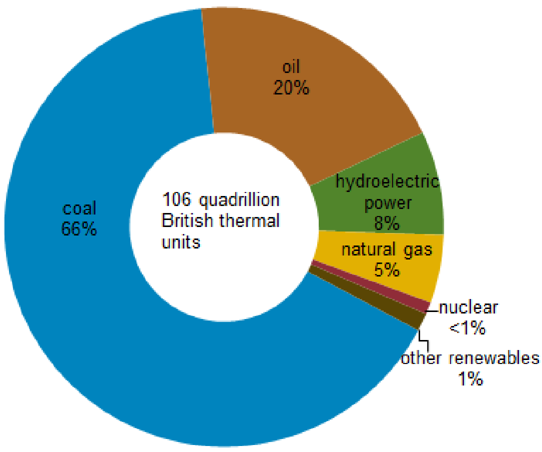


Figure 3.4: Total primary energy consumption in China by different fuels in 2012

Notes: The total may not equal 100% due to independent rounding. The analysis includes commercial fuel only and does not include biomass that is used outside power generation. Source: US Energy Information Administration (EIA), 2015a)

This new policy has significant implications for Australia's LNG exports. China is Australia's largest trade partner and one of the largest importers of Australian liquefied natural gas (LNG). The Chinese government's new energy policy is expected to boost Australian LNG exports to China in the future. However, in Australia, the demand for cleaner energy is also increasing with this exerting pressure for Australia to improve its energy mix (reducing the use of coal). Thus, Australia needs to balance between LNG exports and the domestic demand for gas. Therefore, the cost of the energy mix for securing energy security is contemplated as a risk to the LNG supply chain in Australia.

SCR9: Introduction of a carbon tax

Natural gas is a relatively clean form of energy compared to other forms of fossil fuel, such as coal and oil. The introduction of a carbon tax is expected to lead to increased demand for a cleaner fuel, such as liquefied natural gas (LNG). Globally, initiatives are being taken to reduce carbon emissions (e.g. requirements under the Kyoto Protocol). Australia ratified the Kyoto Protocol in December 2007. Since that date, different Australian governments, and particularly the Labor governments, have taken some initiatives to reduce carbon emissions through pricing carbon and proposing that a carbon tax would be introduced on 1 July 2012 (Leather et al., 2013). However, in an update, the International Emissions Trading Association (IETA) (2014) reported that, in early March 2014, "repeal legislation" was passed in the Coalition-controlled House of Representatives which was later passed in the Senate. The political uncertainty on carbon tax in Australia is expected to continue in different forms over the coming years. However, any tax on carbon is expected increase the demand for LNG in the domestic market, thus affecting LNG exports and demanding a balance between the two. Therefore, the introduction of a carbon tax is treated as a risk to the LNG supply chain in Australia.

SCR10: Adoption of new emissions trading scheme

The Parliament of Australia (PA) (2010) website defined emissions trading as:

> Emissions trading uses a property rights approach to provide incentives for individuals to conserve their environment by clarifying their rights to and responsibilities for common property. The common property in question is the quality of the environment and, in this particular case, the quality of the atmosphere.

The four main variations on emissions trading systems presented on the website are: (i) cap-and-trade systems; (ii) baseline-and-credit schemes; (iii) project-based schemes; and (iv) hybrid schemes. The International Emissions Trading Association (IETA) reported on March 2014 that Australian governments had been intending to move forward with an emissions trading scheme (ETS) for the previous 10 years (Sopher and Mansell, 2014). However, political contention on the ETS continues to prevail among the political parties. Although progress has been made in policies relevant to controlling carbon emissions (such as ratification of the Kyoto Protocol in December 2007), Australia is yet to come to a consensus among the major parties on an emissions reduction scheme. Adoption of any emissions reduction scheme is expected to increase domestic demand for cleaner fuels, such as LNG or natural gas. However, the Australian government has to establish the balance between domestic LNG demand and international LNG demand. Therefore, adoption of a new ETS is treated as a risk to the LNG supply chain in Australia.

SCR11: Strong community concerns regarding non-conventional gas exploration

The fracking and hydraulic fracturing technology used in non-conventional gas development may pollute ground water, air and land use. Community concerns have been reported in Australia related to the development of non-conventional gas (such as coal seam gas and shale gas). For example, the Australian Broadcasting Corporation (ABC) reported on 28 January 2015 that: "[t]he Victorian Government is extending its ban on coal seam gas (CSG) exploration and fracking, pending a Parliamentary inquiry to examine the science and impact of the methods used" (Ferguson, 2015). The Renew Economy website, on 28 November 2012, reported on increased community concerns over non-conventional gas, with the concerns including water and air pollution, land use, fugitive emissions, and inadequate assessment and regulation (Shearman, 2012). Leather et al. (2013) described environmental concerns in Australia related to coal seam gas (CSG) and shale gas, reporting that hydraulic fracturing is a contentious issue globally, and also that US influence through the deregulation of its national standard was affecting Australia. It is important to note that, environmental risks are perceived differently in different society. Also, mitigation plan of an environmental risks (or impact) are different in different societal and environmental context. This situation becomes more complex when economic, political and social dimensions are added to an environmental issue and its mitigation. Therefore, it is not straight forward to draw a conclusion in a comparison between to different country on a particular issue. Therefore, community concerns are regarded as a risk to the LNG supply chain in Australia.

SCR12: Plant start-up delays

Liquefied natural gas (LNG) projects are complex and involve large investment: they may have offshore and onshore components, subsea installation, national and international construction components, complex engineering design and project scheduling, etc. Some examples of complexity of LNG supply chain include (i) LNG projects require billions of dollars investment, (ii) longer project life cycle (could be over 40 years), (iii) longer contractual customer arrangements (may be over 20 years) which demands financial satiability. Considering such large investment and longer project life cycle, any changes in fiscal policy my influence the economic viability of the proposed or existing projects as well as investment attractiveness of future projects (Shell Companies in Australia, 2009). Stated simply, an LNG project is a complicated venture representing different components (upstream, midstream and downstream) of the supply chain. The complexity of LNG projects poses risks to delivering the project on time and within budget. In Australia, some LNG projects face start-up delays: this obviously has economic and market consequences. The cause of plant start-up delays could range from labour disputes to delay in the construction of an overseas component. For example, the *Sydney Morning Herald* (SMH) on 25 May 2015 reported "Inpex, Chevron facing delays as worries grow on LNG start-ups" (Macdonald-Smith, 2015a). One of the causes noted was the bottleneck in manufacturing a massive offshore platform at a South Korean shipyard. This problem indicated the huge risk in the start-up of LNG projects in Australia during the next two or three years. A few months later, on 2 September 2015, the *Sydney Morning Herald* reported that the labour dispute associated with the Gorgon LNG project in Western Australia was threatening the already delayed construction schedule. Due to the complex nature of LNG projects, plant start-up delay appears as a risk to the LNG supply chain in Australia.

SCR13: Supply of gas in domestic market at lower cost hence reduced LNG exports

The applications of LNG as a fuel have continued to evolve over the past few years. Figure 3.5 shows some recent applications of LNG as a fuel (International Gas Union [IGU], 2015). The IGU (2015) reported on the evolving role of LNG as the potential physical form of natural gas in all industries which use hydrocarbon energy, with such industries including rail, road, marine, aviation, heavy machinery, drilling, mining, power generation and agriculture. In addition, the IGU (2015) highlighted that the market for LNG as a transport fuel is growing rapidly due to its advantage over pipeline supply in serving consumers in remote areas. Australia is a large continent where supply by pipeline to many remote places is not economically viable. Therefore, LNG has the potential to grow as a fuel in the domestic market and, in Australia, to serve as a fuel in remote areas.

In a news article in *The Australian* published on 26 February 2014, it was reported that about 250 LNG-powered trucks were already operating in Australia (Chambers, 2014). This strengthens the already expressed opinions on using natural gas domestically for industrial development, generating high-value petrochemical products and creating jobs. For example, Leather et al. (2013) reported on concerns that Australia should exploit natural gas to generate high-value petrochemical products through industrial use. However, when considering the high cost of labour in Australia compared to neighbouring economies, gas may need to be supplied at a lower cost in order to develop a competitive local industry sector. Therefore, the evolving role of LNG as a fuel for a range of industries may shape many policies related to energy, industry and economic development in the coming years. These factors pose challenges to the Australian government in shaping these policies to optimize the benefits of LNG through balancing the demand between domestic and international markets. Hence, supplying gas in the domestic market appears as a risk to the LNG supply chain in Australia.

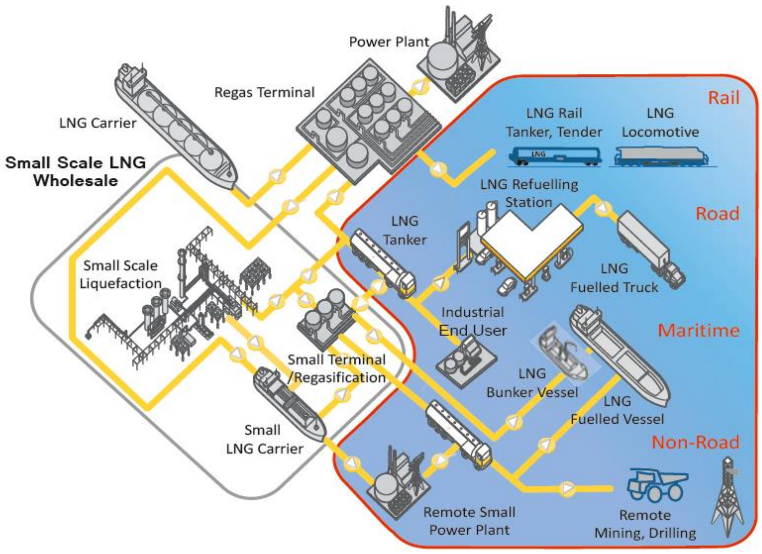


Figure 3.5: Applications of LNG as a fuel
Source: IGU (2015)

SCR14: Competition from other exporters in global LNG market

Some major LNG exporters (other than Australia) to the international market are proving to be competitive in price. Analysis from a report compiled by the Carbon Tracker Initiative, a London-based think tank, on the relative break-even costs for planned LNG projects around the world are presented in Figure 3.6 (Diss, 2015). As shown in Figure 3.6, the break-even price for most US and Canadian projects was US$10/mmBtu (one million British thermal units) with Australian projects positioned a little higher up the curve (Diss, 2015). The report warned that the Australian LNG price would need to be competitive to add more supply to the international market in coming decades. Therefore, to compete in the international market, Australia needs to offer a competitive price to supply LNG in the coming years due to increasing competition from other exporters. Hence, competition from other exporters in the international market is regarded as a risk to the LNG supply chain in Australia.

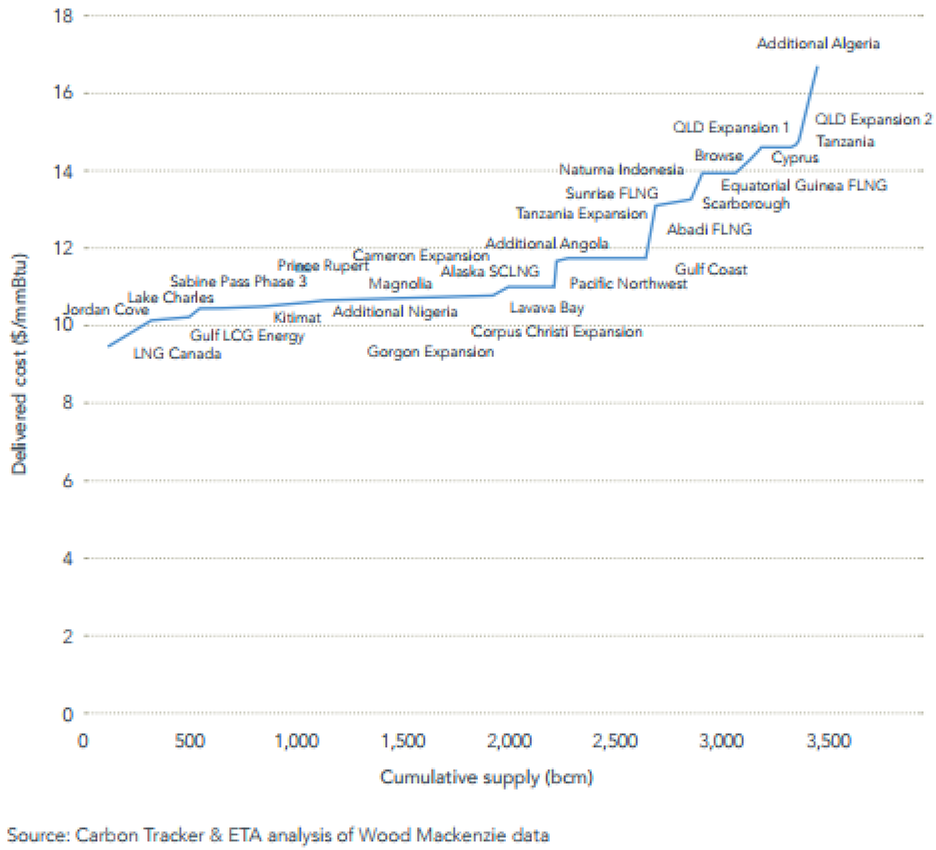


Figure 3.6: Graphic from Carbon Tracker Initiative report of relative break-even costs for planned LNG projects around the world

Note: bcm=billion cubic metres. Supplied: Carbon Tracker Initiative; source: Diss (2015)

SCR15: Emergence of new exporters in global LNG market

Algeria was the first country to export LNG in 1964, with the LNG trade growing slowly from then until the early 1990s. In 2014, 19 countries were exporting LNG with Papua New Guinea (PNG) the last country to join (Figure 3.7). In most LNG-exporting countries, some LNG projects are under construction, some are near completion, while some are ready to join the export market. For example, in 2013, Australia was the third largest exporter of LNG with a little less than 10% of global market share and was expected to become the largest producer by 2018 as some Australian projects under construction came into production (Reserve Bank of Australia [RBA], cited in Jacobs, 2011). Globally, a good number of LNG liquefaction and regasification terminals are at different stages of development. For example, as reported by Global LNG Limited (GLL) (2015), around 16 LNG projects are under construction, 19 projects are planned and 29 projects are proposed or under study. Therefore, competition is expected to increase in the coming years for LNG exports with the emergence of new exporters in the global LNG market. Hence, the emergence of new exporters in the global LNG market is considered as a risk to the LNG supply chain in Australia.

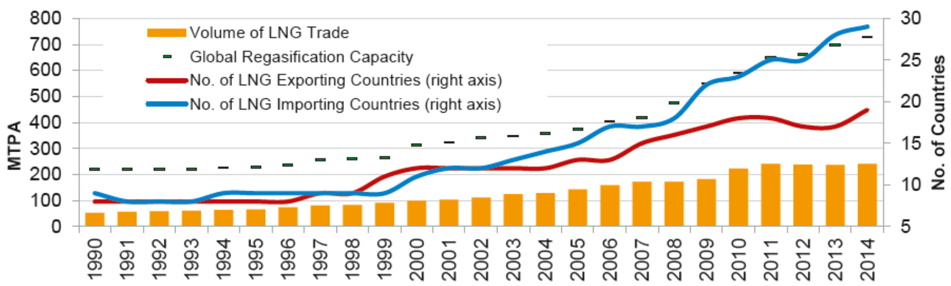


Figure 3.7: LNG trade volume, number of importing and exporting countries, 1990–2014

Note: MTPA=million tonnes/annum. Sources: Information Handling Services (IHS), International Energy Agency (IEA), *World LNG Report 2015 Edition* (IGU, 2015)

SCR16: Discovery of new reserves, for example, East Africa

A large gas reserve was discovered in Africa in the last five years, with the International Energy Agency (IEA) in its *Africa Energy Outlook 2014* reporting the discovery of over 5 trillion cubic metres (Tcm) of gas resources in the East African coastal waters off Mozambique and Tanzania (IEA, 2014). The *Africa Energy Outlook 2014* also highlighted that nearly 30% of the global oil and gas discovered in the last five years was in Sub-Saharan Africa. The discoveries of oil and gas in recent times are presented in Figure 3.8. The recent discoveries of oil and gas resources in Africa may attract a large portion of global investment in the energy sector for which a country like Australia may have to strongly compete to attract investment although different regions have unique advantages. For example, for Australia, political stability is high but cost is also high; on the other hand, for Africa, political stability is low but cost is also low. Therefore, the discovery of new reserves of oil and gas across the world, particularly in Africa, is regarded as a risk to the LNG supply chain in Australia.

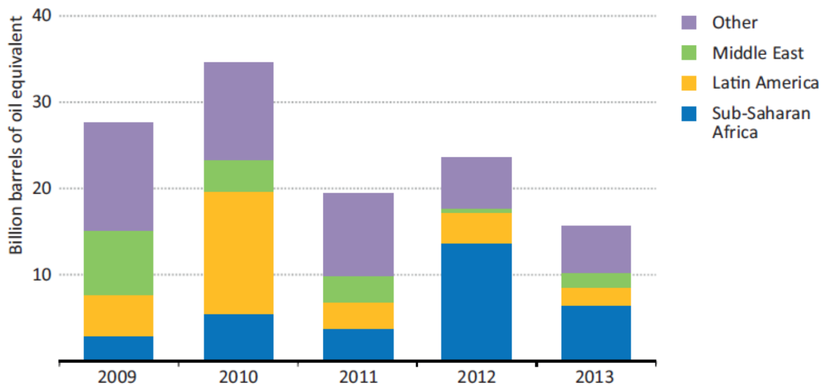


Figure 3.8: Global discoveries of oil and gas (with Sub-Saharan Africa)
Source: IEA (2014)

SCR17: Emergence of US shale gas revolution

The shale gas development in the United States (US) has happened over the past two decades and now the US is in a position to export LNG to the European market or to the Asia-Pacific market. The US Energy Information Administration (EIA) in its *Annual Energy Outlook 2015* reported an increase of 35% in total dry natural gas production in the US from 2005–2013, with production growth resulting largely from the development of shale gas (EIA, 2015b).

The EIA (2015b), in the same report, provided projections on US net imports of natural gas which would continue to decline through to 2040 beginning from 2007, while gross exports of natural gas were projected to increase for the same period. Natural gas production in the US in recent times and future projections are presented in Figure 3.9. Apart from gas reserves and production, exports of LNG from the US to the Asia-Pacific market will depend on many factors in coming years such as: (i) price of LNG at different spot markets; (ii) demand for growth of energy; (iii) price of oil; (iv) cost competitiveness of other LNG producers; (v) distance and transportation cost, etc. Taking into consideration the many influential factors, the US shale gas revolution is leading to the US becoming a potential competitor in the Asia-Pacific LNG market. Therefore, the US shale gas revolution is considered as a risk to the LNG supply chain in Australia.

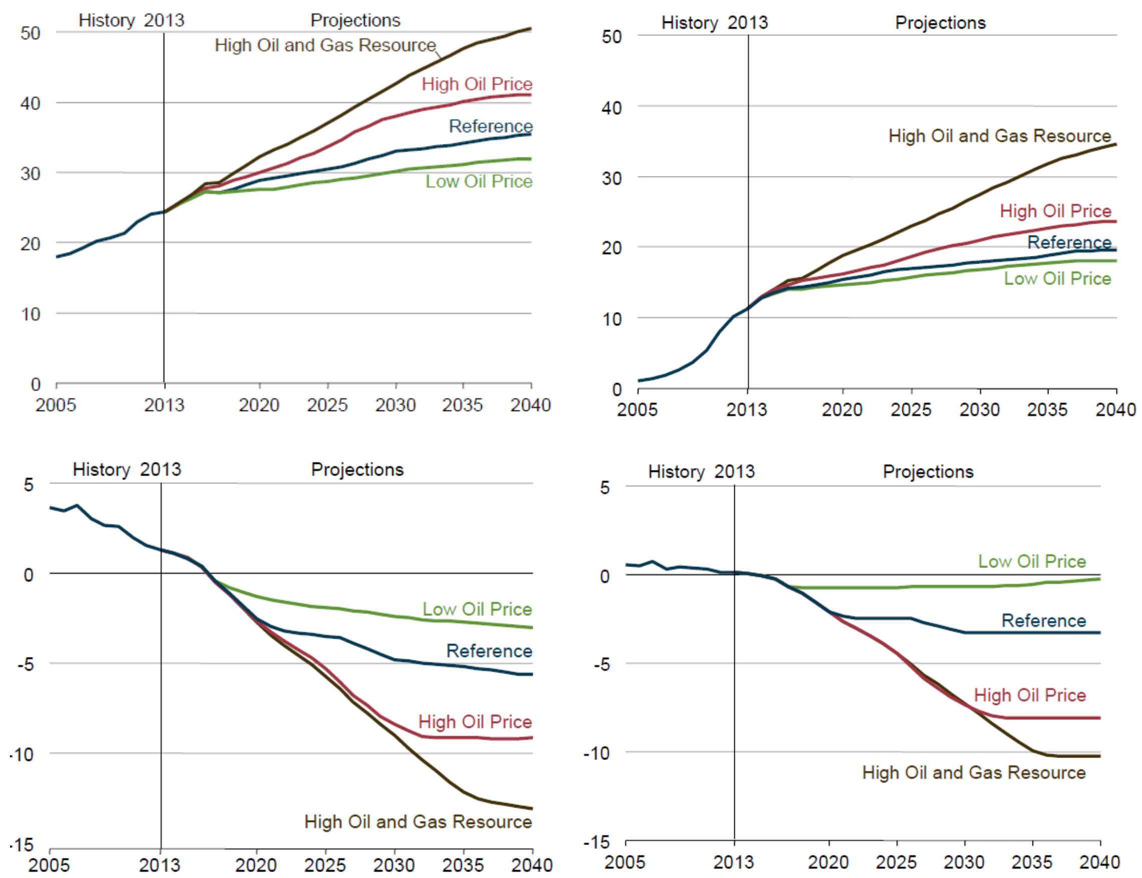


Figure 3.9:(a) US total dry natural gas production; (b) US shale gas production; (c) US total natural gas net imports; and (d) US LNG net imports in four cases, 2005–2040 (trillion cubic feet)

Source: *Annual Energy Outlook 2015* (US Energy Information Administration (EIA), 2015b)

SCR18: Extraction of natural gas from methane hydrate in Japan

Methane hydrates, or clathrates, are defined as "a type of frozen "cage" of molecules of methane and water" (BBC, 2013). Japan has recently reported the first ever successful extraction of natural gas from methane hydrates off its central coast (British Broadcasting Corporation [BBC], 2013). Other countries trying to extract gas from methane hydrate include Canada, the US and China. At present, little is known about the global occurrence of methane hydrate. However, based on a recent different regional assessment, the United Nations Environment Programme (UNEP) in 2014 summarized a rough first-order estimate of methane hydrate (Figure 3.10) for different global regions that could occur in sand reservoirs (Beaudoin et al., 2014). Although still at the experimental stage, with advances in technology, the extraction of gas from methane hydrate could be a potential source of energy in the future particularly for nations which do not have many conventional sources of energy, such as Japan. Therefore, the extraction of natural gas from methane hydrate is considered as a risk to the LNG supply chain in Australia.

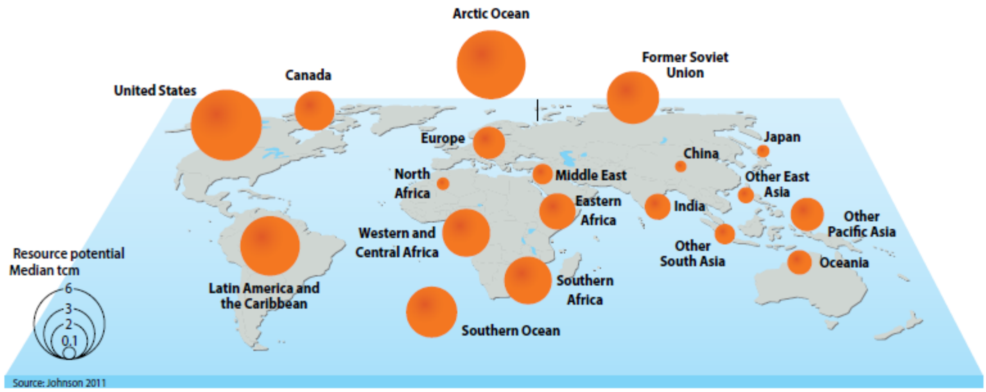


Figure 3.10: Methane hydrate potential by global region
Tcm=trillion cubic metres
Sources: Johnson (2011); Beaudoin et al. (2014)

SCR19: Multiple regulatory risks

Multiple regulatory risks at different levels of governance (such as federal, state or territory and local) appear as a problem in the approval and regulatory processes in Australia. The findings of the Business Council of Australia's (BCA) Project Costs Task Force in its 2013 report in relation to improving the government approval process for major capital projects noted increased cost, delays and uncertainty in the planning and environmental approval process for major capital projects. The report (BCA, 2013) warned that the difficulties in the approval process impacted on the cost competitiveness of capital projects causing deferment of investment and costing jobs and productivity. Highlighting recent reforms regarding the environmental approval process, the report (BCA 2013, p.36) noted the additional cost to business but without improvement in environmental outcomes.

The findings from the report, *The economic impact of floating LNG on Western Australia,* (Economics and Industry Standing Committee [EISC], 2014) noted considerable industry concern regarding regulatory processes. For example, Finding 68 articulated that "considerable industry concern exists in relation to the complexity and apparent inefficiency of Australia's regulatory regime for resource projects". The report suggested (in Recommendation 33) that the Western Australian government and the Commonwealth government work together as a matter of priority to expedite the reduction of the regulatory burden on resources projects. It is noted that the focus of SCR 2 is that different states have different policies for the same matter while the focus of SCR19 is that for a particular matter there are different policies for different level of governance (such as local, state and federal).

SCR20: Emergence of LNG spot market and short-term contracts

The LNG spot market and short-term contracts have increased exponentially over the past decade (Kwok, 2012), constituting approximately 25% of the global LNG trade in 2012 (Figure 3.11[a]) (Cassidy and Kosev, 2015). The International Energy Agency (IEA) reported that the short-term purchase of LNG comprised 25–30% of the global LNG trade whereas before the 2000s, it had been less than 5% (IEA, 2013). Traditionally, the LNG market was dominated by long-term contracts to support the significant capital investments in extraction, transportation, storage and re-gasification which are an integral part of the LNG supply chain and to allow very limited or no right to upward or downward quantity adjustments (Kwok, 2012). The reasons for the emergence of the spot market and short-term contracts are explained by Kwok (2012) as: (i) variable demand and supply influenced by many factors including weather; (ii) seasonal variation of consumption; (iii) delay or disruption of domestic gas production; (iv) price and availability of other fuels; (v) demand for cleaner energy; (vi) flexibility to fill in the gaps due to short supply; and (vii) exploitation of prices between alternative LNG markets.

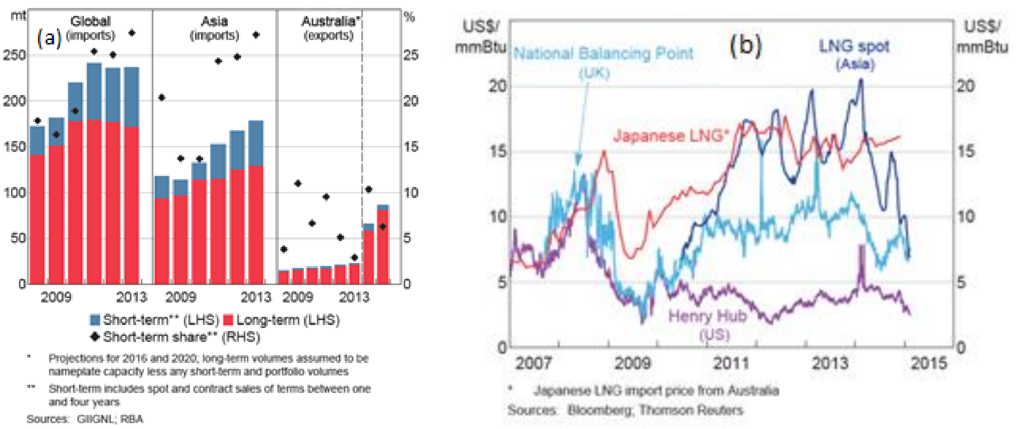


Figure 3.11: (a) International LNG trade by type showing trade in global imports, Asian imports and Australian exports; and (b) price of LNG in different markets
Source: Cassidy and Kosev (2015)

The emergence and recent growth of the LNG trade in spot market and short-term contracts were interpreted by the Reserve Bank of Australia (RBA) in 2015 (Jacobs, 2011) as a reflection of factors such as: (i) increased flexibility in some contracts to facilitate short-term sales;

(ii) an increase of demand in Japan following the Fukushima disaster; and (iii) diversification of the sources of supply and demand for LNG (Cassidy and Kosev, 2015). With the emergence of the spot market, securing long-term contracts is becoming increasingly difficult, therefore affecting the securing of upstream investment. Thus, the emergence of the spot market and short-term contracts are regarded as a risk to the LNG supply chain in Australia.

SCR21: High cost due to remoteness of projects

The Business Council of Australia (BCA) in its Project Costs Task Force (2013) report indicated that the remote environment of major capital projects increased the cost and exacerbated other drivers of cost, for example, the lack of skilled professionals. Very limited policy options are available to deal with the remoteness of LNG projects in Australia (BCA, 2013). Citing research carried out by Independent Project Analysis in 2012 and previous research conducted by the BCA, the report showed that the average cost premium for large complex processing projects, such as downstream components of LNG projects, was 50% higher in Australia compared to the US Gulf Coast (BCA, 2013, p.14). The report added that supply chain challenges were exacerbated by remoteness; for example, (i) a large proportion of workers work on a fly-in and fly-out basis; (ii) high cost of construction of the accommodation and other facilities (such as roads and recreational arrangements); (iii) high cost to attract skilled human resources; (iv) high cost to mobilize and maintain equipment; and (v) high cost of arranging consumables. Therefore, high cost due to the remoteness of LNG projects appeared as a risk to the LNG supply chain in Australia.

SCR22: Increase in competition from other fuels

In contrast to the literature on LNG before September 2014, the literature on LNG since that date has raised many negatives in reporting the prospects of the growth of LNG as a fossil fuel. One main reason for negative reports on the prospects of LNG growth is the drop in oil price since September 2014 (Figure 3.12). For example, regarding the future of Australia's LNG projects, on 4 June 2015, the *Sydney Morning Herald* (SMH), citing the International Energy Agency (IEA), reported a potential US$20 billion (A$25.7 billion) hit to annual revenue due to the previous year's halving of the crude oil price, and warned of an uphill battle for future projects (Macdonald-Smith, 2015b).

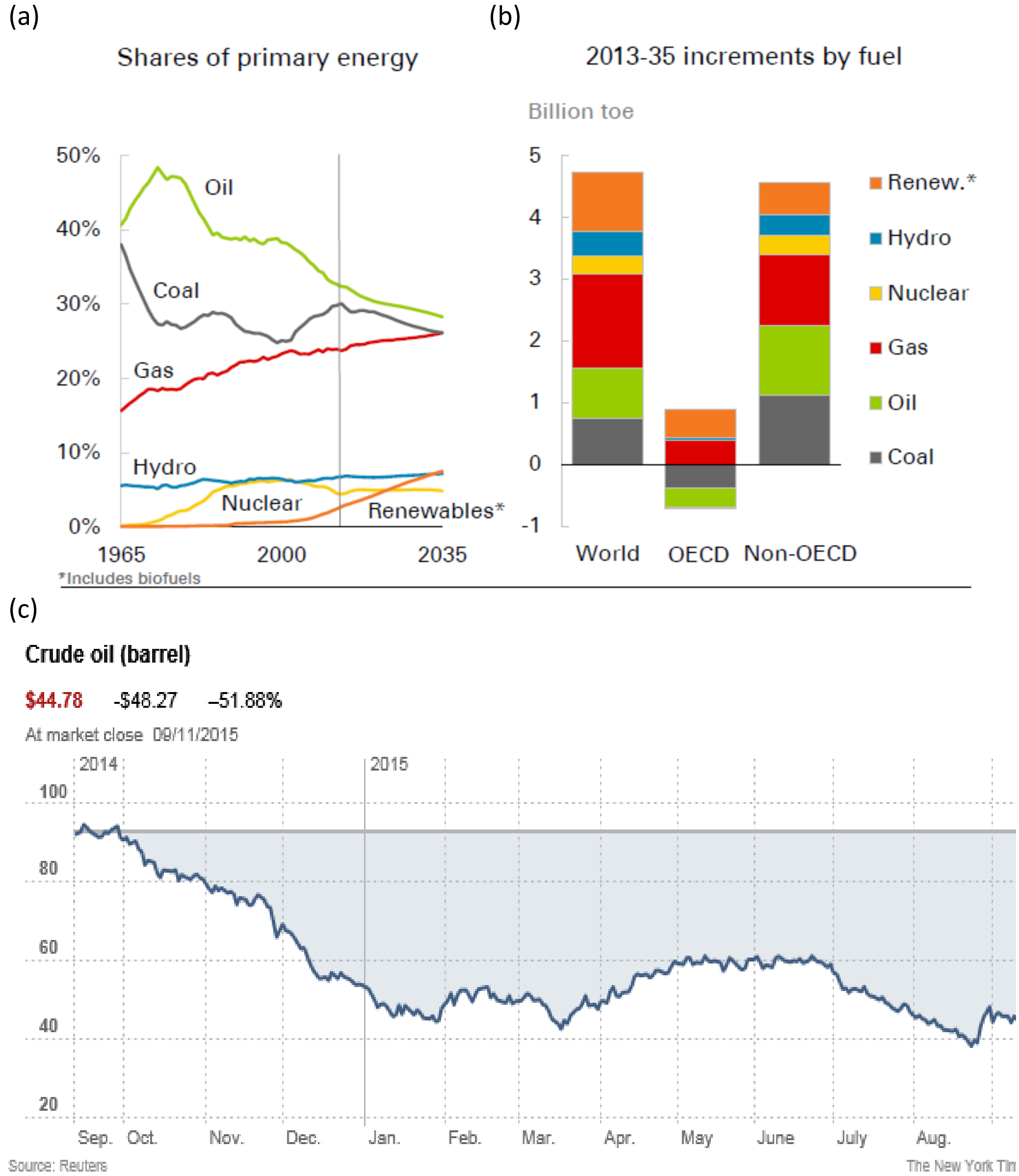


Figure 3.12: (a) Relative position of different fuels (fossil fuel continues to supply most of the world's energy); and (b) drop in oil price since September 2014

Notes: Brent crude oil, the main international benchmark, was trading around US$48 a barrel and the American benchmark was at around US$45 a barrel on Saturday, 12 September 2015. OECD=Organisation for Economic Co-operation and Development; toe=tonnes of oil equivalent.

Source for Figure 3.12 (a): *Energy Outlook 2035* (BP, 2015); and source for Figure 3.12(b): Krauss (2015)

This clearly reflects a basic fundamental of the energy market: a drop in price from competition between the fuels is one key parameter among many parameters, such as efficiency, availability, accessibility, country's policy, etc. Therefore, it is evident that LNG not only has to compete with other fuels in the energy market as an existing fuel, but it also must broaden its market share. The dynamics of the energy market will continue to change in the future as a natural process due to reasons including: technology and innovation (e.g. US shale gas revolution); changes in government policy (e.g. US is producing more oil than ever before); and demand for clean energy (e.g. demand for renewable energy growth with this growth expected to continue in the future) (Figure 3.12). The dynamics of the energy market are quite complex in nature and are influenced by multiple factors ranging from a simple economic indicator such as the slowing economy in China to conflicts in the Middle East. For example, BP (2015) Energy Outlook reported a range of factors which may influence the actual outcome of energy market in the future which include demand and pricing; political stability; general economic conditions; legal and regulatory developments; availability of new technologies; natural disasters and adverse weather conditions; wars and acts of terrorism or sabotage (BP, 2015). Any of these factors might be a determinant of future competition between LNG and other fuels. The drop in the oil price in recent times has occurred for several reasons (e.g. the slowdown of growth in China's economy). Therefore, competition from other fuels is regarded as a risk to the LNG supply chain in Australia.

SCR23: Flexible capability of technology adaptation

Liquefied natural gas (LNG) is a technology-intensive industry and the invention of new technology as well as the capability to adopt new or adapt existing technology will influence its success in the market. For example, due to advances in technology, unconventional gas (such as coal seam gas [CSG], shale gas and tight gas) has become a large source of the extractable gas reserves in many countries across the world. In addition, the extraction and processing of unconventional gas (such as shale gas) depends on how capable a country is in adapting the technology involved in the process. The adaptation of technology includes the technology itself, the understanding of private–public and government arrangements and environmental concerns. One example of limited flexibility in adopting the technology used to explore for coal seam gas (CSG) is the limited number of available rigs in Australia and the challenges involved in mobilizing these rigs across the country (Leather et al., 2013). The future success of the LNG supply chain in Australia will depend on how technology evolves around the energy industry, as well as the policies and responses of different governments towards those technologies, while considering economic and environmental outcomes. Therefore, the flexible capability of technology adaptation is regarded as a risk to the LNG supply chain in Australia.

SCR24: Customer demand priority shifts to another energy mix

The energy mix changes over time for many reasons such as: (i) advances in technology; (ii) innovation of new sources of energy (e.g. shale gas, tight gas, tight oil or renewables); (iii) demand for cleaner energy; (iv) change in policy (e.g. economic policy, environmental policy); (v) ensuring energy security; (vi) geopolitics (e.g. from sanctions to war); and (vii) natural calamities (such as the Fukushima disaster) as well as extreme weather (such as the recent power blackout in South Australia). British Petroleum (BP), in its *Energy Outlook 2035* (BP, 2015), termed the variability of the energy market as “continuous change is the norm for energy markets”, adding that gas is the fastest growing fossil fuel while coal is the slowest, with renewables expected to have continued rapid growth in the future. In a dynamic energy market, LNG has to find its share in the total energy mix. Therefore, if customer demand priority shifts to another energy mix, this is regarded as a risk to the LNG supply chain in Australia.

SCR25: Over-proposed LNG projects

Recent news articles have reported excess capacity in existing LNG projects around the world. For example, a news article published by the Australian Broadcasting Corporation (ABC) on 7 July 2015 reported that "… too much capacity has already been created". In a news article published on 4 June 2015, the *Sydney Morning Herald* (SMH) reported that the International Energy Agency (IEA) in its annual gas market report (2015) questioned the business case for the flood of investment in the LNG industry in Australia in such a short time frame (Macdonald-Smith, 2015b). Leather et al. (2013) also reported on the viability of future LNG projects in Australia considering that there were already too many existing projects worldwide. Therefore, over-proposed LNG projects are regarded as a risk to the LNG supply chain in Australia.

SCR26: Unstable fiscal stability and fiscal credibility

Fiscal stability and fiscal credibility are of paramount importance in attracting investment. In a submission to the Review of Australia's Tax System, Shell Companies reported that Australia has a well-deserved reputation of low sovereign risk and a relatively predictable and stable fiscal environment (Shell Companies in Australia, 2009), with this also reported by Leather et al. (2013). The submission (Shell Companies in Australia, 2009) also highlighted the importance of this stability and predictability in regard to LNG projects as: (i) projects require billions of dollars in upfront investment; (ii) the project life cycle could be over 40 years; and (iii) contractual customer commitments could be over 20 years. Therefore, changes in fiscal arrangements (after the upfront investment) can alter the economic viability of projects and also jeopardize future investment attractiveness (Shell Companies in Australia, 2009).

As reported by Leather et al. (2013), since 2010, several Australian governments (Labor and Liberal/Coalition) have undertaken the contentious negotiation, implementation and repeal of (i) the carbon tax and (ii) the resource super profits tax. This has fostered mistrust in the Australian government by industry and business with regard to fiscal stability (Leather et al., 2013). The Australian Petroleum Production and Exploration Association (APPEA, 2014) suggested in a pre-Budget submission to the Australian government that the government must deliver a stable, predictable and competitive tax regime to attract investment. Therefore, unstable fiscal stability and fiscal credibility are regarded as a risk to the LNG supply chain in Australia.

SCR27: Lack of skilled staff in LNG projects

The Business Council of Australia's (BCA) Project Costs Task Force (2013) reported that the lack of skilled workforce in capital projects resulted in the inflated cost of labour during the investment boom. The skilled areas cited in the report included project managers, engineers and other skilled professionals, as well as skilled trades. The BCA (2013) reported that the lack of skilled workforce had driven the need to train skilled workforce from other sectors, with this possibly leading to poor indirect productivity and increased cost of construction. In a strategic analysis paper, Briggs (2010) reported the impact of the skilled labour shortage on resources projects, highlighting that it is an ongoing risk to energy and mineral resources' projects and has long-term consequences in regional and national economies. In recent times, the skill shortage in the Australian LNG industry has been reported in other literature (Grudnoff, 2012). Thus, the lack of skilled staff is considered as a risk to the LNG supply chain in Australia.

SCR28: Slowed recovery from global economic slowdown

The Australian Broadcasting Corporation (ABC) on 30 April 2015 reported the continued slow recovery of the US over the last six years following its worst economic crisis in recent times (Ryan, 2015). Similarly, the United Nations (UN) report on the World Economic Situation and Prospects (WESP) reported in 2015 that the continued expansion of the global economy during 2014 was at a moderate and uneven pace, and noted that it was still saddled with the prolonged recovery process from the Global Financial Crisis (GFC) (UN, 2015). The recent financial crisis in Greece, price falls of resources in the world market, less demand for commodities and signs of the slowed growth of the Chinese economy are all slowing down the recovery from the Global Financial Crisis (GFC). As is the case with other energy sources, the demand for LNG is directly related to economic growth. Though demand for LNG depends on many factors, in a report, the Energy Quest (2009) reported about easing demand for LNG in the economic slowdown. The report noted that the recession has affected energy demand and prices across the world and identified the financial and economic crisis as fourth global factor which has influence on Australian natural gas market. Therefore, slowed recovery from the global economic slowdown is considered as a risk to the LNG supply chain in Australia.

SCR29: Long-term supply contract revision

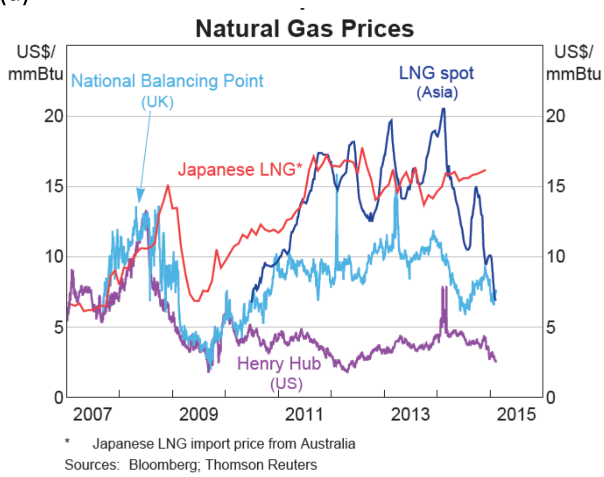
Historically, in Australia, long-term contracts were negotiated when fields were developed in the 1970s-80s, providing the benefits of investment certainty to the producers and supply security to the importers (Leather at al., 2013). Most Australian LNG projects have been under long-term supply contracts with buyers in the Asia-Pacific market (Leather et al., 2013), and the price of LNG exports has been linked to the price of oil (Cassidy and Kosev, 2015). Australian long-term LNG supply contracts have recently come under pressure for renegotiation for many reasons. One important reason is the pricing of LNG in the Asia-Pacific and global markets as a whole which is influenced by factors including: price of other fuels; countries' policies; natural disasters; competition from other fuels; advances in technology (e.g. fracking); emergence of new suppliers; economic slowdown; emergence of spot markets; energy security; investment security; flow of revenue; etc. The *Financial Review* (June, 2015) reported that the gap between spot market and contract prices for LNG in Asia has widened in recent times and noted this as an important reason for revision of long-term contracts (Macdonald-Smith, 2015c). Davis (2014) acknowledged a similar idea as he noted the contract price diverging from the market price. In a discussion paper, Hartley (2013) reported on the demand for greater flexibility in long-term contracts with an increased desire to take advantage of spot and short-term arbitrage opportunities. Therefore, securing long-term contracts is becoming increasingly challenging and is regarded as a risk to the LNG supply chain in Australia.

SCR30: Fluctuation of LNG price due to oil production

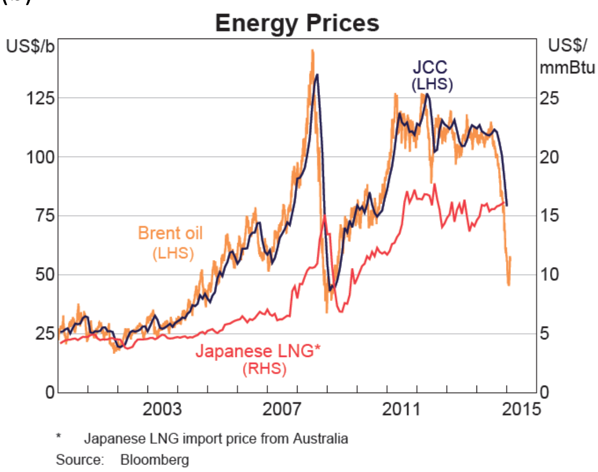
The natural gas market is globally segmented (Jacobs, 2011), for example, into the Atlantic region (covering Europe and North America) and the Asia-Pacific region. Due to differences in the market structure and pricing conventions in different market segments, significant differences in the price of natural gas are possible around the world (Cassidy and Kosev, 2015) (Figure 3.13[a]). Historically, pricing of LNG in the Asia-Pacific region has been linked to the price of oil (Rogers and Stern, 2014), with current pricing of Australian LNG exports based on the conventions of the Asia-Pacific region with long-term contracts (Cassidy and Kosev, 2015). The LNG purchasing agreements in Asia are generally long term in nature, usually in the order of 15–20 years, and the link between LNG and oil prices is negotiated confidentially between customers and producers (Cassidy and Kosev, 2015). In general, contracts are linked to the price of Japan Customs-cleared (JCC) crude oil which is highly correlated with the lagged price of Brent crude oil (Cassidy and Kosev, 2015) (Figure 3.13[b]). The price of oil in the international market fluctuates for many reasons (such as geopolitics, war, economic growth, supply–demand, etc.), with the price of LNG in the Asia-Pacific region aligned to these price fluctuations as is the price of Australian LNG exports (Figure 3.13[b]). With the fall in the oil price in the international market during 2014–15, the price of Australian LNG exports also fell due to this link with the oil price.

In Figure 3.13(c), the analysis shows the price sensitivity of Australian LNG exports with an outlook to 2020 for three scenarios: (i) “reference case” which assumes that Brent crude oil prices follow futures prices; (ii) “low case” where oil prices fall to US$40 per barrel; and (iii) “high case” which assumes oil prices increase to US$100 per barrel as at February 2015 (Figure 3.13[c]) (Cassidy and Kosev, 2015). Thus, the price of oil is an important determinant of the price of LNG in the international market. The fluctuation of the LNG price due to oil production is therefore considered as a risk to the LNG supply chain in Australia.

(a)



(b)



(c)

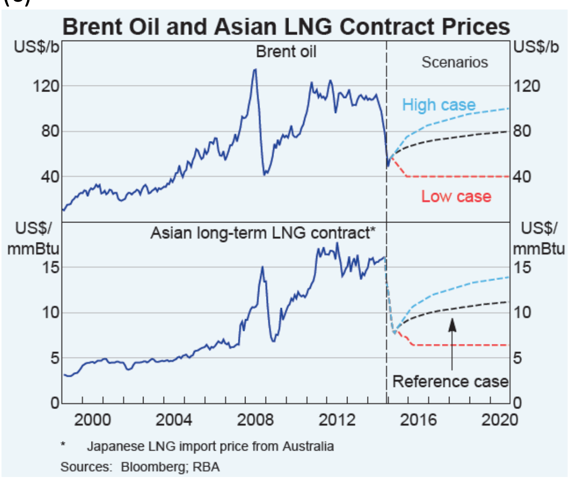


Figure 3.13: (a) Natural gas price difference in three different markets in recent times; (b) energy prices compared with Japanese LNG import price; and (c) forecast price scenario for LNG exports from Australia with outlook to 2020 as at February 2015

Notes: LHS=left-hand side; RHS=right-hand side. Source: Cassidy and Kosev (2015)

SCR31: Severe weather causing low productivity

Very hot and dry conditions, heatwaves, high temperatures, bushfires, tornadoes and series of thunderstorms are some examples of the severe weather that may occur in many parts of Australia throughout the year depending on prevailing weather patterns for a particular part of the country. These hazards may disrupt an LNG project whether it is under construction or in operation. For example, hot weather can reduce labour productivity (BCA, 2013) and workers may need longer breaks, etc.

SCR32: Emergency shutdown of the plant due to floods

In the northern part of Australia (northern Queensland, the Northern Territory and northern Western Australia), summer is the wet season with monsoons and tropical activity. A tropical cyclone or a tropical low pressure system carries a lot of moisture and can produce heavy rainfall along tracts of land resulting in flooding in coastal areas which may extend far inland. Floodwaters in coastal areas may drain into the ocean in a couple of days but, in inland areas or for large rivers, floodwaters may take a couple of weeks or even months to reach the ocean (Bureau of Meteorology [BoM], 2015). In some inland areas, inundation may remain for months, cutting access roads to mine or plant sites. Inundation of the plant or surrounding areas, cut-off access roads, and mobilization of equipment or human resources are key challenges that may arise from flooding.

SCR33: Emergency shutdown of the plant due to tropical cyclones

The north, north-east and north-west coastline of Australia is a cyclone-prone part of the Australian coastline, with the north-west of Western Australia, from Broome and Exmouth, the most cyclone-prone part overall (BoM, 2016). Officially, the Australian cyclone season is from November to April with a limited number of cyclones occurring in November and generally about 13 cyclones forming each year in this region of Australia (90–160Â° E). Therefore, cyclones play an important role in the LNG supply chain from upstream (project construction) to downstream (plant operation to distribution). The severity of tropical cyclones in Australia is categorized on a scale of 1–5, weakest to strongest, based on wind speed. Whether built onshore or offshore, LNG projects must be designed to withstand these strong winds, thus increasing the capital and operation costs. For example, the new floating platform for the Prelude FLNG project is built and moored with the capability of withstanding the wind speed of a category 5 cyclone (Leather et al., 2013). In addition, the operation of LNG plants and the distribution and supply of LNG are disrupted due to cyclones. In its first quarter report for the period ended 31 March 2015, Woodside Petroleum Ltd. reported that production volumes were lower compared to the previous quarter due to lower volumes of LNG at Pluto and lower oil volumes, with these associated with cyclone activity (Woodside, 2015). Due to cyclones, construction work needed to stop, workers and equipment needed to be moved to safe places, LNG production was disrupted, and the tanker moored to a jetty needed to sail to a safer place.

3.5 Identification of LNG Supply Chain Risk Mitigation Strategies

Following the identification of supply chain risks (SCRs) (Table 3.1), risk mitigation strategies (RMSs) for LNG supply chain risk mitigation were formulated based on the available literature, as presented in Table 3.2. In total, 30 RMSs were identified for mitigating LNG supply chain risks (SCRs). As previously noted, some of the risks were interrelated rather than being independent, with the same being true for risk mitigation strategies (RMSs). Furthermore, some RMSs may have a role in mitigating more than one risk. For example, implementation of a RMS may mitigate a SCR completely which is directly related to it and also mitigate other SCR(s) partially which are interrelated to the SCR there by to the RMS.

In this study of LNG supply chain risk management (SCRM), the Australian government is deemed as the lead agency, large organization or entity, of which LNG companies or businesses comprise a part. The Australian government is expected to lead and formulate different policy measures with the different LNG companies expected to play their part to guide the government and follow the policies. The LNG companies are also expected to have their own strategies to adapt to the changes in the LNG business environment in the coming decades. The LNG SCRs and RMSs proposed in this study do not necessarily suggest to a particular government entity, LNG company or business that they alone should implement or be responsible for these actions: instead, the government and LNG companies are together responsible for reducing the risks to the LNG supply chain.

Table 3.2: LNG supply chain risk mitigation strategies considered in this study

Strategy Code	LNG Supply Chain Risk Mitigation Strategies	References
RMS1	Establish secure communication between stakeholders	(Stecke and Kumar, 2009; Stevenson and Spring, 2007)
RMS2	Involvement of stakeholders in different stages of project	(Carter and Rogers, 2008)
RMS3	Addressing community concerns about LNG projects	(Carter and Rogers, 2008; Jain et al., 2011; Hart, 1995)
RMS4	Emphasising involvement of community	(Stimpson et al., 2015)

Strategy Code	LNG Supply Chain Risk Mitigation Strategies	References
RMS5	Addressing end-user confidence	(Christopher and Lee, 2004; Power et al., 2001; Forrester, 1958, 1961; Evans et al., 1993; Handfield and Nichols, 1999)
RMS6	Balanced carbon tax policy formulation	(Leather et al., 2013; Leather and Wood, 2012)
RMS7	Increase domestic use of LNG/natural gas	(Leather et al., 2013)
RMS8	Policy to increase likelihood of on-schedule delivery	(Leather et al., 2013; Bureau of Resources and Energy Economics [BREE], 2012)
RMS9	Policy to address lack of skilled human resources	(Klibi et al., 2010)
RMS10	Select appropriate project location	(Stecke and Kumar, 2009)
RMS11	Adopting RMSs in different stages from planning to operation	(Giunipero and Eltantawy, 2004); Gualandris and Kalchschmidt, 2012)
RMS12	Monitor global trends	(Stecke and Kumar, 2009)
RMS13	Establish trust in relationship with state or territory and federal governments	(Leather et al., 2013)
RMS14	Multiple facilities with flexible/redundant resources	(Li et al., 2009; Rouis, 2010; Stevenson and Spring, 2007)
RMS15	Consistency of local, state or territory and federal government policies	(Leather et al., 2013; Economics and Industry Standing Committee [EISC], 2014)
RMS16	Insurance coverage for hazards and unexpected risks	(Boedecker and Morgan, 1980; Schroeder, 1998; Manuj and Mentzer, 2008; Stecke and Kumar, 2009)
RMS17	Signing a long-term contract	(Leather et al., 2013; Ghadge et al., 2010)
RMS18	Having redundant customers	(Tummala and Schoenherr, 2011; Stecke and Kumar, 2009)
RMS19	Balancing cost by region	(Kilgore, 2004; Vachon and Klassen, 2006)
RMS20	Balancing revenue flows by region	(Chopra and Sodhi, 2004)
RMS21	Building flexible global capacity	(Manuj and Mentzer, 2008; Chopra and Sodhi, 2004; Christopher and Lee, 2004)
RMS22	Robust back-up system	(Sheffi and Rice, 2005; Stecke and Kumar, 2009; Chopra and Sodhi, 2004)
RMS23	Building responsive production	(Chopra and Sodhi, 2004;Sheffi and Rice, 2005)
RMS24	Building responsive delivery capacity	(Chopra and Sodhi, 2004; Christopher and Lee, 2004; Stevenson and Spring, 2007; Stecke and Kumar, 2009)
RMS25	Balanced emissions trading scheme (ETS) policy formulation	(Mo et al., 2016)
RMS26	Policy for an economic slowdown	(Jüttner and Maklan, 2011)
RMS27	Policy for labour disputes	(Chopra and Sodhi, 2004; Klibi et al., 2010)
RMS28	Policy for currency fluctuations	(Manuj and Mentzer, 2008; Chopra and Sodhi, 2004)
RMS29	Monitor existing and new competitors	(Li et al., 2005; Trkman et al., 2007; Trkman and McCormack, 2009; Modi and Mabert, 2007)
RMS30	Establish secure communication links within the company	(Stevenson and Spring, 2007; Stecke and Kumar, 2009; Golden and Powell, 1999)

3.6 Short Descriptions of LNG Supply Chain Risk Mitigation Strategies

RMS1: Establish secure communication between stakeholders

Stecke and Kumar (2009) suggested that reliable and robust communication can be helpful to control and coordinate the operations of a dispersed supply chain. Stevenson and Spring (2007) noted that the sharing of real-time information is facilitated by inter-organisational information systems (IS) and Internet technologies which provide the organization with the means to be more effective in coordinating the supply chain at the network level. The information system components that they mentioned include: electronic data interchange (EDI); advanced planning and scheduling (APS) systems; collaborative planning, forecasting and replenishment (CPFR) systems; and customer and supplier relationship management (C/SRM) modules of enterprise resource planning (ERP) packages. Therefore, establishing secure communication between stakeholders could minimize the SCRs which are related to this RMS of the LNG supply chain.

RMS2: Involvement of stakeholders in different stages of project

The stakeholders are different at each of the different stages of the LNG supply chain. For example, stakeholders relevant to the upstream (production and storage) part of the supply chain are concerned with: investment in the LNG project; the feasibility study of the project; project location; project construction; commissioning; production; storage facilities; environmental studies; project governance; finding suitable buyers; etc. Stakeholders relevant to the midstream (storage, transportation and receiving terminals) part of the supply chain are concerned with: storage facilities; port facilities; transport facilities (tanker); maritime governance and security; receiving terminal facilities and their compatibility; the spot market; etc. In the downstream part of the supply chain, stakeholders are concerned with receiving terminals, storage facilities, conversion facilities, distribution network; end-user requirements, etc. Each stage of the supply chain is influenced and guided by governance, management, laws, policy, procedures, guidelines, etc. which are developed and maintained by different stakeholders involved in different stages of the supply chain. It is important that relevant stakeholders were involved at different stages of the supply chain so that their requirements were met. Therefore, the lack of involvement of any particular stakeholder (or stakeholder group) could create vulnerability for the supply chain. Hence, the involvement of stakeholders in different stages of a project is essential for a reliable LNG supply chain. Carter and Rogers (2008) reported the need to actively engage with stakeholders (in addition to reporting to stakeholders) and to use their feedback and input to both secure buy-in and improve supply chain processes.

RMS3: Addressing community concerns about LNG projects

Not only are LNG projects large in size, but they involve a huge level of investment. The project duration is significant both in terms of the construction and operation phases. The project construction is a large-scale multidisciplinary engineering project which involves social, economic and environmental impacts, particularly on a community scale. The LNG projects based on non-conventional gas extraction (such as coal seam gas [CSG]) raise a higher level of community concern relative to those projects based on extracting conventional natural gas. For a reliable supply chain, community concerns need to be minimized and appropriate strategies need to be in place to address these concerns. In a study of corporate social responsibility (CSR) and psychosocial risk management, Jain et al. (2011) suggested engaging with all stakeholders, including non-traditional stakeholders. Carter and Rogers (2008) introduced the concept of the integration of environmental, social and economic criteria to allow an organization for achieve long-term economic viability in supply chain management (SCM). Hart (1995) stressed the need for companies to open their operations to greater public (local communities and external stakeholders) scrutiny.

RMS4: Emphasising involvement of community

The engagement of communities at relevant stages of the LNG project could be extremely important to minimizing community concerns. This engagement could include community consultation at different stages of an LNG project, such as at the planning and design phases, during the social and environmental impact assessments, as well as during the construction and implementation phases. Information related to social and environmental safety measures and standard practices associated with LNG projects also needs to be made available to the community in order to gain their confidence in the project. In addition, mitigation plans to minimize possible social and environmental impacts need to be developed in consultation with the community to give the appropriate level of attention to their concerns regarding the project. Stimpson et al. (2015) reported differences in risk management measures in different circumstances when related to corporate social responsibility (CSR), noting that there is no one-size-fits-all approach to risk management. Therefore, Stimpson et al. (2015) suggested that companies (e.g. oil and gas or other resources' companies) should adopt a risk mitigation approach and an appropriate response to the different risks to which each project, jurisdiction and community are subject.

RMS5: Address end-user confidence

End-user (or buyer) confidence is vital for a reliable LNG supply chain. Some key elements that may influence end-user confidence in the LNG supply chain include reliability of supply, competitive price, quality and compatibility of LNG supply, etc. One of the key advantages of the LNG supply chain is that it has the opportunity to avoid geopolitical barriers (overcoming this limitation of gas supplied through pipelines). Thus, a great proportion of the LNG market is where gas supply is not possible through pipelines or where geopolitical barriers exist. Thus, reliability of supply is extremely important to the end-user (or buyer) and plays a critical role in achieving end-user confidence. However, reliability of supply can be influenced by factors such as: order cycle time; order current status; demand forecasts; supplier's capability to deliver; production capacity; transportation reliability (Christopher and Lee, 2004); natural or man-made hazards; etc. As many exporters are present in the global LNG market, end-users have the opportunity to choose among exporters to achieve a competitive price. The LNG exporter should also be aware of the end-user's needs in terms of quality and compatibility requirements relevant to the storage capacity of the receiving terminal and the subsequent requirements of the distribution network to consumers.

Considerations of end-user demand (requirements) at various stages of the LNG supply chain are valuable for achieving end-user confidence. Forrester (1958, 1961) noticed that a typical distortion was created in demand patterns when dynamic complexity occurred in transferring demand from the end-user along a supply chain. Power et al. (2001) reported that many different sources were isolated as a result of the complexity of the supply chain's dynamics and that this isolation included flows of information between and within companies and materials flows between companies, as well as chaos theory (Evans et al., 1993). Handfield and Nichols (1999) stressed the importance of encompassing all activities associated with the flow and transformation of goods in the supply chain from the raw materials stage (such as extraction) through to the end-user, and including the flow of information. Therefore, end-user demand (requirements) should be reflected at various stages of the LNG supply chain from the start to the end.

RMS6: Balanced carbon tax policy formulation

Global warming and climate change are at the forefront in shaping government policies across the world. The recent Paris Agreement (2015) on climate change is expected to boost consumption of natural gas (and thus, of LNG) globally as a relatively clean source of energy compared to coal. The carbon tax has been a much debated issue in Australia for the past couple of years. The carbon tax was introduced in Australia on 1 July 2012 by the Australian government led by the Australian Labor Party (ALP) (Leather et al., 2013). This action was followed by adjustment of the Australian emissions reduction scheme through linking it to the European Union Emissions Trading System (EU ETS) in August 2012 (Leather and Wood, 2012). The carbon tax was then abolished by the Australian government led by the Coalition (Liberal and National Parties) on 17 July 2014 with effect from 1 July 2014. The Australian government is expected to ratify the Paris Agreement in the next year or so. With ratification of the Paris Agreement, the Australian government may need to revise policies related to carbon (or greenhouse gas [GHG]) emissions. Long-term consistent policies on carbon (GHG) emissions will be to the benefit of the LNG industry in Australia and will shape other relevant policies (such as energy policies).

RMS7: Increase domestic use of LNG/natural gas

Demand for cleaner energy is increasing globally. The Australian government is expected to ratify the Paris Agreement (2015) in a year or so, with this is expected to increase domestic demand for natural gas and LNG in Australia. The demand could result from multiple sources, such as the gradual closing down of coal-fired power stations and more reliance on gas-fired power generation, and the use of gas (including LNG) in transportation. Moreover, technology related to storage and transportation of LNG is now significantly improving and this provides the opportunity to use LNG in remote parts of Australia where gas pipelines would not be considered feasible. Thus, ratification of the Paris Agreement and improvements in technology are expected to expedite the demand for LNG in the domestic market in Australia. The domestic demand for natural gas as well as for LNG should also be increased through using it in the generation of industrial and petrochemical products (Leather et al., 2013). This would require necessary policy adjustments as well as new policy formulation to accommodate the increased demand for LNG in the domestic market.

RMS8: Policy to increase likelihood of on-schedule project delivery

On-schedule delivery of a project (and completion of a project within a reasonably estimated cost) is important for the LNG supply chain for timely commissioning and entry into a competitive market. Delay in project delivery increases the likelihood of losing potential buyers. In Australia, multiple reasons can cause delays in LNG project delivery and cost blow-outs. Leather et al. (2013) reported that site-specific factors (e.g. the remoteness of the project); a tight engineering and construction market; and an increase in materials cost (e.g. steel, cement, etc.) as well as limited project delivery capacity (e.g. lack of capable engineering companies and skilled human resources) (Bureau of Resources and Energy Economics [BREE], 2012) are some of the major causes of cost blow-outs. These reasons also indirectly delay project delivery. Therefore, different policy measures are necessary to increase the likelihood of on-schedule project delivery for current and future LNG projects. For example, appropriate strategies need to be adopted to increase the capacity of engineering companies through facilitating competition between local and global engineering companies. Sufficient inventory or flexible contracts for critical construction materials (such as steel, cement, etc.) need to be maintained based on the forward estimate for timely project completion. This policy initiative would need to be coordinated through public–private partnerships under an appropriate project management framework.

RMS9: Policy to address lack of skilled human resources

Liquefied natural gas (LNG) plants require skilled human resources at different stages (including construction, operation and maintenance). However, as with most engineering projects, the construction of LNG projects requires more human resources than are required for operation and maintenance. In Australia, the construction of many LNG projects has been started in a narrow time gap (within only a short period of time). This requires a huge number of skilled human resources of diverse backgrounds (e.g. engineers, project management professionals, skilled tradespeople with different trades, accountants, etc.) as well as support services (e.g. catering, cleaning, etc.). Appropriate policies and strategies need to be adopted to manage this high demand for a diverse skilled workforce. The policies to manage this demand may focus on the deliberate delay of some projects to maintain a stable workforce or the outsourcing of a huge workforce for the duration of the project. Both policy options have pros and cons: the deliberate delay of some projects may not be acceptable to the project owners, while outsourcing a huge workforce requires substantive changes in legislation relevant to visas, immigration and other workforce laws. In a review of the design of robust value-creating supply chain networks (SCNs), Klibi et al. (2010) identified three broad categories of SCN vulnerability. They identified human resources under one of these categories. Therefore, an appropriate policy to address the need for skilled human resources for timely completion of LNG projects requires both public and private partnerships to complement each other's gaps.

RMS10: Selection of appropriate project location

The selection of an appropriate project location is of great importance for an LNG project due to several factors. These factors include that LNG projects are large and multidisciplinary engineering projects, while project durations are long considering both construction and operation phases require auxiliary infrastructure (e.g. accommodation, support services, recreational facilities, etc.). Safety is also a major issue for such a large investment. Accessibility plays a significant role owing to the huge number of workers as well as the transportation and handling of the enormous amount of construction materials. Natural hazards (e.g. cyclones and floods) as well as man-made hazards (e.g. threats from terrorism) are also important factors which require attention. Community concerns, environmental factors, and cultural, archaeological and heritage considerations are also important elements that need to be considered in site selection. Stecke and Kumar (2009) suggested selecting a safe location for the different parts of the supply chain, taking into consideration multiple factors, such as transportation, natural hazards, terrorist attacks, etc. Therefore, appropriate strategies need to be adopted for selecting a site for the LNG project that takes into account multiple criteria while considering longer-term benefits.

RMS11: Adopting RMSs in different stages from planning to operation

Risk avoidance, risk buffering and risk management practice each has its advantages and limitations. Although it does not incur costs, risk avoidance is not considered to be a professional practice. Giunipero and Eltantawy (2004) urged that the benefits gained from risk management practices should be evaluated and the costs incurred for such a proactive approach be used to determine when, at what level and at what cost the risk management practices should be adopted. However, the adoption of a risk management approach is a management decision problem which requires management support (Giunipero and Eltantawy, 2004). Zsidisin et al. (2000) outlined the difficulty of evaluating a risk management approach for some situations such as the non-occurrence of a risk and thereby justifying the time and resources utilized in the risk management plan. Gualandris and Kalchschmidt (2012) found that companies that could not manage supply chain risks might reduce their ability to satisfy customer needs and thereby reduce their competitive advantage. They also argued that the impact of SCRM is context-dependent, meaning that it is dependent on the criticality of purchases, the difficulty of supply markets, environmental turbulence and the level of global sourcing. For critical conditions of these factors, supply risk becomes of more relevance and SCRM provides competitive advantage. Considering the complexity level of the LNG supply chain, the adoption of RMSs at different stages of the LNG project is recommended.

RMS12: Monitor global trends

The LNG supply chain is dynamic and transforms over time. As it is a relatively new industry, laws, regulations, technology, customer preference and other factors affecting the LNG supply chain are evolving. For example, the adoption or revision of a carbon emissions policy can create greater demand for cleaner energy (such as LNG) in a country (an economy). Stecke and Kumar (2009) noted that disruption of the supply chain may result from changes in customer preference, laws and regulations, and technology. They reported that, in most cases, changes in trends occur slowly and allow organizations time to respond accordingly, although some changes in trends may occur suddenly (e.g. changes in laws and regulations).

RMS13: Establish trust in relationship with government

The need for a trusted relationship between investors and the government is paramount for securing long-term investment in LNG projects in a competitive environment. Leather et al. (2013) reported that "… contentious negotiations and eventual implementation of the resource super-profits tax since 2010 have fostered mistrust in the Australian Government regarding fiscal stability by business, industry and investors, both domestic and foreign". They emphasized a sovereign government's commitment to stick to its policies and fiscal agreements as an element of sovereign trust through which the increased level of trust enhances the potential of securing longer-term investment. Moreover, during the past decades, Australia's sovereign risk has been lower than that of Middle Eastern and African nations. These authors accentuated the need for Australia to turn its attention to sovereign risk, fiscal stability and fiscal credibility to secure long-term investment.

RMS14: Multiple facilities with flexible resources

The timely and flexible reconfiguration of supply chain resources is needed to respond to changes in supply or demand (Li et al., 2009; Rouis, 2010). Stevenson and Spring (2007) reviewed flexibility in the supply chain from different perspectives. They found that flexibility influences the design of the supply chain at various stages, starting from the plant and through to the end-user. A supply chain network can be considered as a flexible network that is able to cope with a competitive environment without the adoption of "extreme measures" (Stevenson and Spring, 2007). The flexibility of a supply chain can be increased through organizing the provision of multiple facilities with flexible resources along the supply chain. For example, instead of one large plant, two or more plants at different locations are expected to provide better flexibility and more resilience in the supply chain. In this case, if a plant is inaccessible or not available (e.g. due to a natural or man-made disaster), then the other plant would still be in use. An example of flexible resourcing is diversifying human resources, such as having a combination of permanent, contractual and casual employees which can allow the number of employees to be allocated as required.

RMS15: Consistency of local, state or territory and federal government policies

Consistency in policies between local, state or territory and federal governments is vital for global LNG companies to operate in harmony across a country like Australia. Most conventional natural gas reserves are located in Western Australia and the Northern Territory while most unconventional gas reserves are located in the eastern states. In addition, the greater proportion of the domestic gas market is in the eastern part of the country where most of the population lives. Therefore, consistency of policies (e.g. environmental policy, gas pricing policy, land use policy, state government's domestic gas reservation policy, etc.) between local, state or territory and federal governments is necessary. Leather at al. (2013) reported on policy gaps between federal and state governments in Australia and highlighted the need for a consistent policy approach for the LNG industry. Similarly, the Economics and Industry Standing Committee (EISC, 2014) identified policy gaps between federal and state governments in Australia and urged them to close the gaps through working together.

RMS16: Insurance coverage for hazards and unexpected risks

Buying insurance to cover the risks that may occur at different stages of the LNG supply chain could be one primary strategy to minimize risk. Boedecker and Morgan (1980) reported that innovative products (such as proprietary and high service requirement products) may be sold through forward integrated supply chains. Similar to innovative products, LNG may also need to be sold by a forward linkage supply chain (e.g. through a long-term contract) to attract investors for long-term investment. Schroeder (1998) suggested that banks and insurance companies could create innovative partnerships through buying stakes in other companies, thereby forming strategic alliances and being able to sell a wider and more complex portfolio of financial products (Manuj and Mentzer, 2008). In a similar way to innovative products, LNG supply chain risks could be insured through strategic alliances consisting of global companies, banks and insurance companies. Stecke and Kumar (2009) advocated buying insurance coverage for various components and types of catastrophes as an option to reduce supply chain risk. They also proposed that various components of the supply chain could be insured to cover the risk of accidents, loss of assets, loss of profits, extra costs, etc.

RMS17: Signing a long-term contract

Securing a long-term contract provides certainty to investors in LNG projects through a longer-term return. It also provides the importer with some form of energy security from the LNG exporter through the certainty of receiving gas in the longer term. However, securing a longer-term contract depends on many factors, such as pricing mechanisms, political stability, competition from other forms of energy, developments in technology, etc. (Cassidy and Kosev, 2015). Australia is in a good position compared to other LNG exporters in the region to secure long-term contracts due to proximity to the East Asian market, large gas reserves, political stability, etc. On the other hand, factors, such as the emergence of the US as a LNG exporter and the discovery of new gas reserves in East Africa, may indicate more competition in securing long-term contracts. Leather et al. (2013) reported the need for long-term contracts for the LNG industry in Australia. In another study, Ghadge et al. (2010) noted that long-term business partnerships are a feature of the aerospace industry to minimize SCRs as supply chain systems in this industry are more vulnerable due to high quality standards, global sourcing and high service requirements. Thus, in considering some aspects of the unique nature of the LNG supply chain (e.g. large investment, global sourcing and international venture), to minimize SCRs, LNG projects require long-term investment.

RMS18: Having redundant customers

Redundant customers can be retained through assessing the global forecast demand for LNG as well as potential new buyers in the market. In addition, a redundant customer could be an importer with flexible or excess storage capacity. This type of customer could be treated as a redundant customer in order to accommodate excess supply in an oversupply situation. The relationship or contract with such a customer could provide flexibility in an oversupply situation. Stecke and Kumar (2009) noted that flexible or redundant resources at multiple facilities in different geographical locations can provide the ability to mitigate disruption.

Tummala and Schoenherr (2011) found that having a small customer base was a risk to the supply chain. Therefore, through broadening the customer base, SCRs can be mitigated.

RMS19: Balancing cost by region

Balancing the cost of minimizing SCRs and the cost by region can be achieved through redesigning elements (Kilgore, 2004) of the supply chain (e.g. human resources management, logistics management, financial management, etc.). Vachon and Klassen (2006) reported that concentration of the supply base (such as resources or activities) in the supply chain may increase disruption risks. For example, a natural disaster like earth quack, flood or fire in an industrial production zone may result in significant loss of production impacting the supply chain. While in a geographically distributed production facilities impact of such disaster is likely to be less relative to a concentrated facility. Sourcing different resources or parts of supply chain activities from different regions could also be more economic than concentrating them into one location. Therefore, decentralizing or diversifying resources or activities of the supply chain is expected to minimize SCRs as well as reducing the risk mitigation cost of the supply chain.

RMS20: Balancing revenue flows by region

Balancing revenue flows by region is a mitigation strategy for financial risks to the supply chain. Chopra and Sodhi (2004) suggested that a company can diversify its export market as well as focusing on one or two local markets to diversify its revenue flow. For example, Toyota, as part of its manufacturing strategy, allows each plant to serve the local market and at least one overseas market to balance (diversify) its revenue flow in order to mitigate financial risks to the supply chain (Chopra and Sodhi, 2004). In a similar way, the revenue flow of the LNG supply chain can be balanced through serving LNG to the local market as well as to the international market to reduce the risk to the supply chain.

RMS21: Building flexible global capacity

Building excess capacity is a means to reduce supply chain uncertainties and risks (Christopher and Lee, 2004). Chopra and Sodhi (2004) suggested that a company can minimize supply chain risk (such as inventory risk) through having excess capacity. For example, Toyota can manage demand variations by running a plant at 80% capacity and can also avoid the need to have a large inventory (Chopra and Sodhi, 2004). Manuj and Mentzer (2008) reported that supply chain flexibility (e.g. by building excess capacity) provides the inherent capacity to minimize risk through being able to respond to emerging and unexpected circumstances. Thus, by building excess or flexible capacity of different components of the LNG supply chain (e.g. flexible capacity at plant level, flexible storage capacity, flexible transport capacity, etc.), risk can be minimized throughout the supply chain. For example, a flexible capacity at plant level along with flexible transport capacity may increase or decrease production and distribution of LNG to maximize the demand in the spot market. Similarly, flexible storage capacity of LNG likely to facilitate the maximizing advantage of LNG spot market. Therefore, building flexible global capacity is likely to mitigate some risks in LNG supply chain.

RMS22: Robust back-up system

In today's world, a supply chain network is highly integrated through information systems. Chopra and Sodhi (2004) noted that with a more integrated information system, the risk of failure in the supply chain persists and increases. They suggested a robust back-up system as a defence to avoid such a failure and to minimize the risk to the supply chain. Stecke and Kumar (2009) suggested that maintaining robust back-up of critical components can be done with a limited budget and is advantageous in minimizing supply chain risks (SCRs). For example, back-up of components could include: maintaining a back-up generator for power generation; maintaining a redundant communication system; keeping a good inventory of critical parts for the LNG plant; maintaining redundant storage facilities; maintaining redundant transport facilities, etc. Sheffi and Rice (2005) added that having safety stock, retaining redundant suppliers (even if higher costs are associated with secondary suppliers) and a deliberate low capacity utilization rate are common forms of redundancy for a back-up system. They regarded costs associated with a back-up system as an insurance premium but discouraged having extra inventory or extra capacity as these, in general, could be detrimental to a lean operation.

RMS23: Building responsive production

Loss of production capacity may occur due to man-made hazards (such as terrorism, accident, fire, etc.) or natural hazards (such as cyclone, flood, tsunami, etc.). This loss of capacity can be replaced by increased production from other plants, provided that redundant capacity has been maintained. For example, Sheffi and Rice (2005) reported that, due to a fire, Aisin Seiki Co., a supplier to Toyota, had to halt production for nine days while it replaced the lost capacity using its *keiretsu* (“business network”). The authors suggested that, while maintaining redundant production lines could be costly, multiple capabilities at each plant location are likely to add flexibility to production, reducing risk to the supply chain. Thus, the production responsiveness of the LNG supply chain depends on its own production capacity as well as on the production capacity of related suppliers. In another example, Chopra and Sodhi (2004) reported that due to a fire in a plant in New Mexico, Royal Philips Electronics NV lost millions of microchips. Nokia Corp, a major customer of the plant, almost immediately switched its microchips order to other Philips plants in the US and around the globe to maintain its production. Therefore, building responsive production capacity is expected to minimize risk to the LNG supply chain.

RMS24: Building responsive delivery capacity

The delivery of LNG involves key elements of the supply chain such as storage capacity, port facilities, number and capacity of LNG tankers, receiving terminal facilities and storage capacity. To meet the flexibility of demand (i.e. a surge or drop), a responsive delivery capacity is essential. The demand for LNG may fluctuate for many reasons such as changes in government policies, increasing demand for cleaner energy, natural disasters (e.g. the tsunami in Japan), technological development and competition from other energy sources (e.g. drop in the oil price). To adjust to such changes in the market, building a responsive delivery capacity for LNG needs to be considered in the planning and design stage of the supply chain. The responsive delivery of LNG is likely to achieve a greater market share through capturing surges in the spot market as well surges in short-term demand and can also reduce the risk of oversupply in a slow demand situation. Stecke and Kumar (2009) articulated the need to have a flexible and alternative transport system to mitigate supply chain risks (SCRs). Stevenson and Spring (2007) noted that distribution (or delivery) is a component of the supply chain which requires flexibility to mitigate supply chain risks (SCRs). Chopra and Sodhi (2004) reported that forecast risks can be lowered for a supply chain through having responsive delivery capacity. Christopher and Lee (2004) noted that financial risk may arise due to the non-delivery of goods. Therefore, having responsive delivery capacity appears to be a risk mitigation strategy for mitigating risks to the LNG supply chain.

RMS25: Balanced emissions trading scheme (ETS) policy formulation

A balanced emissions trading scheme (ETS) can provide restrictions on carbon emissions as well as driving economic growth through attracting investment to cleaner energy and by encouraging companies to become cleaner. The formulation and adoption of an ETS should be well thought out so that, while not imposing both a financial and regulatory burden on business, at the same time, it effectively reduces carbon emissions. Thus, adoption of a balanced ETS in Australia still requires significant study to be undertaken. For instance, Mo et al. (2016) assessed the possible impact of the adoption of an ETS in China on low carbon investment (e.g. investment in wind power). A balanced ETS is expected to increase demand for gas as well as for LNG in the domestic market and to also attract investment in the LNG sector in Australia.

RMS26: Policy for an economic slowdown

Appropriate policy for an economic slowdown is likely to help business to cope with unknown risks associated with the supply chain and to better manage such risks. In an empirical study of supply chain resilience associated with the Global Financial Crisis (GFC), Jüttner and Maklan (2011) found that four resilience capabilities (or policies) helped companies to restrain negative effects from an economic slowdown (or recession). The supply chain resilience capabilities revealed by these authors were: (i) flexibility (e.g. response to unpredictable change in demand); (ii) velocity (e.g. quick response to unpredictable change in demand); (iii) visibility (e.g. shifting to cost-effective supply sources); and (iv) collaboration (e.g. lower sourcing costs and counteractive measures to avoid non-availability). Therefore, the adoption of a policy for an economic slowdown appears to be suitable for reducing the risk to the LNG supply chain.

RMS27: Policy for labour disputes

Appropriate policies for labour disputes, work conditions, remuneration and other work benefits need to be considered by the LNG industry as part of the broader aspect of human resources management (HRM) for several reasons. For example, most LNG projects in Australia are located in remote areas; the majority of workers are employed on a fly-in fly-out (FIFO) basis; most of the work is of a specialized nature; etc. Therefore, having an understanding of the workers, their requirements and the work conditions is important for a successful project. Stecke and Kumar (2009) highlighted that understanding employees can bring huge returns, and a close relationship with workers can help to avoid strikes and production stoppages. Klibi et al. (2010) reported that labour disputes may stop work for a period of time and could be an adverse cause of disruption to the supply chain. Therefore, policies for labour disputes are expected to contribute to mitigating supply chain risks (SCRs).

RMS28: Policy for currency fluctuations

Investment in LNG projects is an international venture which involves multiple companies and organizations (and/or governments) from different countries. Thus, currency fluctuations or exchange rates have a considerable impact on project investment and revenue flow in the operation phase. Chopra and Sodhi (2004) identified strategies to counter the exchange rate risk to the supply chain including creating financial hedges, balancing cost and revenue flows by region, and building flexible global capacity. Manuj and Mentzer (2008) reported that risk associated with currency fluctuations in the operation phase of SCRM is typically “covered” by buying insurance or hedging foreign exchange exposure. Therefore, appropriate policy measures to minimize risk associated with currency fluctuations in the LNG supply chain may be adopted as part of supply chain risk management (SCRM).

RMS29: Monitor competition from existing and new competitors

Competition between LNG suppliers in the Asia-Pacific market has intensified in recent times with increased capacity from existing suppliers (e.g. Qatar, Australia) as well as the emergence of new suppliers (e.g. the US). Li et al. (2005) reported that competition in the global market was now regarded as between supply chains rather than between organizations, with this later also reported by Trkman et al. (2007) as "competition is based on supply chains". Considering competition as being between supply chains, Trkman and McCormack (2009) stated that a firm's position in a larger network can be better understood through studying its supply chain. The reason is that a product or service is a function of a particular firm's supply chain capabilities as well as its supplier network providing input to the firm (Modi and Mabert, 2007). Therefore, monitoring competitive supply chains in a common market is likely to reduce risks to the LNG supply chain.

RMS30: Establish secure communication links within the company

Stevenson and Spring (2007) highlighted that the flow of real-time information in a supply chain is as important as the flow of goods. Through citing other authors (e.g. Golden and Powell, 1999), they reported that information sharing can allow flexibility and better responsiveness within the supply chain. Stecke and Kumar (2009) affirmed the need and benefits of a reliable and robust communication system for a distributed global supply chain, articulating that such a system may assist to manage and coordinate the operations of a dispersed supply chain. Considering the LNG supply chain as a dispersed and complex supply chain, secure communication links within the company is anticipated to reduce the risks to the supply chain, thereby bringing benefits to the company.

3.7 Chapter Summary

In this chapter, a vulnerability map has been prepared to carry out the early step of identifying LNG supply chain risks (SCRs). Using the vulnerability map, LNG SCRs have been identified through the review of the literature. The SCRs have been explained to set the context for the risks used in the current study. To mitigate the SCRs, a set of RMSs has been formulated based on the review of the literature. Short descriptions of the RMSs have been provided in the context of this study. The SCRs and RMSs are assumed to be independent; however, in reality, interrelationships may exist between SCRs and risk mitigation strategies (RMSs).

CHAPTER 4

RESEARCH METHODOLOGY

4.1 Chapter Introduction

This chapter presents the research methodology adopted in the current study. The research paradigm, research methods and a conceptual research framework are developed, showing the linkages and relationships of the methods and approaches adopted in this study. Different research paradigms are explained before selecting the appropriate research paradigm as a set of beliefs for guiding the action undertaken in the methods used to achieve the research objectives. The research process is outlined through different steps. The QFD method used for the prioritization of LNG supply chain risks (SCRs) and risk mitigation strategies (RMSs) is explained. The QFD method has been extended through formulating and solving an optimization problem for LNG supply chain risk management (SCRM). A simulation model has been developed through extending the optimization problem. Finally, the proposed QFD framework for supply chain risk research is presented which has three parts: (i) the quality function deployment (QFD) method for supply chain risk management (SCRM); (ii) the SCRM optimization model; and (iii) the SCRM simulation model. The parts of the QFD-based research framework are detailed followed by a summary of the chapter.

4.2 Research Paradigm

A research paradigm is a basic set of beliefs that guide actions undertaken to achieve research objectives. While epistemology refers to assumptions about the knowledge area and the process of obtaining knowledge (Myers, 1997), the research paradigm provides a conceptual framework (Bogdan and Biklen, 1998) demonstrating how the research is organized. The research paradigm establishes the basis research framework including the selection of appropriate methods; the data requirement and data collection process; the analysis and interpretation of the data; the presentation of the findings; and the role of the researcher in the research process.

Several paradigmatic stances for categorizing research paradigms have been taken by different authors. Guba and Lincoln (1994) presented four types of paradigms: positivism, post-positivism, critical theory and constructivism. Creswell (2003) expressed ideas of different paradigms as post-positivism, constructivism, pragmatic and participatory. Burrell and Morgan (1979) articulated the paradigm as a framework of functionalism, intrepretivism, radical humanism and radical structuralism. In a comparison, the functionalist paradigm is associated with positivism and the remaining three paradigms are aligned with the anti-positivist stance. Although the paradigmatic stances of scientific research on paradigms vary among researchers, three paradigms are prominent in social sciences, management and organizational studies in establishing a study’s methodological basis (Gephart, 1999). The paradigms are positivist, interpretive (constructive) and critical post-modern. The positivist research paradigm is concerned with the discovery of universal laws associated with objective or hard system assumptions which science can measure (Guo and Sheffield 2008). On the other hand, the interpretive paradigm is concerned with uncovering human thoughts and beliefs about knowledge, with this associated with the constructionist stance (Guo and Sheffield, 2008). The critical post-modern paradigm deals with the changing nature of signs as fundamental social phenomena which sustain the objective, subjective and inter-subjective character of society or social order (Gephart, 1999). This paradigm also includes how signs saturate our living experiences yet are more distant and detached from the things they signify or to which they refer (Gephart, 1999). In another classification, Onwuegbuzie and Leech (2005) grouped research into two paradigms: positivist and interpretivist. In a study of the paradigmatic stances of knowledge and theory development in the field of SCRM, Burgess et al. (2006) found that 97% belonged to the functionalist paradigm while 3% fell into the anti-positivist paradigm. Hence, most of SCM research studies are positioned within the positivist paradigm while only a few falls into the interpretivist paradigm. Application of mixed paradigm is not common in SCRM literature. A search of literature of SCRM resulted with no application of mixed paradigm in SCRM.

The objectives of the interpretive paradigm are to explain a research problem not only in its social context, but also in relation to how the problem is embedded in the context and how it interacts in the context (i.e. how it impacts or is impacted upon). In addition, the interpretive paradigm does not separate the research problem from the researcher and participants, instead relying on the researcher’s interpretation and assumptions of the research problem and how the researcher interacts with the problem (Creswell, 2003). On the other hand, the positivist paradigm assumes that the researcher is independent of the research problem; that the research process is free from subjective judgment (Krauss 2005; Johnson and Onwuegbuzie 2004); and that the research problem has an objective reality that can be explained through a causal relationship with accurate measurement (Straub et al., 2004). Under the positivist paradigm, research is guided by formal propositions; variables can be measured quantitatively; and inferences can be drawn from data collected from a sample population. The current study of LNG SCRM involves both qualitative variables (identifying SCRs and RMSs) and associated quantitative (measurement) variables to measure the relationship between the qualitative variables. The measurement variables are used for prioritizing SCRs and RMSs, examining relationships between SCRs and RMSs, determining the optimal level of risk mitigation, determining the optimal set of RMSs, etc. The data required for the quantitative analysis were collected through a survey with the participation of LNG experts. Prior to the survey, SCRs and RMSs were identified through the researcher's review of the literature, with this subsequently verified by an LNG industry expert. The identification and verification of LNG SCRs and RMSs are thus considered to fall into the interpretive paradigm. In determining the level of risk mitigation, an optimization model was developed. For verification and generalization of the results of the optimization model, a simulation model was developed. Hence, exploring relationships between SCRs and RMSs, prioritizing SCRs and RMSs, the development of optimization and simulation models, and the collection of data for the quantitative analysis are all considered to fall into the positive paradigm. Therefore, the research paradigm of the current research is a combination of both interpretive and positive paradigms (Figure 4.1).

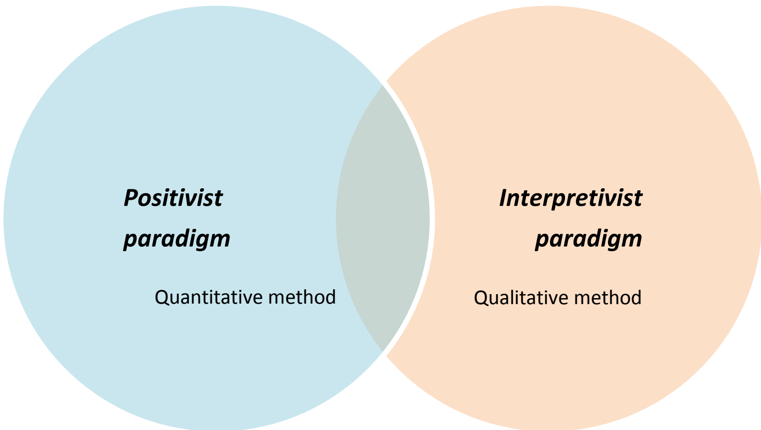


Figure 4.1: Research paradigm with combination of positivist paradigm and Interpretivist paradigm

4.3 Research Methods

The correct selection of appropriate research methods under the research paradigm has immense importance in achieving successful and appropriate research outcomes. As noted by Crotty (1998), research methodologies are related to "the strategy, plan of action, process or design lying behind the choice and use of particular methods, and linking the choice and use of methods to the desired outcomes" and also carry "the techniques or procedures used to gather and analyse data related to some research questions". Guba and Lincoln (1994) reported that methods are of secondary importance to the research paradigm:

> Both qualitative and quantitative methods may be used appropriately with any research paradigm. Questions of method are secondary to questions of paradigm, which we define as the basic belief system or worldview that guides the investigation, not only in choices of method but in ontologically and epistemologically fundamental ways.

In this research on LNG SCRM, both qualitative and quantitative methods have been used following interpretive and positivist paradigms (Figure 4.1). A combination of both qualitative and quantitative methods in a single study is termed as mixed methods (Teddlie and Tashakkori 2012; Tashakkori and Teddlie, 1998, 2003), with this approach becoming increasingly popular in recent times (Teddlie and Tashakkori 2012; Johnson et al., 2007). One of the key advantages of mixed methods is that each method complements the other method through filling gaps or addressing its limitations; thus, mixed methods appear to be a great tool for research. Figure 4.2 presents a summary of the qualitative and quantitative methods used in this study. The qualitative phase of the study was conducted at the early stage of the research where it identified LNG supply chain variables, supply chain risks (SCRs) and risk mitigation strategies (RMSs). Measurement variables were then identified as part of the quantitative phase to measure the supply chain variables (SCRs and RMSs) and their relationships, to prioritize SCRs and RMSs and to carry out additional quantitative analysis (e.g. the development of optimization and simulation models). The data required for carrying out the quantitative analysis were collected through a survey of participants, comprising experts from the LNG industry. Thus, the questionnaire and survey collected information on variables from both the qualitative and quantitative phases (Figure 4.2). Hence, the survey worked as a bridge between the qualitative and quantitative phases as it combined the two research methods. Figure 4.2 presents a summary of the key activities under the qualitative method, the quantitative method and the survey.

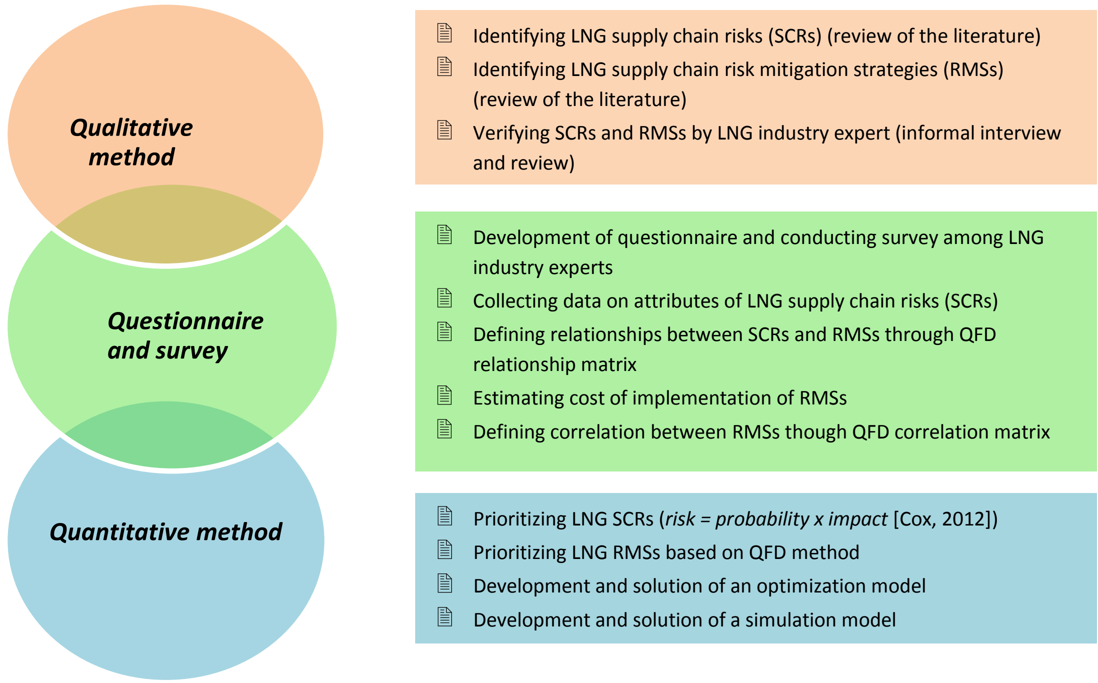


Figure 4.2: Research methods demonstrating qualitative and quantitative methods linked through questionnaire and survey

Depending on the choice of methods, their combination and the objective of their application, mixed methods can be classified into different types. As reported by Creswell (2003, 2008) and Creswell and Clark (2007), the mixed-methods approach in research can be grouped into four categories: triangulation design, embedded design, explanatory design and exploratory design (Figure 4.3). In triangulation design, data are collected using both methods with the qualitative method used to validate results obtained from the quantitative method (Creswell, 2003). Similar to triangulation design, in embedded design, data are collected using both methods; however, data collected by one method play an auxiliary role in the overall design (Creswell, 2003). In explanatory design, the findings of the quantitative analysis are supported by the analysis of the qualitative data (Creswell, 2003). In contrast to explanatory design, exploratory design begins with the qualitative method followed by the quantitative method (Creswell, 2003). In this research on LNG SCRM, it was crucial to identify SCRs and RMSs at an early stage. The identification of SCRs and RMSs needed to be carried out through qualitative analysis, and thus followed the interpretive paradigm (as explained earlier and further detailed below).

The rationales of considering identifying risks and mitigation strategies under interpretative paradigm are (i) uncovering the SCRs and RMSs by the searcher, this involvement of the researcher and (ii) contextualization of the SCRs and RMSs in context of Australian LNG industry. Here, the LNG SCRs and RMSs were uncovered and structured in this research by the researcher through review of literature and verified by one of the experts. The SCRs and RMSs were not in a structured form previously prior to this research. Thus, these are construct of this research as understood and interpreted by the researcher and the relevant expert. The LNG SCRs and RMSs identified here are contextualized in relation to LNG supply chain of Australia. Then, exploring the relationships between SCRs and RMSs and undertaking the subsequent prioritization of SCRs and RMSs, followed by developing the optimization and simulation models, demanded quantitative analysis. Therefore, the current study on LNG SCRM belongs to the exploratory category of the mixed methods approach (as shown in Figure 4.3).

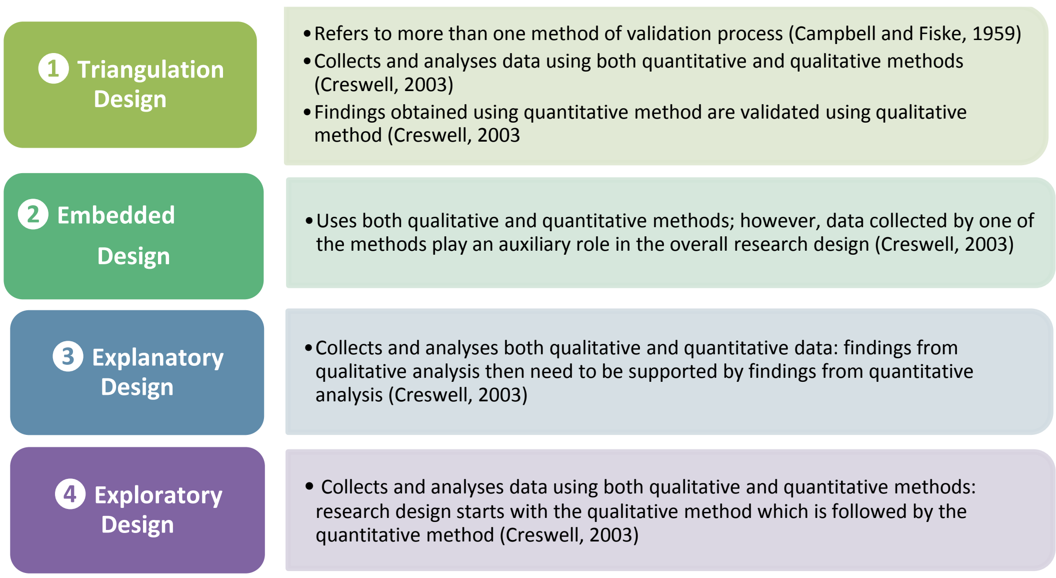


Figure 4.3: Research method adopted for LNG SCRM study: mixed-methods approach similar to exploratory design

4.4 Research Framework

A conceptual research framework shows the relationships between the research problem, the methods and tools used in the research process, and the outcome of the research. The conceptual framework used in this study on LNG SCRM is summarized in Figure 4.4.

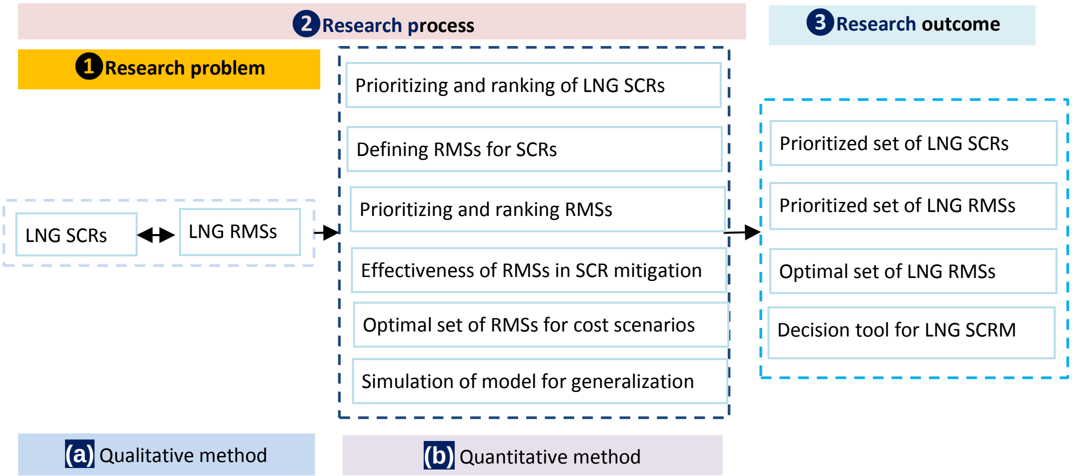


Figure 4.4: Conceptual research framework for LNG supply chain risk mitigation

The research framework links three broad parts of this research: (i) the research problem, (ii) the research process and (iii) the research outcome (Figure 4.4). The key research problem of LNG SCRM is to identify and mitigate supply chain risks (SCRs). The RMSs for the LNG supply chain were identified through an extensive review of the literature (as presented in Chapter 3). A set of RMSs was identified to mitigate the SCRs (also presented in Chapter 3). The identification of RMSs and SCRs and their attributes was carried out through using the qualitative method (Figure 4.4). The research process included the identification of SCRs and RMSs, their subsequent analysis and prioritization, and finding an optimal set of risk mitigation strategies (RMSs). To prioritize SCRs, the current study adopted the widely used approach of risk prioritization, that is, *risk = probability x impact* (Cox, 2012). To define the relationships between SCRs and RMSs, the study used the QFD method's relationship matrix (Han et al., 2001). The study then prioritized and ranked the RMSs following the QFD method (Han et al., 2001). To find the optimal set of RMSs, a QFD-based optimization model (Park and Kim, 1998; Chowdhury and Quaddus, 2015) was developed and solved. To explain the variability of the optimization process results, a simulation model was developed and solved. Details of the qualitative and quantitative methods used, including the data collected for analysis, are explained in Section 4.5 below. The key outcomes of the research included a prioritized set of SCRs and RMSs, an optimal set of RMSs for different cost scenarios, and a decision tool for LNG SCRM in Australia (Figure 4.4).

4.5 Research Process

The research process followed in this study, based on the conceptual framework shown in Figure 4.4, has been summarized in Figure 4.5. The research process consists of three parts: (i) QFD Part 1: Quality function deployment (QFD) for LNG SCRM; (ii) QFD Part 2: Optimization problem for LNG SCRM; and (ii) QFD Part 3: Simulation problem for LNG supply chain risk management (SCRM). The research process is described through eight stages as steps of the research process. These stages are: (a) Stage 1: LNG supply chain risk and strategy identification; (b) Stage 2: Data requirement; (b) Stage 3: LNG supply chain risk prioritization; (d) Stage 4: LNG supply chain risk mitigation strategy prioritization; (e) Stage 5: Development of optimization problem; (f) Stage 6: Solving optimization problem; (g) Stage 7: Developing a simulation model; and (h) Stage 8: Solving the simulation model.

The work flow of LNG supply chain risk mitigation, as presented in Figure 4.5, basically has three parts: (a) the QFD method for the prioritization of LNG supply chain risk and risk mitigation strategies, (b) optimization problem for selecting an optimal set of supply chain risk mitigation strategies under resource constraints for different cost scenarios; and (c) development of a simulation model. In the following sections, the research process of LNG SCRM is explained in reference to Figures 4.5.

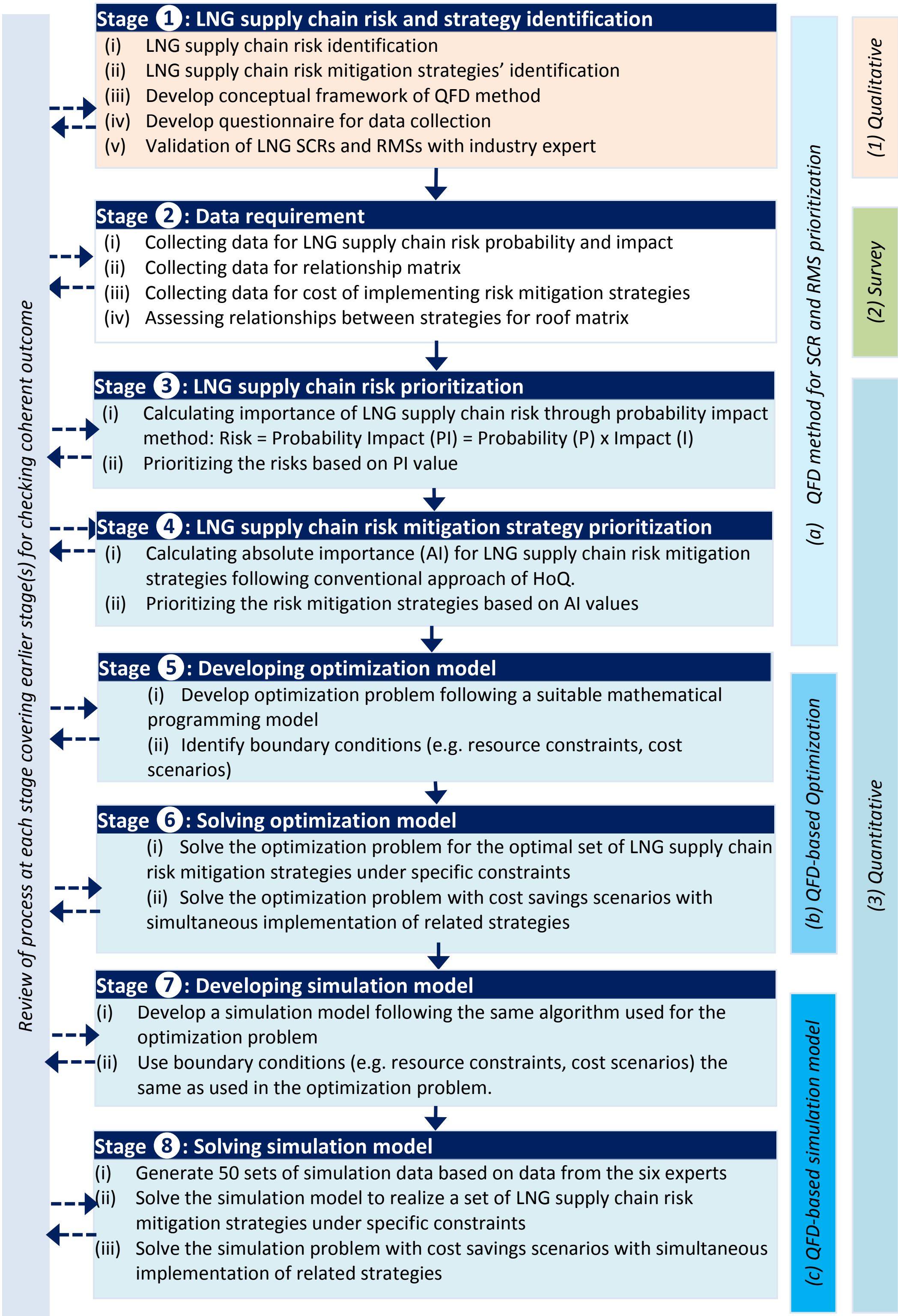


Figure 4.5: Research process flow diagram: different stages of QFD method and optimization problem for LNG supply chain risk management

4.6 Development of a QFD Framework for Supply Chain Risk Management (SCRM)

4.6.1 QFD Part 1: Quality function deployment (QFD) for LNG SCRM

The quality function deployment (QFD) method is a powerful analytical framework presenting various sections or rooms which contain the results of research and analysis on customer groups (Walker, 2002). This framework helps the organization to develop products or services that accommodate customer needs as well as the organization's competence and resources (Wang and Hong, 2007). Through applying the QFD method, the organization can identify important priorities, find new opportunities, expand market share and increase profits (Chen and Bullington, 1993; Govers, 2001; Chien and Su, 2003; Hunt and Xavier, 2003). The QFD method is an important trade-off tool to balance customer needs and the affordability to the organization of accommodating those needs (Walker, 2002; Chien and Su, 2003); therefore, it can be used as a powerful tool for strategic planning (Wang and Hong, 2007). In using the QFD method, according to Hauser and Clausing (1988), the relationship matrix "relieves no one of the responsibility of making tough decisions. It does provide the means for all participants to debate priorities". This implies that the relationship matrix is an important framework which facilitates the selection of priorities.

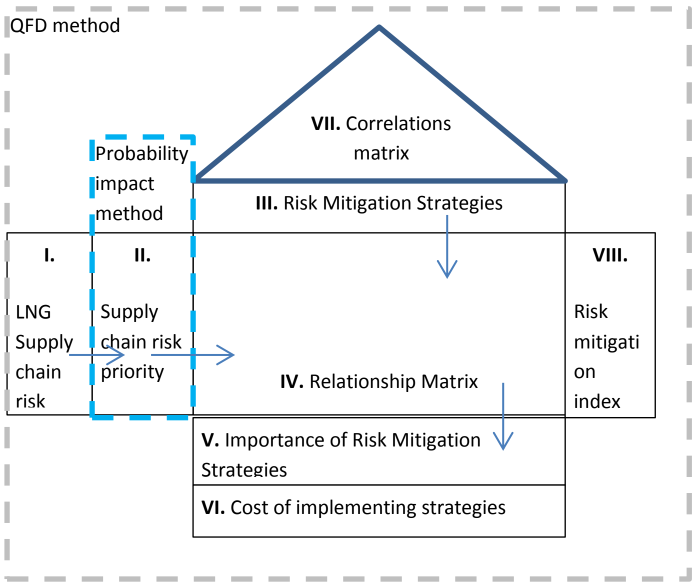


Figure 4.6: Conceptual QFD method for LNG supply chain risk management model

The QFD method of LNG supply chain risk management (SCRM) has the following eight components: (i) LNG supply chain risk; (ii) LNG supply chain risk prioritization; (iii) supply chain risk mitigation strategies; (iv) relationship matrix of supply chain risks and mitigation strategies; (v) importance of risk mitigation strategies; (vi) cost of implementing risk mitigation strategies; (vii) correlation matrix of risk mitigation strategies; and (viii) risk mitigation index (Figure 4.6). A conceptual relationship matrix for LNG SCRM with the relationship rating scale and attributes of the components of the QFD method is shown in Figure 4.7.

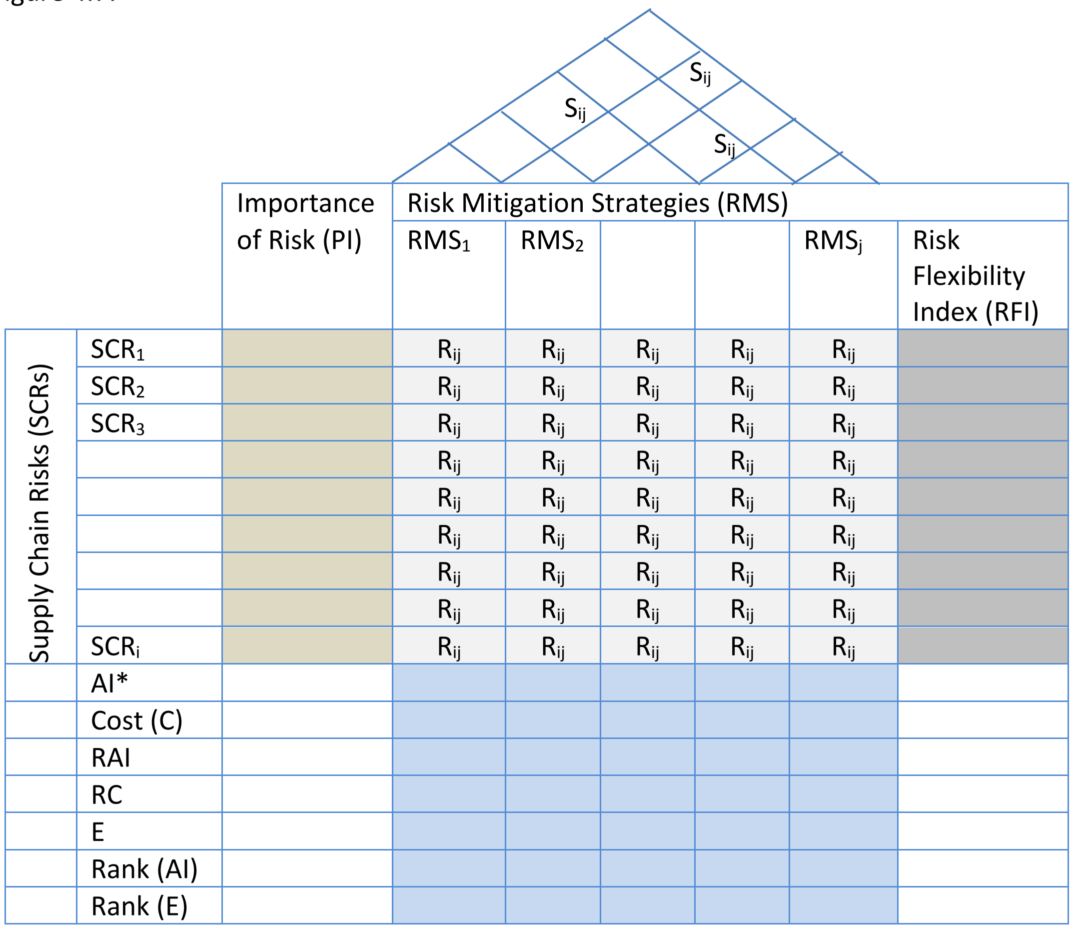


Figure 4.7: Conceptual relationship matrix of QFD method for LNG supply chain risk management

Notes: *AI=absolute importance; RAI=relative absolute importance; RC=relative cost; E=effectiveness; Rank (AI)=ranking of RMSs based on AI; Rank (E)=ranking of RMSs based on effectiveness; R_{ij}=relationship score between SCR_i and RMS_j; S_{ij}=cost savings for simultaneous implementation of RMS_i and RMS_j

4.6.1.1 Stage 1: LNG supply chain risk and strategy identification

The four tasks accomplished in Stage 1 were: (i) LNG supply chain risk identification; (ii) LNG supply chain risk mitigation strategies' identification; (iii) development of the QFD method's conceptual framework; and (iv) development of the questionnaire for data collection. The voice of customers is the first component of a relationship matrix which usually comes from a customer survey or marketing research. In the current study on LNG SCRM, an extensive review of the literature was used to identify the LNG supply chain risks (SCRs) (see Chapter

3). Through this review, 33 supply chain risks (SCRs) were identified for the LNG industry in Australia, with these reviewed by an industry expert (see Table 5.1). These 33 LNG SCRs comprised the first component of the relationship matrix for LNG supply chain risk management (SCRM).

As with the risk identification, LNG supply chain risk mitigation strategies (RMSs) were identified through the extensive literature review and were verified by an industry expert (see Table 5.1). In total, 30 RMSs were identified for mitigating the 33 supply chain risks (SCRs). Details of the RMSs are presented in Chapter 3. Once the SCRs and RMSs had been identified, a conceptual framework for the QFD method's relationship matrix was developed (Figure 4.7) with different components of the QFD method as relevant to LNG SCRM. The conceptual framework identified the key areas of analysis that needed to be performed, the data requirement for carrying out the analysis, and the data type and structure. Following the QFD method conceptual framework, a questionnaire was developed for data collection. Details of the questionnaire development are presented in Chapter 5.

4.6.1.2 Stage 2: Data requirement (including questionnaire, verification and survey)

Data for LNG SCRM were collected covering the following four areas of the QFD method: (i) LNG supply chain risk probability and impact; (ii) relationship matrix; (iii) cost of implementing risk mitigation strategies (RMSs); and (iv) assessing the relationship between the strategies for the roof matrix (the correlation matrix). The assessment of risks considered the likelihood of occurrence, that is, the probability and possible impact. Hence, data on risks were collected to cover two aspects, namely, risk probability and impact of risk. A scale of 0–9 was used for risk probability with 0 representing that the risk cannot occur, 5 representing that it may or may not occur (i.e. equal chance of the risk either occurring or not occurring) and 9 representing that the risk was certain to occur. The 0–9 scale was used for impact assessment with 0 representing "Low" impact, 5 representing "Moderate" impact and 9 representing "High" impact. Each risk was scored by the experts for its probability of occurrence and its likely impact (see Table 5.1 for details of experts).

A cell in the relationship matrix represents the level of relationship between the risk (defined as SCR_i) and the *j*th strategy (defined as RMS_j) (Figure 4.7). To define the level of relationship between SCR and RMS, a conventional scale (of the QFD method) of 1, 5 and 9 was adopted in this study with 1 representing "Little relevance", 5 representing "Moderately relevant" and 9 representing "Highly relevant" (Park and Kim, 1998). The cells of the relationship matrix were completed by the experts with appropriate scores that were relevant to defining the level of relationship between SCR and RMS.

Implementation of each RMS involves cost, with this being a fundamental constraint of the modern business world. In a competitive business environment, minimization of cost at different stages of the supply chain is crucial for profit maximization and sustainability. Hence, an SCRM study would appear incomplete without cost considerations. To measure the cost of implementing each strategy, a scale of 0–100 was used with 0 representing no cost to implement the strategy and 100 representing the maximum cost to implement the strategy. A cost value for implementing the strategy of from 0–100 was assigned to each strategy by the experts (see Table 5.1).

The roof of the QFD method is a powerful matrix for identifying and defining relationships between the strategies. The relationship between two strategies with respect to their impact and cost in risk mitigation could be: (i) independent (i.e. no relationship); (ii) a positive relationship (i.e. simultaneous or combined application of both strategies complement each other, resulting in higher impact of risk mitigation at lower cost compared to their independent or separate implementation): and (ii) a negative relationship (i.e. implementation of one strategy adversely affects the other strategy in terms of risk mitigation and cost of implementation). Both positive and negative relationships could be extended further to define the degree of the relationship (e.g. low, moderate or high) which would result in a complicated relationship for RMSs in SCRM. For simplicity, in this study, only a positive relationship or no relationship has been considered with a low, moderate or high degree of relationship. Individual implementation of two positively related strategies could achieve a certain level of risk mitigation (say X) with a certain cost (say Y). Simultaneous or combined implementation of positively related strategies could achieve the same level of risk mitigation (X) with a lower cost (i.e. <Y) resulting in cost savings in the SCRM process. From her understanding of LNG SCRM in Australia which was based on the extensive literature review, the researcher assigned the relationships between the strategies. However, the relationship between the strategies for LNG SCRM was more dynamic than static compared to the relationship between SCR and RMS in the relationship matrix of the QFD method. The dynamic nature of the LNG supply chain was the reason for the dynamic relationship between the strategies. For example, the LNG supply chain is prone to change in local, national and international laws; local as well as national and international geopolitical issues; national and international fiscal policy; technology and innovation (such

as the invention of new technology e.g. shale gas, tight gas, coal seam gas [CSG], methane hydrate etc.); shift in national and international policy due to reasons including natural disasters (e.g. the Fukushima disaster), etc. In addition, defining the relationships of this component (the correlation matrix) of the SCRM model is a useful part of the experiment for the researcher who can check the different levels of cost savings that organizations, entities or companies could achieve through simultaneous or combined implementation of risk mitigation strategies (RMSs). Therefore, it was found to be more appropriate for the researcher rather than the experts to assign the nature and level of relationship between the RMSs to keep the SCRM model more dynamic over the short-time scale (i.e. at least for the research period, e.g. the 2–3 years for this study).

4.6.1.3 Stage 3: LNG supply chain risk prioritization

In SCRM, prioritization of risk is a basic step. It is not practical to mitigate or address every risk in the supply chain, either partially or fully, mostly due to resource constraints. Prioritization helps to identify the important risks among all the risks, with these needing to be mitigated to meet the organization's goals or objectives, such as profit maximization, risk minimization, cost minimization or sustainability of the supply chain. Not many techniques are available for prioritizing supply chain risks (SCRs). For example, Cox (2012) reported that many risk management initiatives and software tools used around the world ranging from enterprise risk management (ERM) to terrorism risk assessment programs uses a simple conceptual framework. The framework estimates the values or qualitative ratings of a few (typically, two or three) attributes of risk, such as "probability and impact" in ERM applications, "threat, vulnerability, consequence" in terrorism applications (Cox, 2012). This framework probably easy to understand by most common users (as attributes are less), relatively less challenging to collect data on risks, computation is simple, presentation of data and results are simple (such as frequency analysis, heat diagram). Therefore, this frame work is the most widely used method of risk prioritization employed in private and public organizations is measuring risk indices using the risk formula: risk = probability x impact (Cox, 2012). The simple and most widely used method of risk prioritization employed in private and public organizations is measuring *risk indices* using the risk formula: *risk = probability x impact* (Cox, 2012). To prioritize risks, a few (usually two or three) components of risk are estimated (quantitative or qualitative) to find risk indices using a risk indices formula that is tailored to the industry or discipline, such as *risk = probability x impact* for enterprise risk management; *risk = exposure x probability x consequence* in occupational health and safety risk management; or *risk = threat x vulnerability x consequence* for terrorism risk assessment (Cox, 2012). Traditionally, risks have been prioritized through risk indices: in the current study, we have applied the risk indices method (*risk = probability x impact*) to prioritize supply chain risk (SCR). The relative probability impact of a particular risk *i* can be calculated using the following formula:

$$RPI_i = \frac{PI_i}{\sum_{i=1}^{m} PI_i} \ldots\ldots\ldots\ldots\ldots\ldots\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

where,

RPI_i = Relative probability impact of risk *i*

PI_i = Probability impact of risk *i*

$m =$ 1, 2, 3, ………………………, 31, 32, 33. Risk (SCR) identification number

4.6.1.4 Stage 4: LNG supply chain risk mitigation strategy prioritization

In the conventional QFD method, the absolute importance of a particular design requirement is calculated through summing the product of the relative importance of customer requirements and its relationship value with the design requirement. Here, in this study on LNG SCRM, the absolute importance (AI) of a particular RMS can be calculated using the following formula:

$$AI_j = \sum_{j=1}^{n} \sum_{i=1}^{m} (RPI_i) R_{ij} \ldots\ldots\ldots\ldots\ldots\ldots\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.2)$$

where,

AIj = Absolute importance of strategy *j*

RPI_i = Relative probability impact of risk *i*

$R_{i\,j}$ = Relationship rating assigned in relationship matrix for risk *i* and strategy *j*

i =1……., *m*; (here, 1, ………, 33). Risk (SCR) identification number

j = 1……., *n*; (here, 1, …………., 30). Strategy (RMS) identification number

Here, RPI_i represents the relative importance of a particular risk *i* with respect to other risks.

For comparison between the experts' opinions (see Table 5.1), a relative scale of AI is used. The relative absolute importance (RAI) of RMSs is calculated through dividing the AI value of an RMS by the sum of the AI values of all the RMSs for an expert. The RAI for a particular RMS can be calculated using the following formula:

$$RAI_j = \frac{AI_j}{\sum_{j=1}^{n}(AI_j)} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (4.3)$$

where

RAI_j

RAI_j = Relative absolute importance of strategy *j*

AI_j = Absolute importance of strategy *j*

j = 1, 2, ... , 30. Strategy (RMS) identification number

4.6.1.4.1 Risk flexibility index

In this study, a new concept, the *risk flexibility index (RFI)* has been introduced to measure the flexibility of the risk in terms of its mitigation with appropriate risk mitigation strategies (RMSs). The RFI is a measure of the number of RMSs available for mitigating a risk. Thus, a risk with more RMSs available for its mitigation is more flexible in comparison to a risk which has less RMSs available for its mitigation. A proportionate linear relationship exists between the RFI and the number of RMSs available for mitigating the risk, as presented in Figure 4.8. For example, a SCR might be mitigated through implementation of any number of RMS (e.g. 1-30), here measured as RFI, which could vary with in the range for different SCRs. Thus, the relationship between RFI and number of RMS has to be a proportionate number of RMSs involved in mitigating the SCR. As each of the SCR is treated as independent to each other, RFI also be independent for a SCR. Thus, the relationship if plotted on for all SCRs should fall in a line varying low to high (e.g. 1-30). An advantage of the RFI of a risk is that it describes a certain characteristic of the risk that informs a manager or policy maker about how much risk flexibility exists in mitigating that risk.

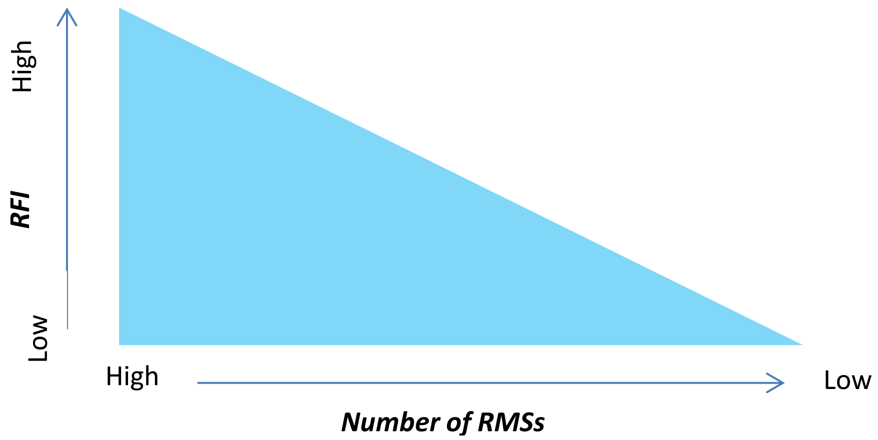


Figure 4.8: Conceptual diagram of risk flexibility index (RFI)

Note: The horizontal axis (x-axis) shows the number of RMSs available for mitigating the risks and the vertical axis (y-axis) shows the RFI of the risks.

4.6.1.4.2 Cost of implementing strategies

Prioritizing risks using risk indices allows decision makers to focus on the greatest risks, those that need to be mitigated to minimize risks to the LNG supply chain. In a similar way, prioritizing RMSs helps decision makers to choose the important strategies to implement to minimize more risk through the implementation of a small number of RMSs, but strategies which are highly preferred. The objective of risk prioritization and strategy prioritization is to identify priority areas within SCRM so resources can be allocated from limited budgets to attain greater minimization of risks. As strategy implementation involves cost, without cost estimation for the implementation of strategies, important information that is vital for informed decision making would be omitted (Cox, 2008, 2009). Thus, in management decision making, it is not necessary for higher risks to be mitigated to achieve greater risk mitigation as the cost to mitigate these risks could be much higher compared to the costs of mitigating other risks. Similarly, implementation of important and highly preferred RMSs may cost more compared to the implementation of other strategies (e.g. preferred or less preferred RMSs) which may mean that it is not necessary to implement important and highly preferred strategies to achieve greater risk mitigation for the supply chain. In management decision making, the cost of risk mitigation (here, the cost of implementation) is a crucial factor in the allocation of limited resources to achieve greater risk mitigation. In this study, risk mitigation is achieved through identification, prioritization and implementation of risk mitigation strategies (RMSs). Therefore, the estimation of the cost of RMS implementation is necessary for effective decision making with regard to supply chain risk mitigation. Here, the cost of implementing RMSs has been determined based on expert opinion (as assigned by one expert). The scale used for the cost of implementing an RMS is 0–100, where 0 means no cost is required for implementing a strategy and 100 means the highest cost of implementing a strategy. Thus, the individual expert (see Table 5.1) has scored a number from 0–100 against each strategy as the cost of implementing the strategy.

It is obvious that the cost of implementation of each strategy, as assigned by an individual expert (see Table 5.1), could be different for different experts: hence, the sum of the cost of implementing all strategies would be different. Thus, for comparison of the cost of a particular strategy, as assigned by six experts, the cost of implementation of the supply chain risk mitigation strategy needed to be normalized. Here, for each expert, the relative cost of a particular RMS is calculated through dividing the cost of implementing a strategy by the sum of the cost of implementing all strategies, as assigned by the individual expert. Thus, the sum of all relative cost (RC) values of the supply chain RMSs should be equal to 1 for each of the experts. This means that each expert has 1 unit of cost and he/she has to assign a fraction of this unit against each RMS with the sum of costs of all the RMSs to be equal to 1, with this represented by the following equation:

$$RC_j = \frac{C_j}{\sum_{j=1}^{n}(C_j)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.4)$$

where

RC_j = Relative cost of implementing strategy j

C_j = Cost of implementation of strategy j

j = 1, 2, ………………………………….., 30. Strategy (RMS) identification number

4.6.1.4.3 Effectiveness of a strategy in risk mitigation

It is important to know in LNG SCRM how much risk mitigation can be achieved with the implementation of a particular strategy per unit of cost which can be termed as *effectiveness of a strategy (ES)*. The absolute importance (AI) of a strategy means the level of risk mitigation that can be achieved in the supply chain if the strategy is implemented. The estimated cost of a strategy represents the resources required to implement the strategy. Here, a strategy has two attributes, one is its impact on SCRM and the other is the cost incurred in implementing the strategy. The effectiveness of a strategy in risk mitigation can be measured as the level of risk mitigation achieved per unit of cost or resources utilized in the risk mitigation process of SCRM. Mathematically, ES can be expressed as:

$$ES_j = \frac{AI_j}{C_j} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.5)$$

where

AI_j = Absolute importance of strategy *j*

C_j = Cost of implementation of strategy *j*

j = 1, 2, ……………………………………………………., 30. Strategy (RMS) identification number

In calculating the effectiveness of a strategy (ES), instead of the actual cost assigned by the experts for each strategy, a normalized cost has been used to allow for better comparison between the results from different experts. The normalization of cost is done through dividing the cost of implementation of each strategy by the sum of the total cost of implementation of all strategies where the sum of all normalized cost is equal to 1. Similarly, instead of absolute importance (AI), relative AI (RAI) is used for easier comparison of the results derived based on data from the different experts, as the total value for AI from different experts is different. Hence, the effectiveness of a particular strategy, calculated by using relative absolute importance (RAI) and relative cost (RC), is termed as the *relative effectiveness (RE)* of a strategy. Thus, the mathematical expression of the relative effectiveness (RE) of a strategy can be calculated as formulated below:

$$RE_j = \frac{AI_j / \sum_{j=1}^{n}(AI_j)}{C_j / \sum_{j=1}^{n}(C_j)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.6)$$

where

AI_j = Absolute importance of strategy *j*

C_j = Cost of implementation of strategy *j*

j = 1, 2, …………………………………………………, 30. Strategy (RMS) identification number

4.6.2 QFD Part 2: Development of optimization model for LNG SCRM

4.6.2.1 Stage 5: Development of optimization model

In most cases, SCRM studies conclude with risk prioritization. In addition, most applications of the QFD method conclude by developing a relationship matrix and calculating the absolute importance (AI) of design requirements. Very few studies extend to the selection of design requirements and the optimization of design requirements against constraints.

Park and Kim (1998) used the QFD method to translate customer attributes into design requirements in order to achieve greater customer satisfaction. They then developed an optimization problem to select an optimal set of design requirements within a limited budget to achieve maximum customer satisfaction despite this constraint. Following Park and Kim's (1998) concept, a similar optimization problem can be developed for LNG SCRM. The amount of risk mitigation from the implementation of an RMS can be measured as the absolute importance (AI) of the risk mitigation strategy (RMS). Hence, the total amount of risk mitigation from a set of RMSs is the sum of AI of the RMSs that have been implemented, with this expressed as follows:

$$f(x) = \sum_{j=1}^{n} (AI_j) x_j \quad \dots\dots\dots\dots\dots\dots \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (4.7)$$

where,

$f(x)$ = Amount of risk mitigation

AI_j = Absolute importance from implementing j^{th} risk mitigation strategies

x_j = Variable representing all the RMSs, with j = 1, ……………………., n

Here, x_j could be either 1 or 0 depending on whether or not a particular RMS is implemented.

The implementation of each RMS involves cost, with the total cost of implementing all the RMSs able to be calculated through the following equation:

$$g(x) = \sum_{j=1}^{n} c_j x_j \quad \dots\dots\dots\dots\dots\dots \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (4.8)$$

where,

$g(x)$ = Total cost of implementing all the RMSs

c_j = Cost of implementing j^{th} risk mitigation strategies

x_j = Variable representing all the RMSs, with j = 1, ……………………., n

In practice, risk cannot be eliminated; rather, it can be minimized. In addition, risk mitigation involves efforts and resources resulting in costs being subsequently incurred and, ultimately, in reduced outcomes or lower profit. Thus, the organization or entity cannot afford to allocate enough resources to eliminate all the risks which would make the supply chain without risk. To make the supply chain functional, to avoid major disruption to the supply chain or to make the supply chain sustainable, entities either allocate a particular budget for risk mitigation or want to know the amount of resources required to attain a certain level of risk mitigation. Therefore, risk has to be minimized taking into consideration the budget available for risk mitigation, and the total cost of implementing RMSs must be kept within the budget (B) which can be expressed as follows:

$$g(x) \leq B \ldots\ldots\ldots\ldots\ldots\ldots \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.9)$$

With a limited budget, it is not possible to implement all the risk mitigation strategies (RMSs). Hence, to achieve the maximum level of risk mitigation within a limited budget, the RMSs which have the higher levels of AI values (with a lower cost) must be selected. This leads to an optimization problem which can be formulated as follows:

$$Maxf(x) = \sum_{j=1}^{n} (AI_j) x_j \ldots\ldots\ldots\ldots\ldots\ldots \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.10)$$

s.t. $g(x) \leq B$ for j = 1, ……………., n

$$g(x) = \sum_{j=1}^{n} c_j x_j$$

$$x \in X$$

In calculating the cost of implementing all the RMS, each RMS is treated independently, that is, no relationship is considered to exist between the risk mitigation strategies (RMSs). In reality, however, strategies are not always independent; instead, some strategies are related or interdependent. Relationships between two strategies can be positive, negative or null. A positive relationship can be defined as one in which the implementation of one strategy complements the objective or outcome of the other strategy. A negative relationship can be defined as one in which the implementation of one strategy opposes, deters or hinders the objective or outcome of the other strategy. A null relationship means that no relationship exists between the two strategies; that is, the two strategies are independent and, hence, the implementation of one strategy does not affect the other one in any way. Measuring of positive or negative relationships can be scaled using different measurement scales, such as “Strong”, “Medium” or “Low”. In the current study, for simplicity, only positive relationships between two strategies are considered. Most common phenomenon of the relationship among the RMSs are either positive or neutral. However, negative relationship might exist between two RMSs though not-common. A negative relationship means implementation of a particular RMS likely to aggravate some SCRs completely or partially instead of complete or partial mitigation. Defining such relationship between RMSs is considered extremely difficult and to some extent controversial as primary objective of any RMS is to mitigate SCR. This is why negative relationship among the RMSs are not considered in this study though such relationship is theoretically possible.

As two positively related strategies complement each other in achieving their objective or outcome, the joint implementation of two independent RMSs could achieve an equal amount of risk mitigation (to what is achieved through their separate implementation) with less effort. For example, let us assume X_1 and X_2 are two positively related RMSs; and that the amount of risk mitigation that can be achieved through their separate implementation is P_1 and P_2 with the respective cost of C_1 and C_2. As X_1 and X_2 are two positively related strategies, their joint implementation would complement each other or one would complement the other in achieving their respective (or one’s) level of risk mitigation. Hence, through joint implementation or the implementation of both strategies X_1 and X_2, $P_1 + P_2$ amount of risk mitigation can be achieved with a total cost lower than $C_1 + C_2$. This means that cost savings occur when two positively related strategies are implemented jointly or together.

The "roof" matrix of the QFD method presents the relationships between the risk mitigation strategies (RMSs) (Figure 4.7). Cost savings from the joint implementation of two positively related strategies can be calculated based on the relationship as shown in the QFD method’s correlation matrix. If x_i and x_j are two positively related RMSs and cost savings from the joint implementation of these strategies is s_{ij} , then total savings from all positively related strategies can be calculated as follows (Park and Kim, 1998):

$$Cost\ savings, k(x) = \sum_{i=1}^{n}\sum_{j>i}^{n} s_{ij}\, x_i x_j \ldots\ldots\ldots\ldots\ldots\ldots\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.11)$$

Therefore, another constraint scenario is the implementation cost of RMSs when considering cost savings from the joint implementation of positively related strategies. The optimization problem can be solved using an integer programming algorithm for maximizing the amount of risk mitigation through the selection of appropriate risk mitigation strategies (RMSs). In this study, we solved the optimization problem for LNG SCRM to select an optimal set of RMSs both with and without cost savings from the joint implementation of positively related risk mitigation strategies (RMSs). The cost constraint function with cost savings, (x), for solving the optimization problem of LNG SCRM can be presented as follows:

$$R(x) = g(x) - k(x) \ldots\ldots\ldots\ldots\ldots\ldots\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.12)$$

$$\text{s.t. } R(x) \leq B$$

$$x \in X$$

4.6.2.2 Stage 6: Solving the optimization model

The optimization of LNG SCRM for selecting an optimal set of RMSs within a particular budget is a quadratic integer programming problem as presented in Stage 5. The absolute importance (AI) score of an RMS represents its importance or effectiveness in mitigating supply chain risks (SCRs). The higher the AI score, the better the RMS in satisfying the need to mitigate supply chain risks (SCRs). Thus, one criterion for solving the optimization problem is to select RMSs with greater AI scores to maximize the objective function and the total amount of risk mitigation with a lower number of strategies implemented. The other criterion for optimization is to select RMSs which involve lower cost so more RMSs can be implemented within a limited budget to maximize the objective function. Combining the two criteria for optimization, we must select RMSs with greater AI scores which involve lower implementation cost to maximize the objective function, that is, to maximize the total amount of risk mitigation with a limited budget. The Solver tool in Microsoft (MS) Excel can solve a quadratic integer program and it was thus used to solve the optimization problem of selecting an optimal set of RMSs within a limited budget for LNG SCRM. The approach adopted in developing and solving the optimization model is based on the study by Park and Kim (1998). The optimization problem has been solved both with and without cost savings from the joint implementation of positively related RMSs. In addition, the optimization problem has been solved for different budget scenarios which are 10%, 20%, 30%, through to 90%, respectively, of the total cost of implementing all the risk mitigation strategies (RMSs).

4.6.3 QFD Part 3: Development of simulation model for LNG SCRM

In the current study, a simulation model was developed to further explain the findings of the solution to the optimization problem. The solution of the optimization problem was based on data from six experts who provided six scenarios of the mitigation of LNG SCRs in which: (i) the level of risk mitigation was achievable for different cost scenarios and (ii) a selected set of RMSs was provided for these cost scenarios. The additional sets of data from the experts (see Table 5.1) provided additional scenarios of LNG supply chain risk mitigation through solving the optimization problem. Thus, the optimization problem, solved with these six sets of data, provided only six scenarios of LNG supply chain risk mitigation and the optimization problem was solved with the averaged data of the six experts providing another scenario. In addition, the variation between the experts in scoring risk parameters (e.g. risk probability and risk impact), in the relationships between risk and risk mitigation strategy and in estimating the cost of implementing RMSs shows that these vary within a range. This meant that a wide range of values was possible for a variable varying within the range defined by the six experts. To derive a larger picture of LNG supply chain risk mitigation with more risk mitigation scenarios, additional sets of data were needed. However, collecting data on LNG SCRs is difficult for several reasons. Therefore, in the current study, a simulation model was developed to overcome the limitations of the limited data and to address the variation between the experts in defining risk and strategy parameters.

4.6.3.1 Stage 7: Development of simulation model

The simulation model developed here for LNG supply chain risk mitigation is an extension of the optimization problem and kept the algorithm and solution process exactly the same as used in the optimization problem with the sets of simulated data. Therefore, the simulation model presented here is simply the optimization problem, as explained in the previous section, and the process of solving the simulation model is the same as the process previously explained in solving the optimization problem. The only difference between the optimization model and the simulation model is the generation of a set of data to solve the simulation model. Hence, a method was developed here to generate a set of data for input into the simulation model which is explained in the following subsection.

4.6.3.2 Stage 8: Solving the simulation model

The score of SCR attributes (i.e. probability and impact) and of RMS attributes (e.g. cost) and the relationship score between SCRs and RMSs are expected to be different for different experts (see Table 5.1). For example, the relationship scores between SCR1 and RMS1, as assigned by the six experts, are P, Q, R, S, T and U with the minimum and maximum of these being P and U, respectively (Figure 4.7). Therefore, the relationship score (R_{11}) as defined by the six experts has six discrete values. However, in reality, this means that the value of R_{11} could be any value within the range bounded by the minimum (P) and the maximum (U) score, as defined by the experts. If an additional set of data could be collected from another expert, then the score of HoQ_{11} could be either any value within the range of P and U or any value outside the range of P and U, thus further extending the range. Therefore, based on the sets of data already collected, the boundary condition of the variation range of each SCR and RMS attribute was defined by the minimum and maximum scores of the attribute, with it assumed that the risk and strategy scores would be any score within the range. Thus, considering a random value of an SCR and an RMS attribute (including cost), infinite sets of data were possible by varying the scores of the parameters within the range defined by the experts. In the current study, 50 sets of data were generated and the simulation problem was solved for these 50 sets. The RAND() function of MS Excel was used to generate random values of SCR or RMS attributes varying within the specified range. The formula used for generating random values for an attribute is as follow:

$$Rand\ Score = P + (U - P) * RAND(.) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.13)$$

where,

Rand Score = Any score of an SCR or RMS attribute or cost varying within the range as defined by the six experts

P = Minimum score of a parameter as defined by the six experts

U = Maximum score of a parameter as defined by the six experts.

The RAND() function of MS Excel produces any random value between 0 and 1. Therefore, using the above formula, many different scores of an SCR attribute can be calculated all of which will be within the range defined by the experts.

4.7 Chapter Summary

This chapter has detailed the research methodology used in this study. The research paradigm, research methods and research framework were explained as the basis for selecting the appropriate theoretical foundation of the study. The methods for research on SCRM were reviewed in order to adopt a suitable method for the current study on LNG supply chain risk management (SCRM). The proposed research method for this LNG SCRM study was explained in a step-by-step process including the optimization problem formulation and way in which it was solved with this followed by the simulation model. The simulation model was developed using the algorithm from the optimization problem and a method was developed for generating data for input into the simulation to solve the model.

CHAPTER 5

PRIORITIZATION OF LNG SUPPLY CHAIN RISKS FOR AUSTRALIA

5.1 Chapter Introduction

The prioritization of LNG supply chain risks (SCRs) is important for several reasons, such as: targeting SCRs of high likelihood or impact; achieving greater risk reduction within limited resources; and allocating limited resources to gain maximum risk reduction. In this chapter, reasons for the prioritization of SCRs are outlined, and SCRs are prioritized following the method explained in Chapter 4. The data required for the prioritization of SCRs and for the overall SCRM of the LNG industry, based on the method adopted (as outlined in Chapter 4), are identified. The data collection method and process are elaborated, including the questionnaire design and development, the survey, the background of survey participants and the processing of the collected data. As part of the prioritization process, SCRs are categorized and ranked to identify the SCRs of high likelihood and high impact. The SCRs are categorized using a relative scale. A method of deriving the weightage is developed and applied to rank the SCRs based on the experts' consensus. The variations of the probability and impact scores assigned by the experts are presented and explained. In addition, the variability of SCR attributes and risk indices are explained and their implications in SCRM are discussed. This chapter concludes with a summary.

5.2 Reasons for LNG Supply Chain Risk Prioritization

In practical terms, in the majority of SCRM cases, SCRs cannot be eliminated so instead they must be mitigated. Not all risks are equal in terms of the likelihood of occurrence and the impacts or threats they pose to the supply chain. Some risks are easy to mitigate while, for some, it is difficult to find and implement appropriate risk mitigation strategies (RMSs). In addition, the mitigation of different SCRs involves different costs and resources. For example, in a study of an optimal set of design requirements to solve an air quality problem, Park and Kim (1998) reported that implementation of different design requirements involve different cost. Rarely are risks independent: instead, they are interdependent and the relationships between risks can be either positive or negative relationship. A positive relationship means increase in likelihood if occurrence of an SCR also tends to increase of likely hood of occurrence of the related SCR. For example, an increase in chance of risk of cyclone may also increase chance of risk of flooding in a particular area. In the contrary, a negative relationship among SCRs means the SCRs are not mutually related, such as increase in likelihood of occurrence may decrease likelihood of occurrence of the related SCRs. For example, an increase in rainfall activity increases risk of flooding but decrease risk of bush fire for an area. Thus, in SCRM, instead of individual risk analysis, it is better to analyse risks holistically. In a resource-constrained world, with limited resources and budget, it is almost impossible to mitigate all supply chain risks (SCRs). Thus, along with risk identification, the prioritization of risks is important as it identifies the SCRs with high likelihood of occurrence and high impact as mitigation of these SCRs is likely to result in a greater level of risk mitigation. The prioritization of SCRs is also likely to be beneficial so limited resources can be allocated to achieve a greater level of risk mitigation.

5.3 Data Collection

This research required both primary and secondary data. A questionnaire was developed for a survey which collected primary data including information on SCR attributes, RMS attributes, relationships between SCRs and RMSs, and the cost of implementing risk mitigation strategies (RMSs). The questionnaire and the survey are described in the following two sections.

5.3.1 Questionnaire for LNG supply chain risk management

As part of the questionnaire development, summaries of the SCRs in the LNG supply chain and the associated RMSs were prepared based on the existing literature (as presented in Chapter 3). The LNG SCRs and RMSs summaries for Australia were vetted by an industry expert. A panel of experts for data collection was identified and communication was developed to be sent to these experts with the survey.

The survey questionnaire (presented in Appendix C) for LNG SCRM in Australia consists of two sections: (i) attributes of SCRs, such as probability of occurrence and likely impact of LNG SCRs; and (ii) attributes of RMSs, such as relationship scores between SCRs and RMSs and the associated costs of RMS implementation. The questionnaire gained approval through Curtin University's ethics approval process.

Thirty-three (33) LNG SCRs are listed in Section I of the questionnaire. The SCRs vary greatly in regard to their probability of occurrence and likely impact on the supply chain. In designing the survey questionnaire for this study, closed-ended questions were adopted. A 3-point Likert scale (Likert, 1932) and numeric visual analogue scales (VAS) (Van Laerhoven et al.,

2004) were used in combination to measure the probability of occurrence and likely impact of all SCRs (Appendix C).

The empirical investigations conducted by Bendig (1954) and Komorita (1963) indicated that the reliability test of the data is independent of the number of categories utilized in the Likert scale. Their finding was supported by an investigation carried out by Jacoby and Matell (1971) on the optimal number of alternatives to use in the construction of a Likert-type scale when considering reliability and validity. Jacoby and Matell (1971) concluded that a 3-point Likert scale is sufficient. However, Awang et al. (2016) noted that, in developing a questionnaire, the Likert scale could be coded for 5 points, 7 points or 10 points, after taking into consideration the level of hierarchy that respondents would require to indicate agreement with a particular question. In a comparative study measuring the performance of two categories of Likert measurement scales (5 points and 10 points) while employing the same sample size and research subject, Awang et al. (2016) found that the 10-point Likert scale was more efficient than the 5-point Likert scale in the operation of a measurement model. Awang et al. (2016) also reported the inadequacy of the 5-point scale in determining the intention of respondents. This was particularly found to be the case when attempting a parametric test on statistical inference. In another study that compared the Likert scale with visual analogue scales (VAS), Van Laerhoven et al. (2004) revealed that children preferred the Likert scale over both the numeric VAS and the simple visual analogue scale (VAS). The numeric VAS used by Van Laerhoven et al. (2004) consisted of a series of numbers from 1 to 10 with 1 representing the beginning of the Likert scale and 10 representing the end. However, classifying the categories for a 10-point Likert scale could be cumbersome for two SCR attributes and it would be difficult for respondents in assigning appropriate categories for the SCR attributes. For example, defining each increment of the 0-10-point Likert scale with appropriate meaningful terminology (such as 0- cannot occur, 10 certain to occur) for two SCR attributes (probability and Impact) could be challenging. Each of the increment terminology (such as moderate, medium, likely) of the scale could be interpreted differently by different respondent in a survey if the terminologies are not contextualized appropriately. In addition, ultimately, the categories of SCR attributes needed to be transferred into a numeric scale to carry out further analysis (e.g. prioritization of SCRs based on attributes, and determining risk indices leading to QFD-based optimization and simulation models). Therefore, a combination of the 3-point Likert scale (Likert, 1932) and numeric visual analogue scales (VAS) (Van Laerhoven et al., 2004) was employed in the current study to collect primary data on SCR attributes (i.e. probability and impact). In the combined scale

(Appendix C), the 3-point Likert scale is divided into 10 equal parts which are numbered from 0–9 representing the start and end of the Likert scale. The first rationale for selecting a 0–9 scale was that the probability of occurrence of an SCR may be such that there is little or no chance of it happening. In such a case, the probability score would need to be 0. Similarly, the impact of the SCR could be such that it might have little or no impact if it occurred. Thus, the impact scale should also start from 0. A second rationale for selection of the 0–9 scale was consistency of this scale with the QFD scale (1-5-9) which was adopted to measure the RMS attributes in relation to the SCR attributes. The 1-5-9 QFD scale is discussed later below.

The combination of the 3-point Likert scale (Likert, 1932) and numeric visual analogue scales (VAS) (Van Laerhoven et al., 2004) ranging from 0–9 are presented in Appendix C. To measure probability, the mid-point of this scale is appointed as the value of 5, with this used for the equal probability option: ”May or may not occur”. The start of the scale is appointed as 0 which represents a probability of "Cannot occur" for any chance of a particular SCR occurring. The endpoint of the scale has the value of 9 which is described as "Certain to occur" with 100% chance of a particular SCR occurring. The three points of impact scale of an SCR are appointed as "Low"," Moderate "and "High" with the range of 0–9. The mid-point shows "Moderate" impact and the two endpoints on the scale describe "Low" and "High" impact of an SCR, respectively.

Section II of the questionnaire consists of questions seeking data related to the QFD method's relationship matrix and the cost of RMS implementation. The relationship matrix of the HoQ defines the relationships between SCRs and RMSs whereas an individual cell in the relationship matrix defines the relationship between an individual risk and a strategy. If no relationship exists between the risk and a particular strategy, the cell remains empty. For a "Weak", "Medium" and "Strong" relationship between SCRs and RMSs, a cell in the relationship matrix has been assigned a value of 1, 5 and 9, respectively (Park and Kim, 1998). Although different rating scales (e.g. 1-3-9, 1-3-5, 1-5-9, 1-2-4 and 1-6-9) are used to define relationships in the QFD method's relationship matrix, none of the scales provides a justification for the choice of these scales (Park and Kim, 1998). The 1-5-9 scale is chosen in the current study as this scale is consistent with the scale used in Section I of the questionnaire. The consistency between these two scales facilitates the uniformity of further analysis, such as SCR and RMS prioritization, and development of optimization and simulation models. To assess the cost of RMS implementation, a scale of 0 to 100 is used with 100 representing the highest cost required for implementation and 0 representing that no cost is required.

5.3.2 Survey

To carry out the survey, firstly, an email was sent to LNG companies in Australia requesting the availability of LNG experts to participate in the survey. The email explained the expectations of the experts for the survey and the time commitment. In addition, a similar request to participate in the survey was sent to LNG experts overseas. A list of overseas or global LNG experts was prepared following the review of the LNG literature which included reports, journals, books and conference papers. A very limited response was received in the primary stage of the survey. After approximately six months' correspondence, six LNG experts (a combination of local and global) provided their consent to participate in the survey. The questionnaire was sent to the experts to collect their opinions and they provided their invaluable opinions by completing the questionnaire. The experts had no concerns or queries about the questionnaire: they appreciated it and wished the researcher good luck with this research.

5.3.3 LNG experts as survey participants

A summary of the experts who participated in the survey is presented in Table 5.1. Although the number of experts who participated in the survey was limited, their expertise on LNG was comprehensive and most were leading personalities in the global natural gas industry including liquefied natural gas (LNG). To preserve the anonymity of the experts, Table 5.1 summarizes some of their key expertise and background. Despite the limited number of experts, it was important to note their geographical distribution which covered most of the major continents where global LNG suppliers and recipients are located.

Table 5.1: Brief summary of LNG experts who were survey participants

Experts	**Country**	**Institution type**	**Brief background of professional history**
Expert 1	Australia	Independent researcher	Internationally known engineer in the oil and gas industry, worked in several countries and author of several journals on Australian natural gas resources including LNG.
Expert 2	USA	University	Accountant, legal practitioner, academic, author of book on LNG, leading scholar on world natural gas markets with focus on LNG and shale gas development, visiting academic of world-renowned universities.
Expert 3	UK	International energy consultant	Specialist in a range of energy-related topics including natural gas and LNG. Key parts of his

Experts	Country	Institution type	Brief background of professional history
			work include portfolio and risk analysis, project contracts, fiscal design. In particular, specialist in portfolio evaluation, acquisition, divestment and management decisions through integration of technical, economic, fiscal, risk and strategic information.
Expert 4	USA	Leading consultant on natural gas economics	World-renowned energy economics specialist, engineer, natural gas policy expert, author of several policy papers on LNG, visiting faculty member of world-renowned universities and recipient of prestigious awards for contribution on energy economics and to its literature.
Expert 5	Canada	Practising engineer	Experienced practising engineer, currently working in a leading oil and gas company in Canada, previously worked in natural gas company in Bangladesh.
Expert 6	Bangladesh	Independent consultant	Experienced engineer in the oil and gas industry, worked as independent consultant for international bank, previously worked for an energy company in Bangladesh.

5.3.4 Processing data collected from LNG experts

The completed questionnaires had little missing data. In addition, the scale used for defining relationships between SCRs and RMSs received a good response from the experts. On only a couple of occasions in one questionnaire did a respondent misunderstand the 1-5-9 scale; for example, the relationship between SCR and RMS was scored as a 6 instead of a 5. However, this did not impact on the overall analysis. In the conventional QFD method, the traditional 1-5-9 scale represents “Weak”, “Medium” and “Strong” relationships (Park and Kim, 1998). A score of 6 represents a “Medium” relationship (which is also the case for a score of 5). The relationship score between an SCR and an RMS is ultimately used to calculate the absolute importance (AI) of a risk mitigation strategy (RMS). Therefore, the scoring of RMSs does not influence the analysis or outcome of the research to a great extent. Furthermore, the scoring of the relationship matrix leads to a question for future research which could explore the possibilities of using a continuous scale in the QFD method instead of the traditional scale (such as 1-5-9 or 1-3-9).

5.4 LNG Supply Chain Risk Prioritization

Risk prioritization is widely used and applied for firm and enterprise risk management (ERM) and, in terms of firm and ERM, a range of research has been carried out (Cox, 2012).

However, SCRM is an emerging area of research and risk prioritization for SCRM is relatively new (Sodhi et al., 2012). The reasons could be the involvement of an enormous number and a great variety of SCRs, the interrelationships of SCRs and RMSs as well as SCRM's excess number of stakeholders. As LNG is a new commodity in the international energy market, very limited work has been carried out on LNG supply chain management (SCRM). The complexity of LNG SCRM further escalates due to the influence of factors such as national and international policy; large capital investment; geopolitics; technology and innovation; country socio-economic and political contexts; long distances; threats and terrorism, etc. (Jensen, 2003). Therefore, the identification and prioritization of LNG SCRs are important, followed by the identification of RMSs and resource allocation for better SCRM. In this section, LNG SCR has been prioritized using a widely used risk index system: *Risk (R) = Probability (P) x Impact (I)* (Cox, 2012). Here, each SCR has two attributes, *probability* and *impact,* and their product, *probability impact (PI),* results in the SCR's index score. The result of the formula is a probability impact (PI) score for a particular SCR which indicates the relative magnitude, size or importance of the SCR in the overall SCR table. As the scores provide the indication of the relative position of an SCR in a risk table, together these are treated as *risk indices* (Cox, 2012).

5.5 LNG Supply Chain Risk Categorization

Categorizing risks into groups is beneficial in overall risk prioritization. Here, for simplification and better understanding, LNG SCRs are classified into three categories as "High (∆)", "Medium (∆)" and "Low (•)" based on *probability*, *impact* and *probability impact scores* (*risk indices*). In categorizing the risks, a *relative scale* is used instead of a *scoring scale*.

5.5.1 Relative scale for risk categorization

To categorize SCRs, a relative scale is used for each attribute of risk, such as the *probability, impact* and *probability impact (risk indices).* A conceptual diagram of the scoring scale and relative scale is shown in Figure 5.1. The *scoring scale* is used to collect the score of risk attributes (e.g. probability) in the questionnaire (Appendix C) used in the survey. For example, the scoring scale for probability is 0–9, low to high. However, in reality, the analysis of the scoring of SCR attributes (e.g. probability) shows that none of the SCRs were assigned a score of 0; a very limited number of risks were assigned a score between 1 and 3; and a few risks were assigned a score of 9, in this case for probability. When the mean of an SCR attribute (e.g. probability) is calculated based on the score assigned by the six experts (Table

5.1), it was observed that part of the lower end and upper end of the scoring scale remained unutilized. For the mean of the SCR attribute, only the utilized part of the scoring scale is considered as the *relative scale* for that SCR attribute. This relative scale is divided into three equal parts from low to high: the scale is marked as "Low (●)", "Medium (Δ)" and "High (Δ)" as shown in Figure 5.1(b).

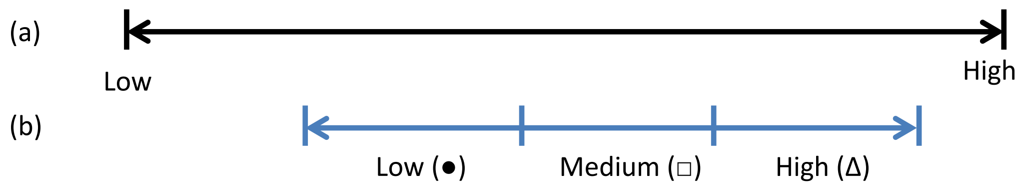


Figure 5.1: Conceptual diagram of scoring scale and relative scale for categorizing LNG SCRs: (a) *scoring scale* and (b) *relative scale*

Note: (a) indicates the scoring scale and (b) is the relative scale, utilizing part of the scoring scale, which is categorized into three equal parts as "Low", "Medium" and "High".

The relative scale uses only the utilized part of the scoring scale of 0–9 for probability and impact while the part from 0–81 is used for risk indices. The top third of the utilized part of the scale is categorized as "High (Δ)", the middle third is categorized as Medium(□)" and the lower third is categorized as "Low (●)". Table 5.2 presents a summary of the relative scale for probability, impact and risk indices used in this study to categorize the LNG supply chain risks (SCRs). It is noted that the numbers in Table 5.2 represent scales used to categorize the SCR as "High", "Medium" and "Low" based on SCR attributes (probability and impact) and risk indices. Based on the scoring scales of probability and impact (both 0–9), the possible scoring scale of risk indices is 0–81. However, the risk indices scale score in this study, based on the mean values of probability and impact, is 17.25–63.97, the lowest and highest of the mean risk indices scores of all supply chain risks (SCRs). The risk indices score is calculated based on the mean values of probability and impact assigned to individual SCR by the experts (Table 5.1). This risk indices scale (17.25–63.97) is then divided into three equal parts which are marked as "Low" (17.25 < 32.82), "Medium" (32.82 ≤ 48.40) and "High" (> 48.40–63.97). The rationale of this scaling is to minimize the effect of the unutilized part of the 0–9 scale for probability and impact scoring as well as the unutilized part of the scale for probability, impact and risk indices that arises due to the averaging of expert scores during analysis.

Table 5.2: Relative scale for categorizing probability, impact and risk indices

Category	Notation	Risk attribute scale		
		Probability (P)	Impact (I)	Risk Indices (PI)
High	Δ	> 6.94–8.33	> 6.50–7.83	> 48.40–63.97
Medium	□	5.56 ≤ 6.94	5.17 ≤ 6.50	32.82 ≤ 48.40
Low	•	4.17 < 5.56	3.83 < 5.17	17.25 < 32.82

5.5.2 LNG supply chain risk categories based on risk attributes

Based on the corresponding relative scales (Table 5.2), LNG SCRs are categorized (in Table 5.3) for each of the risk attributes (i.e. probability, impact and risk indices). The risk categories are summarized in Table 5.3 which shows the mean of each SCR attribute score (based on the scoring scale) and the respective category (based on the relative scale) for each of the 33 supply chain risks (SCRs). Synopses of the risk category for each risk attribute are outlined in Table 5.4.

Based on the risk indices, of the 33 SCRs, 12 risks are categorized as “High”, 14 risks as “Medium” and the remaining seven (7) risks as “Low” (Tables 5.3 and 5.4). The “High” risks (Table 5.3) are SCR6, SCR11, SCR12, SCR14, SCR15, SCR16, SCR17, SCR21, SCR25, SCR27, SCR29 and SCR30. An objective of risk prioritization is to identify high SCRs which may affect the supply chain resulting in supply chain disruption with high losses. In this respect, the categorization of LNG SCRs using risk indices appears to be useful as it identifies SCRs according to their relative size; the likely threat they produce; the importance of the risk receiving attention; and the likelihood of occurrence. All of these risk characteristics are measured through two attributes of SCRs, namely, probability (i.e. likelihood of occurrence) and impact (i.e. threat it produces if it occurs). As an outcome of this SCR prioritization, risk managers and/or policy makers can now focus on the 12 “High” SCRs out of the 33 SCRs identified for LNG SCRM in Australia. Further resources can then be allocated to mitigate the 14 “Medium” SCRs followed by the seven (7) “Low” SCRs (Tables 5.3 and 5.4). This is how the identification, prioritization and categorization of LNG SCRs help in LNG SCRM in Australia. This list of 12 high priority risks comprises the primary focus areas of management and policy makers in reducing risks to the LNG supply chain.

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Table 5.3: LNG supply chain risk categories based on risk attributes

Risk ID No.	Short Description of LNG Supply Chain Risk	Probability		Impact		Risk Indices	
		(P)	Cat.*	(I)	Cat.*	(PI)	Cat.*
SCR1	Downgrade of investment attractiveness for new plants	6.3	□	7.2	Δ	45.4	□
SCR2	Occurrences of policy differences from state to state	7.0	Δ	5.8	□	40.8	□
SCR3	Increasing international pipeline gas supply	4.5	●	5.2	●	23.3	●
SCR4	Higher cost of skilled human resources than paid by other competitors	7.0	Δ	6.7	Δ	46.7	□
SCR5	Lower productivity for LNG production	4.2	●	5.2	●	21.5	●
SCR6	Strong A$ (local currency)	7.7	Δ	7.2	Δ	54.9	Δ
SCR7	Different types of reception terminal and storage facilities	4.5	●	3.8	●	17.3	●
SCR8	Cost of energy mix for securing energy security	6.5	□	5.7	□	36.8	□
SCR9	Introduction of a carbon tax	6.5	□	7.2	Δ	46.6	□
SCR10	Adoption of new emissions trading scheme	6.3	□	6.7	Δ	42.2	□
SCR11	Strong community concerns regarding non-conventional gas exploration	7.0	Δ	7.7	Δ	53.7	Δ
SCR12	Plant start-up delays	7.5	Δ	7.3	Δ	55.0	Δ
SCR13	Supply of gas in domestic market at lower cost hence reduced LNG exports	6.6	□	6.4	□	42.2	□
SCR14	Competition from other exporters in global LNG market	7.5	Δ	7.0	Δ	52.5	Δ
SCR15	Emergence of new exporters in global LNG market	8.2	Δ	7.8	Δ	64.0	Δ
SCR16	Discovery of new reserves, for example, East Africa	8.2	Δ	7.3	Δ	59.9	Δ
SCR17	Emergence of US shale gas revolution	8.3	Δ	7.5	Δ	62.5	Δ
SCR18	Extraction of natural gas from methane hydrate in Japan	5.2	●	7.0	Δ	36.2	□
SCR19	Multiple regulatory risks	6.3	□	6.2	□	39.1	□
SCR20	Emergence of LNG spot market and short term contracts	7.5	Δ	6.2	□	46.3	□
SCR21	High cost due to remoteness of projects	7.8	Δ	7.3	Δ	57.4	Δ
SCR22	Increase in competition from other fuels	6.2	□	6.0	□	37.0	□
SCR23	Flexible capability of technology adaptation	5.8	□	6.6	Δ	38.3	□
SCR24	Customer demand priority shifts to another energy mix	4.8	●	6.0	□	29.0	●
SCR25	Over-proposed LNG projects	7.2	Δ	7.2	Δ	51.4	Δ
SCR26	Unstable fiscal stability and fiscal credibility	5.7	□	6.0	□	34.0	□
SCR27	Lack of skilled staff in LNG projects	6.7	□	7.3	Δ	48.9	Δ

Risk ID No.	Short Description of LNG Supply Chain Risk	Probability		Impact		Risk Indices	
SCR28	Slowed recovery from global economic slowdown	6.2	□	5.7	□	34.9	□
SCR29	Long-term supply contract revision	6.5	□	7.7	Δ	49.8	Δ
SCR30	Fluctuation of LNG price due to oil production	6.8	□	7.2	Δ	49.0	Δ
SCR31	Severe weather causing low productivity	4.7	●	5.3	□	24.9	●
SCR32	Emergency shutdown of the plant due to floods	4.2	●	5.8	□	24.3	●
SCR33	Emergency shutdown of the plant due to tropical cyclones	5.2	●	5.5	□	28.4	●

* Δ: High, □: Medium and ●: Low

The mitigation of these medium risks is likely to reduce the vulnerability of the LNG supply chain immediately but to a lower level than achieved through the mitigation of high risks. Thus, this risk categorization is a basic approach for managing LNG SCR as it identifies the primary, secondary and tertiary levels of risk mitigation in order to mitigate high, medium and low levels of risk and, thus, to reduce supply chain vulnerability. The primary level of risk mitigation could be mitigating SCRs with high risk indices score, as mitigation of such SCRs is likely to reduce much risk of the supply chain relative of the other SCRs. Similarly, the secondary level of risk mitigation may focus on mitigation of SCRs with medium risk indices, which would reduce greater level of risk relative to the SCRs with low risk indices score, and these can be considered in tertiary level of risk mitigation of the supply chain.

Table 5.4: Summary of risk category in terms of probability, impact and risk indices

Category	Notation	Risk attribute and number of risks in each category		
		Probability (P)	Impact (I)	Risk Indices (PI)
High	∆	12	18	12
Medium	□	13	12	14
Low	•	8	3	7

In addition to SCR categorization based on risk indices, the risk categorization based on probability and impact (Tables 5.3 and 5.4) is also useful. For example, most risks identified in this study have high or medium impact and only three are categorized as low impact (Table 5.3). On the other hand, eight (8) SCRs categorized as low probability (Table 5.4). Specific SCRs under these categories can be found in Table 5.3. The categorization of an SCR based on probability and impact provides further insight into a particular risk in order to understand that SCR’s nature. For example, SCR1 and SCR2 are both categorized as “Medium” risks based on risk indices. However, SCR1 falls under the “Medium” category for probability and the “High” category for impact, while SCR2 falls under the “High” category for probability and the “Medium” category for impact. This additional information is useful for management decision making, particularly in setting the strategic direction for SCR mitigation. For example, in mitigating risks of the same category (based on the risk indices), management may set a strategic priority either to mitigate the SCRs with “High” probability or those with “High” impact.

SCR categorization based on risk attributes summarizes risk into different categories and also provides some insights which are useful in setting risk mitigation strategies (RMSs). However, in the categorization process, some information about SCRs is lost. For example, it is quite difficult to identify the relative importance of a particular SCR for SCRs in the same category.

If management wishes to mitigate some (but not all) SCRs of a particular category, it is quite difficult to identify or prioritize those risks in that category. Therefore, the relative position of SCRs is also important in SCRM which can be identified with further analysis. The ranking of SCRs based on risk attributes provides the relative position of each SCR based on risk attributes.

5.6 LNG Supply Chain Risk Ranking

The LNG SCRs are ranked based on the mean values of the SCR attributes (probability, impact and risk indices), as summarized in Table 5.5. The weightage (W), weighted average (WA) and rank based on weighted average (R [WA]), presented in Table 5.5, are discussed in Section 5.8. The Rank (A) column under each attribute in the table represents the relative position (termed as "rank") for each SCR with respect to the attribute. For example, SCR15 appears as 1 in the list based on risk indices. The rank for SCR15 based on probability and impact is 2 and 1, respectively (Table 5.5). Similarly, SCR17 appeared as 2 in the ranking based on risk indices, while the corresponding rank based on probability and impact is 1 and 4, respectively. Usually, most of the top-ranked SCRs based on risk indices are ranked high in both probability and impact. However, it is evident from Table 5.5 that the ranks of probability and impact need not be consistent with each other. Some risks have high probability while their impact is low. For example, SCR20 is ranked as 6 based on probability but is ranked as 20 based on impact, resulting in a rank of 15 based on the risk indices.

The ranking of SCRs based on their attributes shows the relative positions of all supply chain risks (SCRs). This particular information is useful in management decision making for targeting a particular SCR based on ranking. The ranking of SCRs clearly shows the advantage of mitigating a particular SCR compared to other SCRs (in Table 5.5). For example, mitigating SCR15 would reduce more risk to the LNG supply chain than would be the case by mitigating SCR17. The SCR ranking based on SCR attributes is also beneficial in implementing strategic decisions in SCR mitigation. For example, based on the strategic decision to either mitigate SCRs based on probability or on impact, management can target a particular SCR for mitigation ahead of other SCRs. Therefore, in addition to the SCR categorization (as shown in Table 5.3), ranking based on SCR attributes provides further information on relative position of each SCR which is useful in supply chain risk management (SCRM).

Table 5.5: Variability in risk probability score, risk impact score and risk indices

Note: this table shows the range from minimum to maximum, average value and standard deviation based on expert opinions

	Probability								Impact								Risk Indices							
Risk Id. No.	Min*	Max	Avg. (A)	Std. dev.	Weightage (W)	Weighted avg. (WA)	Rank (A)	Rank (WA)	Min	Max	Avg. (A)	Std. dev.	Weightage (WA)	Weighted avg. (WA)	Rank (A)	Rank (WA)	Min	Max	Avg. (A)	Std. dev.	Weightage (W)	Weighted avg. (WA)	Rank (A)	Rank (WA)
SCR1	5	7	6.3	0.8	1.4	8.9	19	8	6	8	7.2	0.8	1.5	10.4	9	7	30	56	45.7	8.9	1.3	57.5	16	11
SCR2	5	8	7.0	1.3	1.2	8.3	10	12	5	7	5.8	1.0	1.3	7.6	25	21	25	56	41.3	12.0	1.2	47.5	19	18
SCR3	2	7	4.5	2.1	1.0	4.7	30	32	2	8	5.2	2.6	1.0	5.2	31	32	4	56	24.0	17.8	1.0	25.2	31	33
SCR4	5	9	7.0	1.4	1.2	8.1	10	16	5	8	6.7	1.2	1.2	8.1	16	16	25	72	47.8	16.8	1.1	50.7	13	16
SCR5	3	7	4.2	1.6	1.1	4.6	32	33	3	7	5.2	1.5	1.1	5.9	31	31	12	42	21.5	11.0	1.2	25.3	32	32
SCR6	6	9	7.7	1.5	1.1	8.7	5	9	6	8	7.2	1.0	1.3	9.3	9	12	36	72	56.0	17.7	1.1	58.8	5	8
SCR7	3	7	4.5	1.4	1.2	5.2	30	30	2	5	3.8	1.0	1.3	5.0	33	33	12	20	16.3	3.2	2.0	32.7	33	30
SCR8	5	8	6.5	1.4	1.2	7.5	16	20	5	7	5.7	1.0	1.3	7.3	27	23	25	49	36.8	9.7	1.2	45.0	23	20
SCR9	3	9	6.5	2.4	1.0	6.5	16	25	6	8	7.2	1.0	1.3	9.3	9	12	18	72	47.2	19.9	1.0	48.4	14	17
SCR10	3	9	6.3	2.5	1.0	6.3	19	27	5	8	6.7	1.2	1.2	8.1	16	16	15	72	43.8	21.3	1.0	44.4	17	21
SCR11	5	9	7.0	1.4	1.2	8.1	10	16	6	9	7.7	1.0	1.3	9.8	2	11	30	81	54.7	17.1	1.1	57.8	7	10
SCR12	6	8	7.5	0.8	1.4	10.4	6	6	7	8	7.3	0.5	1.8	12.8	5	3	48	64	54.8	5.8	1.5	81.1	6	4
SCR13	5	8	6.6	1.1	1.2	8.1	15	13	6	7	6.4	0.5	1.7	10.9	19	5	30	56	42.4	9.2	1.2	52.7	18	15
SCR14	5	9	7.5	1.8	1.1	8.1	6	14	5	9	7.0	1.5	1.1	7.9	14	18	25	81	54.7	23.2	1.0	54.7	7	14
SCR15	7	9	8.2	1.0	1.3	10.6	2	5	6	9	7.8	1.0	1.3	10.2	1	10	42	81	64.5	13.9	1.1	71.4	1	5
SCR16	8	9	8.2	0.4	2.0	16.3	2	1	7	8	7.3	0.5	1.8	12.8	5	2	56	64	59.8	4.2	1.7	103.0	3	1
SCR17	8	9	8.3	0.5	1.7	14.6	1	2	7	8	7.5	0.5	1.7	12.7	4	4	56	72	62.5	6.0	1.5	91.3	2	2
SCR18	4	6	5.2	0.8	1.5	7.5	26	21	4	8	7.0	1.5	1.1	7.9	14	18	20	48	36.3	10.3	1.2	43.6	24	23
SCR19	5	8	6.3	1.2	1.2	7.7	19	19	5	8	6.2	1.2	1.2	7.6	20	22	25	56	40.0	14.0	1.1	44.2	20	22
SCR20	7	8	7.5	0.5	1.7	12.7	6	4	5	7	6.2	0.8	1.5	9.0	20	15	40	56	46.3	7.5	1.3	61.8	15	7
SCR21	7	9	7.8	1.0	1.3	10.2	4	7	6	8	7.3	0.8	1.4	10.3	5	8	42	72	58.0	13.0	1.1	65.3	4	6
SCR22	4	8	6.2	1.5	1.1	7.0	22	22	4	8	6.0	1.9	1.1	6.4	22	27	16	64	37.8	17.0	1.1	40.0	22	24
SCR23	5	7	5.8	0.8	1.4	8.1	24	15	5	8	6.6	1.3	1.2	7.7	18	20	30	56	38.4	10.7	1.2	45.6	21	19
SCR24	3	7	4.8	1.6	1.1	5.4	28	29	4	8	6.0	1.4	1.2	6.9	22	24	15	49	29.7	13.9	1.1	32.8	27	29
SCR25	5	8	7.2	1.3	1.2	8.4	9	11	6	8	7.2	1.0	1.3	9.3	9	12	30	64	51.7	12.8	1.1	58.4	9	9
SCR26	3	7	5.7	1.5	1.1	6.4	25	26	3	8	6.0	2.0	1.1	6.3	22	29	9	56	36.3	18.0	1.0	38.0	24	26
SCR27	5	8	6.7	1.0	1.3	8.5	14	10	6	8	7.3	0.8	1.4	10.3	5	8	30	64	49.5	12.1	1.1	56.8	11	12
SCR28	4	8	6.2	1.6	1.1	6.8	22	23	4	8	5.7	1.6	1.1	6.3	27	30	16	64	36.3	17.3	1.1	38.3	24	25
SCR29	5	8	6.5	1.2	1.2	7.8	16	18	7	9	7.7	0.8	1.4	10.8	2	6	35	72	50.2	13.0	1.1	56.4	10	13
SCR30	6	7	6.8	0.4	2.0	13.7	13	3	7	8	7.2	0.4	2.0	14.3	9	1	42	56	49.0	4.4	1.7	82.3	12	3
SCR31	4	6	4.7	0.8	1.4	6.5	29	24	4	6	5.3	1.0	1.3	6.8	30	25	16	36	25.0	7.1	1.4	34.0	29	27
SCR32	3	6	4.2	1.3	1.2	4.9	32	31	3	7	5.8	1.5	1.1	6.7	25	26	9	36	24.8	10.6	1.2	29.5	30	31
SCR33	4	7	5.2	1.2	1.2	6.3	26	28	4	7	5.5	1.4	1.2	6.4	29	28	16	49	29.5	12.9	1.1	33.2	28	28

*Min=minimum; Max=maximum; Avg.=average; Std. dev.=standard deviation

5.7 Variability of LNG Supply Chain Risk Probability, Risk Impact and Risk Indices

Categorization and ranking are useful tools for prioritization and identification of important supply chain risks (SCRs). Categorization helps in grouping the SCRs into different categories based on risk attributes (i.e. probability, impact and risk indices). Ranking provides information about the relative position of an SCR in the overall SCR table based on attributes. However, categorizing and ranking based on mean values of SCR attributes does not explain the level of consensus among the experts. It is important to know the level of consensus in the mean value of the SCR attribute that is used to categorize and rank. Knowing the level of consensus in the mean value is expected to provide greater confidence in the results obtained in the prioritization of SCRs through categorization and ranking.

Analysis of the scores of SCR attributes (i.e. probability, impact and risk indices) shows that the risk attributes vary across a range (Table 5.5). Minimum, maximum and average values as well as the standard deviation are used as measures to explain the variability of SCR attributes (Table 5.5). Minimum and maximum values represent the range of an SCR attribute while the standard deviation demonstrates the level of variation among the experts. While the mean value of a risk attribute determines the position of an SCR in the category and ranking tables (Tables 5.3 and 5.5), the range within which the data are distributed determines the level of consensus (Table 5.5) among the experts (Table 5.1). Distribution of the data in a narrow range results in a lower value of standard deviation meaning that there is greater consensus among the experts. An SCR with a different distribution range but with the same mean could result in a different level of consensus among the experts. For example, SCR8, SCR9 and SCR29 have the same mean probability score of 6.5 which is categorized as “Medium” risk (Table 5.2) and ranked as 16 (Table 5.4) based on the probability attribute. However, the distribution ranges of the probability attribute for these three risks are different. The standard deviations of the probability attribute of SCR8, SCR9 and SCR29 are 1.4, 2.4 and 1.2, respectively (Table 5.5), which indicates that the level of consensus among the experts is lower in scoring the probability attribute of SCR9 compared to SCR8 and SCR29 which have the same mean score. Hence, analysis of the standard deviation along with the range of SCRs provides further insight into the consensus among the experts in scoring SCR attributes. Thus, for better understanding of a particular SCR, along with the mean scores of attributes, their variation range also need to be considered. This analysis reveals that the categorization and ranking of an SCR based on the mean of a risk attribute does not reflect consensus among the experts. Therefore, information on the consensus of the experts is likely to provide greater confidence in the results of SCR prioritization.

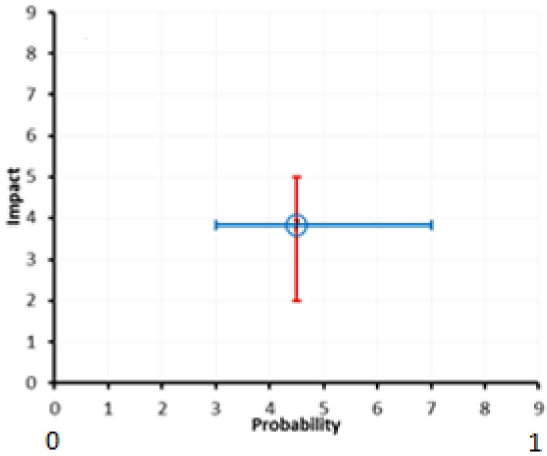


Figure 5.2: Domain variability of risk probability and risk impact for SCR7

Note: Range is shown from minimum to maximum and average value based on experts' opinions. It is noted that 9, 5 and 0 represent probabilities of 1, 0.5 and 0 respectively.

The LNG SCR attribute scoring is subjective with scoring varying from expert to expert. A range of probability and impact scores is possible depending on the number of experts participating in the survey. For example, the average probability and impact scores of SCR7 are 4.5 and 3.8, respectively. The probability and impact scores for SCR7 vary from 3–7 and 2–5, respectively (Figure 5.2). Therefore, the probability and impact scores for SCR7 may vary within the specified range based on expert opinion, instead of being based only on the average score. This means that the probability and impact scores for SCR7 could be any real number varying within the specified range based on expert opinion. Even with the inclusion of additional experts in the survey, the range of probability and impact scores may extend further, although the central tendency of the data may have been improved in the case of a large number of responses. Thus, a large number of realizations could occur for probability and impact scores for SCR7, while varying within the specified range.

5.8 Ranking Risk on Consensus Basis

The standard deviation of the SCR attributes (i.e. probability, impact and risk indices) is a measure of the level of agreement among the experts. Better agreement is represented by a smaller standard deviation value. For example, the standard deviation of risk indices for SCR12 is 5.8 while for SCR11, the standard deviation is 17.1 (Table 5.5). Therefore, the experts are more in consensus in scoring the SCR attribute of SCR12 compared to that of

SCR11. Therefore, the standard deviation scores as presented in Table 5.5 provide an indication of the level of agreement among the experts in scoring the SCR attributes and, ultimately, the risk indices. Hence, in this study, the standard deviations of the SCR attributes are used to derive a weightage score, derived from a weightage scale, to measure the extent of consensus among the experts. The weightage scale and consensus ranking of SCRs that considers their weightage are explained in the following Section 5.8.1. Based on the weighted mean of the SCR attributes, the SCRs are ranked, with this discussed in Section 5.8.2 and presented in Table 5.5.

5.8.1 Weighted scale for consensus ranking of LNG supply chain risks

A weightage scale was developed to generate the weightage for SCR attributes (i.e. probability, impact and risk indices). The scale is derived from the measures of the standard deviations of the SCR attributes. The standard deviation measures the dispersion of an SCR attribute as expressed by the experts (Table 5.1). The greater the value of the standard deviation, the lower is the level of consensus among the experts on an SCR attribute. Thus, the inverse of the standard deviation should measure the level of consensus in the data of an SCR attribute. Hence, a greater value of the inverse of the standard deviation represents a higher level of consensus among the experts on an SCR attribute. For example, the standard deviations of the probability attribute of SCR16 and SCR10 are 0.4 and 2.5, respectively. This means that the experts are more in agreement in scoring the probability attribute of SCR16 compared to that of SCR10. Similarly, the inverse of the standard deviations of the probability attribute of SCR16 and SCR10 are 2.5 and 0.4, respectively. This means that, according to the inverse of the standard deviations, the experts are more in agreement in scoring the probability attribute of SCR16 (inverse of the standard deviation is high) compared to that of SCR10 (inverse of the standard deviation is low).

A conceptual weightage scale for the SCR attributes is presented in Figure 5.3. The horizontal axis (x-axis) represents the normalized value of the inverse of the standard deviation of an SCR attribute in a scale of 0–1. The vertical axis (y-axis) represents the weightage score in a scale of 1–2. The normalization of the inverse score of the standard deviation of SCR attributes has one key advantage. It converts the different ranges of scales for different SCR attributes (i.e. probability, impact and risk indices) into one single scale 0–1. A particular SCR which has the lowest normalized score of 0 for the inverse of the standard deviation will have a weight of 1, meaning that there is no additional weightage. A particular SCR having a 0 score of normal of the inverse standard deviation means that this particular SCR will have the highest standard deviation among all SCRs for that particular attribute. Thus, no additional weightage score is assigned to that supply chain risk (SCR). The highest score assigned to an SCR attribute is 2, with the highest score of 1 of the normal inverse of the standard deviation. As it has the highest score of 1 of the normal inverse of the standard deviation, this means that this particular SCR attribute has the lowest score of the standard deviation among all SCRs for that particular attribute. Mathematically, the weightage scale is defined as expressed in the following equation:

$$Weight\ (W) = 1 + Normal\ [inverse\ (std.dev.)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (5.1)$$

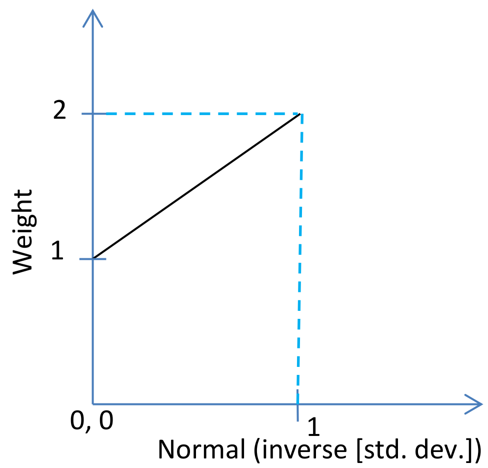


Figure 5.3: Conceptual weighted scale for consensus categorization and ranking of LNG supply chain risk attributes

5.8.2 Consensus ranking of LNG supply chain risks using weighted scale

The LNG SCRs are ranked based on the weighted means of the SCR attributes (i.e. probability, impact and risk indices). Table 5.5 presents a summary of the weightage, weighted mean and rank based on the weighted mean for each SCR attribute. The ranking that considers the weightage is termed “consensus ranking”. The comparison of the ranking of an SCR that is considered with and without weightage demonstrates changes in ranking. For example, the ranking of SCR17 for probability, impact and risk indices is 1, 4 and 2, respectively, while the consensus ranking is 2, 4 and 2, respectively, with corresponding weightage of 1.7, 1.7 and 1.5, respectively. The higher weightage indicates that the experts have shown good agreement in scoring these SCR attributes. In another example, the ranking of SCR30 for the probability, impact and risk indices is 13, 9 and 12, respectively, while the corresponding consensus ranking is 3, 1 and 3, respectively, with corresponding weightage of 2, 2 and 1.7, respectively. The very high weightage value of SCR attributes for SCR30 shows a very high level of consistency among the experts which has contributed to SCR30 being one of the top ranked SCRs based on consensus ranking. The ranking of SCR11 for probability, impact and risk indices is 10, 2 and 7, respectively, while the corresponding consensus ranking is 16, 11 and 10, respectively. This means that consensus among the experts in scoring the risk attributes for this SCR is relatively low (1.2, 1.3 and 1.1, respectively). The consideration of consensus through deriving the weightage and the subsequent use of the weightage in ranking the SCR based on its risk attributes are beneficial in prioritizing supply chain risks (SCRs). For example, one of the benefit of consideration of consensus in prioritization of SCR is that resources could be diverted to mitigate high priority SCRs (with consensus) which would ensure expected outcome as most of the experts agreed on these SCRs. Thus, consensus prioritization of SCRs would be useful to risk managers to divert resources to mitigate high priority SCRs (with consensus) with appropriate justification (such as higher level of expert's agreement) of such act. In the current study, it is evident that consensus ranking can represent the level of agreement demonstrated by the experts in scoring different risk attributes.

5.9 Domain Variability of Risk

The mean value of an SCR attribute is a single additional realization of the data collected from the six experts. The minimum and maximum scores of an SCR attribute could be used to define the boundary condition of that attribute within which it may vary. Depending on the sample size of the survey, these boundary conditions may also vary. In the current study, the scoring of SCR attributes is collected from the six LNG experts with boundary conditions defined using the minimum and maximum scores. The possible distribution of SCR attributes may vary within the boundary conditions. Hence, the analysis of SCR attributes and the subsequent risk prioritization should not be bounded only on discrete analysis through the mean, median or standard deviation. Instead, many possible realizations within the boundary conditions need to be considered in the SCR prioritization. Figure 5.4 presents the mean probability and impact score for SCR7 along with the range within which these could vary based on expert opinion. As explained earlier, huge numbers of realizations are possible for SCR7 while varying within the specified range. In Figure 5.4, 100 random realizations are presented. To generate the 100 realizations for SCR7, the random function, RAND(), of MS Excel is used. Figure 5.4 shows the possible variability of the probability score from 3–7 and that it could be any real number within this range, while the impact score could vary from 2–5 and this also could be any real number within the specified range. Thus, as shown geometrically in a scatter plot, the position of SCR7 could be at any point in a rectangle bounded by the four corners (boundary conditions) as (3,2), (7,2), (7,5) and (3,5).

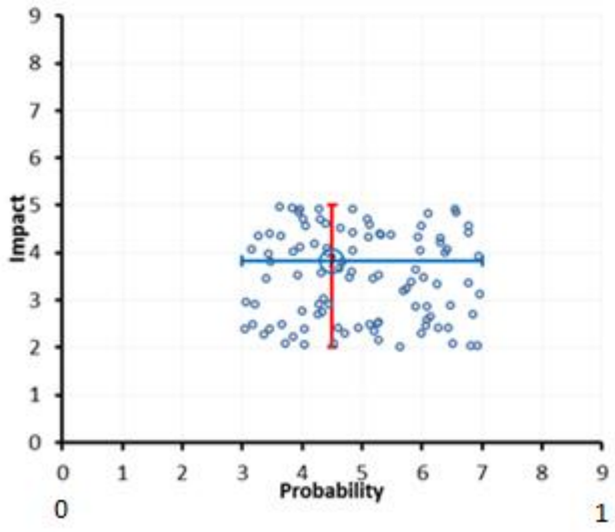


Figure 5.4: Domain variability of risk probability and risk impact for SCR7

Note: This shows the range from minimum to maximum and the average value based on expert opinions as well as the possible random distribution of values of risk probability and impact in 100 realizations. It is noted that 9, 5 and 0 represent probabilities of 1, 0.5 and 0 respectively.

5.10 Extending Application of Risk Parameters in LNG SCRM

Many risk management studies, including SCRM studies, conclude with the identification, assessment and prioritization of risks (Cox, 2012; Sodhi et al., 2012). Only a limited number of studies extend to strategy identification, prioritization and response to mitigate supply chain risks (SCRs) (Sodhi et al., 2012). Furthermore, studies on the allocation of resources and finding an optimum set of RMSs within scenarios with limited resources are very few in number in some specific disciplines such as LNG supply chain risk management (SCRM). In the current study, one of the first steps in LNG SCRM is the prioritization of LNG supply chain risks (SCRs). Risk mitigation strategies (RMSs) are assigned and prioritized for mitigating SCRs based on the *absolute importance* of the RMSs where absolute importance is calculated following the QFD method. Data on the cost of implementing each of the RMSs are collected through the survey. An optimization model is developed for selecting optimal sets of RMSs for different cost scenarios. The optimization model can be used as a management decision tool for allocating limited resources to maximize the level of risk mitigation. In addition, the variability of SCR attributes (i.e. probability and impact) leads to uncertainty in determining risk indices and the position of SCRs on the ranking table. Bradley (2014) suggested that a framework for managing catastrophic risk must cope with difficulties and highlighted the following points: (i) “probabilities of disruptions and probability distributions for the impact of events can only be roughly estimated” and (ii) “decision makers’ decision preferences must take both probability and impact into account without aggregating them into a single measure”. This implies that variability and uncertainty in SCR parameters are natural and usual in risk studies and that these cannot be estimated in firm numbers: instead, they need to be measured in a range with possible variability within the range. The same idea is acknowledged and depicted in the current study as shown in Figure 5.4. To address the variability and uncertainty of SCR attributes and RMS attributes, a simulation model was developed. The simulation model could simulate possible scenarios of LNG SCRM while varying within the domain variability as defined by the experts. Therefore, this study of LNG SCRM is comprehensive in nature covering from risk identification through to optimization and simulation.

5.11 Applying Risk Prioritization in Risk Mitigation using QFD

Using the quality function deployment (QFD) method, the SCR prioritization input was taken for further analysis of SCRs, RMSs, prioritization of RMSs and allocation of cost. In this study, although a consensus or weighted ranking was developed to categorize and prioritize LNG SCR, this consensus ranking (or consensus risk indices) was not used in the subsequent SCR and RMS analysis. Instead, the SCR attributes without consensus were used to analyse LNG SCRM. This research focused on development of a systematic approach for SCRM following QFD method and applied this approach for LNG SCRM of Australia. Here, several new concepts (variability domain of SCRs, consensus mean, weightage scale, risk flexibility index, simulation model etc.) are introduced and explored at different stages of the approach. Incorporation of any of the new concepts at a particular stage of the analysis is likely to influence the results at next stages which would lead to carry out analysis with and without consideration of the concepts and comparison of results. Such phenomenon would result into many different scenarios of method with enormous volume of analysis resulting into distraction of key objectives of the research. These possibilities are put as recommendation for future research.

5.12 Chapter Summary

As reported in this chapter, the LNG SCRs were prioritized through categorization and ranking based on their risk attributes (i.e. probability, impact and risk indices). To categorize the risk for each of the SCR attributes, this study used a relative scale. The risk categories were summarized in a tabular form which could be used as a useful tool for risk prioritization based on risk attributes. Along with the categorization table, the ranking of SCRs is expected to enhance the understanding of management and policy makers about LNG supply chain risks (SCRs). It is expected that the ranking would be useful in setting and implementing risk mitigation strategies (RMSs). The chapter described how a method was developed and applied to derive the weightage to measure consensus among the experts in scoring a particular SCR attribute. The method included a weightage scale to derive the weightage of a risk attribute. Based on the weighted mean of the SCR attributes, the SCRs were ranked. The weighted rank of SCRs incorporated the consensus of the experts in scoring a particular SCR attribute. The study then compared both rankings (with and without consensus). The consensus ranking was found useful in capturing the consensus among the experts on scoring the SCR attributes. The chapter also explained the variability in estimating SCR attributes. The study found that the challenges of the variability of the scores of SCRs could be addressed through further extending the study to RMS prioritization, finding the cost of implementing RMSs, and developing and solving the optimization problem. The mean of an SCR attribute was observed to be an additional realization along with the collected data about that attribute. Many realizations were found to be possible within the boundary conditions of the risk attribute. In addition, the chapter presented an example of the simulation of risk attributes (i.e. probability and impact) for a particular supply chain risk (SCR).

CHAPTER 6

LNG SUPPLY CHAIN RISK MITIGATION FOR AUSTRALIA

6.1 Chapter Introduction

The identification of risk mitigation strategies (RMSs), prioritization of these strategies, estimation of the cost of implementing these strategies and the allocation of resources are key steps in supply chain risk management (SCRM), with these following risk identification and risk prioritization. In the current study, RMSs for LNG SCRM have been identified through an extensive review of the literature (presented in Chapter 3). The methods for LNG SCRM are detailed in Chapter 4 and LNG SCRs are prioritized in Chapter 5. In this chapter, RMSs identified for LNG SCRM are presented and prioritized. Risk mitigation strategies (RMSs) are assigned for mitigating each supply chain risk (SCR) using the QFD method's relationship matrix. The relationship matrix shows the relationship between an SCR and an RMS with the level of the relationship defined with a scale. This chapter presents a summary of the relationship matrix based on mean scores from the six experts as well as being defined by an individual expert. The absolute importance (AI) for RMSs is calculated following the QFD method's conventional approach. The RMSs are then prioritized based on absolute importance (AI). The costs are summarized of implementing the RMSs as assigned by the experts, and also based on mean scores. The relative cost of implementing RMSs is calculated in order to carry out the comparison between the costs assigned by the experts. The relative absolute importance (RAI) of each RMS has been calculated to compare the scores of each RMS as defined by the experts. The level of risk mitigation achievable through the implementation of an RMS for a unit relative cost is calculated which is referred to as the "relative effectiveness (RE)" of a risk mitigation strategy (RMS). The RMSs are compared based on their relative effectiveness (RE) in risk mitigation. The RMSs are ranked based on relative effectiveness (RE) and compared with the ranking based on absolute importance (AI). The number of available RMSs for mitigating an SCR is presented with this referred to as the "risk flexibility index (RFI)". A holistic approach to LNG SCRM is discussed which takes into consideration resource constraints. The need is highlighted for an optimization model to maximize the level of risk mitigation within limited resources or budget. Variations in the scores for SCR attributes and RMS attributes lead to the development of a simulation model for supply chain risk management (SCRM). The simultaneous implementation of RMSs is shown to result in cost savings. The cost savings relationships between interrelated RMSs are presented in the roof of the QFD matrix before the chapter summary is provided.

6.2 LNG SCRM Risk Mitigation Strategy Identification

The mitigation of each risk of the LNG supply chain requires implementation of a number of risk mitigation strategies (RMSs). Therefore, LNG supply chain RMSs were identified through the review of the literature for mitigation of the supply chain risks (SCRs). Table 6.1 presents a summary of LNG supply chain RMSs, with the details of the RMSs presented in Chapter 3. For convenient reference to each RMS in different sections of this thesis including tables and figures, the RMSs are assigned codes which are also presented in Table 6.1.

Table 6.1: LNG supply chain risk mitigation strategies considered in this study

RMS Code	Short title of LNG supply chain RMSs
RMS1	Establish secure communication between stakeholders
RMS2	Involvement of stakeholders in different stages of project
RMS3	Addressing community's concerns about LNG projects
RMS4	Emphasising involvement of community
RMS5	Addressing end-user confidence
RMS6	Balanced carbon tax policy formulation
RMS7	Increase domestic use of LNG/natural gas
RMS8	Policy to increase likelihood of on-schedule delivery
RMS9	Policy to address lack of skilled human resources
RMS10	Select appropriate project location
RMS11	Adopting RMSs in different stages from planning to operation
RMS12	Monitor global trends
RMS13	Establish trust in relationship with state or territory and federal governments
RMS14	Multiple facilities with flexible/redundant resources
RMS15	Consistency local, state or territory and federal government policies
RMS16	Insurance coverage for hazards and unexpected risks
RMS17	Signing a long-term contract
RMS18	Having redundant customers
RMS19	Balancing cost by region
RMS20	Balancing revenue flows by region
RMS21	Building flexible global capacity
RMS22	Robust back-up system
RMS23	Building responsive production
RMS24	Building responsive delivery capacity
RMS25	Balanced emissions trading scheme (ETS) policy formulation
RMS26	Policy for an economic slowdown
RMS27	Policy for labour disputes
RMS28	Policy for currency fluctuations
RMS29	Monitor existing and new competitors
RMS30	Establish secure communication links within the company

6.3 Relationship Matrix of QFD Method

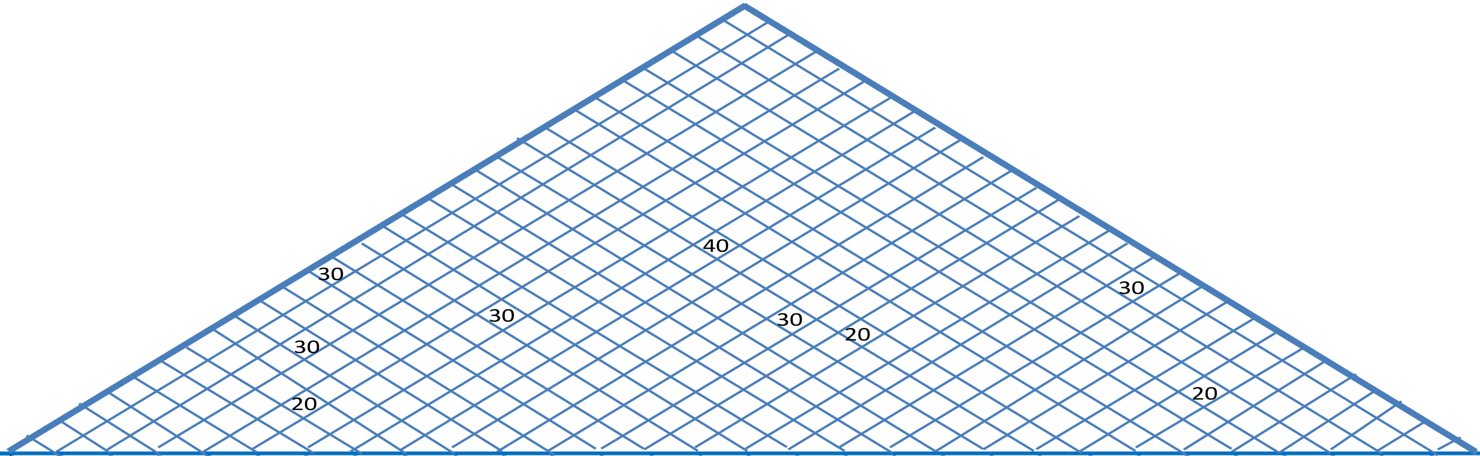
Information on supply chain risks (SCRs), and the relative importance (probability impact [PI]) of SCRs and risk mitigation strategies (RMSs) is contained in the QFD method's relationship matrix (Appendix D). The importance of an SCR is the product of probability (P) and impact (I) with this termed as the "probability impact (PI)". The relative importance (W) of an SCR is calculated by dividing the PI score by the sum of the PI scores of all SCRs (Appendix D). Thus, the relative scale of importance of SCRs facilitates comparison between the scoring of the experts. An individual cell in the relationship matrix defines the relationship between an SCR and an RMS (Appendix D). If no relationship exists between the risk and a particular strategy, the cell remains empty. For a weak, medium and strong relationship between the SCR and the RMS, a cell in the relationship matrix has been assigned 1, 5 and 9, respectively, as shown in Appendix D (Park and Kim, 1998).

6.3.1 "What" and "how" of the relationship matrix

The "what" and "how" are two key elements of the QFD method's relationship matrix. For LNG SCRM, the "what" represents the "supply chain risk (SCR)" and the "how" represents the "risk mitigation strategy (RMS)". Here, to reduce the SCR (through reduction of either each of the attributes such as probability and impact or both), it must be alleviated which can be achieved through implementation of the risk mitigation strategy (RMS). For example, SCR9 is a "what" in the QFD method's relationship matrix for LNG supply chain risk management (SCRM): however, SCR9 can be mitigated through the implementation of some RMSs, with different ones suggested by different experts (as shown in Appendix D). (Short descriptions of the SCRs and RMSs are available in Chapter 3.) The relationship between all 33 SCRs (the "whats") and the 30 RMSs (the "hows") are presented in Appendix D as defined by the experts (details of experts are available at Table 5.1).

6.3.2 Selecting strategies for supply chain risk mitigation

A risk manager or decision maker can either adopt an approach of mitigating an SCR discretely or holistically. For example, in a limited budget scenario, an objective of prioritization of risks based on attributes is to decide which risks to address first (Cox, 2012). On the other hand, in a study of blended value based modelling for E-Business sustainability, Dewan (2014) presented a holistic approach of supply chain risk mitigation using QFD based optimization. A pre-condition or assumption of the discrete mitigation of an SCR is that SCRs are independent and that no relationships exist between supply chain risks (SCRs). In the case of discrete mitigation of each SCR, the QFD method's relationship matrix provides information on relationships between all SCRs and RMSs (Appendix D). The score of each cell of the relationship matrix defines the level of relationship between an SCR and an RMS (Appendix D). A weak, medium or strong relationship between the SCR and the RMS are represented by 1, 5 or 9, respectively (Appendix D). In line with the relationship defined in the relationship matrix, a risk manager is able to select RMSs to be implemented to mitigate a supply chain risk (SCR). Figure 6.1 presents a summary of the relationship matrix based on the mean scores of the experts (Table 5.1). The mean relationship scores between an SCR and an RMS (Figure 6.1) is a measure of the consensus of the experts in recommending an RMS for a particular supply chain risk (SCR). The greater the score between an SCR and an RMS, the more important the RMS is for mitigating the supply chain risk (SCR). Moreover, mitigation of an SCR involves a set of RMSs and implementation of a set of RMSs achieves mitigation of other SCRs (Figure 6.1 and Appendix D). Therefore, instead of the discrete mitigation of each SCR, a holistic approach towards implementation of RMSs is preferred for LNG supply chain management (SCRM).



	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30	RFI*	
																																		S	M
SCR1	6.3	7.2	0.032	3.2	3.5	5.2	1.7	5.7	1.3	2.5	7.5	7.5	7.0	5.3	6.3	7.3	4.2	6.5	1.7	7.7	4.0	3.7	1.5	1.7	0.2	1.8	1.7		3.3	2.7	2.7	5.3	4.5	29	4.0
SCR2	7.0	5.8	0.029	0.8	1.5	3.5	0.2	1.8	3.0	3.3	0.8	3.3	0.8	0.8		4.7	1.7	7.2				0.5	2.5	1.5	1.5			3.5	0.2	3.3		0.8	1.5	23	2.1
SCR3	4.5	5.2	0.017	0.8				6.2		1.8	1.7	0.8		2.5	4.3			0.2		2.5	2.5	1.8	0.8	4.2			1.7		0.2		0.2		0.8	17	1.9
SCR4	7.0	6.7	0.033	3.3	0.5	0.3	1.2				4.3	7.5	6.2	4.3	0.2	2.3	1.0	0.8	0.2	0.8	0.2	3.0	1.7	0.8	1.5	1.5	0.8		2.0	4.8	2.8	1.5	1.5	26	2.1
SCR5	4.2	5.2	0.015	1.2	2.5	1.8	3.3	4.5		0.8	3.2	6.0	4.3	0.7	2.8	0.2	4.7		0.2	1.5	0.8	2.2	4.7	5.3	6.7	6.7	4.7		1.5	3.5	1.5	1.5	1.5	27	2.9
SCR6	7.7	7.2	0.039					0.2	2.0		0.8	0.8	4.7		1.5	1.5	1.5	1.5		1.5	1.5	5.3	3.7	2.0	0.8	1.5	1.5		4.8	0.8	9.0	1.5	1.5	22	2.3
SCR7	4.5	3.8	0.012	1.7				4.0			2.5	0.8	4.8	1.8	6.2		0.5			0.8		0.8	0.8	2.8	0.2	0.8	3.3		0.2			1.5	1.5	18	2.0
SCR8	6.5	5.7	0.026	0.2	2.5		0.2	3.3	3.5	3.0	0.8		2.0	4.7	1.5	0.3	3.3	2.7	0.2	5.3	0.3	0.2	1.7	7.0	1.0	1.0	1.8		0.8	0.2	1.5	3.3	1.5	27	2.0
SCR9	6.5	7.2	0.033	2.5				0.3	7.5					0.2	0.2	5.3	2.8	5.5					2.5	4.5				5.7						11	3.4
SCR10	6.3	6.7	0.030	2.5				0.3	6.8					0.2		4.0		4.5				3.5	2.5	0.8				7.0						10	3.2
SCR11	7.0	7.7	0.038	6.2	8.3	9.0	7.7	1.7	2.7				6.0	5.3	5.3	7.0		4.7			0.8	0.8	0.2	1.8	1.5					0.8		1.5	6.2	19	4.1
SCR12	7.5	7.3	0.039	3.5	4.0	1.8	3.0	1.5				2.5	5.5	5.7	1.5	4.7	3.5	0.2		3.0	0.2	2.3	1.5	5.7	1.5	1.5	1.5		1.5	3.3		4.0	5.5	24	2.9
SCR13	6.7	6.3	0.030	0.8	0.8	4.2	4.2	3.3		3.0	0.8		4.2	0.8	0.8	6.2	0.2	6.0					1.0	3.3	1.5	1.5	0.8		0.8			1.5	1.5	21	2.3
SCR14	7.5	7.0	0.038					5.5	3.8		6.2	6.2	4.8	6.2	4.8	1.5	1.2	1.5		4.5	5.3	1.0	2.5	7.2	0.8	2.5	2.5		0.2			6.8	1.5	21	3.6
SCR15	8.2	7.8	0.046	1.7	1.7			5.5	3.8	0.8	6.2	5.8	3.5	4.7	5.8		3.5	1.5		5.7	3.7	1.2	1.7	7.2	1.5	4.7	3.3					6.8	2.3	22	3.8
SCR16	8.2	7.3	0.043	0.8				7.7	3.8		6.3	4.7	3.5	3.3	3.7		2.8	0.8		5.7	5.0	2.5	0.8	7.0	1.5	4.7	5.3					7.5	1.5	20	4.0
SCR17	8.3	7.5	0.045					4.2	4.7		7.7	6.0	2.7	3.3	6.0	1.0	1.8	0.8		6.0	5.3	4.5	4.3	6.3	1.5	2.0	1.3					6.2	1.5	20	3.9
SCR18	5.2	7.0	0.026	0.8				1.0	1.7		3.0	3.0	1.7	1.3	6.8		2.7			4.5	2.5	1.3	4.7	2.5		2.0	2.0			0.8		4.8	1.5	19	2.6
SCR19	6.3	6.2	0.028	3.5	5.5	4.2	0.5	3.8	2.5	1.5	0.3	1.8	6.0	4.3	4.2	5.5	1.5	4.7		1.2		3.8	5.5	7.2	1.5							1.5	3.0	22	3.3

	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30	RFI* S	RFI* M
SCR20	7.5	6.2	0.033	0.2	0.8			1.0					1.8	3.3	0.8	0.8	3.3			7.7	0.8		1.7	4.7	1.5	4.7	4.0					4.2	1.2	17	2.5
SCR21	7.8	7.3	0.041	3.2	1.0	2.5	1.7	2.3			2.2	6.8	7.0	1.8	1.2	1.8	2.5	3.3		1.5	2.2	5.3	3.7	6.5	1.5	1.2	2.0			1.7	1.7	4.0	2.3	25	2.8
SCR22	6.2	6.0	0.026	1.5		1.5		2.0	1.8		2.0	1.8	2.8	4.7	3.3	1.5	3.8	1.5		6.3	7.5	1.5	1.5	6.2	1.5	1.7	2.5					5.3	1.5	22	2.9
SCR23	6.0	6.8	0.029	0.8		0.2					5.3	3.8	2.5	1.5	6.7	0.2	3.3							1.5		0.7	0.7					1.5	1.5	14	2.2
SCR24	4.8	6.0	0.021	1.0	0.2			5.3		3.0	1.0	1.8	3.0	4.0	0.8	0.8		0.3		6.8	7.0		3.3	5.5	1.5	4.0	3.3					1.5	1.5	20	2.8
SCR25	7.2	7.2	0.037	3.2	3.0	3.2	3.0	3.2		3.0	3.3	3.3	3.5	2.2	1.7					4.5	2.8			2.3	0.2	1.2	1.8					3.3	1.5	19	2.6
SCR26	5.7	6.0	0.024	3.3	2.5	0.2		3.0			3.0		1.5	0.8	0.8	3.0	2.5	6.0					2.5	6.0	1.5	1.7	1.7					1.5	1.5	18	2.4
SCR27	6.7	7.3	0.035	1.5	0.8	1.5		1.5			1.5	9.0	6.2	4.3	1.5		1.5					3.5	0.8	1.5	1.5					3.3		2.7	4.0	17	2.7
SCR28	6.2	5.7	0.025	0.2	1.5		0.8	2.3			4.0	4.7	5.5	0.8	0.3	0.8	0.3	3.0			3.3	3.0	4.7	6.5	0.8				6.0			1.5	1.5	20	2.6
SCR29	6.5	7.7	0.036	1.5	1.5	0.2		5.7			6.0	3.0	3.3	2.7		1.5	2.5	1.5		3.8	4.7		5.3	5.3	1.5	0.5	0.8		0.2	0.8		4.7	1.5	22	2.7
SCR30	6.8	7.2	0.035	4.2	5.0	5.0	1.5	1.8			3.0	1.5	4.7	1.5			0.5			4.5	3.8	3.7	3.0	4.8	1.5	3.3	1.5		2.5			1.5	1.5	21	2.9
SCR31	4.7	5.3	0.018	5.2	4.3	4.3	0.8				0.2	0.8	6.2	5.0			2.5		2.8	0.8			3.3	4.5	3.2	5.8	0.8					0.8	5.5	18	3.2
SCR32	4.2	5.8	0.017	3.0	3.7	4.3		1.5					5.5	3.0			2.5		6.2	0.8			3.3	3.8	4.7	4.5						0.8	3.8	15	3.4
SCR33	5.2	5.5	0.020	4.5	4.3	3.7		1.5					6.8	5.0			2.5		6.2	0.8			3.3	4.5	6.0	4.5						0.8	3.8	15	3.9
C				20	32	43	45	51	31	38	77	62	73	49	39	46	48	50	34	48	40	38	43	82	71	63	48	19	27	38	30	40	33		
AI				2.0	1.8	1.7	1.0	2.8	1.7	0.6	2.8	3.1	3.9	3.0	2.5	2.0	2.0	2.1	0.3	2.9	2.1	1.9	2.4	4.4	1.4	1.9	1.6	0.5	0.8	0.8	0.7	3.1	2.2		

*Notations: C=Cost (mean); AI=Absolute Importance (mean); RFI=Risk Flexibility Index; M=Mean; S=Sum

Figure 6.1: Relationship matrix of QFD method

Note: This demonstrates the relationships between SCRs and RMSs based on the mean scores of the experts.

6.4 Prioritization of LNG Supply Chain Risk Mitigation Strategies

The QFD's relationship matrix is a pictorial presentation showing all SCRs and RMSs of the LNG supply chain (Figure 6.1 and Appendix D). Each individual cell demonstrates the level of the relationship between an SCR and a risk mitigation strategy (RMS). This helps decision makers in selecting the appropriate RMS for mitigation of a supply chain risk (SCR). But not all RMSs can achieve a similar level of risk mitigation for a particular supply chain risk (SCR). Some RMSs are more important than others in mitigating a particular supply chain risk (SCR). Therefore, different RMSs have different levels of importance as they can achieve different levels of risk mitigation for different supply chain risks (SCRs). Thus, the prioritization of RMSs is an important step in LNG SCRM, with this prioritization using the QFD method described in this section.

6.4.1 Risk mitigation strategy prioritization based on absolute importance

Risk mitigation strategies (RMSs) are prioritized based on their *absolute importance* (AI). The AI of an RMS is calculated through summing the product of importance (or weightage) of the SCR and the corresponding relationship score between the SCR and the RMS. The AI scores for each RMS based on the mean score of SCRs and relationship score of SCRs are presented in Figure 6.1, while the AI for each RMS based on the individual expert's scores are presented in Appendix D. A higher AI score represents the higher importance of the risk mitigation strategy (RMS).

The ranking of RMSs is carried out based on AI scores and the ranking defines the relative positions of the risk mitigation strategies (RMSs) (Figure 6.1 and Appendix D). The ranking converts the detailed measures of importance of RMSs into a sequence of ordinal numbers. Thus, the ranking transforms the complex mathematical measures of importance of RMSs into sequential ordinal numbers. Therefore, the ranking of RMSs facilitates the selection by risk managers of an RMS which has higher importance relative to the other risk mitigation strategies (RMSs).

The ranking of RMSs is based on the six experts' score with the mean scores summarized in Table 6.2. Strategies with a higher rank are important strategies for supply chain risk management (SCRM). The implementation of an RMS with a higher rank should achieve a greater level of risk mitigation compared to that of an RMS with a relatively lower rank. The ranking of the RMSs reflects this principle of prioritization of RMSs based on absolute importance (AI). For example, RMS21 is identified as the top ranked strategy for risk mitigation with the highest value of AI based on mean scores (Figure 6.1 and Table 6.2). RMS21 is also ranked as one of the highest RMSs by five of the six experts (with Expert 4 the exception) (Table 6.2). RMS10 is ranked second among the 33 RMSs based on the AI calculated from the mean scores of the experts (Table 6.2). Five of the six experts (with Expert 3 the exception) also scored RMS10 as one of the highest ranked strategies (Table 6.2). Therefore, the ranking of RMSs based on AI scores is useful in selecting the important RMSs for supply chain risk management (SCRM).

Table 6.2: Summary of ranking of RMSs based on absolute importance (AI) of risk mitigation strategies (RMSs).

Expert	**Ranking Risk Mitigation Strategies based on Absolute Importance**																													
	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
M*	15	19	21	24	7	20	28	8	3	2	5	9	14	16	13	30	6	12	18	10	1	23	17	22	29	26	25	27	4	11
1	8	13	18	25	10	29	27	20	17	6	5	7	15	19	12	28	16	22	21	14	3	4	9	11	30	24	23	26	2	1
2	10	9	13	19	6	16	21	3	2	1	15	17	14	18	12	26	4	8	7	11	5	23	23	30	25	28	29	22	27	20
3	23	25	19	24	5	17	30	14	22	12	10	15	16	2	13	29	4	8	11	3	1	26	7	9	21	20	18	28	6	27
4	13	18	16	15	6	3	26	2	1	4	7	5	8	21	14	20	10	28	23	29	12	27	24	25	19	30	17	22	9	11
5	21	20	19	27	13	11	28	6	3	2	8	14	17	10	16	30	4	12	9	5	1	29	18	15	25	23	24	26	7	22
6	18	20	15	22	12	11	23	7	3	2	5	10	14	19	17	30	6	8	16	9	1	29	13	21	25	24	27	26	4	28

*M=mean of all experts; 1=Expert 1; 2=Expert 2; 3=Expert 3; 4=Expert 4; 5=Expert 5; 5=Expert 6

6.4.2 Cost of implementation of risk mitigation strategies

In SCRM, implementation of an RMS to mitigate SCRs involves cost. The cost of implementing an RMS is an important factor which needs to be considered in selecting a risk mitigation strategy (RMS). A scale of 0–100, lowest to highest, is used to score the costs of implementation of risk mitigation strategies (RMSs). The mean costs of implementing RMSs are calculated based on the scores of the six experts and presented in Figure 6.1. The costs of implementation of RMSs assigned by the experts (Table 5.1) are summarized in Appendix D. For some RMSs, a greater level of risk mitigation can be achieved with higher costs. For example, the mean costs of implementation of RMS21, RMS10 and RMS9 are 82, 73 and 62, respectively, with corresponding rankings of 1, 2 and 3 (Figure 6.1). The cost of implementing an RMS could put the RMS in an advantageous condition among RMSs of a similar absolute importance (AI). For example, the mean cost of implementation of RMS4 and RMS12 is 40 with their corresponding ranking, based on AI, being 4 and 12 (Figure 6.1). This means that, for the same cost of implementation, a greater level of risk mitigation can be achieved with RMS4 compared to RMS12. Therefore, in SCRM, the cost of implementation of an RMS is an important determinant.

The total cost of implementation of RMSs scored by the experts (Table 5.1) varies from expert to expert (Appendix D). Hence, for comparison of the cost of an RMS, a relative scale of cost is required. The *relative cost (RC)* of implementation of an RMS is derived through dividing the cost of implementation of a particular RMS by the total cost of implementation of all RMSs as assigned by an expert. Therefore, the relative cost of implementation of RMSs converts to the sum of implementation of all costs to a scale value of 1 (Table 6.3) for the expert's score as well as the mean score.

The relative cost of implementation of RMSs as provided by all experts and the mean score of the experts are summarized in Table 6.3. The table reveals that different RMSs require different levels of relative cost for their implementation. For example, RMS1 is one of the least costly strategies to implement for SCRM with a relative cost varying below 0.02. Some other less costly RMSs include RMS2, RMS25, RMS26 and RMS28. Comparison shows that the experts have reasonably good agreement in assigning cost to implement RMSs varying within a range (Table 6.3). For example, the experts have shown very good agreement in defining the cost to implement RMS1 (Table 6.3). In a few cases, their costs varied across a wide range in particular for some relatively costly risk mitigation strategies (RMSs). For example, Expert 3's costs for the implementation of RMS10, RMS14 and RMS21 varied widely for other experts, with Expert 4 showing a similar wide variation for RMS17 (Table 6.3). Some of the RMSs which require higher cost of implementation include RMS8, RMS10 and RMS21 (Table 6.3). Table 6.3 is useful for explaining the costs of implementation of RMSs and the variation in these costs as defined by different experts.

Table 6.3: Summary of relative cost (RC) of risk mitigation strategies (RMSs)

Note: This was calculated from the scores of all experts and the mean score.

Expert	**Relative cost (RC) of implementation of Risk Mitigation Strategies**																													
	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
M*	0.01	0.02	0.03	0.03	0.04	0.02	0.03	0.06	0.05	0.05	0.04	0.03	0.03	0.04	0.04	0.03	0.04	0.03	0.03	0.03	0.06	0.05	0.05	0.04	0.01	0.02	0.03	0.02	0.03	0.02
1	0.02	0.05	0.04	0.05	0.02	0.01	0.03	0.05	0.05	0.03	0.03	0.03	0.05	0.02	0.04	0.01	0.03	0.03	0.02	0.02	0.04	0.05	0.04	0.04	0.01	0.03	0.04	0.03	0.05	0.05
2	0.01	0.01	0.03	0.04	0.07	0.03	0.02	0.05	0.04	0.05	0.05	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.07	0.05	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.01
3	0.01	0.01	0.03	0.01	0.02	0.03	0.05	0.07	0.03	0.09	0.02	0.01	0.02	0.10	0.02	0.03	0.02	0.02	0.03	0.05	0.10	0.06	0.05	0.05	0.03	0.01	0.02	0.02	0.01	0.01
4	0.02	0.02	0.02	0.02	0.06	0.02	0.02	0.08	0.08	0.06	0.04	0.02	0.02	0.02	0.03	0.02	0.09	0.02	0.02	0.02	0.04	0.02	0.02	0.03	0.02	0.02	0.04	0.02	0.06	0.04
5	0.01	0.02	0.03	0.04	0.04	0.02	0.04	0.06	0.04	0.06	0.03	0.03	0.03	0.03	0.04	0.02	0.03	0.03	0.03	0.04	0.07	0.06	0.05	0.04	0.01	0.02	0.02	0.02	0.03	0.02
6	0.02	0.01	0.04	0.02	0.03	0.03	0.02	0.04	0.04	0.05	0.04	0.04	0.03	0.04	0.05	0.03	0.04	0.04	0.03	0.02	0.05	0.06	0.05	0.04	0.02	0.02	0.04	0.02	0.02	0.02

*M=mean of all experts (presented in 1st row); 1=Expert 1; 2-=Expert 2; 3=Expert 3; 4=Expert 4; 5=Expert 5; 6=Expert 6

6.4.3 Relative absolute importance (RAI) of risk mitigation strategy

To facilitate comparison between the experts, a relative scale of AI is used. The *relative absolute importance (RAI)* value is calculated for each RMS and derived from the experts' scores and mean scores (experts' details in Table 5.1). The RAI of an RMS is derived through dividing the individual AI value by the sum of AI values of all RMSs calculated based on an individual expert's score or mean score. Therefore, the sum of RAI values of all RMSs calculated based on each of the expert's scores and the mean score equals 1. Thus, the RAI value facilitates the comparison of the importance of an RMS based on the expert's score and the mean score.

In SCRM, the RAI is the measure of the relative importance of a strategy. A higher value of RAI of an RMS represents a greater level of risk mitigation capacity compared to other risk mitigation strategies (RMSs). Table 6.4 presents a summary of RAI values of risk mitigation strategies (RMSs). RMS21 was found to be one of the most important RMSs with a mean RAI value of 0.07 (Table 6.4). This means that the implementation of RMS21 would provide a greater level of risk mitigation in comparison to implementation of other risk mitigation strategies (RMSs). The value of RAI for RMS21 varied in a wide range from approximately 0.04–0.13 (Table 6.4) for different experts (Table 5.1). The large variation in RAI values means that the experts' values varied across a wide range. The differences among the experts is a natural phenomenon of their perception of SCRs attributes, relationship among the SCRs and RMSs, cost of implementation of RMSs as captured in the survey.

The second most important strategy for LNG supply chain risk mitigation is RMS10, with an average RAI value of 0.07 (with rounding) and varying from approximately 0.04–0.06 (Table 6.4). The variation range (0.04–0.06) indicates that the experts have shown greater agreement in their scores for RMS10 compared to their scores for RMS21. The average RAI score of less important strategies is less than 0.02, while the variation range of RAI values is also narrow. This means that the experts are in greater agreement in scoring RMSs with a lower RAI value compared to their scores for RMSs with a higher RAI value. Therefore, the relative position of an RMS compared to all RMSs (as shown in Table 6.4 using a relative scale) facilitates the comparison between experts in prioritizing RMSs for supply chain risk management (SCRM).

Table 6.4: Summary of relative absolute importance (RAI) of risk mitigation strategies (RMSs)

Note: This is calculated based on scores from the six experts and the mean score.

Expert	Relative Absolute Importance of Risk Mitigation Strategies																													
	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
M*	0.03	0.03	0.03	0.02	0.05	0.03	0.01	0.05	0.05	0.07	0.05	0.04	0.03	0.03	0.03	0.01	0.05	0.04	0.03	0.04	0.07	0.02	0.03	0.03	0.01	0.01	0.01	0.01	0.05	0.04
1	0.05	0.03	0.03	0.01	0.04	0.00	0.01	0.02	0.03	0.05	0.06	0.05	0.03	0.02	0.04	0.00	0.03	0.02	0.02	0.03	0.07	0.07	0.04	0.04	0.00	0.01	0.02	0.01	0.08	0.08
2	0.04	0.05	0.04	0.02	0.06	0.03	0.02	0.06	0.07	0.09	0.03	0.03	0.04	0.02	0.04	0.01	0.06	0.05	0.05	0.04	0.06	0.01	0.01	0.00	0.01	0.01	0.00	0.02	0.01	0.02
3	0.01	0.01	0.02	0.01	0.06	0.02	0.00	0.03	0.01	0.04	0.04	0.03	0.03	0.08	0.03	0.00	0.07	0.04	0.04	0.07	0.13	0.01	0.05	0.04	0.01	0.02	0.02	0.01	0.06	0.01
4	0.03	0.02	0.03	0.03	0.06	0.08	0.01	0.08	0.10	0.07	0.06	0.06	0.06	0.01	0.03	0.02	0.04	0.01	0.01	0.01	0.04	0.01	0.01	0.01	0.02	0.00	0.03	0.01	0.05	0.04
5	0.02	0.03	0.03	0.01	0.04	0.04	0.00	0.05	0.06	0.07	0.05	0.04	0.03	0.05	0.03	0.00	0.06	0.04	0.05	0.05	0.08	0.00	0.03	0.03	0.01	0.01	0.01	0.01	0.05	0.02
6	0.03	0.03	0.03	0.02	0.04	0.04	0.02	0.05	0.06	0.07	0.05	0.04	0.03	0.03	0.03	0.00	0.05	0.04	0.03	0.04	0.08	0.01	0.04	0.02	0.01	0.02	0.01	0.01	0.05	0.01

*M=mean of all experts; 1=Expert 1; 2=Expert 2; 3=Expert 3; 4=Expert 4; 5=Expert 5; 6=Expert 6

6.4.4 Relative effectiveness of risk mitigation strategies

Two key attributes of an RMS are its importance in mitigating SCRs (measured as AI [absolute importance] or RAI [relative absolute importance]) and its cost of implementation (measured as C [cost] or RC [relative cost]). Therefore, in measuring the effectiveness of an RMS in mitigating SCRs, both attributes of an RMS need to be considered. Hence, the effectiveness of an RMS can be measured as its capacity in mitigating SCRs per unit of cost. For comparison between the experts (see Table 5.1), a relative scale of effectiveness is used. Hence, the relative effectiveness (RE) of an RMS is a measure of the level of risk mitigation that can be achieved per unit of relative cost (RC). Thus, the RE of an RMS can be a measure of the performance of RMSs in mitigating supply chain risks (SCRs). The RAI defines the relative importance of an RMS compared to other RMSs in supply chain management (SCRM).

The RE score of an RMS is very useful to risk managers for SCRM as it represents a relative measure of the level of risk mitigation achievable per unit of relative cost (RC). For example, the RAI values of RMS1 vary from approximately 0.01–0.045 (Table 6.4) with a mean score of 0.03. Thus, the RAI of RMS1 depicts that RMS1 is not a very highly preferred (or important) RMS compared to other risk mitigation strategies (RMSs). The relative cost (RC) of the implementation of RMS1 is very low, varying from 0.01–0.02 with a mean value of 0.01 (Table 6.3). Due to a low RC, RMS1 is one of the strategies with very high relative effectiveness (RE) (Table 6.5). This means that RMS1 would result in a greater level of risk mitigation per unit of relative cost (RC) compared to other risk mitigation strategies (RMSs). Thus, considering the cost of implementation, RMS1 appears to be one of the highly effective risk mitigation strategies (RMSs). Therefore, the costs of implementation of RMSs need to be considered when undertaking RMS prioritization.

The distribution of RE values (Table 6.5) of RMSs for LNG supply chain risk mitigation among the different experts shows a reasonably good agreement with a few exceptions (Table 6.5). Most of the RE values vary within 0–3.5. A fairly close distribution of RE values for a strategy means that the experts agreed reasonably well in: (i) defining the SCR parameters (i.e. risk probability and risk impact); (ii) identifying the appropriate RMS and defining the relationship score between SCRs and RMSs; and (iii) estimating the cost of implementation of risk mitigation strategies (RMSs).

Table 6.5: Summary of relative effectiveness (RE) of LNG supply chain risk mitigation of each risk mitigation strategy

Note: This was calculated based on the scores of the experts.

Expert	Relative Effectiveness of Risk Mitigation Strategies																													
	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS 9	RMS30
M*	2.3	1.3	0.9	0.5	1.3	1.3	0.4	0.8	1.2	1.2	1.4	1.4	1.0	0.9	0.9	0.2	1.4	1.2	1.1	1.3	1.2	0.4	0.7	0.7	0.6	0.6	0.5	0.5	1.8	1.5
1	2.9	0.6	0.7	0.2	2.0	0.1	0.2	0.5	0.5	1.7	2.0	1.6	0.6	1.6	0.9	0.2	1.1	0.7	1.0	1.5	1.6	1.3	1.0	0.9	0.0	0.5	0.5	0.4	1.5	1.6
2	3.3	3.4	1.1	0.6	0.9	1.0	0.9	1.2	1.8	1.6	0.6	0.9	1.1	0.7	1.2	0.2	1.5	1.2	1.2	1.1	0.9	0.2	0.2	0.2	0.8	0.5	0.3	1.3	0.6	3.3
3	1.3	1.2	0.6	1.3	3.1	0.6	0.1	0.4	0.5	0.4	2.2	2.9	1.4	0.8	1.7	0.2	3.6	2.3	1.3	1.5	1.3	0.1	1.0	0.9	0.5	1.6	0.9	0.4	6.1	0.7
4	2.2	1.4	1.7	1.3	0.9	3.3	0.4	1.1	1.2	1.1	1.5	2.6	2.4	0.6	1.1	0.7	0.4	0.4	0.5	0.3	0.9	0.2	0.3	0.2	0.8	0.3	0.7	0.6	0.9	0.9
5	1.7	1.2	1.0	0.2	0.9	2.0	0.1	0.8	1.3	1.2	1.7	1.3	1.0	1.6	0.9	0.2	1.9	1.5	1.6	1.3	1.1	0.1	0.6	0.9	1.4	0.7	0.5	0.5	1.7	1.0
6	1.6	2.2	0.9	0.8	1.4	1.3	0.7	1.2	1.5	1.4	1.3	1.1	1.1	0.7	0.6	0.1	1.4	1.2	1.1	1.8	1.5	0.1	0.7	0.5	0.7	0.6	0.3	0.5	3.0	0.7

*M=mean of all experts; 1=Expert 1; 2=Expert 2; 3=Expert 3; 4=Expert 4; 5=Expert 5; 6=Expert 6

6.4.5 Risk mitigation strategy prioritization based on relative effectiveness

The LNG supply chain RMSs are prioritized and ranked based on their RE score with the basis of calculation being scores from the experts (Table 5.1) and the mean score. Table 6.6 presents a summary of the RMSs as prioritized and ranked. The top three RMSs based on the mean RE score are RMS1, RMS29 and RMS20. The corresponding ranking of RMS1, RMS29 and RMS 30 based on the mean AI score are 15, 4 and 11, respectively (Table 6.2). Similarly, the top three RMSs based on the mean AI score are RMS21, RMS10 and RMS9 (Table 6.2), while the corresponding ranks of these RMSs based on the mean RE score are 11, 12 and 14, respectively (Table 6.6). A comparative analysis of rankings based on the AI score and RE score of RMSs shows that hardly any similarities exist between the two rankings (Table 6.2 and Table 6.6). Thus, prioritization of the RMSs on the basis of RE values resulted in a different priority set of RMSs compared to the priority set of RMSs based on AI values. Hence, consideration of the costs of implementing strategies in SCRM draws a completely different picture compared to scenarios without costs. Therefore, LNG supply chain risk mitigation should be carried out with consideration of the costs of RMS implementation.

The distribution of ranking of RMSs based on RE scores shows both agreement and variation among the experts. For example, ranking based on RE scores is more in agreement for RMS8, RMS16, RMS22, RMS23, RMS24 and RMS28 for the six experts. However, ranking for RMS2, RMS5, RMS11, RMS29 and RMS30 varied widely between different experts. The agreement and variation among the experts highlight the sensitivity of prioritizing RMSs based on a particular attribute of RMSs such as ranking based on AI or RE scores. However, although both forms of prioritization have merit, prioritization based on RE scores should be considered superior over prioritization based on AI scores as RE scores incorporate the cost attribute of risk mitigation strategies (RMSs).

Table 6.6: Summary of risk mitigation strategies (RMSs)

Note: These were prioritized based on RE values of the six experts and their consensus mean score.

Expert	Risk mitigation strategies ranked based on relative effectiveness																													
	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RM 27	RMS28	RMS29	RMS30
M*	1	7	19	27	9	8	29	20	14	12	5	4	16	18	17	30	6	13	15	10	11	28	22	21	24	23	26	25	2	3
1	1	19	17	27	3	29	26	24	22	4	2	7	20	8	16	28	12	18	14	10	6	11	13	15	30	21	23	25	9	5
2	3	1	12	23	19	15	18	11	4	5	22	16	13	21	9	27	6	10	8	14	17	28	28	30	20	25	26	7	24	2
3	11	15	22	14	3	21	30	25	24	26	6	4	10	19	7	28	2	5	12	9	13	29	16	17	23	8	18	27	1	20
4	4	7	5	8	14	1	23	11	9	10	6	2	3	20	12	18	24	25	22	26	15	29	27	30	17	28	19	21	16	13
5	3	14	18	27	20	1	29	22	10	13	5	12	17	7	21	28	2	8	6	11	15	30	24	19	9	23	25	26	4	16
6	4	2	17	18	7	10	21	13	6	9	11	15	14	19	25	30	8	12	16	3	5	29	22	26	20	24	28	27	1	23

*M=mean of all experts; 1=Expert 1; 2=Expert 2; 3=Expert 3; 4=Expert 4; 5=Expert 5; 6=Expert 6

6.4.6 Risk flexibility index (RFI) as a concept

A new concept has been introduced in this study to define the nature of SCRs which is to consider RMSs that are available to mitigate supply chain risks (SCRs). Hence, the *risk flexibility index* (RFI) is a measure of the nature of an SCR in terms of the general or specific characteristics of the SCR against its set of risk mitigation strategies (RMSs). Some SCRs are general in nature while some are specific in relation to their mitigation with the available risk mitigation strategies (RMSs). For example, as presented in Figure 6.1, all RMSs, with the exception of RMS25) are recommended (with different levels of risk mitigation achievable) for mitigating SCR1. Thus, SCR1 can be regarded as a general risk for the supply chain in terms of assigning risk mitigation strategies (RMSs). This means that any of the RMSs, with the exception of RMS25, if implemented would achieve a level of risk mitigation for SCR1. On the other hand, a total of 14 RMSs are assigned for mitigating SCR23 (Figure 6.1). This means that the level of risk mitigation for SCR23 can only be achieved if one of these 14 RMSs is implemented. Thus, the number of available RMSs is relatively lower for SCR23 compared to SCR1. Therefore, for mitigating supply chain risk, SCR1 is more flexible in selecting RMSs compared to SCR23. Hence, the greater the number of RMSs that are available for a particular SCR, the greater the flexibility there is for mitigation of its risk.

The number of RMSs available, referred to as the *risk flexibility index*, for mitigating a particular SCR based on the mean score as assigned by the six experts is presented in Figure 6.1. The RFI of SCRs as assigned by the individual expert can be derived from the relationship matrixes presented in Appendix D. Although the experts varied across a range in assigning RMSs for a particular SCR, in most cases, they were consistent in assigning the number of risk mitigation strategies (RMSs). For example, although the experts assigned between 17 and 28 RMSs for SCR1, importantly, all of them assigned a high number of strategies. Similarly, for SCR33 and SCR34, all the experts assigned a relatively lower number of RMSs for mitigating these two supply chain risks (SCRs). Some variations were evident among the experts in assigning RMSs but only for a limited number of supply chain risks (SCRs). For example, for SCR4, SCR5 and SCR6, Expert 1 varied from the other five experts in assigning RMSs for these three strategies (Appendix D) by assigning a relatively large number of strategies in comparison. However, for most of the other SCRs, Expert 1 showed consistency with the other experts in assigning RMSs (Appendix D). Thus, the RFI of an SCR provides useful information on the availability of RMSs for mitigation of that risk compared to other SCRs.

6.5 Holistic Approach to Supply Chain Risk Mitigation and Optimization Problem

To mitigate an SCR, a set of RMSs needs to be implemented with different levels of risk mitigation for different RMSs (Figure 6.1 and Appendix D). In addition, implementation of a particular RMS achieves different levels of risk mitigation for different SCRs (Figure 6.1 and Appendix D). Therefore, mitigation of a single SCR is not an effective and efficient way of carrying out supply chain risk management (SCRM). Hence, it is not the preferred choice of a manager or decision maker to mitigate individual risks. Instead, managers and decision makers are keen to mitigate the risks of a supply chain in a holistic way to optimize the benefits of supply chain risk management (SCRM). By adopting a holistic approach for risk mitigation, maximization of the level of risk mitigation can be achieved with limited cost and resource allocation. However, selection of a set of RMSs for mitigating the risks of a number of SCRs is a difficult task. The problem becomes more difficult when questions are raised about the allocation of limited resources for the implementation of risk mitigation strategies (RMSs). From the perspective of practicality and a realistic point of view, managers and decision makers want maximum risk mitigation with limited cost or resource allocation. Therefore, SCRM presents an optimization problem in which a set of RMSs has to be implemented for risk mitigation with limited cost and resource allocation.

In this study, an optimization method for supply chain risk mitigation for the LNG supply chain has been developed and solved through the following steps followed by supply chain risk prioritization: (i) assigning strategies to mitigate each risk (QFD method's relationship matrix); (ii) defining the level of relationship between SCRs and RMSs (QFD method's relationship matrix); (iii) measuring the flexibility of mitigating a risk (through risk flexibility index [RFI]); (iv) prioritizing supply chain RMSs (using QFD method's relationship matrix); (v) estimating the cost of implementing RMSs (QFD method's relationship matrix); and (vi) measuring the effectiveness of risk mitigation strategies (RMSs). The optimization problem is presented in Chapter 7.

6.6 Basis for a Simulation Model for Supply Chain Risk Management

A simulation model needs to be considered in LNG SCRM in addition to an optimization model. The two attributes of SCRs, that is, probability and impact, vary across a range based on the scores of the experts. This variation of SCR attributes results in a variation (within a range) of a calculated attribute of SCRs, *risk indices*. The risk indices come as an input which is considered as the weightage of an SCR in the QFD method in calculating the AI score of an RMS in prioritizing risk mitigation strategies (RMSs). As is the case with SCR attributes, the score defining the relationship between SCRs and RMSs, as represented in the QFD method's relationship matrix, also varies across a range as scored by the experts. An additional attribute in prioritizing RMSs that also varies across a range, depending on the experts' opinions, is the cost of implementation of risk mitigation strategies (RMSs). The prioritization of SCRs and the subsequent prioritization of RMSs leading to an optimization problem based on the mean score of the experts is a single realization of a large number of possible outcomes of supply chain risk management (SCRM). Therefore, to reflect the variation among the experts, a simulation model needs to be developed to prioritize SCRs and risk mitigation strategies (RMSs). In the current study, a simulation model has been developed to prioritize SCRs and RMSs following the solving of an optimization problem for LNG SCRM. The simulation model for LNG SCRM is presented in Chapter 8.

6.7 Dependencies among Risk Mitigation Strategies

Most of the practical problems of the QFD method involve some degree of dependencies among the design requirements (represented here as RMSs) (Wasserman, 1993). In this study, some RMSs are independent while some are dependent on each other in terms of risk mitigation when implemented. The simultaneous implementation of dependent RMSs could result in cost savings depending on the level of relationship (or correlation) that exists between two or more correlated risk mitigation strategies (RMSs). Here, the relationship between dependent RMSs is expressed as a percentage (%) of the total cost of the dependent RMSs that could be saved if they were implemented simultaneously. The relationship between dependent RMSs is presented in the "roof" or the correlation matrix in Figure 6.1 and Appendix D. For example, RMS1 and RMS13 are dependent; thus, simultaneous implementation of these two RMSs will result in 30% of savings of the total costs that would have been incurred with the implementation of two risk mitigation strategies (RMSs). The information on dependencies between the RMSs and cost savings from simultaneous implementation of dependent RMSs is particularly important in the optimization and simulation models for LNG supply chain risk management (SCRM).

6.8 Chapter Summary

In this chapter, the LNG supply chain RMSs have been identified. These strategies were assigned for each SCR with the relationships between SCRs and RMSs defined using the QFD method's relationship matrix. The relationships were defined based on expert opinions collected through the survey. The absolute importance (AI) scores of the RMSs were calculated following the QFD method's conventional approach. The RMSs were prioritized based on the AI scores of the individual expert and the mean score. The RMSs were ranked based on their priority or the AI score. This ranking of RMSs would be useful for risk managers or decision makers in selecting an RMS with a greater level of risk mitigation than the other risk mitigation strategies (RMSs). The costs of implementation of RMSs were presented, with the relative cost (RC) calculated to facilitate comparison between the experts. The relative absolute importance (RAI) scores, calculated for each RMS by the experts, were compared. The RAI scores enable comparison between the experts of the importance of each RMS, reflecting both their agreement and variation. The relative effectiveness (RE) scores of the RMSs were calculated based on the different experts' opinions and compared. The RMSs were ranked based on their RE scores. Few if any similarities were observed between two rankings based on AI and RE scores. The main reason for this difference between the two rankings was that the RE score calculation took into consideration the cost of RMS implementation. This underlined the importance of considering the cost when prioritizing RMSs in supply chain risk management (SCRM). However, it is evident that the ranking based on RE scores was superior to the ranking based on AI scores with the former therefore recommended over the latter for management decision making. The risk flexibility index (RFI) was calculated based on the RMSs available to mitigate a supply chain risk (SCR). The RFI is a measure of the level of RMS flexibility in mitigating a supply chain risk (SCR). The chapter discussed the holistic approach to SCRM, with the outcome being that this approach was found to be preferred over mitigating each risk individually. With resource constraints and practicality concerns, it was considered neither desirable nor possible to mitigate all supply chain risks (SCRs). Instead, achieving the maximum level of risk mitigation with limited resources (or budget) was considered more practicable, with this leading to the development of an optimization model.

The experts showed reasonable agreement in defining the different SCR and RMS attributes with this reflected in different measures, such as the ranking of SCRs and risk mitigation strategies (RMSs). Considering the level of agreement between the experts, the level of variation was also anticipated. Therefore, the variation between the experts within a range guided this study on LNG SCRM to develop a simulation model. The chapter explained the dependencies between two or more risk mitigation strategies (RMSs). Simultaneous implementation of two or more dependent RMSs was found to be most likely to result in cost savings. Finally, the chapter reported the study's work in defining and summarizing the relationships between the dependent risk mitigation strategies (RMSs).

CHAPTER 7

OPTIMIZATION MODEL FOR SCRM

7.1 Chapter Introduction

Effective and optimal use of resources for supply chain risk mitigation is essential in a resource-constrained environment. In Chapter Six, risk mitigation strategies (RMSs) were prioritized. The purpose of optimization is to maximize the level of risk mitigation and select the optimal set of RMSs for a particular cost scenario or the available budget. This chapter reports on the development of an optimization model for LNG SCRM, with this model then solved for different cost scenarios.

The chapter discusses the conceptual framework of analysis to explain the results from the optimization model. The simultaneous implementation of RMSs results in some savings in implementing more strategies for a cost scenario or budget; hence, the optimization problem is solved both with and without cost savings. The cost scenarios are explained which the optimization model is used to solve. The optimization of LNG SCRM is described in detail including the steps and process. The chapter also outlines the formulation of the optimization model for SCRM based on the QFD method. Estimates of cost savings from the simultaneous application of dependent RMSs are delineated. Testing for the sensitivity of the optimization model is carried out on the basis of the results from the optimization based on the experts'. An ensemble of the optimization results is produced to demonstrate the ranges of levels of risk mitigation achieved for the different cost scenarios. The selection process for the optimal set of RMSs is rendered using the ensemble approach for different cost scenarios. The chapter reports the optimization results based on the consensus means. The optimization results based on the consensus mean and the ensemble mean are compared and the preferred optimization process is recommended. The variability of optimization results and of the data from the experts is explained, and the need for a simulation model is expounded. The chapter concludes with a summary.

7.2 Conceptual Framework of Analysis Based on Optimization Model

The conceptual framework adopted to carry out the analysis based on the optimization model is presented in Figure 7.1. An optimization model was firstly formulated which included defining the objective function and cost constraint. The optimization model was solved based on data from the individual expert as well as on the consensus means of data from the experts. The results of optimization from the individual expert were then combined to derive the ensemble mean of the optimization results. A comparative analysis was carried out between the two results (the ensemble mean and the consensus mean). Based on the findings of the comparative analysis, two outcomes were recommended: (i) the preferred approach to optimization and (ii) the need to develop a simulation model for LNG supply chain risk management (SCRM).

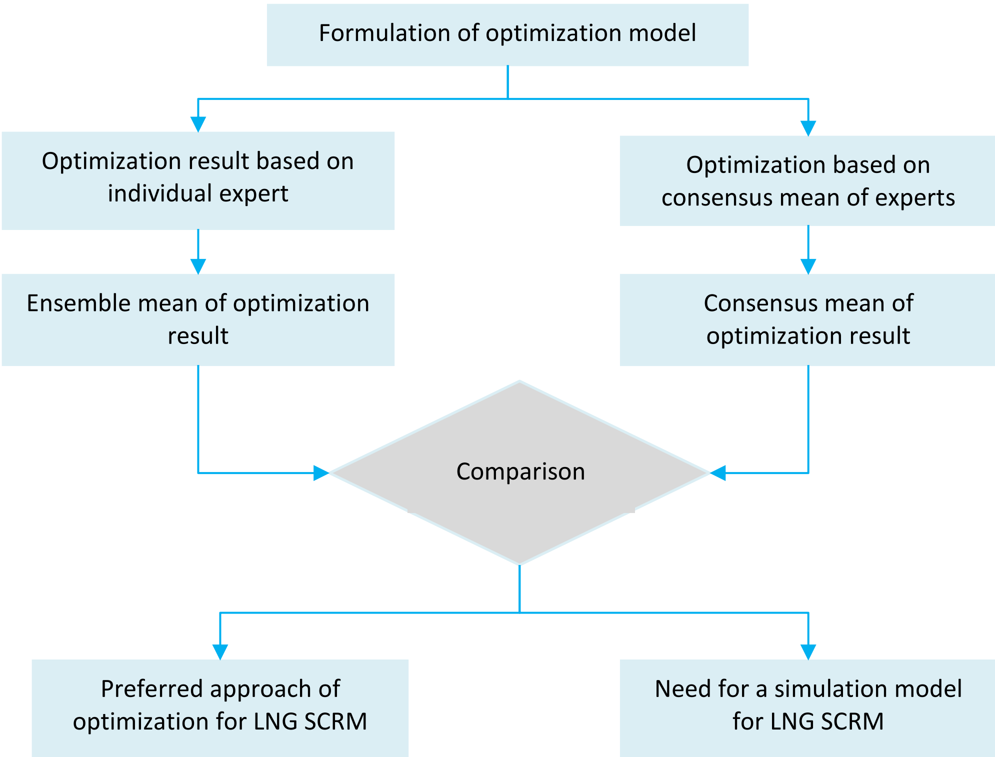


Figure 7.1: Conceptual framework of analysis based on optimization model for LNG SCRM

7.3 Estimating Cost Savings in Simultaneous Application of Dependent RMSs

In SCRM, not all RMSs are independent: instead, some are dependent or correlated. Relationships or dependencies exist between or among some of the risk mitigation strategies (RMSs). The "roof" (correlation matrix) of the QFD method represents the relationships between the RMSs (details explained in Chapter 4, Figure 4.7). The level of relationship between the RMSs varies. The relationships between two correlated RMSs are categorized as "weak", "medium" and "strong" (Table 7.1). The implementation of correlated strategies involves each strategy complementing the other in resources utilization. Thus, the simultaneous implementation of correlated RMSs is most likely to result in some savings of resources or cost in supply chain risk management (SCRM) (Park and Kim 1998; Dewan, 2014;

Chowdhury and Quaddus, 2015). The level of savings depends on the relationship between the correlated strategies and costs of implementation of the strategies.

The dependencies between the RMSs are identified and their levels of relationships are defined through consultation with two experts (details of experts are available in Table 5.1). The qualitative relationship between two correlated RMSs is converted into a quantitative measure through determining the percentage of cost savings if two correlated strategies are implemented simultaneously. The current study also undertook this in consultation with two experts. A summary of the correlated RMSs, their level of relationship and their corresponding cost savings as a percentage are presented in Table 7.1. For weak, medium and strong relationships, the corresponding cost savings (presented as "Savings (%)" in Table 7.1) suggested by the experts are 10%, 20% and 30%, respectively, of the total cost of the interrelated risk mitigation strategies (RMSs) (Table 7.1). The costs of implementation of the RMSs as defined by the experts are available in Appendix D. The subsequent cost savings from the simultaneous implementation of the correlated RMSs based on Expert 1's opinion is also shown in Table 7.1. For example, the simultaneous implementation of RMS1 and RMS13 results in a saving of 39 (30% of 130) while their respective implementation costs are 30 and 100.

Table 7.1: Summary of correlated RMSs, their relationships and cost savings

RMS_j	RMS_j	Relationship between RMSs	Savings (%) $S_{j,j}$	Cost (C_j) of implementing strategy RMS_j*	Cost (C_j) of implementing strategy RMS_j**	Cost savings: $S_{j,j}$ = % $S_{j,j}$ ($C_j + C_j$)
RMS1	RMS13	Medium	30	30	100	39
RMS3	RMS10	Medium	30	70	60	39
RMS5	RMS8	Weak	20	40	100	28
RMS6	RMS15	Medium	30	10	80	27
RMS8	RMS22	Strong	40	100	100	80
RMS12	RMS21	Medium	30	60	80	42
RMS14	RMS22	Weak	20	30	100	26
RMS18	RMS29	Medium	30	50	100	45
RMS23	RMS27	Weak	20	80	70	30

*-represent cost related to RMS presented in column 1 and **-represents cost related to RMS presented in column 2. Note: This is from the simultaneous implementation of the correlated RMSs based on Expert 1's opinion.

7.4 Development of Cost Scenarios

In a resource-constrained environment, it is difficult to find the resources to implement all RMSs to mitigate all SCRs in the LNG supply chain. It is thus important to know the level of risk mitigation achievable for different cost scenarios. Hence, for solving the optimization model, nine cost scenarios are developed based on the percentage of the total cost of implementing the risk mitigation strategies (RMSs). Table 7.2 summarizes the cost scenarios. The nine cost scenarios are defined as S1, S2, S3, ..., S8 and S9 with the corresponding percentage of the total cost of implementation of RMSs as 90%, 80%, 70%, ..., 20% and 10%. The costs of implementation of RMSs as scored by the experts are available in Appendix D. The cost scenarios are defined for each expert and also for the consensus mean score of all experts. For example, the cost of implementation of all RMSs (based on a 0–100 scale), as defined by Expert 1, is 1920 (Appendix D and Table 7.2). Thus, the cost scenarios for solving the optimization problem are defined as 90% (S1), 80% (S2), 70% (S3), ..., 20% (S8) and 10% (S1) of 1920. A similar approach is adopted in defining the cost scenario for the other experts and the consensus mean of the experts. The optimization model is solved for each of the cost scenarios for each expert and the consensus mean.

Table 7.2: Summary of cost scenarios for solving optimization model for SCR

Scenarios	Cost or Budget (%)	Cost or Budget Based on Experts' Opinion						
		1	2	3	4	5	6	Mean
	100%	1920.0	1500.0	1030.0	640.0	1405.0	1660.0	1359.0
S1	90%	1728.0	1350.0	927.0	576.0	1264.5	1494.0	1223.3
S2	80%	1536.0	1200.0	824.0	512.0	1124.0	1328.0	1087.3
S3	70%	1344.0	1050.0	721.0	448.0	983.5	1162.0	951.4
S4	60%	1152.0	900.0	618.0	384.0	843.0	996.0	815.5
S5	50%	960.0	750.0	515.0	320.0	702.5	830.0	679.6
S6	40%	768.0	600.0	412.0	256.0	562.0	664.0	543.7
S7	30%	576.0	450.0	309.0	192.0	421.5	498.0	407.8
S8	20%	384.0	300.0	206.0	128.0	281.0	332.0	271.8
S9	10%	192.0	150.0	103.0	64.0	140.5	166.0	135.9

7.5 Optimization of LNG Supply Chain Risk Management

Two key factors that drive the optimization process of SCRM are: (i) having a limited budget or resource constraints and (ii) obtaining the maximum benefit from the resources utilized. Once the risks were identified and the strategies were selected for risk mitigation, supply chain risk mitigation could then be achieved through implementation of the risk mitigation strategies (RMSs). However, in reality, the implementation of each of the RMSs involves costs which appear as a constraint in the SCRM process. Another important factor that drives the SCRM optimization process is the level of risk mitigation required. In reality, all SCRs do not need to be mitigated and a supply chain can be functional through mitigating risks at a desired level as agreed by management. Therefore, managers or decision makers are interested in knowing the level of risk mitigation that can be achieved for different cost scenarios as well as the relevant set of selected RMSs to be implemented for the respective cost scenarios. For a particular cost scenario, managers want to achieve the maximum level of risk mitigation from the resources to be utilized for risk mitigation. Therefore, the main principle followed in developing the optimization model is maximizing the level of risk mitigation through the implementation of an optimal set of RMSs for a particular cost scenario.

7.5.1 Formulation of optimization model for SCRM following QFD method

An optimization model for maximizing the level of risk mitigation through the implementation of RMSs is formulated following the method explained in Section 4.6.2 in Chapter Four. Figure 7.2 summarizes the steps for formulating the optimization model based on data (opinions) collected from Expert 1 from among the six experts (see Table 5.1). A QFD matrix for the optimization model based on data (opinions) from Expert 1 is presented in Figure 7.3. The QFD matrixes for the optimization model based on data (opinions) from all six experts are summarized in Appendix D. The weight (W_i) represents the relative probability impact (RPI_i) of SCR_i which is calculated using the following formula (also see Figure 7.3):

$$W_i = RPI_i = \frac{PI_i}{\sum_{i=1}^{33} PI_i}$$

where,

RPI_i = Relative probability impact of risk *i*

PI_i= Probability impact of risk *i*

Step 1: Identifying supply chain risks (SCRs) and defining SCR attributes

Step 2: Defining weight of SCRs

Step 3: Identifying risk mitigation strategies (RMSs)

Step 4: Defining relationships between SCRs and RMSs using relationship matrix

Step 5: Defining cost of implementing RMSs

Step 6: Calculating absolute importance (AI) and relative AI (RAI) of RMSs

Step 7: Defining objective function *f(x)* of optimization model

Step 8: Defining correlation matrix of optimization model

Step 9: Defining constraints of optimization model

Step 10: Defining cost scenarios of optimization model

Step 11: Solving the optimization model for the cost scenarios

Figure 7.2: Steps in formulating and solving optimization model

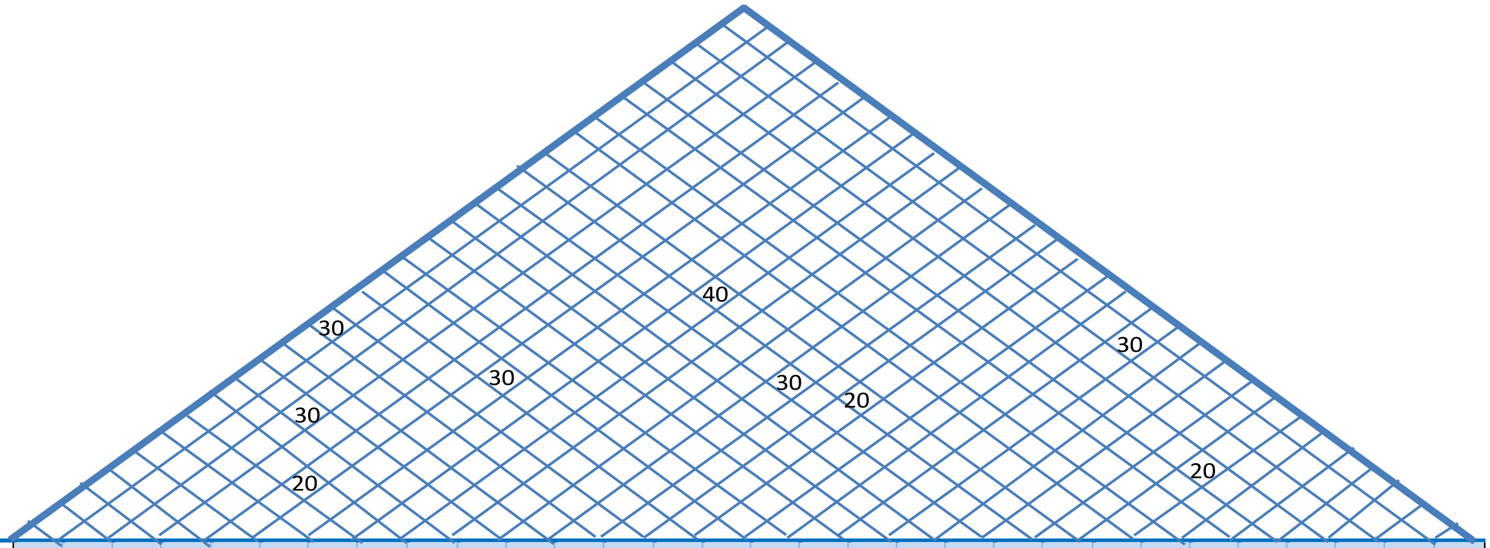
The objective function of the optimization model is to maximize the absolute importance (AI) of the selected risk mitigation strategies (RMSs.) The AI of the RMSs represents the level of risk mitigation if the RMSs are implemented. Thus, the maximization of the objective function represents the maximization of the level of risk mitigation achieved through the implementation of risk mitigation strategies (RMSs). The objective function of the optimization problem for LNG SCRM is a quadratic integer programming problem and is expressed as:

$$Max f(x) = \sum_{j=1}^{30} (AI_j) x_j$$

or,

$$Max f(x) = AI_1 X_1 + AI_2 X_2 + AI_3 X_3 + AI_4 X_4 + AI_5 X_5 + AI_6 X_6 + AI_7 X_7 + AI_8 X_8 + AI_9 X_9 + AI_{10} X_{10} + AI_{11} X_{11} + AI_{12} X_{12} + AI_{13} X_{13} + AI_{14} X_{14} + AI_{15} X_{15} + AI_{16} X_{16} + AI_{17} X_{17} + AI_{18} X_{18} + AI_{19} X_{19} + AI_{20} X_{20} + AI_{21} X_{21} + AI_{22} X_{22} + AI_{23} X_{23} + AI_{24} X_{24} + AI_{25} X_{25} + AI_{26} X_{26} + AI_{27} X_{27} + AI_{28} X_{28} + AI_{29} X_{29} + AI_{30} X_{30}$$

The AI scores of the RMSs are calculated in this study following the QFD method's conventional approach. In addition, the objective function is to maximize the total AI scores of the RMSs to achieve the maximum level of risk mitigation from the selected risk mitigation strategies (RMSs). However, it is important to note that the conventional QFD method does not consider trade-offs between the levels of risk mitigation achieved from selected RMSs and the cost (or budget) required for implementing the risk mitigation strategies (RMSs) (Park and Kim, 1998). Thus, the optimization model developed here is an extension of the conventional QFD method where the AI scores are calculated based on the QFD method. Resources are a key (probably the critical) constraint in SCRM, hence, requiring consideration. A similar idea was emphasised by King (1989) in considering the organizational resources used in the targeted selling price of the product in its market. Park and Kim (1998) considered cost as a constraint in their determination of an optimal set of design requirements using the QFD method. Following the same principle, Chowdhury and Quaddus (2015) also applied cost as a constraint in a multiple objective optimization based on the QFD approach.



(i)	Pi	Ii	Wi	RMS1 (X_1)	RMS2 (X_2)	RMS3(X_3)	RMS4(X_4)	RMS5(X_5)	RMS6(X_6)	RMS7(X_7)	RMS8(X_8)	RMS9(X_9)	RMS10(X_{10})	RMS11(X_{11})	RMS12(X_{12})	RMS13(X_{13})	RMS14(X_{14})	RMS15(X_{15})	RMS16(X_{16})	RMS17(X_{17})	RMS18(X_{18})	RMS19(X_{19})	RMS20(X_{20})	RMS21(X_{21})	RMS22(X_{22})	RMS23(X_{23})	RMS24(X_{24})	RMS25(X_{25})	RMS26(X_{26})	RMS27(X_{27})	RMS28(X_{28})	RMS29(X_{29})	RMS30(X_{30})
SCR1	5	6	0.023	5	5	5	5	9	1	5	9	9	9	5	9	9	9	9	5	5	9	5	1	5	1	9	5			9	5	9	9
SCR2	7	7	0.038	5	9	5	1	5	1	5	5	5	5	5										9	9				1	5		5	9
SCR3	5	6	0.023	5				5				5			5			1		5		5	5	5					1		1		5
SCR4	7	6	0.032	9			1					9	5	5	1	1	5	5	1	5	1	1	1	5	9	9	5		5	9	5	9	9
SCR5	3	7	0.016	1	5	1	1	5		5	5	9	1	1	5	1	1		1	9	5	1	1	5	9	9	9		9	9	9	9	9
SCR6	6	7	0.032								5	5	9		9	9	9	9		9	9	5		5	5	9	9		9	5	9	9	9
SCR7	3	4	0.009										1		1		1			5		5	5	1	1	5	5		1			9	9
SCR8	7	7	0.038		9		1							9	9	1	5	5	1	9	1	1	5	9	5	5	5		5	1	9	5	9
SCR9	3	6	0.014											1	1	9	1	5															
SCR10	3	5	0.011											1																			
SCR11	5	6	0.023		9	9	5	5						9	9	9		9			5	5	1		9					5		9	9

(i)	Pi	Ii	Wi	RMS1 (X_1)	RMS2 (X_2)	RMS3(X_3)	RMS4(X_4)	RMS5(X_5)	RMS6(X_6)	RMS7(X_7)	RMS8(X_8)	RMS9(X_9)	RMS10(X_{10})	RMS11(X_{11})	RMS12(X_{12})	RMS13(X_{13})	RMS14(X_{14})	RMS15(X_{15})	RMS16(X_{16})	RMS17(X_{17})	RMS18(X_{18})	RMS19(X_{19})	RMS20(X_{20})	RMS21(X_{21})	RMS22(X_{22})	RMS23(X_{23})	RMS24(X_{24})	RMS25(X_{25})	RMS26(X_{26})	RMS27(X_{27})	RMS28(X_{28})	RMS29(X_{29})	RMS30(X_{30})
SCR12	7	7	0.038	9	9	1		9					5	9	9	9	1	1		5	1	1	1	9	9	9	9		9	5		9	9
SCR13	5	6	0.023	5	5	5	5	5					5	5	5	5	1						1	1	9	9	5		5			9	9
SCR14	7	6	0.032									5	9	9	9	9	1	9				1	5	9	5	5	5		1			9	9
SCR15	7	6	0.032	5				9					5	9	9			9				1		9	9	9	5					9	9
SCR16	8	7	0.043	5				5			5		5	5	5			5				5		9	9	9	9					9	9
SCR17	8	7	0.043					5			9		9	5	5			5				5		9	9	5	5					9	9
SCR18	6	8	0.037	5				1					5	1	5		5					5	9			5	5			5		9	9
SCR19	6	6	0.028	1				5		9		1	5	9	9		9			5		9	9	9	9							9	9
SCR20	7	6	0.032	1	5			5					1	5	5	5	5			5	5			5	9	9	9					9	5
SCR21	7	7	0.038	9	1	5	5					9	5	9	5			9			5		5	9	9	5	5					9	9
SCR22	8	8	0.049	9		9		5				1	5	9	9	9	9	9		9	9	9	9	9	9							9	9
SCR23	6	6	0.028	5		1					9		5	9	9	1								9								9	9
SCR24	7	7	0.038	5										5	5	5				5	5		5	9	9	9	9					9	9
SCR25	5	6	0.023	1		1		5					5	1										1	1	1	5					5	9
SCR26	6	7	0.032	5	1	1		1					9	5	5									9	9							9	9
SCR27	7	8	0.043	9	5	9		9			9	9	9	9	9		9						5	9	9							9	9
SCR28	6	6	0.028	1	9		5				5	5	5	5		5		9						9	5							9	9
SCR29	7	7	0.038	9	9	1		5			9		9	9		9		9					9	9	9				1	5		9	9
SCR30	6	7	0.032	9	9	9	9	9				9	9	9										9	9	9	9					9	9
SCR31	5	6	0.023	5	5	5	5				1	5	5	9						5			5	1	1	5	5					5	9
SCR32	5	7	0.027	1	5	5		9					5	1						5			5	1	1							5	5
SCR33	7	7	0.038	5	5	5		9					9	9						5			5	5	5							5	5
C				30	100	70	100	40	10	50	100	100	60	60	60	100	30	80	20	50	50	40	40	80	100	80	80	10	50	70	60	100	100
AI				4.5	3.3	2.5	1.2	4.0	0.1	0.6	2.4	2.6	5.3	6.1	5.0	2.9	2.4	3.6	0.2	2.8	1.8	2.0	3.0	6.6	6.5	4.2	3.8	0.0	1.4	1.7	1.1	7.8	8.3

Pi=probability of SCRi; Ii=impact of SCRi; W=weight of SCR; X_1, X_2 …., X_{30}=decision variables for RMSs; C_j=cost of RMS_j; AI_j=absolute importance of RMS_j

Figure 7.3: QFD matrix for optimization model

Note: based on data (opinions) from Expert 1

To facilitate the comparison of the level of risk mitigation achievable for the same cost scenario, a relative scale of AI is adopted. In the relative scale, the sum of the relative absolute importance (RAI) of all RMSs is equal to 1. The RAI score of a particular RMS is calculated using the formula below:

$$RAI_j = \frac{AI_j}{\sum_{j=1}^{30}(AI_j)}$$

where

RAI_j = Relative absolute importance of strategy *j*

AI_j = Absolute importance of strategy *j*

j = 1, 2, …………………………………………………., 30. Strategy (RMS) identification number

Hence, the objective function of the optimization model based on RAI is formulated as below:

$$MaxRf(x) = \sum_{j=1}^{30}(RAI_j)x_j$$

Or,

$MaxRf(x) = RAI_1 X_1 + RAI_2 X_2 + RAI_3 X_3 + RAI_4 X_4 + RAI_5 X_5 + RAI_6 X_6 + RAI_7 X_7 + RAI_8 X_8 + RAI_9 X_9 + RAI_{10} X_{10} + RAI_{11} X_{11} + RAI_{12} X_{12} + RAI_{13} X_{13} + RAI_{14} X_{14} + RAI_{15} X_{15} + RAI_{16} X_{16} + RAI_{17} X_{17} + RAI_{18} X_{18} + RAI_{19} X_{19} + RAI_{20} X_{20} + RAI_{21} X_{21} + RAI_{22} X_{22} + RAI_{23} X_{23} + RAI_{24} X_{24} + RAI_{25} X_{25} + RAI_{26} X_{26} + RAI_{27} X_{27} + RAI_{28} X_{28} + RAI_{29} X_{29} + RAI_{30} X_{30}$

Two constraints are defined in maximizing the objective function. In the optimization process, the complete implementation of an RMS is considered with no provision for partial implementation. This means that, in SCRM, RMSs can either be selected or not selected. A 0-1 integer programming model suits the concept of full implementation of RMSs where 0 represents the RMS not selected and 1 represents the RMS selected for implementation, as applied by Park and Kim (1998) and Chowdhury and Quaddus (2015). The cost or resource constraint is defined where the objective function has to be maximized within the cost (budget) available as defined in the cost scenario (Table 7.2). Hence, two separate cost functions (with cost savings and without cost savings) are used to define the cost constraints of the optimization model. In addition, the optimization model is solved for the two cost functions independently. The cost functions are (i) a simple linear cost function (Wasserman, 1993), $g(x)$, and (ii) a quadratic cost function (Park and Kim, 1998), $R(x)$. The linear cost function for this optimization model is expressed as follows:

$$g(x) = \sum_{j=1}^{30} c_j x_j$$

$$x \in X$$

Or,

$g(x) = C_1 X_1 + C_2 X_2 + C_3 X_3 + C_4 X_4 + C_5 X_5 + C_6 X_6 + C_7 X_7 + C_8 X_8 + C_9 X_9 + C_{10} X_{10} + C_{11} X_{11} + C_{12} X_{12} + C_{13} X_{13} + C_{14} X_{14} + C_{15} X_{15} + C_{16} X_{16} + C_{17} X_{17} + C_{18} X_{18} + C_{19} X_{19} + C_{20} X_{20} + C_{21} X_{21} + C_{22} X_{22} + C_{23} X_{23} + C_{24} X_{24} + C_{25} X_{25} + C_{26} X_{26} + C_{27} X_{27} + C_{28} X_{28} + C_{29} X_{29} + C_{30} X_{30} \leq B$

Where,

$g(x)$ = Total cost of selected RMSs (for a cost scenario it needs to be either less than or equal to a given budget)

B = available budget.

X = 0-1 decision variable with 0 representing the RMS not selected and 1 representing the RMS selected.

Solving the optimization model with maximization of the objective function, while considering the linear cost constraint function, is widely known as the 'Knapsack' problem approach (Park and Kim, 1998). It is important to note that, according to the 'Knapsack' approach, all RMSs are independent and no relationships exist between the risk mitigation strategies (RMSs).

However, as discussed in Section 7.3 in this chapter, some RMSs are interdependent and complement each other during implementation with the likely result of cost savings. In addition, Wasserman (1993) suggested that most practical QFD problems involve some degree of dependencies among the design requirements (in this study, the RMSs). Considering the likely cost savings from correlated RMSs, Park and Kim (1998) modified the linear cost function into a quadratic cost function. In the quadratic cost function, the total cost savings from correlated RMSs are deducted from the linear cost function. The total cost savings from correlated RMSs are calculated using the formula below:

$$Cost\ savings, k(x) = \sum_{i=1}^{30} \sum_{j>i}^{30} s_{i,j}\, x_i x_j$$

Where, $s_{i,j}$ is the cost savings from two correlated RMSs, RMS_i and RMS_j

x_i is a decision variable for RMS$_i$, 0 if RMS RMS$_i$ is not selected and 1 if RMS$_i$ is selected

x_j is a decision variable for RMS$_j$, 0 if RMS RMS$_j$ is not selected and 1 if RMS$_j$ is selected.

Thus, the quadratic cost function for this optimization model is expressed as:

$$R(x) = g(x) - k(x)$$

$$\text{s.t. } R(x) \leq B$$

$$x \in X$$

Or,

$$R(x) = C_1 X_1 + C_2 X_2 + C_3 X_3 + C_4 X_4 + C_5 X_5 + C_6 X_6 + C_7 X_7 + C_8 X_8 + C_9 X_9 + C_{10} X_{10} + C_{11} X_{11} + C_{12} X_{12} + C_{13} X_{13} + C_{14} X_{14} + C_{15} X_{15} + C_{16} X_{16} + C_{17} X_{17} + C_{18} X_{18} + C_{19} X_{19} + C_{20} X_{20} + C_{21} X_{21} + C_{22} X_{22} + C_{23} X_{23} + C_{24} X_{24} + C_{25} X_{25} + C_{26} X_{26} + C_{27} X_{27} + C_{28} X_{28} + C_{29} X_{29} + C_{30} X_{30} - S_{1,13} X_1 X_{13} - S_{3,10} X_3 X_{10} - S_{5,8} X_5 X_8 - S_{6,15} X_6 X_{15} - S_{8,22} X_8 X_{22} - S_{12,21} X_{12} X_{21} - S_{14,22} X_{14} X_{22} - S_{18,29} X_{18} X_{29} - S_{23,27} X_{23} X_{27} \leq B$$

The objective function of the optimization model is maximized subject to the two cost functions: (i) the linear cost function and (ii) the quadratic cost function. The optimization model is then solved for each cost scenario (as shown in Table 7.2).

7.5.2 Optimization results based on individual expert's opinions

The optimization model based on data from Expert 1 (details of experts are in Table 5.1) has been solved for the defined cost scenario (as in Table 7.2). The optimization process adopted is a non-linear quadratic integer programming and formulation of the optimization model which is as explained in Section 7.5.1. The results from solving the optimization model based on Expert 1's data are summarized in Table 7.3 while the results from all experts' data are combined in Appendix E. The optimization process for maximizing the objective function, while keeping the cost within the budget, is an iterative process. Here, the Solver function of MS Excel was used to solve the optimization problem.

According to Expert 1 (Table 5.1), the total cost required to implement all RMSs to achieve 100% risk mitigation (without considering cost savings) is 1920 (Table 7.2). In reality, it is almost impossible to allocate the full resources required for risk mitigation; that is, resource availability appears as a constraint in optimizing the objective function. Therefore, the optimization model is solved for the nine cost scenarios (Table 7.2) defined in Section 7.4 with the two cost constraints as defined in Section 7.5.1. Table 7.3(a) summarizes the optimization results based on linear cost constraints (without cost savings), while optimization results based on quadratic cost constraints (with cost savings) are summarized in Table 7.3(b). A comparative picture between the two optimization results (based on linear and quadratic cost constraints) is summarized in Table 7.3(c). For scenario S1 (90% of total cost), considering the linear cost constraint, the level of risk mitigation achieved is 0.974 (in a scale of 0-1) through the implementation of 25 RMSs (except for RMS4, RMS6, RMS16, RMS25 and RMS28) with an available budget of 1728 and a utilized budget of 1720 (89.6% of total cost) (Table 7.3). Considering the quadratic cost constraint for scenario S1, a full (1.000) level of risk mitigation was achieved through implementation of all RMSs, except for RMS2, with a utilized budget of 1554 (80.94% of total cost). It is important to note here that RMS25 has not been assigned any relationship with SCRs in the QFD method's relationship matrix by Expert 1, therefore, resulting in an AI score of 0 (Figure 7.3). This means that RMS25 has no contribution in supply chain risk mitigation, as defined by Expert 1. In other words, it is immaterial in maximizing the objective function whether or not RMS25 is selected. Thus, full (1.000) level of risk mitigation is achieved without the implementation of RMS25 (Table 7.3).

Analysis of the optimal level of risk mitigation and the corresponding RMSs to be implemented (as shown in Table 7.3) reveals that optimization subject to the quadratic cost constraint is superior when compared to the optimization results based on the linear cost constraint. The cost savings from simultaneous implementation of interrelated RMSs result in the implementation of more RMSs for the same budget or more cost scenarios that consider the quadratic cost constraint than those that consider the linear cost constraint. A comparative analysis of optimization results based on the two cost constraints (Table 7.3[c]) demonstrates that, for all the cost scenarios, more RMSs are selected with the quadratic cost constraint for a particular cost scenario. For example, in the case of scenario S3, six additional RMSs (RMS6, RMS8, RMS9, RMS13, RMS16, RMS26) are selected with the quadratic cost constraint compared to those with the linear cost constraint, resulting in a greater level of risk mitigation (0.970 compared to 0.872) with a slightly higher budget utilization (1344.0 compared to 1320.0) (Table 7.3[c]). The comparative analysis shown in Table 7.3(c) can be used as a management tool for LNG supply chain risk management (SCRM). In limited budget scenarios (such as S1, S2, ….., S9), a supply chain risk manager can choose a scenario depending on the available budget or the desired level of risk mitigation. Relevant RMSs for implementation can then be selected to achieve the desired level of risk mitigation as shown in Table 7.3(c).

Table 7.3(a): Summary of optimization results for different cost scenarios calculated based on Expert 1’s opinion without cost savings

Cost scenario and budget			Risk mitigation without savings			Selected RMSs under different cost scenarios (considering linear cost constraint)																													
Scenario	Budget available*		Budget used																																
(i)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1728	89.6	1720.0	0.974	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0	1	1
S2	80	1536	79.7	1530.0	0.929	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	0	1	1
S3	70	1344	68.8	1320.0	0.872	1	1	1	0	1	0	0	0	0	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	0	1	0	1	1
S4	60	1152	59.9	1150.0	0.813	1	1	0	0	1	0	0	0	0	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	0	0	0	0	1	1
S5	50	960	50.0	960.0	0.741	1	0	0	0	1	1	0	0	0	1	1	1	0	1	0	0	1	0	1	1	1	1	1	1	0	0	0	0	1	1
S6	40	768	39.6	760.0	0.638	1	0	0	0	1	1	0	0	0	1	1	1	0	1	0	0	1	0	0	1	1	1	0	0	0	0	0	0	1	1
S7	30	576	29.7	570.0	0.518	1	0	0	0	1	0	0	0	0	1	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1
S8	20	384	19.8	380.0	0.354	1	0	0	0	1	1	0	0	0	1	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
S9	10	192	9.9	190.0	0.200	1	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

*Total cost is 1920.0 (details of cost scenarios are available in Table 7.2 and details of experts are available in Table 5.1); 0=RMS is not selected and 1=RMS is selected

Table 7.3(b): Summary of optimization results for different cost scenarios calculated based on Expert 1’s opinion with cost savings

Cost scenario and budget			Risk mitigation with savings			Selected RMSs under different cost scenarios (considering quadratic cost constraint)																													
Scenario	Budget available*		Budget used																																
(i)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1728	80.94	1554.0	1.000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
S2	80	1536	79.90	1534.0	0.998	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1
S3	70	1344	70.00	1344.0	0.970	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1
S4	60	1152	59.58	1144.0	0.910	1	1	1	0	1	1	0	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1
S5	50	960	49.69	954.0	0.834	1	0	1	0	1	1	0	1	0	1	1	1	1	1	1	0	1	1	0	1	1	1	1	0	0	0	1	0	1	1
S6	40	768	39.74	763.0	0.726	1	0	1	0	1	1	0	1	0	1	1	1	0	1	1	0	0	1	0	0	1	1	1	0	0	0	0	0	1	1
S7	30	576	29.90	574.0	0.582	1	0	0	0	1	0	0	1	0	1	1	1	0	1	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	1
S8	20	384	19.79	380.0	0.413	1	0	0	0	1	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
S9	10	192	9.90	190.0	0.203	1	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

*Total cost is 1920.0 (details of cost scenarios are available in Table 7.2 and details of experts are available in Table 5.1); 0=RMS is not selected and 1=RMS is selected

Table 7.3(c): Comparison of optimization results considering linear and quadratic cost constraints for different cost scenarios calculated based on Expert 1’s opinion

Cost scenario and budget			Risk mitigation without savings			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used			Budget used																																
(i)	%	Actual	%	Actual	$f(x)$	%	Actual	$f(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1728	89.6	1720.0	0.974	80.94	1554.0	1.000	☑	☑	☑	✓	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑		☑	☑	✓	☑	☑
S2	80	1536	79.7	1530.0	0.929	79.90	1534.0	0.998	☑	☑	☑	✓	☑	✓	✓	✓	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑	☑	☐	✓	☑	✓	☑	☑
S3	70	1344	68.8	1320.0	0.872	70.00	1344.0	0.970	☑	☑	☑		☑	✓		✓	✓	☑	☑	☑	✓	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑		✓	☑		☑	☑
S4	60	1152	59.9	1150.0	0.813	59.58	1144.0	0.910	☑	☑	✓		☑	✓		✓		☑	☑	☑	✓	☑	☑	☐	☑	✓	☑	☑	☑	☑	☑	☑	✓				☑	☑
S5	50	960	50.0	960.0	0.741	49.69	954.0	0.834	☑		✓		☑	☑		✓		☑	☑	☑	✓	☑	✓		☑	✓	☐	☑	☑	☑	☑	☐			✓		☑	☑
S6	40	768	39.6	760.0	0.638	39.74	763.0	0.726	☑		✓		☑	☑		✓		☑	☑	☑		☑	✓		☐	✓		☐	☑	☑	✓						☑	☑
S7	30	576	29.7	570.0	0.518	29.90	574.0	0.582	☑				☑			✓		☑	☑	☑		✓			✓			☑	☑	✓							☐	☑
S8	20	384	19.8	380.0	0.354	19.79	380.0	0.413	☑				☑	☐		✓		☑	☑	☑								☐	☑	✓								
S9	10	192	9.9	190.0	0.200	9.90	190.0	0.203	☑				☑					✓	☑	☐																		

*Total cost is 1920.0 (details of cost scenarios are available in Table 7.2 and details of experts are available in Table 5.1); ☐=RMS selected considering linear cost constraint and ✓=RMS selected considering quadratic cost constraint

The set of selected RMSs and the level of risk mitigation achievable for different cost scenarios for each of the experts are presented in Appendix E. The RMSs selected for low relative cost scenarios (e.g. S9, S8 and S7) are more important compared to the other RMSs in LNG supply chain risk management (SCRM). In a limited budget scenario (particularly for lower budget), the optimization process maximizes level of risk mitigation through selection of RMSs with high relative effectiveness (RE), meaning RMSs which can mitigate relatively greater level of risk mitigation with lower relative cost. Although all RMSs (Table 6.1) are important in LNG SCRM, RMSs included for higher cost scenarios (such as S1, S2 and S3) are relatively less effective compared to the RMSs selected for low and medium cost scenarios. The selection of an RMS for a particular cost scenario depends on its score against each risk, the cost of implementation of the strategy and its relative effectiveness (RE) in mitigating the LNG supply chain risks (SCRs.) The selection of an RMS for a relative cost scenario is complex, with this determined through a process of the QFD method followed by solving the optimization problem for the particular cost scenario.

Through solving the optimization problem, four RMSs (RMS1, RMS5, RMS11 and RMS12) are selected for cost scenario S9 for Expert 1 considering the linear cost constraint (Table 7.3[a]). For the same scenario considering the quadratic cost constraint, RMS12 has been dropped and RMS10 selected, thus keeping the total number of RMSs the same. Additional RMSs selected for cost scenario S8 compared to cost scenario S9, considering the linear cost constraint, are RMS6, RMS20 and RMS21 where, considering the quadratic cost constraint, RMS8 and RMS22 are added while dropping RMS6 and RMS20 (Table 7.3[c]). An additional level of risk mitigation is achieved for the same cost scenario, considering the quadratic cost constraint compared to the linear cost constraint (Table 7.3 and Appendix E). Therefore, the results of the optimization model considering the quadratic cost constraint appeared superior compared to the results considering the linear cost constraint.

The selected set of RMSs for a particular cost scenario can be different for different experts (Appendix E). The selection of a set of RMSs for a particular cost scenario are determined based on expert opinion which depends on factors such as SCR attributes, the relationship score between SCRs and RMSs and the cost of implementation RMSs (as shown in Appendix D). Therefore, based on an individual expert's opinion (details of experts are in Table 5.1), it is likely that a selected set of RMSs for a particular cost scenario (Table 7.2) could be different from other sets of selected RMSs (Appendix E) for the other experts. An important aspect of this optimization result (Appendix E) of selected RMSs for a particular cost scenario (Table

7.2) is that consensus is observed among the experts in the selected set of risk mitigation strategies (RMSs). A quick overview of Figures A7.3–7.8 (Appendix E) provides an impression that reasonable agreement prevails among the experts for selected RMSs for different cost scenarios. A sensitivity analysis of the consensus among the experts based on the optimization results is presented in the following section.

7.5.3 Sensitivity analysis of optimization model

Sensitivity of the optimization model is carried out through analysing changes in the level of risk mitigation with changes in cost. The level of supply chain risk mitigation can be achieved for different cost scenarios based on data from all experts without cost savings (linear cost constraint) and with cost savings (quadratic cost constraint) as presented in Figure 7.4. A relative cost scale (0-1) is used to facilitate the comparison between the experts for the level of risk mitigation and associated cost. A summary of the total actual cost assigned for implementing all RMSs by the experts for supply chain risk mitigation is presented in Table 7.4 (details of the cost of implementation of the RMSs are available in Appendix D). Using the total cost of implementing all RMSs, the actual cost can be calculated for any relative cost of a different expert.

With a higher budget or costs allocated, a greater level of risk mitigation is achievable (Figure 7.4). A quadratic relationship exists between the level of risk mitigation and the cost (or relative cost). The rate of the level of risk mitigation (level of risk mitigation per unit of relative cost) decreases gradually with an increase in budget and the rate diminishes increasingly for a budget greater than 50% of the total cost (0.5 relative cost). This phenomenon of the diminishing rate of the level of risk mitigation with an increasing budget (Figure 7.4) was observed for all optimization problems based on the data from all experts (details of experts are in Table 5.1). For example, for optimization considering the linear cost constraint (without savings) based on Expert 1, the level of risk mitigation is 0.200 for scenario S9 (10% of total cost or 0.1 relative cost). With a 10% increase of cost (budget), the level of risk mitigation increases to 0.354 (an increase of 0.154) (Table 7.3[a] and Figure 7.4[i]). On the other hand, an increase in budget from 70% (scenario S3) to 80% (scenario S2) results in an increase of the level of risk mitigation from 0.872 to 0.929 (an increase of 0.057) (Table 7.3[a] and Figure 7.4[i]). The phenomenon of the diminishing rate of the level of risk mitigation with an increasing budget is true for optimization both with linear cost constraint and with quadratic cost constraint. It is important to note that, with the diminishing rate of the level of risk mitigation for an increase in the budget, for very high-end risk mitigation (e.g. cost scenario S1, S2, S3), management may decide to optimize resource utilization to a certain level of total cost. For example, management may decide to implement scenario S3 (70% of total cost) which, in most cases, achieves a level of risk mitigation close to 0.9 (for all experts) without cost savings and close to 0.95 with cost savings (Tables A7.3–7.8, Appendix E and Figure 7.4).

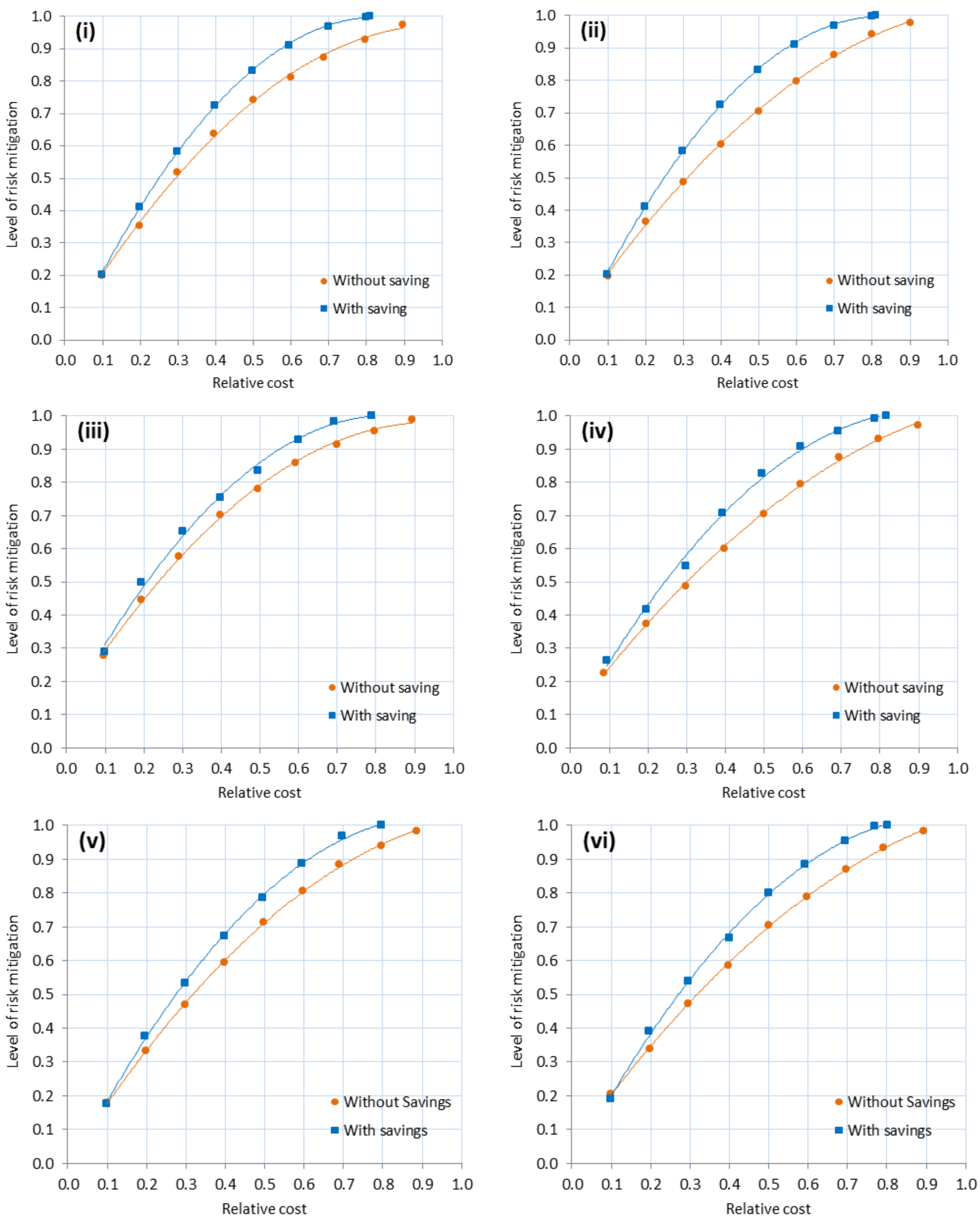


Figure 7.4: Comparison of level of risk mitigation for selected risk mitigation strategies
Notes: This was under different budget (cost) scenarios without cost savings (considering linear cost constraint) and with cost savings (considering quadratic cost constraint) based on opinions of Experts 1, 2, 3, 4, 5 and 6.

Table 7.4: Total cost summary for LNG supply chain optimization based on experts' opinions

Experts	1	2	3	4	5	6
Total cost	1920	1500	1030	640	1405	1660

The differences in the level of risk mitigation for linear cost constraint (without cost savings) and quadratic cost constraint (with cost savings) increases from low cost (budget) to high cost. The gap narrows slightly closer to the very high cost end. For all the experts, close to a 100% level of risk mitigation could be achieved with around 90% of budget (or cost) spent without cost savings while the same or a higher level of risk mitigation could be achieved with around 80% of budget (or cost) spent with cost savings (Figure 7.4 and Appendix E). Very little gain can be achieved in terms of the level of supply chain risk mitigation with an increase of budget from 70–80% with cost savings (Figure 7.4 and Appendix E). Details of the budget available, budget utilization and the level of risk mitigation achievable within the budget for different cost scenarios without cost savings and with cost savings for individual experts are summarized in Appendix E. Thus, sensitivity analysis (Figure 7.4) demonstrates that the results of the optimization model are consistent based on data from different experts although the results vary for different experts. However, the variation in the level of risk mitigation for different cost scenarios (Figure 7.4) based on data from the experts requires an ensemble analysis approach be taken toward the optimization results to explain the variability of the results. The ensemble approach to the optimization results is presented in the next section.

7.5.4 Ensemble approach to optimization results from experts

Analysis reveals that the level of risk mitigation and the selected set of RMSs for a cost scenario are not exactly the same for any two experts, instead varying among the six experts (Appendix E). These variations among the experts are due to variations in defining SCR attributes, the relationship between SCRs and RMSs, and the cost of implementing the risk mitigation strategies (RMSs). Thus, the relationship between the level of risk mitigation and the cost scenarios (Figure 7.4) derived based on data from the experts are six different trajectories which are similar but not the same. Therefore, the ensemble approach to the relationships defines a possible range of levels of risk mitigation achievable for different cost scenarios (Figure 7.5).

An ensemble approach to the relationship between the level of risk mitigation achievable and the cost scenarios based on the six experts is presented in Figure 7.5, for without cost savings (considering linear cost constraint) and with cost savings (considering quadratic cost constraint). In addition, a summary of selected sets of RMSs for different cost scenarios based on the experts is presented in Table 7.5. Based on the experts' opinions, the level of risk mitigation varies across a range for a cost scenario (Figure 7.5). Thus, any value within the range is a possible level of risk mitigation achievable for a particular cost scenario. The ensemble approach to the relationships captures the variation in the optimization results based on the data from the experts. Hence, the relationship between the level of risk mitigation and cost should be used as guide to determine the likely (the possible) level of risk mitigation within a range for a particular cost scenario or budget. Therefore, the level of risk mitigation for a particular cost (scenario) is a likely value of the risk mitigation within a range rather than a firm number (as shown in Figure 7.5).

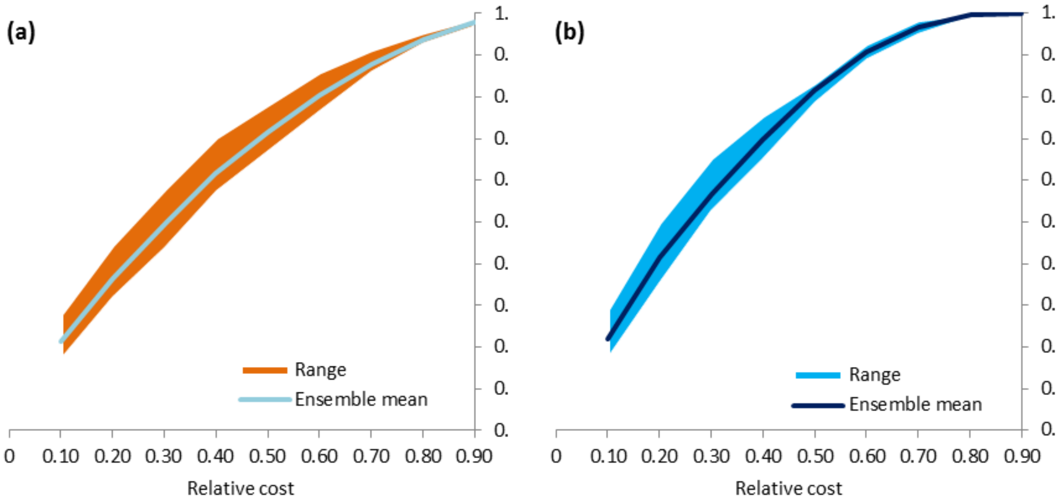


Figure 7.5: Summary of level of risk mitigation for selected risk mitigation strategies

Notes: under different budget (cost) scenarios based on opinions of Experts 1, 2, 3, 4, 5 and 6: (a) without cost savings (considering linear cost constraint) and (b) with cost savings (considering quadratic cost constraint).

An important step in SCRM is to determine the level of supply chain risk mitigation achievable within a particular cost or budget scenario. Another step is to identify a set of selected RMSs for that particular cost scenario. Figure 7.5 can be used to determine the level of risk mitigation for any cost or budget scenario. The optimization problem can then be solved for that particular cost (budget) to select the optimal set of risk mitigation strategies (RMSs). Thus, the relationship between the level of risk mitigation and cost can be used as a management decision tool to determine the level of risk mitigation for a cost scenario.

7.5.5 Selecting RMSs with ensemble approach

Supply chain risk management (SCRM) is a management decision problem for which the manager has to make decisions regarding the desired level of risk mitigation, the allocation of budget and the set of RMSs to be implemented. The analysis of SCR and RMS attributes along with mathematical models, such as the optimization model, assist managers to make an informed decision to achieve the maximum level of risk mitigation for a budget. The optimization results obtained based on the experts' opinions (Table 5.1), although consistent, have some variations in the level of risk mitigation, the budget utilized and the set of RMSs to be implemented (Tables A7.3-7.8, Appendix E) for a particular cost scenario (Table 7.2). Therefore, instead of relying on a single set of results, an ensemble mean of the results appears to be a preferable approach considering the bias or uncertainty that may occur if relying on a single expert.

The optimal sets of selected RMSs for different cost scenarios for the ensemble of experts (Table 5.1) are summarized in Table 7.5. The selected RMSs are presented as a percentage of the ensemble mean of the optimization results for the six experts. For example, RMS3 has been selected on five occasions out of six in the optimization results based on the six experts for cost scenario S3 (70% of total cost), for both cost constraints (linear and quadratic). Therefore, RMS3 is scored 83% in selected RMSs for cost scenario S3. A score of 100% means that all experts agreed on the implementation of an RMS for a particular cost scenario where any lower score represents partial disagreement. The greater the score the greater is the agreement among the experts. Therefore, in the case of an ensemble mean of the results, it is suggested that RMSs with a score lower than 100% should be implemented based on the order of preference in the level of agreement among the experts provided the total costs of implementation of the RMSs remain within the budget. For example, after implementing RMSs of a score of 100%, RMSs with a score of 83% should be implemented followed by those with a lower score as long as the total cost of implementation remains within the budget for a cost scenario (Table 7.5). In addition, there could be a situation of RMSs with the same score where the budget would be exceeded if all the RMSs were implemented. In such cases, the preference among the RMSs with the same score should be determined based on their relative effectiveness (RE) as shown in Table 6.5 in Chapter Six.

Table 7.5(a): Summary of optimization results for different cost scenarios based on ensemble of all experts (considering linear cost constraint)

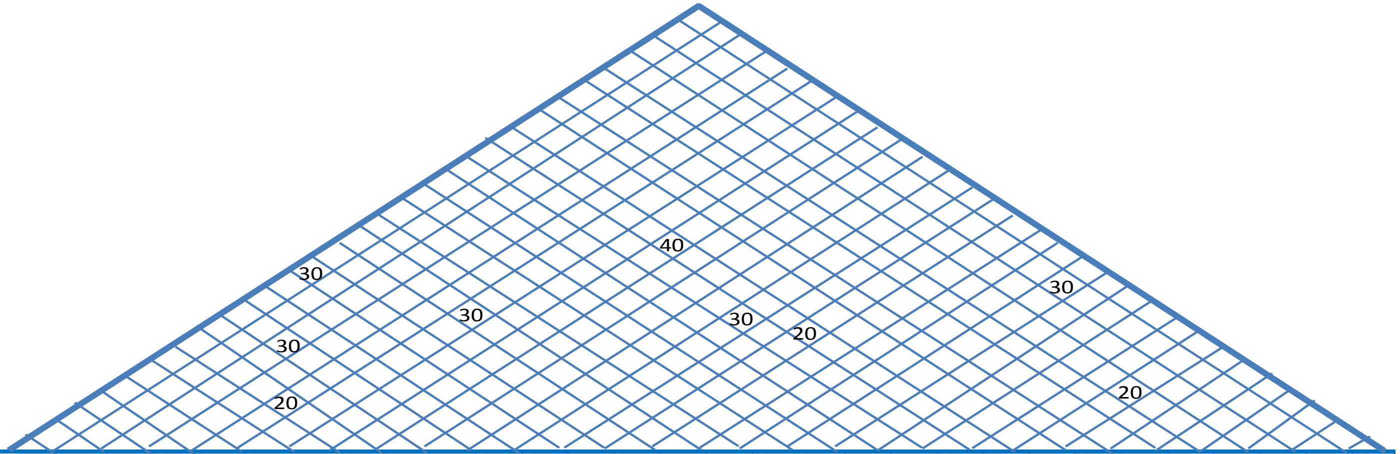
Cost scenario and budget			Risk mitigation without savings			Selected RMSs under different cost scenarios (% of ensemble mean)																													
Scenario	Budget available*		Budget used																																
	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1223.3	89.5	1215.8	0.980	100	100	100	83	100	83	50	100	100	100	100	100	100	100	100	33	100	100	100	83	100	33	83	67	83	83	100	83	100	83
S2	80	1087.3	79.7	1082.5	0.938	100	100	83	50	100	83	50	67	100	100	100	100	100	100	100	17	83	100	100	83	100	17	67	67	83	50	50	67	100	83
S3	70	951.4	69.5	943.3	0.879	100	100	83	50	100	83	33	67	67	83	83	100	83	67	100	0	83	83	83	83	100	17	50	50	50	17	50	17	100	83
S4	60	815.5	59.7	811.7	0.803	100	83	50	33	83	67	17	50	67	83	83	100	67	67	67	17	83	67	83	83	83	17	50	50	17	17	17	17	83	67
S5	50	679.6	49.9	678.3	0.716	100	67	33	33	67	50	0	50	67	83	83	83	67	67	33	0	83	67	67	83	67	17	33	33	17	17	0	17	83	50
S6	40	543.7	39.8	540.8	0.616	100	67	33	33	50	50	0	33	67	83	67	50	50	50	33	0	83	67	33	67	83	17	17	0	17	17	0	0	67	50
S7	30	407.8	29.7	403.3	0.496	83	50	17	0	50	33	0	33	50	50	67	67	33	33	17	0	67	50	33	67	50	0	0	0	17	17	0	0	67	33
S8	20	271.8	19.8	269.2	0.365	100	33	33	50	50	50	0	0	50	33	67	50	33	17	33	0	67	17	17	33	17	0	0	0	17	17	0	0	50	17
S9	10	135.9	9.7	133.3	0.214	83	33	0	0	33	17	0	0	0	0	50	50	17	17	17	0	50	17	0	17	0	0	0	0	17	0	0	17	33	17

Table 7.5(b): Summary of optimization results for different cost scenarios based on ensemble mean of all experts (considering quadratic cost constraint)

Cost scenario and budget			Risk mitigation with savings			Selected RMSs under different cost scenarios (% of ensemble mean)																													
Scenario	Budget available*		Budget used																																
	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1223.3	80.2	1089.8	1.000	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	83	100	100	100	100	100
S2	80	1087.3	78.8	1071.4	0.998	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	67	100	100	100	100	100	100	100	67	83	100	100	100	100	100
S3	70	951.4	69.4	943.6	0.966	100	100	100	83	100	100	50	100	100	100	100	100	100	100	100	33	83	100	100	100	100	100	83	67	67	67	67	33	100	83
S4	60	815.5	59.5	808.6	0.909	100	100	100	50	100	100	33	100	67	83	83	100	100	100	100	0	83	100	83	83	100	100	33	50	67	17	33	50	100	83
S5	50	679.6	49.6	674.9	0.817	100	67	100	33	83	100	0	67	67	83	83	100	100	83	100	0	83	100	50	67	100	50	33	17	0	17	33	33	100	50
S6	40	543.7	39.8	541.1	0.698	100	67	83	33	83	100	0	67	50	67	67	83	83	50	67	0	67	100	33	50	83	50	33	0	33	17	17	17	100	33
S7	30	407.8	29.8	404.6	0.567	100	50	67	33	50	50	0	33	17	83	67	83	67	50	50	0	67	83	17	50	83	33	0	0	17	17	0	0	83	33
S8	20	271.8	19.7	267.4	0.414	83	33	17	17	50	33	0	33	17	33	67	83	67	33	33	0	33	50	0	17	67	33	0	0	0	17	0	0	50	17
S9	10	135.9	9.6	131.3	0.221	83	0	17	0	33	17	0	0	0	33	50	50	33	0	0	0	17	33	0	0	33	0	0	0	17	17	0	0	50	0

7.5.6 Optimization model based on consensus mean

An optimization problem based on consensus mean data for all the experts (Table 5.1) is formulated for maximizing risk mitigation through the implementation of risk mitigation strategies (RMSs). The QFD matrix with consensus mean data for the optimization model is summarized in Figure 7.6. The steps for formulating this optimization problem are explained in Section 7.5.1 and details of the optimization model are outlined in Chapter 4. The steps followed are the same as explained in Section 7.5.1 except that consensus mean data from all experts are used instead of individual expert data (opinions). The objective function and cost constraint are developed following the principles in Section 7.5.1 which are also explained in Chapter 4. The "roof" of the QFD matrix remains the same for all optimization problems as they only define the relationships between the interrelated risk mitigation strategies (RMSs). The optimization problem is solved for linear and quadratic cost constraints for the cost scenarios as defined in Section 7.4.



	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR1	0.032	3.2	3.5	5.2	1.7	5.7	1.3	2.5	7.5	7.5	7.0	5.3	6.3	7.3	4.2	6.5	1.7	7.7	4.0	3.7	1.5	1.7	0.2	1.8	1.7		3.3	2.7	2.7	5.3	4.5
SCR2	0.029	0.8	1.5	3.5	0.2	1.8	3.0	3.3	0.8	3.3	0.8	0.8		4.7	1.7	7.2				0.5	2.5	1.5	1.5			3.5	0.2	3.3		0.8	1.5
SCR3	0.017	0.8				6.2		1.8	1.7	0.8		2.5	4.3			0.2		2.5	2.5	1.8	0.8	4.2			1.7		0.2		0.2		0.8
SCR4	0.033	3.3	0.5	0.3	1.2				4.3	7.5	6.2	4.3	0.2	2.3	1.0	0.8	0.2	0.8	0.2	3.0	1.7	0.8	1.5	1.5	0.8		2.0	4.8	2.8	1.5	1.5
SCR5	0.015	1.2	2.5	1.8	3.3	4.5		0.8	3.2	6.0	4.3	0.7	2.8	0.2	4.7		0.2	1.5	0.8	2.2	4.7	5.3	6.7	6.7	4.7		1.5	3.5	1.5	1.5	1.5
SCR6	0.039					0.2	2.0		0.8	0.8	4.7		1.5	1.5	1.5	1.5		1.5	1.5	5.3	3.7	2.0	0.8	1.5	1.5		4.8	0.8	9.0	1.5	1.5
SCR7	0.012	1.7				4.0			2.5	0.8	4.8	1.8	6.2		0.5			0.8		0.8	0.8	2.8	0.2	0.8	3.3		0.2			1.5	1.5
SCR8	0.026	0.2	2.5		0.2	3.3	3.5	3.0	0.8		2.0	4.7	1.5	0.3	3.3	2.7	0.2	5.3	0.3	0.2	1.7	7.0	1.0	1.0	1.8		0.8	0.2	1.5	3.3	1.5
SCR9	0.033	2.5				0.3	7.5					0.2	0.2	5.3	2.8	5.5					2.5	4.5				5.7					
SCR10	0.030	2.5				0.3	6.8					0.2		4.0		4.5				3.5	2.5	0.8				7.0					
SCR11	0.038	6.2	8.3	9.0	7.7	1.7	2.7				6.0	5.3	5.3	7.0		4.7			0.8	0.8	0.2	1.8	1.5					0.8		1.5	6.2
SCR12	0.039	3.5	4.0	1.8	3.0	1.5				2.5	5.5	5.7	1.5	4.7	3.5	0.2		3.0	0.2	2.3	1.5	5.7	1.5	1.5	1.5		1.5	3.3		4.0	5.5
SCR13	0.030	0.8	0.8	4.2	4.2	3.3		3.0	0.8		4.2	0.8	0.8	6.2	0.2	6.0					1.0	3.3	1.5	1.5	0.8		0.8			1.5	1.5
SCR14	0.038					5.5	3.8		6.2	6.2	4.8	6.2	4.8	1.5	1.2	1.5		4.5	5.3	1.0	2.5	7.2	0.8	2.5	2.5		0.2			6.8	1.5
SCR15	0.046	1.7	1.7			5.5	3.8	0.8	6.2	5.8	3.5	4.7	5.8		3.5	1.5		5.7	3.7	1.2	1.7	7.2	1.5	4.7	3.3					6.8	2.3

	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR16	0.043	0.8				7.7	3.8		6.3	4.7	3.5	3.3	3.7		2.8	0.8		5.7	5.0	2.5	0.8	7.0	1.5	4.7	5.3					7.5	1.5
SCR17	0.045					4.2	4.7		7.7	6.0	2.7	3.3	6.0	1.0	1.8	0.8		6.0	5.3	4.5	4.3	6.3	1.5	2.0	1.3					6.2	1.5
SCR18	0.026	0.8				1.0	1.7		3.0	3.0	1.7	1.3	6.8		2.7			4.5	2.5	1.3	4.7	2.5		2.0	2.0			0.8		4.8	1.5
SCR19	0.028	3.5	5.5	4.2	0.5	3.8	2.5	1.5	0.3	1.8	6.0	4.3	4.2	5.5	1.5	4.7		1.2		3.8	5.5	7.2	1.5							1.5	3.0
SCR20	0.033	0.2	0.8			1.0					1.8	3.3	0.8	0.8	3.3			7.7	0.8		1.7	4.7	1.5	4.7	4.0					4.2	1.2
SCR21	0.041	3.2	1.0	2.5	1.7	2.3			2.2	6.8	7.0	1.8	1.2	1.8	2.5	3.3		1.5	2.2	5.3	3.7	6.5	1.5	1.2	2.0			1.7	1.7	4.0	2.3
SCR22	0.026	1.5		1.5		2.0	1.8		2.0	1.8	2.8	4.7	3.3	1.5	3.8	1.5		6.3	7.5	1.5	1.5	6.2	1.5	1.7	2.5					5.3	1.5
SCR23	0.029	0.8		0.2					5.3	3.8	2.5	1.5	6.7	0.2	3.3							1.5		0.7	0.7					1.5	1.5
SCR24	0.021	1.0	0.2			5.3		3.0	1.0	1.8	3.0	4.0	0.8	0.8		0.3		6.8	7.0		3.3	5.5	1.5	4.0	3.3					1.5	1.5
SCR25	0.037	3.2	3.0	3.2	3.0	3.2		3.0	3.3	3.3	3.5	2.2	1.7					4.5	2.8			2.3	0.2	1.2	1.8					3.3	1.5
SCR26	0.024	3.3	2.5	0.2		3.0			3.0		1.5	0.8	0.8	3.0	2.5	6.0					2.5	6.0	1.5	1.7	1.7					1.5	1.5
SCR27	0.035	1.5	0.8	1.5		1.5			1.5	9.0	6.2	4.3	1.5		1.5					3.5	0.8	1.5	1.5					3.3		2.7	4.0
SCR28	0.025	0.2	1.5		0.8	2.3			4.0	4.7	5.5	0.8	0.3	0.8	0.3	3.0			3.3	3.0	4.7	6.5	0.8				6.0			1.5	1.5
SCR29	0.036	1.5	1.5	0.2		5.7			6.0	3.0	3.3	2.7		1.5	2.5	1.5		3.8	4.7		5.3	5.3	1.5	0.5	0.8		0.2	0.8		4.7	1.5
SCR30	0.035	4.2	5.0	5.0	1.5	1.8			3.0	1.5	4.7	1.5			0.5			4.5	3.8	3.7	3.0	4.8	1.5	3.3	1.5		2.5			1.5	1.5
SCR31	0.018	5.2	4.3	4.3	0.8				0.2	0.8	6.2	5.0			2.5		2.8	0.8			3.3	4.5	3.2	5.8	0.8					0.8	5.5
SCR32	0.017	3.0	3.7	4.3		1.5					5.5	3.0			2.5		6.2	0.8			3.3	3.8	4.7	4.5						0.8	3.8
SCR33	0.020	4.5	4.3	3.7		1.5					6.8	5.0			2.5		6.2	0.8			3.3	4.5	6.0	4.5						0.8	3.8
C		20	32	43	45	51	31	38	77	62	73	49	39	46	48	50	34	48	40	38	43	82	71	63	48	19	27	38	30	40	33
AI		2.0	1.8	1.7	1.0	2.8	1.7	0.6	2.8	3.1	3.9	3.0	2.5	2.0	2.0	2.1	0.3	2.9	2.1	1.9	2.4	4.4	1.4	1.9	1.6	0.5	0.8	0.8	0.7	3.1	2.2

W=weight of SCR; C =cost of RMS; AI=absolute importance of RMS

Figure 7.6: QFD matrix for optimization based on consensus mean of all experts

7.5.7 Optimization results based on consensus mean

The optimization problem based on the consensus mean of all experts has been solved for different scenarios considering linear and quadratic cost constraints. The optimization results based on the average of six expert opinions for without and with cost savings for different cost scenarios (Table 7.2) are presented in Table 7.6.

The level of risk mitigation achievable for cost scenario S9 with linear cost constraint is 0.163 for a cost of 132.5 (Table 7.6[a]). For scenario S9 (without savings), four RMSs are recommended, RMS1, RMS12, RMS29 and RMS30. With cost savings for the same scenario (S9), the number of RMSs remained the same (four) with the level of risk mitigation achieved being 0.176 for a cost of 135.4 (Table 7.6[b]). With an additional cost (2.9), a higher level of risk mitigation (by 0.013) can be achieved with cost savings compared to without cost savings (Table 7.6[c]). Although the number of RMSs remained the same for both cases, the sets of RMSs are different. For scenario S9 with cost saving, the recommended RMSs are RMS1, RMS6, RMS12 and RMS21. Here, with an additional cost (2.9), RMS6 and RMS21 are selected instead of RMS29 and RMS30, resulting in a greater level of risk mitigation. The total AI score of RMS6 and RMS21 is 6.1(1.7+4.4) while the total AI score of RMS29 and RMS30 is 5.3 (3.1+2.2) which means a greater level of risk mitigation is achieved with the higher AI score of the risk mitigation strategies (RMSs) (Figure 7.6). This also highlights that the optimization process with cost savings not only allows additional implementation of RMSs compared to without cost savings but also allows a trade-off among the RMSs to optimize the level of risk mitigation. This phenomenon is prevalent with optimization for mid- to low-cost scenarios (such as S5, S6, S7, S8 and S9) (Table 7.6[c]). For high cost scenarios (such as S4, S3, S2 and S1), additional RMSs are selected with cost saving from the simultaneous implementation of interdependent RMSs (Table 7.6[c]).

Strategies selected for lower budget or lower cost scenarios (such as S9, S8, S7 and S6) are more efficient and/or more important RMSs for LNG SCRM in Australia. In other words, strategies selected for lower budget or lower cost scenarios are more efficient in mitigating LNG supply chain risks (SCRs). These RMSs are efficient as a greater level of supply chain risk mitigation can be achieved through their implementation per unit cost compared to other RMSs which are selected for higher budget or higher cost scenarios, such as S1, S2, and S3. Therefore, Table 7. 6(c) is also useful for identifying important RMSs for LNG SCRM as a whole and also for identifying the most appropriate set of RMSs for a particular budget or cost scenario based on the consensus mean of all experts.

Table 7.6(a): Summary of optimization results for different cost scenarios based on consensus mean of all experts (considering linear cost constraint)

Cost scenario and budget			Risk mitigation without savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used																																
	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1223.3	89.5	1215.8	0.961	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1
S2	80	1087.3	79.7	1083.3	0.911	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	0	1	0	0	1	1
S3	70	951.4	69.6	945.8	0.840	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1
S4	60	815.5	59.5	809.2	0.742	1	1	1	0	1	1	0	0	1	1	1	1	1	0	1	0	1	1	0	1	1	0	0	0	0	1	0	0	1	1
S5	50	679.6	49.8	677.5	0.648	1	1	0	0	1	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	1	0	0	0	0	1	0	0	1	1
S6	40	543.7	39.9	541.7	0.545	1	1	0	0	1	1	0	0	0	1	1	1	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	1	1
S7	30	407.8	29.9	405.8	0.421	1	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	1	1
S8	20	271.8	19.9	270.8	0.291	1	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1
S9	10	135.9	9.7	132.5	0.163	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1

*Total cost is 1359.17 (details of cost scenarios are available in Table 7.2 and details of experts are available in Table 5.1); 0=RMS is not selected; 1=RMS selected

Table 7.6(b): Summary of optimization results for different cost scenarios based on consensus mean of all experts (considering quadratic cost constraint)

Cost scenario and budget			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used																																
	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1223.3	80.3	1091.4	1.000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S2	80	1087.3	77.8	1057.3	0.994	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S3	70	951.4	69.4	943.9	0.956	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1
S4	60	815.5	60.0	814.9	0.884	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	0	0	1	1
S5	50	679.6	49.7	675.8	0.781	1	0	1	0	1	1	0	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	0	0	0	0	1	1
S6	40	543.7	39.7	539.9	0.651	1	0	1	0	1	1	0	1	0	1	0	1	1	1	1	0	0	1	0	1	1	1	0	0	0	0	0	0	1	1
S7	30	407.8	30.0	407.4	0.512	1	0	1	0	0	1	0	0	0	1	1	1	1	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	1	1
S8	20	271.8	20.0	271.3	0.338	1	0	1	0	0	0	0	0	0	1	0	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0
S9	10	135.9	10.0	135.4	0.176	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0

Table 7.6(c): Comparison of optimization results considering linear and quadratic cost constraints for different cost scenarios based on consensus mean of all experts

Cost scenario and budget			Risk mitigation without savings			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used			Budget used																																
	%	Actual	%	Actual	$Rf(x)$	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1223.3	89.5	1215.8	0.961	80.3	1091.4	1.000	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑
S2	80	1087.3	79.7	1083.3	0.911	77.8	1057.3	0.994	☑	☑	☑	✓	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	✓	☑	☑	✓	☑	✓	✓	☑	☑
S3	70	951.4	69.6	945.8	0.840	69.4	943.9	0.956	☑	☑	☑		☑	☑		☑	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	✓	✓	✓	✓	✓	✓		☑	☑
S4	60	815.5	59.5	809.2	0.742	60.0	814.9	0.884	☑	☑	☑		☑	☑		✓	☑	☑	☑	☑	☑	✓	☑		☑	☑	✓	☑	☑	✓			✓	☑			☑	☑
S5	50	679.6	49.8	677.5	0.648	49.7	675.8	0.781	☑	☐	✓		☑	✓		✓	☐	☑	☑	☑	✓	✓	✓		☑	☑	☑	☑	☑	✓				☐			☑	☑
S6	40	543.7	39.9	541.7	0.545	39.7	539.9	0.651	☑	☐	✓		☑	☑		✓		☑	☐	☑	✓	✓	✓		☐	✓		☑	☑	✓							☑	☑
S7	30	407.8	29.9	405.8	0.421	30.0	407.4	0.512	☑		✓		☐	✓				✓	☑	☑	✓		✓		☐	✓		☐	☑								☑	☑
S8	20	271.8	19.9	270.8	0.291	20.0	271.3	0.338	☑		✓		☐					✓	☐	☑	✓				✓	✓	☐										☑	☐
S9	10	135.9	9.7	132.5	0.163	10.0	135.4	0.176	☑					✓						☑									✓								☐	☐

*Total average cost is 1359.17 (details of cost scenarios are available in Table 7.2 and details of experts are available in Table 5.1); ☐=RMS selected considering linear cost constraint; ✓=RMS selected considering quadratic cost constraint

7.5.8 Comparison between consensus mean and ensemble mean of optimization

Comparison of the level of risk mitigation between the consensus mean and the ensemble mean reveals that the level of risk mitigation is greater for the ensemble mean compared to the consensus mean for a cost scenario (Table 7.7). This phenomenon is true for optimization results obtained through solving the model considering both linear and quadratic cost constraints. For example, the levels of risk mitigation for scenario S1 without cost savings obtained through optimization with the consensus mean and with the ensemble mean are 0.961 and 0.980, respectively (Table 7.7).

Table 7.7: Comparison of level of risk mitigation between consensus mean and ensemble mean of optimization for different cost scenarios.

Cost scenario and budget			Optimization with consensus mean						Optimization with ensemble mean					
			Risk mitigation without savings			Risk mitigation with savings			Risk mitigation without savings			Risk mitigation with savings		
Scenario	Budget available*		Budget used			Budget used			Budget used			Budget used		
	%	Actual	%	Actual	$Rf(x)$	%	Actual	$Rf(x)$	%	Actual	$Rf(x)$	%	Actual	$Rf(x)$
S1	90	1223.3	89.5	1215.8	0.961	80.3	1091.4	1.000	89.5	1215.8	0.980	80.2	1089.8	1.000
S2	80	1087.3	79.7	1083.3	0.911	77.8	1057.3	0.994	79.7	1082.5	0.938	78.8	1071.4	0.998
S3	70	951.4	69.6	945.8	0.840	69.4	943.9	0.956	69.5	943.3	0.879	69.4	943.6	0.966
S4	60	815.5	59.5	809.2	0.742	60.0	814.9	0.884	59.7	811.7	0.803	59.5	808.6	0.909
S5	50	679.6	49.8	677.5	0.648	49.7	675.8	0.781	49.9	678.3	0.716	49.6	674.9	0.817
S6	40	543.7	39.9	541.7	0.545	39.7	539.9	0.651	39.8	540.8	0.616	39.8	541.1	0.698
S7	30	407.8	29.9	405.8	0.421	30.0	407.4	0.512	29.7	403.3	0.496	29.8	404.6	0.567
S8	20	271.8	19.9	270.8	0.291	20.0	271.3	0.338	19.8	269.2	0.365	19.7	267.4	0.414
S9	10	135.9	9.7	132.5	0.163	10.0	135.4	0.176	9.7	133.3	0.214	9.6	131.3	0.221

Changes in the scale for the SCR attributes and RMSs attributes in calculating the consensus mean are the main reason for the lower level of risk mitigation with the consensus mean. For example, a conventional scale of 1-5-9 was used to define the relationship between SCRs and RMSs through the QFD method's relationship matrix (Appendix D). In calculating the consensus mean scores of the cells of the relationship matrix, the conventional scale (1-5-9) became a continuous scale of 0–9 with most of the scores falling within 0–5 (Figure 7.6). Similar to the mean score of the relationship score, the consensus mean of the weightage of SCRs is also expected to be lower compared to their ensemble mean score. The changes in SCR attributes and RMS attributes influence the calculation of the AI score. Although the weightage (W) of an SCR and the AI score of an RMS are converted into a relative scale, their consensus mean score and ensemble mean score must be different. These differences in SCR weightage and AI score between the consensus mean and the ensemble mean result in different levels of risk mitigation for the same cost scenario. The consensus mean score measures level of agreement among the experts in scoring SCRs and RMSs attributes and involves a mathematical formula (as explained in section 5.8.1) to measure level of consensus. On the other hand, ensemble mean represents mean of independent assessment of SCRs and RMSs attributes based on the data collected from the experts. Thus, though both (consensus and ensemble mean) are measure of central tendency of SCRs and RMSs attributes, the process involved in calculating these are completely different.

7.5.9 Preferred approach of optimization for SCRM

A comparative analysis of the limitations and advantages of these two approaches (optimization based on the consensus mean and optimization based on the ensemble mean) has been carried out to determine the preferred approach of optimization. There are some limitations of the consensus mean approach of optimization. Firstly, it modifies the scale used for SCR attributes and RMS attributes. These changes in SCR and RMS attribute scale influence the result of the optimization model (as explained in Section 7.5.8). Secondly, the consensus mean approach draws a single trajectory of the relationship between the level of risk mitigation, the cost (budget) and the relevant RMSs for the cost scenarios. Hence, it does not show the variation or differences among the experts. Thirdly, no information on the order of preference is available for the RMSs that were not selected for a cost scenario.

The ensemble mean approach of optimization overcomes all three of the limitations of the consensus mean approach. Firstly, the scale of SCR and RMS attributes remains the same in the optimization process. Secondly, this approach independently solves each set of data from the experts (Table 5.1) reflecting the individual opinion of each expert. Each solution of the optimization model based on expert opinion is a possible trajectory of the relationship between the level of risk mitigation and the cost. Thirdly, the ensemble mean of the optimization results not only draws an agreement among the experts but also shows the range of variation among the experts. Fourthly, the ensemble mean approach of optimization provides additional information on the hierarchical order of preference for implementation of all RMSs for a cost scenario (as explained in Section 7.5.5). Therefore, the ensemble approach of optimization is considered the preferred approach in comparison to the consensus mean approach. A summary highlighting the key differences (in terms of advantages and limitations) between two approaches: optimization based on the consensus mean and optimization based on ensemble mean is presented in Table A7.9 (Appendix E).

7.5.10 Need for a simulation model for SCRM

Along with good consensus among the experts (Table 5.1) on the optimization results of SCRM, considerable variations were also observed. These variations include the range of levels of risk mitigation for a particular cost scenario based on the ensemble mean of the optimization results (as demonstrated in Figure 7.5). In association with the variation in the range of levels of risk mitigation, selected sets of RMSs for different cost scenarios were also varied depending on the experts' opinions (as shown in Appendix E). The range of levels of risk mitigation for a cost scenario was drawn based on the optimization results which were based on data (opinions) from the experts. The QFD matrices presented in Appendix D as part of the optimization model show that the SCR attribute and relationship score between SCRs and RMSs could vary across a wide range based on the corresponding minimum and maximum scores of the attributes as defined by the experts. The same is also true for the cost of implementation of risk mitigation strategies (RMSs). Thus, many realizations are possible between the minimum and maximum scores of an attribute for SCRs and RMSs in the optimization process. One such possible realization of an SCR attribute is explained in Section 5.4.5 (in Chapter 5). Figure 5.4 (in Chapter 5) shows a possible 100 random realizations of an SCR based on its two attributes (probability and impact) with this, in turn, based on minimum and maximum scores as defined by the experts. Similar realizations are possible for the relationship score and cost attribute of RMSs within the minimum and maximum scores defined by the experts. In addition, the data availability from SCRM studies for industries, such as the LNG industry, is expected to be scarce for practical reasons. These reasons include the following: the LNG industry is a relatively new industry, its supply chain is very complex (involving complicated scientific processes, large investment, international ventures, geopolitical issues, evolving technological challenges etc.) and the lack of national and international experts with an understanding of the whole supply chain. In such cases, a relatively small sample size of data could influence the sensitivity of the model with the inclusion or exclusion of an expert. Therefore, a simulation model is suggested for LNG SCRM to overcome the challenges of the current LNG SCRM study. A simulation model for LNG SCRM is developed and solved for 50 simulations in Chapter 8.

7.6 Chapter Summary

This chapter has reported on the optimization of LNG SCRM that has been carried out based on the QFD method. The data and framework of the optimization model have been structured following the QFD approach, with this followed by the development of the objective function and cost constraints. The objective function and cost constraints were developed following the principles adopted by Park and Kim (1998). Two cost constraints have been defined, the linear cost constraint and the quadratic cost constraint. In the linear cost constraint, RMSs are considered independent, thus no cost savings occur. In the quadratic cost constraint, some RMSs are considered to be interdependent with cost savings occurring from the simultaneous implementation of interdependent risk mitigation strategies (RMSs). Cost scenarios were then developed to define the different levels of budget availability. The optimization model has been solved for all cost scenarios considering both cost constraints. The optimization results for quadratic cost constraints were found to be superior with a greater level of risk mitigation for a particular cost scenario either with a greater number of RMSs selected or with a similar number of RMSs with a greater level of risk mitigation. This is due to cost savings from the simultaneous implementation of interrelated RMSs with the quadratic cost constraint.

Two separate optimization model have been developed for solving following the same methodology. Firstly, the optimization model was developed and solved with data from an individual expert and then the ensemble mean of the optimization results was prepared. Secondly, the optimization model was developed and solved with the consensus mean of data from all six experts. The optimization results based on the ensemble mean and the consensus mean were compared. In this chapter, it was revealed that the optimization results based on the ensemble mean are superior compared to those with the consensus mean due to the greater level of risk mitigation for similar cost scenarios. In addition, comparison between the two approaches of optimization demonstrated some advantages of the optimization approach based on the ensemble mean over the optimization approach with the consensus mean. Therefore, optimization based on the ensemble mean approach is preferred over the other approach using the consensus mean. The chapter reported that a sensitivity analysis of optimization results was carried out by comparing the level of risk mitigation against the cost or the budget utilized. Analysis revealed that a relationship that is quadratic nature in nature existed between the level of risk mitigation and the cost (or budget) utilized. In addition, it was shown that the level of risk mitigation diminishes for cost scenarios with a greater budget. Although variations were evident among the experts' opinions observed in the optimization results, agreement was found to be at a greater level in comparison. The variations among the experts were explained along with the limitations of carrying out the LNG SCRM study. This resulted in identification of the need for a simulation model for LNG supply chain risk management (SCRM) which is presented in Chapter 8.

CHAPTER 8

A SIMULATION MODEL FOR SCRM

8.1 Chapter Introduction

This chapter presents details of the simulation model that has been developed following the development of the optimization model described in the previous chapter. The conceptual basis of the simulation model is explained followed by presentation of the simulation model's conceptual framework. The steps are outlined for setting up and solving the simulation model. The result from the single solution of the model is presented. The chapter then describes how the model was solved for 50 simulations where each solution involved maximizing the objective function for nine cost scenarios, while considering both linear and quadratic cost constraints. The ensemble results of 50 simulations are also presented. The ensemble results from the simulations and optimizations are then compared, with an explanation provided of the applications of the simulation results. The advantages of simulation result over optimization are highlighted. The chapter concludes with a summary.

8.2 Conceptual Basis of Simulation Model

The relationships between the level of risk mitigation and the cost scenarios presented in Figure 8.1 are six trajectories of several possible realizations of real-life supply chain risk mitigation. For example, the inclusion of another expert would generate another trajectory in the relationship. Furthermore, the scores assigned by the six experts to different parameters, such as risk probability, risk impact, relationship score between risk and RMSs and costs of implementing RMSs, are different and also vary across a range. Therefore, a range of realizations of the relationships between the level of risk mitigation and the cost scenarios is also possible based on the data of the six experts. Thus, the trajectories drawn in Figure 8.1 are a partial snapshot of a greater picture with a range of trajectories based on the opinions of the six experts. The range of other trajectories of relationships could be drawn through the development of a simulation model based on the data (or opinions) of the six experts. In addition, solving the simulation problem with the optimization algorithm developed in this study would result in a selected set of RMSs for each simulation. Combining a number of simulations would provide a greater consensus on the set of selected RMSs for a particular cost scenario. Hence, a simulation model for the LNG supply chain risk mitigation has been developed and is solved in the following sections.

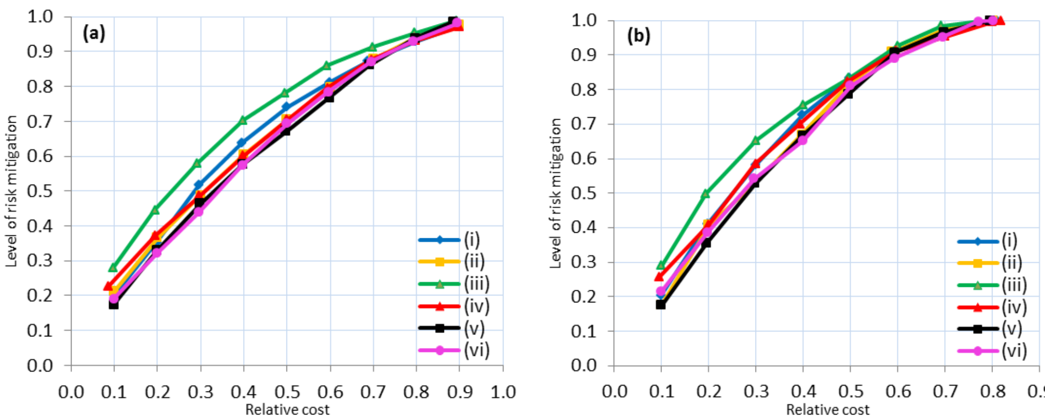


Figure 8.1: Trajectories of relationships between level of risk mitigation and the derived relative cost

Note: based on opinions of the six experts: (a) considering linear cost constraint and (b) considering quadratic cost constraint

8.3 Conceptual Framework of Simulation Model

A conceptual framework of the simulation model based on the QFD method is presented in Figure 8.2. The boundary conditions of the simulation model are defined by the minimum and maximum score of SCR, RMS and cost attributes based on the scores from the six experts. The simulated scores of SCR, RMS and cost attributes are calculated using the formulas shown below. A simulated score of an attribute lies in between its minimum and maximum score as defined by the six experts. The RAND() function of MS Excel was used to generate a random number between 0-1 for a simulation. Thus, using equations 8.1, 8.2, 8.3 and 8.4, a set of random scores of the SCR attributes (probability and impact), RMS attributes (relationship score) and cost attribute is generated for a simulation:

$$\mathrm{SIM}\ \{SCR_i(P)\} = \mathrm{Min}\ (SCR_i\ (P)+[\mathrm{Max}\ \{SCR_i\ (P)\}-\mathrm{Min}\ \{SCR_i\ (P)\}]\ *\ \mathrm{RAND}() \quad (8.1)$$

$$\mathrm{SIM}\ \{SCR_i(I)\} = \mathrm{Min}\ (SCR_i\ (I)+[\mathrm{Max}\ \{SCR_i\ (I)\}-\mathrm{Min}\ \{SCR_i\ (I)\}]\ *\ \mathrm{RAND}() \quad (8.2)$$

$$\mathrm{SIM}\ (R_{ij}) = \mathrm{Min}\ (R_{ij})+\{\mathrm{Max}\ (R_{ij})-\mathrm{Min}\ (R_{ij})\}\ *\ \mathrm{RAND}() \quad (8.3)$$

$$\mathrm{SIM}\ (C_j) = \mathrm{Min}\ (C_j)+\{\mathrm{Max}\ (C_j)-\mathrm{Min}\ (C_j)\}\ *\ \mathrm{RAND}() \quad (8.4)$$

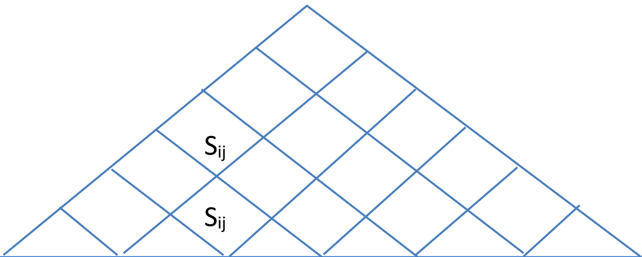
Based on the simulated data of the SCR attributes, the weightages of SCRs were calculated with this then converted into their relative weight (w). In the relative scale of SCR weight, the sum of all weightage of SCRs is equal to 1. The AI of all RMSs was calculated using the relative weight (w) of SCRs and the relationship score of RMSs following the QFD's conventional approach. The AI score then converted into a relative scale where the sum of all AI scores is equal to 1. The objective function for the optimization of the simulation model is defined as maximizing the score of RAI for the cost scenario (which is the same definition of the objective function of the optimization model). It is important to note that the optimization based on AI and RAI should be the same as the order or importance of RMSs does not change when converting AI into relative absolute importance (RAI). The objective function for optimization of the simulation model is thus mathematically expressed below:

$$MaxRf(x) = \sum_{j=1}^{30} (RAI_j)x_j$$

where,

Xj = Decision variable for RMSj

The value of Xj is 0 or 1 where the score is 0 if the RMS is not selected and 1 if the RMS is selected. The maximization of RAI represents the maximization of the level of risk mitigation.



SCR attributes				Risk Mitigation Strategies (RMS)					
SCR probability and impact			SIM Relative Risk (Wi)	RMS$_j$	RMS$_j$	RMS$_j$	RMS$_j$	RMS$_j$	RMS$_j$
Supply Chain Risks (SCRs)	SIM {SCR$_i$ (P)}	SIM {SCR$_i$ (I)}		SIM (R$_{ij}$)	SIM (R$_{ij}$)	……	……	SIM (R$_{ij}$)	SIM (R$_{ij}$)
	SIM {SCR$_i$ (P)}	SIM {SCR$_i$ (I)}		SIM (R$_{ij}$)	SIM (R$_{ij}$)	……	……	SIM (R$_{ij}$)	SIM (R$_{ij}$)
	SIM {SCR$_i$ (P)}	SIM {SCR$_i$ (I)}		SIM (R$_{ij}$)	SIM (R$_{ij}$)	……	……	SIM (R$_{ij}$)	SIM (R$_{ij}$)
	…………………	…………………		……	……	……	……	……	……
	…………………	…………………		……	……	……	……	……	……
	…………………	…………………		……	……	……	……	……	……
	SIM {SCR$_i$ (P)}	SIM {SCR$_i$ (I)}		SIM (R$_{ij}$)	SIM (R$_{ij}$)	……	……	SIM (R$_{ij}$)	SIM (R$_{ij}$)
	SIM {SCR$_i$ (P)}	SIM {SCR$_i$ (I)}		SIM (R$_{ij}$)	SIM (R$_{ij}$)	……	……	SIM (R$_{ij}$)	SIM (R$_{ij}$)
	SIM {SCR$_i$ (P)}	SIM {SCR$_i$ (I)}		SIM (R$_{ij}$)	SIM (R$_{ij}$)	……	……	SIM (R$_{ij}$)	SIM (R$_{ij}$)
		SIM (AI)							
		SIM (C)							
		SIM (RAI)							

Figure 8.2: Conceptual simulation model of LNG supply chain risk management based on QFD method

Notations: P=probability; I=impact; R=relationship between SCR and RMS, AI=absolute importance; RAI=relative absolute importance; S=savings from simultaneous implementation of interrelated RMSs; C=cost of implementation of an RMS; SIM=simulation

The simulation model was solved for two separate cost constraints which were the same as used for the optimization model. The main purpose of the simulation model is to generalize the results of the optimization model through realization of possible range of trajectories of relationship between the level of risk mitigation and the cost scenarios as defined by the experts. Therefore, simulation model is an extension of the optimization model for generalization purpose to cover a range of possible scenarios within the boundary condition set by the experts. Therefore, the process, approach and constraints remain same for the simulation model as of the optimization model within the boundary conditions. The cost constraints are presented below with their details explained in Section 7.5.1 in Chapter 7. The linear cost function for this optimization model is expressed as follows:

$$g(x) = \sum_{j=1}^{30} c_j x_j \ \leq B$$

$$x \in X$$

Where,

$g(x)$ is the total cost of the selected RMSs (for a cost scenario, it needs to be either less than or equal to a given budget,

B = available budget

X = 0-1 decision variable with the score is 0 if the RMS is not selected and 1 if the RMS is selected.

The quadratic cost function for the simulation model is expressed as follows:

$$(x) = g(x) - k(x)$$
$$\text{s.t. } R(x) \leq B$$

$$x \in X$$

The total cost savings from the correlated RMSs are calculated using the formula below:

$$Cost\ savings, k(x) = \sum_{i=1}^{30} \sum_{j>i}^{30} s_{i,j}\, x_i x_j$$

where,

$s_{i,j}$ = Cost savings from two correlated RMSs, RMS_i and RMS_j

x_i = Decision variable for RMS_i, score of 0 if RMS RMS_i is not selected and 1 if RMS_i is selected

x_j = Decision variable for RMS_j, score of 0 if RMS RMS_j is not selected and 1 if RMS_j is selected

The objective function of the simulation model is maximized subject to the two cost functions: (i) the linear cost function and (ii) the quadratic cost functions. For each simulation, a unique amount of the total costs of implementation of RMSs was obtained. Nine scenarios were developed for each simulation based on 90%, 80%, 70%, … down to, 30%, 20%, and 10% of total costs of implementation of risk mitigation strategies (RMSs). The simulation model is then solved for each of the cost scenarios for a particular simulation.

8.4 Simulation Model for LNG Supply Chain Risk Mitigation

A simulation model is formulated based on data from the six experts. The process of formulating the simulation model is explained through the following steps. In addition, the boundary conditions of the simulation model based on data from the experts are presented. The example simulation from the 50 simulations is presented.

8.4.1 Steps in formulating and solving simulation model

The formulation of the simulation model was carried out through the following steps:

(i) Determine the variation of expert opinions for each of the parameters, such as risk probability, risk impact, the relationship between risk and RMS in the QFD method and the cost of implementing each RMS.

(ii) Define the variables of the simulation model and define the boundary conditions of these variables.

(iii) Generate a random set of values for each variable of the simulation model within the boundary conditions as assigned by the experts using the RAND() function of MS Excel.

(iv) With a random set of variables following the QFD method’s conventional approach, the absolute importance (AI) score for each of the RMSs is calculated. The relative absolute importance (RAI) score is then calculated.

(v) The objective function and cost constraints of the simulation model are defined.

(vi) The cost scenarios are defined based on the percentage (%) of the available budget.

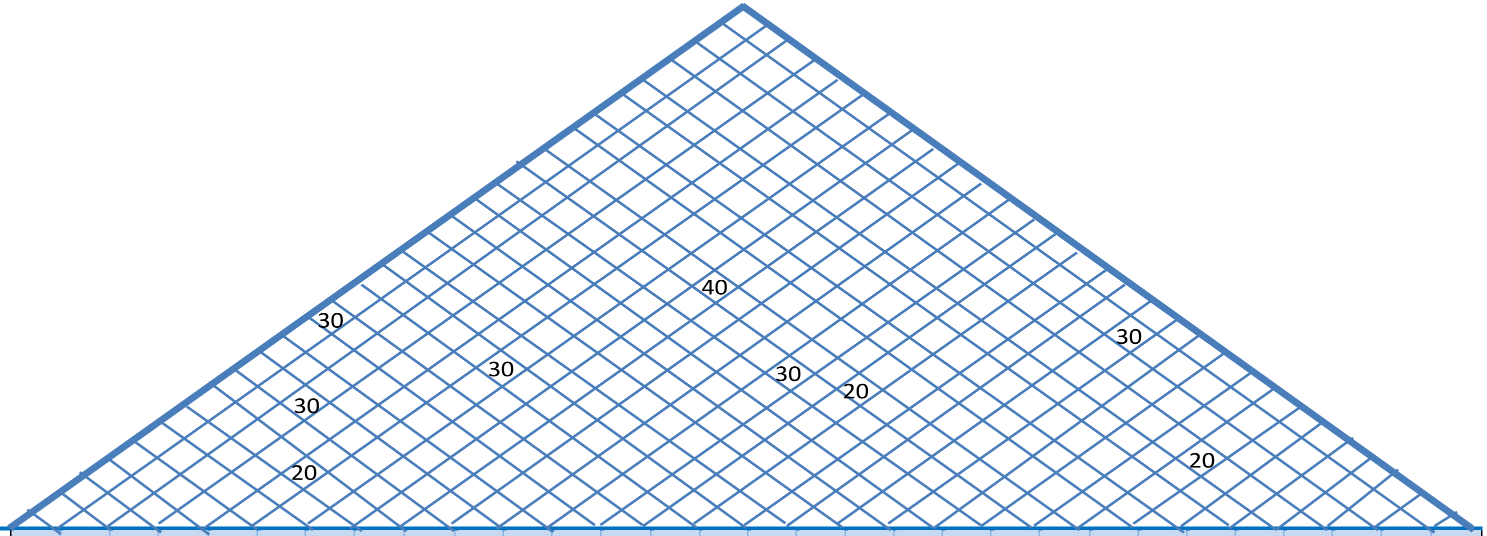
The simulated set of RAI scores and the cost derived from a random set of variables of supply chain risk mitigation are used for optimization based on the nine cost scenarios as defined.

The optimization model developed with the simulated set of RAI scores and cost is solved for both linear cost constraint and quadratic cost constraint for different cost scenarios.

The process with steps (iii) to (viii) has been repeated 50 times to generate 50 sets of simulations.

8.4.2 Setting up simulation model

The boundary conditions of the simulation model were set as minimum and maximum scores of SCR and RMS attributes along with the cost of implementation of the risk mitigation strategies (RMSs). Table A8.1 (Appendix F) presents a summary of the minimum score of SCR and RMS attributes and the cost of implementation of the risk mitigation strategies (RMSs). Similarly, the maximum scores of SCR and RMS attributes and the cost of implementation of the RMSs are summarized in Table A8.2 (Appendix F). For a simulation, the score of SCR attributes, RMS attributes and the cost of implementation of RMSs should be a set of attributes within the range (minimum and maximum) of the attributes. The scores of the simulated set of SCR and RMS attributes and the cost of implementation of RMSs were calculated based on the formula shown in equations 8.1–8.4. As the RAND() function of MS Excel generates a random set of numbers, the scores of the attributes and the cost of each set of 50 simulations should be different from each other. One single set of scores of the attributes is shown in Figure 8.3. From the SCR attributes, the relative weightage (w) of the SCRs were calculated (as explained in Section 7.5.1 in Chapter 7). Based on the relative weightage of the SCRs and relationship score between SCRs and RMSs, the absolute importance (AI) scores of the RMSs are calculated following the conventional QFD method (details explained in Section 7.5.1 in Chapter 7). The AI scores of RMSs were converted into a relative scale of relative absolute importance (RAI), where the sum of all RAI scores is equal to 1. This converts the absolute importance (AI) of RMSs to the same (equal scale) for all simulations. The objective function to maximize the RAI score, subject to two independent cost constraints, was formulated as explained in Section 8.3. The cost constraints used were linear cost constraint and quadratic cost constraint (as explained in Section 8.3, with details available in Section 7.5.1 in Chapter 7). The scores of RAI and the cost of the implementation of RMSs for 50 simulations are summarized in Table A8.2a (Appendix G). The simulation model was solved for the nine cost scenarios (as explained in Section 8.3), independently considering both cost constraints.



	P	I	W	RMS1 (X_1)	RMS2 (X_2)	RMS3(X_3)	RMS4(X_4)	RMS5(X_5)	RMS6(X_6)	RMS7(X_7)	RMS8(X_8)	RMS9(X_9)	RMS10(X_{10})	RMS11(X_{11})	RMS12(X_{12})	RMS13(X_{13})	RMS14(X_{14})	RMS15(X_{15})	RMS16(X_{16})	RMS17(X_{17})	RMS18(X_{18})	RMS19(X_{19})	RMS20(X_{20})	RMS21(X_{21})	RMS22(X_{22})	RMS23(X_{23})	RMS24(X_{24})	RMS25(X_{25})	RMS26(X_{26})	RMS27(X_{27})	RMS28(X_{28})	RMS29(X_{29})	RMS30(X_{30})
SCR1	6.1	7.4	0.033	6.2	5.6	8.4	5.0	7.7	3.4	5.0	9.0	9.0	6.4	5.1	6.2	8.2	8.2	7.9	5.0	7.9	7.7	5.7	3.3	5.0	1.0	3.7	5.0		5.0	6.1	4.1	5.4	9.0
SCR2	5.8	5.6	0.024	5.0	9.0	5.5	1.0	5.7	2.7	5.0	5.0	5.0	5.0	5.0		7.6	5.0	7.3				1.0	5.0	9.0	9.0			5.3	1.0	5.0		5.0	9.0
SCR3	2.9	4.8	0.011	5.0				7.3		5.2	5.0	5.0		5.0	5.3			1.0		5.0	5.0	5.9	5.0	5.0			5.0		1.0		1.0		5.0
SCR4	8.4	7.3	0.046	4.2	1.0	1.0	2.7				6.0	8.6	7.1	6.2	1.0	5.2	1.3	5.0	1.0	5.0	1.0	7.3	1.0	5.0	9.0	9.0	5.0		3.2	6.7	5.6	9.0	9.0
SCR5	5.4	3.3	0.013	2.4	5.0	1.9	3.9	7.8		5.0	8.9	9.0	7.8	1.0	3.3	1.0	2.0		1.0	9.0	5.0	4.7	5.2	6.0	5.8	6.6	1.3		9.0	4.1	9.0	9.0	9.0
SCR6	6.7	7.2	0.036					1.0	6.0		5.0	5.0	3.3		9.0	9.0	9.0	9.0		9.0	9.0	5.5	6.1	1.7	5.0	9.0	9.0		7.9	5.0	9.0	9.0	9.0
SCR7	4.9	2.4	0.009	5.0				2.2			8.8	5.0	7.1	5.3	4.5		1.0			5.0		5.0	5.0	5.6	1.0	5.0	5.0		1.0			9.0	9.0
SCR8	7.6	6.2	0.035	1.0	2.6		1.0	8.9	5.9	9.0	5.0		3.3	7.7	9.0	1.0	5.0	5.5	1.0	6.3	1.0	1.0	5.0	8.4	4.7	3.9	3.5		5.0	1.0	9.0	5.0	9.0
SCR9	8.3	6.6	0.041	5.0				1.0	9.0					1.0	1.0	6.3	5.5	3.8					5.0	9.0				7.9					
SCR10	7.9	6.3	0.037	5.0				1.0	6.7					1.0		7.2		1.4				5.8	5.0	5.0				6.7					
SCR11	5.0	7.6	0.028	8.1	7.3	9.0	5.3	5.0	5.3				9.0	5.0	8.7	8.7		3.0			5.0	5.0	1.0	4.2	9.0					5.0		9.0	8.0

	P	I	W	RMS1 (X_1)	RMS2 (X_2)	RMS3(X_3)	RMS4(X_4)	RMS5(X_5)	RMS6(X_6)	RMS7(X_7)	RMS8(X_8)	RMS9(X_9)	RMS10(X_{10})	RMS11(X_{11})	RMS12(X_{12})	RMS13(X_{13})	RMS14(X_{14})	RMS15(X_{15})	RMS16(X_{16})	RMS17(X_{17})	RMS18(X_{18})	RMS19(X_{19})	RMS20(X_{20})	RMS21(X_{21})	RMS22(X_{22})	RMS23(X_{23})	RMS24(X_{24})	RMS25(X_{25})	RMS26(X_{26})	RMS27(X_{27})	RMS28(X_{28})	RMS29(X_{29})	RMS30(X_{30})
SCR12	7.4	7.7	0.042	4.3	3.1	4.8	9.0	9.0				9.0	8.7	8.0	9.0	5.6	6.0	1.0		5.8	1.0	3.0	2.7	7.1	9.0	9.0	9.0		9.0	5.0		8.8	7.0
SCR13	6.7	6.0	0.030	5.0	5.0	5.0	5.0	5.0		9.0	5.0		5.0	5.0	5.0	8.5	1.0	9.0					1.6	4.0	9.0	9.0	5.0		5.0			9.0	9.0
SCR14	7.0	7.7	0.040					8.9	5.7		6.1	5.4	8.9	7.0	7.9	9.0	4.0	9.0		9.0	6.8	3.9	5.0	8.4	5.0	5.0	5.0		1.0			8.3	9.0
SCR15	8.8	7.3	0.048	5.0	5.0			8.6	9.0	5.0	5.5	8.4	1.7	5.5	2.2		5.2	9.0		7.9	5.2	1.4	5.0	8.4	9.0	5.8	5.0					6.5	5.0
SCR16	8.4	8.0	0.050	5.0				5.6	8.1		6.7	9.0	3.4	5.0	4.4		2.7	5.0		8.2	7.4	5.0	5.0	7.3	9.0	7.7	6.9					9.0	9.0
SCR17	8.5	7.5	0.048					5.0	6.2		5.5	9.0	8.3	5.0	8.5	6.0	4.1	5.0		9.0	6.1	7.0	5.9	7.3	9.0	2.1	2.2					7.7	9.0
SCR18	4.5	5.7	0.019	5.0				4.3	5.0		9.0	9.0	5.0	2.9	7.2		4.8			9.0	5.0	2.8	7.8	5.0		4.9	2.1			5.0		3.3	9.0
SCR19	5.0	7.3	0.027	5.2	7.1	4.5	1.0	5.2	5.0	9.0	1.0	5.6	5.4	8.2	7.2	5.0	9.0	6.8		1.2		8.3	8.0	5.9	9.0							9.0	9.0
SCR20	7.7	6.2	0.036	1.0	5.0			1.9					3.5	5.0	5.0	5.0	5.0			7.5	5.0		5.0	7.9	9.0	5.1	6.9					8.1	3.4
SCR21	7.2	7.6	0.041	5.2	4.3	5.0	5.0	5.0			4.9	6.4	7.1	6.2	4.1	5.9	5.0	7.5		9.0	6.6	8.0	8.0	8.8	9.0	3.3	2.4			5.0	5.0	6.1	7.5
SCR22	5.7	5.7	0.024	9.0		9.0		1.7	1.5		1.0	4.5	4.8	8.5	7.9	9.0	7.0	9.0		1.4	5.6	9.0	9.0	6.1	9.0	5.0	5.0					5.8	9.0
SCR23	5.4	5.5	0.022	5.0		1.0					6.6	8.3	5.0	9.0	6.6	1.0	5.0							9.0		1.0	1.0					9.0	9.0
SCR24	4.1	6.7	0.020	2.7	1.0			7.0		9.0	3.3	2.5	9.0	5.9	5.0	5.0		1.0		6.5	6.6		5.0	6.1	9.0	6.0	5.6					9.0	9.0
SCR25	6.5	7.9	0.038	1.4	9.0	1.9	9.0	8.3		9.0	5.0	5.0	3.2	4.6	5.0					8.1	8.9			1.8	1.0	2.3	3.3					5.0	9.0
SCR26	5.2	4.4	0.017	5.0	2.5	1.0		1.7			9.0		9.0	5.0	5.0	9.0	5.0	6.9					5.0	9.0	9.0	5.0	5.0					9.0	9.0
SCR27	7.0	7.2	0.037	9.0	5.0	9.0		9.0			9.0	9.0	8.5	4.1	9.0		9.0					7.2	5.0	9.0	9.0					5.0		6.9	2.3
SCR28	6.9	5.8	0.030	1.0	9.0		5.0	5.9			8.3	7.4	7.0	5.0	1.0	5.0	1.0	9.0			6.2	9.0	5.8	5.4	5.0				9.0			9.0	9.0
SCR29	5.7	8.1	0.034	9.0	9.0	1.0		6.5			9.0	9.0	6.9	6.2		9.0	5.0	9.0		7.2	8.5		7.7	8.9	9.0	1.0	5.0		1.0	5.0		7.7	9.0
SCR30	6.2	7.9	0.037	7.5	5.7	5.9	9.0	7.0			9.0	9.0	1.6	9.0			1.0			9.0	6.7	8.8	5.1	6.2	9.0	7.9	9.0		5.0			9.0	9.0
SCR31	4.8	4.3	0.015	7.2	8.0	7.7	5.0				1.0	5.0	6.1	7.3			5.0		8.1	5.0			5.0	8.1	6.4	5.6	5.0					5.0	6.9
SCR32	3.6	5.0	0.013	1.5	5.3	8.0		9.0					7.9	2.5			5.0		5.4	5.0			5.0	6.2	6.4	6.4						5.0	5.2
SCR33	4.5	5.9	0.020	5.8	7.9	5.4		9.0					8.8	5.1			5.0		5.2	5.0			5.0	5.4	5.1	6.6						5.0	8.8
C_j				10	66	20	15	68	15	16	53	99	40	60	15	31	64	21	27	54	21	32	40	81	67	79	55	28	28	27	21	94	67
AI_j				4.3	3.6	2.7	2.2	5.3	3.0	2.0	4.8	5.5	5.4	5.3	4.6	4.5	4.1	4.5	0.6	5.2	4.0	3.9	4.7	6.6	6.4	4.2	3.8	0.7	2.0	1.9	1.4	6.8	7.4

P =probability of SCR; I=impact of SCR; W=weight of SCR; X_1, X_2 …., X_{30}=decision variables for RMSs; C_j=cost of RMS_j; AI_j=absolute importance of RMS_j

Figure 8.3: QFD matrix for simulation model of LNG supply chain risk management

Note: The scores of SCR attributes and RMSs attributes are a single set for one simulation.

8.4.3 Results from simulations

The simulation model was solved for 50 simulations with nine cost scenarios, considering both linear and quadratic cost constraints. A summary of the simulation process is shown in Table 8.3. In total, the objective functions were maximized 900 times, considering the two cost constraints and the nine cost scenarios (2x9x50). For each simulation, a nice set of relationships was obtained between the level of risk mitigation and the cost of RMS implementation along with the RMSs selected for each cost scenario. Table 8.4 summarizes the results of one single simulation (out of 50 simulations) . The cost scenarios, level of risk mitigation and corresponding set of selected RMSs for the linear cost constraint are presented in Table 8.4(a) and for the quadratic cost constraint in Table 8.4(b). A comparison of the simulation result (for one simulation) is summarized in Table 8.4(c).

Table 8.3: Summary of optimization runs in simulation process

Simulation model	Objective function	Cost constraint	Cost scenarios (% budget available)	Number of simulations	Total optimization run
1x	1x	2x Linear cost constraint Quadratic cost constraint	9x S1 (90%) S2 (80%) …… …… S8 (20%) S9 (10%)	50x	900

8.4.4 Results from single simulation

The simulation results from one simulation show that a greater level of risk mitigation with a higher budget has a greater number of RMS implementations (Table 8.4). In addition, the level of risk mitigation diminishes with a higher level of budget (cost). A comparison of the results based on linear and quadratic cost constraints shows a greater level of risk mitigation achieved for the quadratic cost constraint for same cost scenarios. For particular cost scenarios, when considering the quadratic cost constraint, a greater level of risk mitigation was achieved, through more RMSs being selected due to cost savings from the implementation of interrelated RMSs. All findings from the results of a single simulation are consistent with the findings from the optimization results, thus highlighting consistency in the setting-up and outcomes of the simulation model through following the principles of the optimization model.

Table 8.4(a): Summary of simulation results for different cost scenarios based on one simulation (considering linear cost constraint)

Cost scenario and budget			Risk mitigation without savings			Selected RMSs under different cost scenarios (linear cost constraint)																													
Scenario	Budget available*		Budget used																																
	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1185.2	89.9	1183.3	0.955	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	0	1	1	1	1	1
S2	80	1053.5	80.0	1053.3	0.891	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	0	1	0	1	1	1	1	1
S3	70	921.8	69.5	915.2	0.822	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	0	1	0	0	1	1
S4	60	790.2	60.0	789.6	0.744	1	0	1	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	0	1	0	0	0	0	1	1	1	1
S5	50	658.5	49.8	655.7	0.660	1	0	1	1	0	1	1	1	0	1	0	1	1	0	1	0	1	1	1	1	1	1	0	0	0	1	1	0	0	1
S6	40	526.8	40.0	526.2	0.578	1	0	1	1	0	1	1	0	0	1	1	1	1	0	1	0	1	1	1	1	0	1	0	0	0	0	0	0	0	1
S7	30	395.1	29.8	391.8	0.469	1	0	0	1	0	1	1	0	0	1	0	1	1	0	1	0	0	1	1	1	0	1	0	0	0	0	0	0	0	1
S8	20	263.4	19.8	261.0	0.361	1	0	1	1	0	1	0	0	0	1	0	1	1	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0
S9	10	131.7	9.8	129.0	0.224	1	0	0	1	0	1	0	0	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 8.4(b): Summary of simulation results for different cost scenarios based on one simulation (considering quadratic cost constraint)

Cost scenario and budget			Risk mitigation with savings			Selected RMSs under different cost scenarios (quadratic cost constraint)																													
Scenario	Budget available*		Budget used																																
	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1185.2	83.0	1092.5	1.000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S2	80	1053.5	78.8	1037.5	0.990	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1
S3	70	921.8	69.6	917.2	0.933	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0	1	1
S4	60	790.2	59.9	789.4	0.867	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1
S5	50	658.5	49.9	657.6	0.779	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	1	1	1	0	0	0	1	0	0	1	1
S6	40	526.8	39.5	520.2	0.670	1	0	1	1	1	1	0	1	0	1	0	1	1	1	1	0	0	1	0	1	1	1	0	0	0	0	0	0	1	1
S7	30	395.1	30.0	395.1	0.553	1	0	1	1	1	1	0	1	0	1	0	1	1	0	1	0	0	1	1	1	0	1	0	0	0	0	0	0	1	0
S8	20	263.4	19.4	256.0	0.400	1	0	1	1	0	1	1	0	0	1	0	1	1	0	1	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0
S9	10	131.7	9.6	126.2	0.257	1	0	1	1	0	1	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8.4(c): Summary of simulation results for different cost scenarios based on one simulation

Cost scenario and budget			Risk mitigation without savings			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used			Budget used																																
	%	Actual	%	Actual	$Rf(x)$	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1185.2	89.9	1183.3	0.955	83.0	1092.5	1.000	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	✓	☑	✓	☑	☑	☑	☑	☑
S2	80	1053.5	80.0	1053.3	0.891	78.8	1037.5	0.990	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	✓	☑		☑	☑	☑	☑	☑	☑	✓	☑		☑	☑	☑	☑	☑
S3	70	921.8	69.5	915.2	0.822	69.6	917.2	0.933	☑	✓	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑	✓	✓		☑	✓		☑	☑
S4	60	790.2	60.0	789.6	0.744	59.9	789.4	0.867	☑		☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	✓	☑		☑	☑	☑	☑	✓	☑	✓				☑	☑	☑	☑
S5	50	658.5	49.8	655.7	0.660	49.9	657.6	0.779	☑		☑	☑	✓	☑	☑	☑		☑	✓	☑	☑	✓	☑		☐	☑	☑	☑	☑	☑				☑	☐		✓	☑
S6	40	526.8	40.0	526.2	0.578	39.5	520.2	0.670	☑		☑	☑	✓	☑	☐	✓		☑	☐	☑	☑	✓	☑		☐	☑	☐	☑	✓	☑							✓	☑
S7	30	395.1	29.8	391.8	0.469	30.0	395.1	0.553	☑		✓	☑	✓	☑	☐	✓		☑		☑	☑		☑			☑	☑	☑		☑							✓	☐
S8	20	263.4	19.8	261.0	0.361	19.4	256.0	0.400	☑		☑	☑		☑	✓			☑		☑	☑		☑			☑	☐	☑	✓									
S9	10	131.7	9.8	129.0	0.224	9.6	126.2	0.257	☑		✓	☑		☑				✓		☑	☑		☑			☐												

*Total average cost is 1316.93.

8.4.5 Ensemble results from simulations

Figure 8.3 and Table 8.5 summarize the results of the ensemble from 50 simulations derived through solving the simulation model for LNG supply chain risk management (SCRM). The level of the risk mitigation range for a cost scenario can be estimated from Figure 8.3. The level of risk mitigation is presented in two forms: (a) and (b) as an area diagram and (c) and (d) as a second-order polynomial relationship. The simulation result presented in the area diagram shows a reduction in the range of the level of risk mitigation for a relative cost of 0.3, compared to a relative cost of 0.2 and 0.4, respectively. However, the inclusion of the relationship between the levels of risk mitigation forms a quadratic relationship. Solving the simulation model for a greater number of cost scenarios would make the limits (range) of the level of risk mitigation fit with this polynomial relationship. The ensemble means of the levels of risk mitigation from the 50 simulations, as presented in Figure 8.3(a) and Figure 8.3(b), show a better polynomial relationship compared to the range.

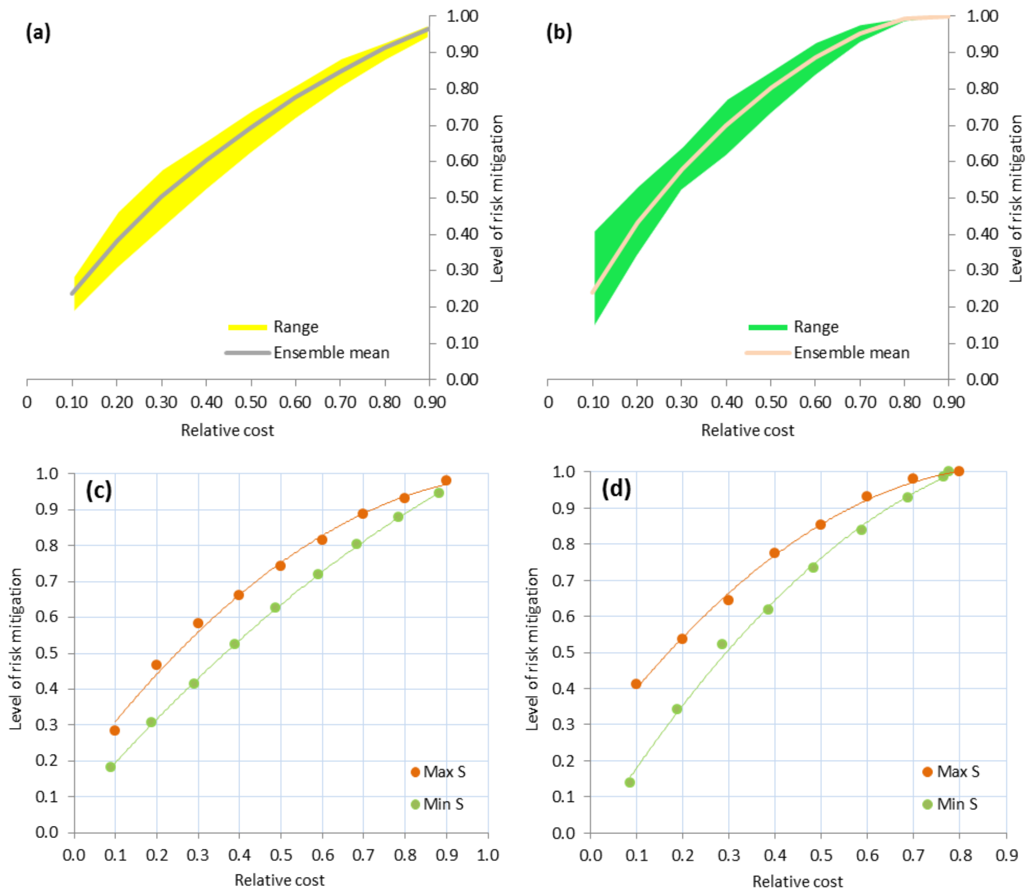


Figure 8.4: Summary of 50 simulations derived through solving simulation model for LNG supply chain risk mitigation: (a) without cost savings and (b) with cost savings, with range of simulation results presented as second-order polynomial relationship in (c) and (d)

A summary of the sets of selected RMSs for 50 simulations for different cost scenarios with and without cost savings is presented in Table 8.5. The simulation results of selected RMSs are presented as the percentage (%) of times an RMS was selected in the 50 simulations. The strategies selected for a particular cost scenario are important strategies to implement to attain the desired level of risk mitigation. The results of the 50 simulations are an outcome of the 50 possible sets of SCR variables within the range assigned by the six experts. An important aspect of the simulation results of the selected set of RMSs for a particular cost scenario is to find out the consensus set of selected RMSs for that particular cost scenario. In this sense, for a particular cost scenario, the RMSs which were selected more times compared to other RMSs can be treated as more important RMSs in comparison with the other RMSs in a consensus opinion of the experts. As basic principle of selection of an RMS is its relative effectiveness in mitigating SCRs which is also same for the optimization process, where relative effectiveness of a RMS is a measure of level of risk mitigation relative to cost. For example, for cost scenario S5 with the linear cost constraint, the selection rates for RMS1, RMS11 and RMS10 were 100%, 92% and 62%, respectively, out of 50 simulations. Therefore, RMS1, RMS11 and RMS10 have a hierarchy of order of importance based on the percentage (%) of times they were selected, from high to low order, based on consensus among the experts, with this able to be implanted in this cost scenario. Thus, for a cost scenario, the percentage (%) of times that RMSs were selected in 50 simulations represents the order of hierarchy for the implementation of RMSs in order to maximize the level of risk mitigation (as shown in Table 8.5). Hence, the ensemble of the simulation results of the selected set of RMSs is useful for finding the order of hierarchy with consensus, based on the opinions of experts, used to achieve the maximum level of risk mitigation for a cost scenario. However, the ensemble of simulation results does not define a selected set of RMSs for a cost scenario: instead, it provides a hierarchy among the risk mitigation strategies (RMSs.) Therefore, a technique was needed to find out how to define the optimal set of RMSs for a particular cost scenario, with this explained in the following section.

8.4.6 Application of ensemble results from simulations

An optimal set of selected RMSs for a cost scenario to achieve the maximum level of risk mitigation is associated with the available budget. The ensemble of simulation results (of 50 simulations) renders a hierarchy of RMSs (based on percentage [%]) to be implemented for each cost scenario (Table 8.5). The criterion for ascertaining the number of RMSs (out of all RMSs) to be implemented for a cost scenario is that the sum of the costs of the implementation of selected RMSs should remain within the available budget for that cost scenario. The ensemble mean cost of RMSs from the simulations is summarized in Table 8.6. The RMSs to be implemented for cost scenario S5 should be selected based on the greater percentage (%) of RMSs scores as presented in Table 8.5(a) for the linear cost constraint provided the total cost of implementation of the selected RMSs remains under 705.2. Thus, the selected RMSs should be RMS1 (100%); RMS17 (100%); RMS20 (100%); RMS30 (96%); RMS11 (92%); RMS12 (92%); RMS18 (92%); RMS15 (82%); RMS29 (82%); RMS21 (80%); RMS22 (80%); RMS6 (68%); RMS5 (66%); and RMS19 (66%) with the total cost of implementation being 628.48. As the utilized cost (budget) is well below the available cost (budget) of 705.2, additional RMSs could be selected for this cost scenario. The next RMSs in the hierarchy based on the simulations are RMS13 (64%) and RMS23 (64%). However, the total cost of implementation of RMSs when RMS13 and RMS23 are included is 731.38 which is greater than the available budget (705.2). Thus, only one of the additional two RMSs (either RMS13 or RMS23) could be implemented. As both of these RMSs have a similar percentage (%)in the hierarchy based on simulations, additional criteria should be used to select the risk mitigation strategy (RMS). The relative effectiveness (RE) of RMSs measures the level of risk mitigation of RMSs per unit of relative cost (RC). Hence, a higher RE value represents a greater level of risk mitigation for a similar cost. RMS23 has a higher value for its RE score compared to RMS13 (Table 8.6). Therefore, RMS23 should be selected as an additional RMS along with the other RMSs mentioned earlier for cost scenario S5 considering the linear cost constraint. The level of risk mitigation (for scenario S5) can be achieved in a range from 0.625–0.744 with an ensemble mean of 0.694, based on 50 simulations.

Table 8.5(a): Summary of simulation results for 50 simulations (considering linear cost constraint)

Cost scenario and budget			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used																																
	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1269.4	89.4	1261.6	0.966	100	94	100	60	100	100	98	100	98	100	100	100	98	96	100	6	100	100	100	100	100	100	100	100	36	94	52	48	100	100
S2	80	1128.4	79.6	1123.2	0.913	100	68	80	36	90	98	72	92	98	100	100	100	92	84	100	0	100	100	98	100	100	100	92	88	26	68	30	30	100	100
S3	70	987.3	69.6	982.3	0.849	100	52	76	30	90	92	60	62	82	94	100	100	72	70	96	2	100	96	86	100	96	100	80	84	12	48	22	14	100	100
S4	60	846.3	59.7	842.7	0.777	100	46	66	26	72	88	48	46	64	84	98	98	68	56	94	0	100	92	74	100	90	94	66	64	12	40	12	20	90	100
S5	50	705.2	49.7	700.4	0.694	100	42	48	20	66	68	38	32	48	62	92	92	64	46	82	2	100	92	66	100	80	80	64	50	14	34	4	6	82	96
S6	40	564.2	39.7	560.6	0.606	100	36	44	20	56	64	28	20	38	48	74	88	46	40	58	0	100	78	56	94	58	76	52	44	4	30	2	10	76	92
S7	30	423.1	29.7	419.5	0.503	100	28	30	12	46	52	22	6	28	30	42	74	44	32	50	0	88	66	40	90	50	66	40	36	8	22	6	8	70	80
S8	20	282.1	19.6	276.8	0.384	100	18	24	12	28	30	16	6	14	16	36	56	34	16	40	2	78	52	30	72	38	52	30	18	4	4	0	4	60	58
S9	10	141.0	9.7	137.3	0.237	88	12	10	2	20	24	8	0	6	2	16	38	20	12	14	4	40	32	16	52	10	34	20	12	2	12	0	6	44	38

Table 8.5(b): Summary of simulation results for 50 simulations (considering quadratic cost constraint)

Cost scenario and budget			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used																																
	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1269.4	81.8	1154.6	1.000	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
S2	80	1128.4	79.0	1114.5	0.994	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	24	100	100	100	100	100	100	100	100	62	100	100	92	100	100
S3	70	987.3	69.5	980.6	0.954	100	80	100	48	100	100	84	100	96	100	100	100	100	100	100	4	100	100	100	100	100	100	98	96	28	70	74	32	100	100
S4	60	846.3	59.6	840.3	0.888	100	56	100	30	100	100	44	100	64	100	98	100	98	92	100	4	100	100	82	100	100	100	84	70	20	40	42	12	100	100
S5	50	705.2	49.7	700.6	0.804	100	36	90	18	94	100	32	100	40	92	74	100	92	74	98	0	98	100	52	98	100	100	62	42	16	34	16	14	100	96
S6	40	564.2	39.6	559.2	0.700	100	22	76	16	78	94	20	98	22	72	54	100	76	64	94	0	94	96	40	80	94	98	46	30	2	26	8	8	92	76
S7	30	423.1	29.6	418.0	0.577	100	24	48	6	66	72	14	88	12	44	36	88	62	54	72	2	72	90	24	74	72	92	34	20	2	14	8	4	86	62
S8	20	282.1	19.7	277.6	0.433	98	16	28	4	40	50	12	54	10	22	32	78	52	36	48	0	50	66	22	56	58	70	24	16	8	10	4	0	60	54
S9	10	141.0	9.7	136.4	0.241	88	10	18	6	22	32	12	16	2	6	16	34	26	8	22	0	32	34	10	56	14	36	14	2	8	12	2	4	36	36

Table 8.6: Summary ensemble mean cost of implementation of RMSs and ensemble mean relative absolute importance (RAI) from 50 simulations

Note: Relative efficiency (RE) and rank are calculated based on ensemble mean cost and ensemble mean of RAI from 50 simulations

Simulation	LNG supply chain risk mitigation strategies (RMSs)																													
	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
Cost	19.38	60.57	40.95	57.61	59.80	28.66	31.93	74.47	70.60	64.54	54.00	36.02	54.13	57.33	48.55	37.32	39.38	34.57	41.60	32.76	66.63	56.39	48.77	49.11	20.54	30.12	47.51	36.54	55.48	55.26
RAI	0.039	0.032	0.024	0.019	0.043	0.023	0.017	0.040	0.043	0.042	0.044	0.037	0.036	0.033	0.038	0.005	0.043	0.033	0.030	0.041	0.052	0.053	0.034	0.032	0.005	0.016	0.016	0.011	0.056	0.063
RE	2.8	0.7	0.8	0.5	1.0	1.1	0.7	0.7	0.9	0.9	1.2	1.4	0.9	0.8	1.1	0.2	1.6	1.3	1.0	1.8	1.1	1.3	1.0	0.9	0.4	0.7	0.5	0.4	1.4	1.6
Rank	1	24	20	27	14	10	23	22	19	17	9	5	16	21	11	30	4	7	13	2	12	8	15	18	29	25	26	28	6	3

8.4.7 Comparison between optimization and simulation results

The levels of risk mitigation for the cost scenarios derived through solving the optimization model and simulation model for the LNG SCRM are presented in Figure 8.5. The distribution of the levels of risk mitigation achievable for a particular cost scenario showed variation between the results from the optimization and simulation models both with and without cost savings. A comparison of the distribution presented in Figure 8.5(a) shows that the boundaries of the distribution of the levels of risk mitigation are widened from both the optimization model and simulation model for cost scenarios S7, S8 and S9 (with lower budgets). However, the limits of distribution have been lowered gradually keeping the range slightly widened for the simulation model compared to that for the optimization model for cost scenarios S1–S6 (with higher relative budgets) (Figure 8.5[a]). The widening of distribution is due to extending the range of SCR attributes and RMS attributes to a wider limit (minimum to maximum) based on the data (opinions) from the six experts.

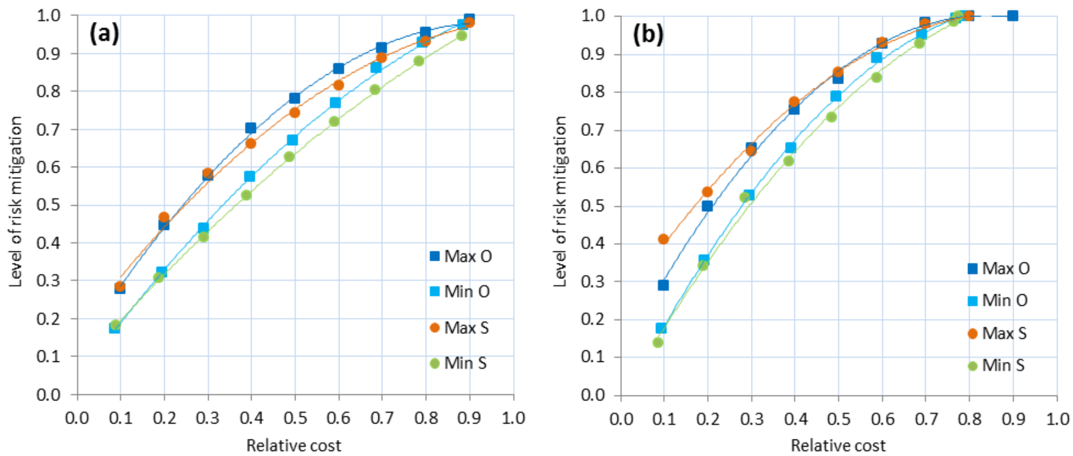


Figure 8.5: Comparison of level of risk mitigation between ensemble of optimization and simulations for LNG supply chain risk mitigation: (a) without cost savings (considering linear cost constraint) and (b) with cost savings (considering quadratic cost constraint).

The simulation model simulates a range of possible combinations of LNG supply risk scenarios based on the limits of SCR attributes and RMS attributes which widens the distribution of the level of risk mitigation in comparison to the distribution from the optimization model. The reason for lowering the distribution of the level of risk mitigation from the simulation model is relatively complex. Because there is a lack of optimistic set SCR and RMS attributes for the simulation model and more likely central tendency set of SCR and RMS attributes within the boundary conditions (bounded by max and minimum). Although the limits of SCR attributes and RMS attributes widen in the simulation model, this does not necessarily increase the scores of the two key measures of the simulation model. Firstly, the calculated absolute importance (AI) scores based on the conventional QFD method set the objective function. Secondly, the costs of implementation of RMSs for supply chain risk mitigation set the constraints of both the optimization and simulation models. One important feature of the simulation model is that, with extended limits of SCR attributes and RMS attributes, the model produces a range of combinations of AI scores and costs for RMSs to maximize the objective function considering the cost constraints. Although the range of combinations of AI scores and costs is derived from the wide range of SCR attributes and RMS attributes, they, in fact, represent a central tendency of the possible realizations.

The rationale for the few changes in the distribution of the levels of risk mitigation between the optimization model and the simulation model considering the linear cost constraint is that there was little flexibility of possible combinations in selecting RMSs for a lower budget. This has been demonstrated through the comparison of selected RMSs between the optimization model and the simulation model as presented in Table 8.7. Anomalies (percentage [%]) in the number of times that RMSs were selected for cost scenarios from both the optimization and simulation models are summarized in Table 8.7. The scores of the selected RMSs represent the optimization results (percentage [%]) deducted from the simulation results (percentage [%]). The anomalies of the RMSs selected between the optimization and simulation models were greater (with more positives) considering the linear cost constraint (Table 8.7[a]) compared with when considering the quadratic cost constraint (Table 8.7[b]) for cost scenarios S7, S8 and S9. This depicts that, with the linear cost constraint, similar RMSs were selected on more occasions in simulations compared to the optimization with a lower level of trade-off among the risk mitigation strategies (RMSs). On the other hand, a higher level of trade-off was observed for the simulation model with the quadratic cost constraint compared to the optimization model under the same constraint resulting in greater variation in the levels of risk mitigation for a lower budget (cost scenarios S7, S8 and S9). The anomalies remained high for the other cost scenarios (S1–S6) with higher budgets with greater positives (for simulation) considering the linear cost constraint. This highlights that the AI scores derived from simulation are relatively modest compared to those from optimization as the level of risk mitigation remains similar for similar cost scenarios (Table 8.7). The modest score of AI from simulation allows the implementation of a greater number of RMSs for a cost scenario although the level of risk mitigation remains similar. Little variation in the level of risk mitigation was observed between the optimization model and the simulation models for higher budgets (cost scenarios S1, S2 and S3) considering the quadratic cost constraint (Figure 8.5[b]). This was considered to be due to little flexibility in trade-offs among the RMSs for this cost scenario as the level of risk mitigation was higher and most of the RMSs were selected for all these cost scenarios. This was also observed in the analysis of the anomalies of selected RMSs for optimization and simulation with little variation in the RMSs selected (Table 8.7[b]) for cost scenarios S1, S2 and S3.

The optimization results comprised six trajectories of relationships (Figure 8.1) based on actual data from the six experts whereas the simulation results (Figure 8.4) were from 50 sets of risk mitigation variables based on the minimum and maximum sets of values of SCR attributes and RMS attributes derived from the scores of experts. Therefore, the simulation result of relationships between the level of risk mitigation and the cost scenario (in Figure 8.4) is a better picture of the relationship (compared to Figure 8.1) based on the experts' opinion. Hence, any trajectories drawn within the range of relationships shown in Figure 8.4 are a possible representation of relationships between the level of risk mitigation and a cost scenario. Thus, instead of a point value of the level of risk mitigation for a cost scenario, the risk manager or policy maker needs to consider a range of values for the level of risk mitigation that are possible within the range shown in Figure 8.4. Furthermore, with the increase in the number of simulations, the distribution of relationships between the level of risk mitigation and a cost scenario may widen further but would show some central tendency in the distribution.

Table 8.7(a): Comparison of summary of simulation vs optimization model results (considering linear cost constraint)

Notes: The scores of the selected RMSs represent the deduction of the optimization results (%) from the simulation results (%). The budget and level of risk mitigation (*Rf(x))* are the ensemble means for both optimization and simulations.

Cost scenario and budget			Risk mitigation through optimization			Risk mitigation through simulation				Selected RMSs under different cost scenarios (without savings)																													
Scenario	Budget available*		Budget used			Budget used																																	
	%	Actual	%	Actual	$f(x)$	Actual	%	Actual	$f(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1223.3	89.3	1215.0	0.981	1269.4	89.4	1261.6	0.966	0	0	0	17	0	17	50	0	0	0	0	0	0	17	0	67	0	0	0	0	0	67	33	33	17	0	0	17	0	17
S2	80	1087.3	79.7	1082.5	0.939	1128.4	79.6	1123.2	0.913	0	0	17	50	0	17	50	33	0	0	0	0	0	17	0	7	17	0	0	0	0	83	33	33	-21	50	50	25	0	17
S3	70	951.4	69.5	943.3	0.880	987.3	69.6	982.3	0.849	0	-20	17	-2	0	17	51	33	29	17	17	0	17	33	0	4	17	17	17	17	0	83	48	46	-22	53	24	15	0	17
S4	60	815.5	59.7	811.7	0.805	846.3	59.7	842.7	0.777	0	-27	50	-3	17	33	11	50	-3	17	15	0	31	25	33	-13	17	33	-1	17	17	83	34	20	20	23	25	-5	17	50
S5	50	679.6	49.9	678.3	0.720	705.2	49.7	700.4	0.694	0	-31	57	-15	27	33	15	50	-27	9	-9	33	25	7	65	0	15	33	-15	15	33	83	29	9	16	17	16	-3	17	63
S6	40	543.7	39.8	540.8	0.619	564.2	39.7	560.6	0.606	0	-45	43	-17	28	44	20	48	-45	-11	-13	50	26	14	61	0	11	29	7	13	27	81	29	30	-15	9	8	8	25	43
S7	30	407.8	29.7	403.3	0.499	423.1	29.7	419.5	0.503	17	-9	15	6	16	39	14	55	-55	11	-31	21	29	21	55	2	5	57	-9	7	22	92	34	20	-15	-3	8	-13	19	45
S8	20	271.8	19.8	269.2	0.365	282.1	19.6	276.8	0.384	-2	-34	11	-29	-10	0	12	54	-57	-11	-18	28	19	19	31	0	-17	33	5	23	41	70	24	16	-9	-7	4	0	10	54
S9	10	135.9	9.7	133.3	0.211	141.0	9.7	137.3	0.237	5	-23	18	6	-11	15	12	16	2	-11	-34	-16	9	-9	5	0	-1	17	10	39	14	36	14	2	8	12	2	-13	3	19

Table 8.7(b): Comparison of summary of simulation vs optimization model results (considering quadratic cost constraint)

Notes: The scores of the selected RMSs represent the deduction of the optimization results (%) from the simulation results (%). The budget and level of risk mitigation (*Rf(x)*) are ensemble means for both optimization and simulations.

Cost scenario and budget			Risk mitigation through optimization			Risk mitigation through simulation			
Scenario	Budget available*		Budget used			Budget used			
	%	Actual	%	Actual	$f(x)$	Actual	%	Actual	$f(x)$
S1	90	1223.3	80.2	1089.8	1.000	1269.4	81.8	1154.6	1.000
S2	80	1087.3	79.1	1074.4	0.999	1128.4	79.0	1114.5	0.994
S3	70	951.4	69.6	946.1	0.967	987.3	69.5	980.6	0.954
S4	60	815.5	59.4	806.9	0.910	846.3	59.6	840.3	0.888
S5	50	679.6	49.6	674.9	0.818	705.2	49.7	700.6	0.804
S6	40	543.7	39.7	540.3	0.695	564.2	39.6	559.2	0.700
S7	30	407.8	29.8	404.8	0.570	423.1	29.6	418.0	0.577
S8	20	271.8	19.7	267.7	0.411	282.1	19.7	277.6	0.433
S9	10	135.9	9.9	134.5	0.220	141.0	9.7	136.4	0.241

Selected RMSs under different cost scenarios (with savings)

Scenario	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15
S1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	0	0	17	0
S3	0	-20	0	-35	0	0	34	0	-4	0	0	0	0	17	0
S4	0	-44	0	-20	0	0	11	0	-3	17	15	0	-2	9	0
S5	0	-14	-10	-15	11	0	32	33	-27	9	-9	0	-8	7	-2
S6	0	-45	-7	-17	11	-6	20	48	-28	5	-13	0	-7	14	27
S7	0	-26	-19	-11	-1	39	14	38	-5	-39	-31	5	-5	21	39
S8	15	-34	-5	-13	-10	33	-5	37	-7	-28	-35	-5	-15	19	48
S9	5	-7	18	6	-11	15	-5	16	2	-11	-34	-16	-7	8	22

Scenario	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0
S2	-43	0	0	0	0	0	0	17	0	-21	0	0	-8	0	17
S3	-29	17	0	0	0	0	0	15	13	-39	3	7	-1	0	33
S4	-13	17	0	-1	17	0	0	51	20	-47	23	9	-21	0	33
S5	0	15	0	2	31	0	33	29	25	16	17	-17	-3	0	46
S6	0	27	13	-10	13	-6	48	13	30	-15	9	-9	-9	9	59
S7	2	-11	23	7	24	-11	42	34	20	-31	-3	8	4	19	45
S8	0	0	16	22	39	-9	53	24	16	8	-7	4	-17	10	54
S9	0	-1	1	10	56	-19	36	14	2	8	-5	2	4	-31	36

8.5 Chapter Summary

This chapter has presented the simulation model which was developed to simulate several scenarios based on the opinions or data collected from the six experts. The simulation model has been solved for 50 simulations with different cost scenarios while keeping the risk mitigation variables (SCR and RMS attributes) within the range of data collected from the experts. As with the optimization results, a summary of relationships between the level of risk mitigation and the cost has been developed with the simulation results and a summary of sets of RMSs selected for different cost scenarios has been presented. The relationship between the level of risk mitigation and the cost established from the simulation results shows a wider spread compared to that from the optimization results. The summary set of selected RMSs developed from the simulation results would help risk managers to find important RMSs for a cost scenario with greater consensus compared to the optimization results which were based on data from the six experts.

CHAPTER 9

DISCUSSION

9.1 Chapter Introduction

In this chapter, key findings from this research are discussed in regard to theoretical relevance, methodological accuracy and practical importance. The findings are discussed consistent with the two research questions, methodological development, application of methods and research objectives. As identified in the two research questions and the associated research objectives, this study reveals the SCRs of the LNG industry in Australia and the RMSs to mitigate the risks which have not been explored previously. A methodology was developed to identify the SCRs and the RMSs which extended further to carry out risk analysis leading to a comprehensive model for (SCRM). The methodology comprised identification of SCRs and RMSs; prioritization of SCRs; defining of the relationships between SCRs and RMSs; prioritization of RMSs; cost estimation for implementation of RMSs; an optimization model for optimal sets of RMSs for different cost scenarios; and a simulation model which, together, encompass a comprehensive approach to SCRM, with this method applied to SCRM of the LNG industry in Australia. The methodology adopted was: (i) a widely used approach for assessing risks (Cox, 2012); (ii) a conventional QFD method (Han et al., 2001); (iii) a QFD-based optimization (Park and Kim, 1998); and (iv) a QFD-based simulation. For the simulation model, the data were simulated using the RAND() function of MS Excel based on defined boundary conditions from primary data. The simulation was model developed and solved following the principles of QFD-based optimization.

This chapter is organized with a focus on the findings from this study. Following the introduction, the highly probable and high impact risks are presented followed by the RMSs to mitigate these risks. The highly important RMSs are explored with optimal sets of RMSs for different cost scenarios. The reliability and validity of the optimization model have important implications on the findings from this research. Hence, model reliability and validity are discussed. This research answers two key research questions of LNG SCRM in Australia with both the questions and answers explained based on findings from the current study. This chapter concludes with a summary.

9.2 Highly Probable and High Impact Risks

The LNG SCRs for Australia are identified (details in Chapter 3) and prioritized (details in Chapter 5) in this study following the methods explained in Chapter 4. The literature suggests that no systematic study has been carried out to identify and prioritize upstream-end to downstream-end SCRs of the LNG industry, particularly in the context of Australia. Maxwell and Zhu (2011) examined the empirical relationship between US LNG imports and Asia's gas prices and a proxy for LNG transportation costs using monthly data for a period from 1997–2007. Furlonge (2011) reported that the LNG business comprises a number of economic activities with inherent risks. As part of the investment decision-making process, Furlonge (2011) proposed an integrated modelling approach to optimize economic returns from LNG considering uncertainty in various input parameters. Cabalu (2010) examined the relative vulnerability of natural gas supply disruptions in seven gas-importing countries (where most imports are LNG) in Asia for 2008. In an earlier study, Cabalu and Manuhutu (2009) investigated the relative vulnerability of eight gas-importing countries in Asia for 2006 using four market risk indicators and two supply risk indicators. Jensen (2003) examined barriers to complex cross-border trade and the likely future of the LNG industry. Pil et al. (2008) assessed the reliability of re-liquefaction systems on LNG carriers, while Neumann (2009) provided evidence on the integration of the transatlantic natural gas market. Leather and Wood (2012) assessed the need to address corporate social responsibility (CSR) challenges to maintain momentum in Northern Australia's LNG projects. In another study, Leather et al. (2013) reviewed the natural gas resources in Australia and their exploitation, reporting some challenges ahead. Simshauser (2010) described the key drivers of investment uncertainty in the Australian energy market as: (i) the Global Financial Crisis (GFC); (ii) structural reliance on debts; (iii) the Emissions Trading Scheme (ETS); and (iv) the LNG trade effects on the gas price. As articulated by Simshauser (2010), not only does Australia have an acute structural reliance on foreign capital, but investment uncertainty has reached an all-time high. Therefore, although some of these studies mention some aspects of the risks of the LNG industry as a whole, none of these studies have identified the SCRs of the LNG industry, particularly in the context of Australia. Hence, the SCRs identified in this study are expected to enhance the literature on LNG supply chain risk management (SCRM). Thus, the SCRs identified in this study represent a comprehensive list of risks to the LNG supply chain in Australia in the current context. In addition, the SCRs have been verified by an industry expert, with this providing a greater level of confidence in the identification of the risks.

The SCRs were prioritized and ranked based on three attributes: (i) risk probability; (ii) risk impact; and (iii) risk indices (or probability impact). The risk indices are calculated based on a widely used formula, *risk indices or risk = probability x impact* (Cox, 2012). For each risk attribute, the SCRs were prioritized based on primary data collected from the six experts as well as based on the simulated data from 50 simulations. A summary of the ranking of the SCRs is presented in Table 9.1. Details of the prioritization of SCRs were presented in Chapter 5. For both primary and simulated data, ranking was carried out based on the consensus mean (Rank [A]) and the simulated consensus mean (Rank [AS]) as well as with the weighted consensus mean (Rank [WA]) and the simulated weighted consensus mean (Rank [WAS]) (Table 9.1). Using the ranking of the SCRs (as summarized in Table 9.1), a risk manager can identify risks based on probability, impact and risk indices. This is expected to be useful in finding the SCRs with high probability, high impact or high probability impact. Therefore, Table 9.1 summarizes a comparative picture of the prioritization of LNG SCRs based on primary data and simulated data and the corresponding weighted mean. Details of the ranking of the SCRs based on the consensus mean of the experts are presented in Section 5.8.2 in Chapter Five (Table 5.4). A summary of the ranking based on simulated data is presented in Table A9.2 (in Appendix H).

The ranking of SCRs based on the consensus mean of the data from the experts is consensus ranking as depicted by the experts. However, this ranking does not consider the variation among the experts. Shi et al (1996) argued in favour of consensus ranking in allocating scarce resources for information systems and proposed a streamlined consensus priority ranking (SCPR) method using a concept to minimize disagreement between individual rankings. However, the proposed method requires commercial integer programming software to find the best consensus ranking. To address the variation among the experts, in the current study, a weightage scale was developed for the risk attributes (details of weightage scale are presented in Section 5.8.1, Chapter Five) to develop the consensus ranking of SCRs based on risk attributes. The principle of the weighting is to minimize disagreement among the experts. Thus, the weighted ranking captured the consensus among the experts as well as variation among them. Hence, weighted rankings are expected to be superior compared to simple consensus ranking.

No literature was found on simulation models of LNG supply chain risk management (SCRM). However, some studies have been carried out on risk assessment, optimization and resilience focusing on part of the LNG supply chain. For example, Berle et al. (2013) explored a systematic approach for optimization, risk assessment and resilience in LNG transportation systems. As reported by Berle et al (2013), previous literature on LNG shipping challenges includes an inventory management problem of a vertically integrated LNG supply chain (Andersson et al., 2010) and creating annual delivery programs in the presence of a spot market (Rakke et al., 2011). A limited number of LNG experts participated in the survey in the current study which is characteristic of such a study (like supply chain risk mitigation of the LNG industry). Due to the small sample size, the results could be influenced by the inclusion or exclusion of a sample set of data. Therefore, a simulation model was developed based on the data collected from the six experts. The ranking of LNG SCRs was carried out based on the risk attributes from the 50 simulations. Similar to the primary data, the rankings of SCRs were also carried out based on the weighted average of the simulated data to capture the variation in the simulated data. Thus, the simulated weighted ranking of the SCRs is expected to be superior compared to the ranking based on the simulated average (Table 9.1). Therefore, simulated weighted average ranking is recommended for prioritizing SCRs in the LNG industry in Australia. Good correlation was found between ranking based on the consensus mean from the experts and the simulated consensus means for all three SCR attributes (0.961 for probability; 0.926 for impact; and 0.977 for risk indices as shown in Table 9.1). Similarly, very high correlation was observed between the two rankings with weighted means (0.950 for probability; 0.938 for impact and 0.962 for risk indices, Table 9.1). This demonstrates that the simulation model improves the ranking while also taking into consideration the variation among the experts.

Table 9.1: Summary of ranking of LNG supply chain risks (SCRs)

Note: This is based on the consensus mean of the risk probability score, the risk impact score and the risk indices along with the ranking based on the consensus mean from 50 simulations.

	SCR Probability				SCR Impact				SCR Indices			
	Consensus mean of six experts		Simulated consensus mean		Consensus mean of six experts		Simulated consensus mean		Consensus mean of six experts		Simulated consensus mean	
Risk Id. No.	Rank (A)*	Rank (WA)	Rank (AS)	Rank (WAS)	Rank (A)	Rank (WA)	Rank (AS)	Rank (WAS)	Rank (A)	Rank (WA)	Rank (AS)	Rank (WAS)
SCR1	19	8	22	12	9	7	10	11	16	11	15	10
SCR2	10	12	12	13	25	21	25	17	19	18	22	16
SCR3	30	32	33	33	31	32	29	31	31	33	32	33
SCR4	10	16	7	14	16	16	17	21	13	16	12	19
SCR5	32	33	26	28	31	31	32	30	32	32	29	30
SCR6	5	9	5	8	9	12	9	8	5	8	7	8
SCR7	30	30	31	29	33	33	33	33	33	30	33	32
SCR8	16	20	17	20	27	23	20	16	23	20	21	20
SCR9	16	25	24	27	9	12	14	10	14	17	18	22
SCR10	19	27	20	26	16	16	16	20	17	21	19	23
SCR11	10	16	10	19	2	11	2	13	7	10	6	14
SCR12	6	6	9	7	5	3	6	4	6	4	5	4
SCR13	15	13	18	16	19	5	18	5	18	15	17	15
SCR14	6	14	8	17	14	18	8	22	7	14	9	18
SCR15	2	5	4	5	1	10	7	14	1	5	3	7
SCR16	2	1	2	2	5	2	4	1	3	1	2	1
SCR17	1	2	1	1	4	4	5	2	2	2	1	2
SCR18	26	21	28	24	14	18	21	26	24	23	26	27
SCR19	19	19	14	10	20	22	19	19	20	22	16	17
SCR20	6	4	6	3	20	15	23	15	15	7	13	6
SCR21	4	7	3	6	5	8	12	9	4	6	4	5
SCR22	22	22	19	21	22	27	26	28	22	24	23	24
SCR23	24	15	21	9	18	20	15	18	21	19	20	13
SCR24	28	29	27	31	22	24	22	25	27	29	27	28
SCR25	9	11	11	11	9	12	11	7	9	9	11	9
SCR26	25	26	30	30	22	29	28	29	24	26	28	29
SCR27	14	10	16	15	5	8	13	12	11	12	14	12
SCR28	22	23	23	25	27	30	24	27	24	25	24	26
SCR29	16	18	15	18	2	6	1	6	10	13	8	11
SCR30	13	3	13	4	9	1	3	3	12	3	10	3
SCR31	29	24	29	23	30	25	30	23	29	27	30	21
SCR32	32	31	32	32	25	26	31	32	30	31	31	31
SCR33	26	28	25	22	29	28	27	24	28	28	25	25
CC			0.961	0.950			0.926	0.938			0.977	0.962

*Notations: Rank (A)=Rank of LNG SCR based on consensus mean; Rank (WA)=Rank of LNG SCR based on weighted consensus mean; Rank (AS)=Rank of LNG SCR based on consensus mean from 50 simulations; Rank (AWS)=Rank of LNG SCR based on weighted consensus mean from 50 simulations; CC=correlation coefficient

9.3 Mitigation Strategies for Highly Probable and High Impact Risks

This study sought to identify appropriate risk mitigation strategies (RMSs) for mitigating LNG supply chain risks (SCRs). Through a comprehensive review of literature, RMSs were identified which were then verified by an LNG expert. Short descriptions of the RMSs were presented in Chapter 3. The literature suggests that no systematic study has been conducted to mitigate the SCRs of the LNG industry, particularly in the Australian context.

However, some studies have identified some risks or challenges of the LNG supply chain and have demanded appropriate RMSs for those risks. For example, in a review of Australia's natural gas resources, Leather et al. (2013) identified some key challenges of the Australian natural gas sector (including LNG and non-conventional gas) and demanded appropriate policy measures to exploit the potential of natural gas, while considering both domestic and international factors. To compete in the global LNG market, Cook (2005) suggested developing the upstream gas liquefaction capacity, highlighting the need for capital, technical skills, experience, safety records, shipping expertise, project management, marketing and project financing. Owing to the lack of appropriate RMSs to mitigate LNG SCRs, a set of RMSs were identified in this study through the review of the supply chain literature (as presented in Chapter 3). The review of the RMSs by the LNG expert provides some confidence in regard to the appropriateness of the RMSs in mitigating SCRs of the LNG industry in Australia. Therefore, the identification of appropriate RMSs for mitigating the SCRs of the LNG industry in Australia is expected to be a useful resource for risk managers and other stakeholders. The RMSs identified also highlight potential policy areas which need attention for appropriate policy measures to be put in place for LNG SCRM in Australia.

This study endeavoured to define the relationships between SCRs and RMSs that have been identified for SCRM of the LNG industry in Australia. The study used the QFD method’s relationship matrix to define the relationships between SCRs and RMSs using primary data collected from six LNG experts. The relationships defined by the experts are summarized in Appendix D, while the relationships based on the consensus mean are presented in Chapter 6 (Figure 6.1). As previously pointed out, no systematic study has been found that has defined the relationship between SCRs and RMSs of the LNG SCRM including in the LNG industry in Australia. However, Chowdhury and Quaddus (2015) utilized the QFD method’s relationship matrix to define the relationship between the vulnerabilities and strategies of the ready-made garment industry of Bangladesh. In another study, Dewan (2014) used the QFD method’s relationship matrix to define the relationships between the blended value requirement and mitigation strategies in modelling E-business sustainability using the case of the banking industry of Bangladesh. Park and Kim (1998) used the relationship matrix to determine an optimal set of design requirements for their example of an air quality improvement problem. Although the QFD method’s relationship matrix has been used to define relationships between the "what" and the "how" across many industries and disciplines, its application in the SCRM literature is rare. The application of the QFD method’s relationship matrix in defining the relationships between SCRs and RMSs brings multiple advantages. For example, it clearly shows the level of relevance of an RMS in mitigating different risks in quantitative (or qualitative) measures (within a defined scale). In addition, it shows, with quantitative (or qualitative) measures, which RMSs are appropriate for mitigating a particular supply chain risk (SCR). This allows mitigation using partial risk management, such as RMSs, to be implemented to mitigate a particular SCR or a set of supply chain risks (SCRs). The use of a quantitative measure in this study allows the differences between the RMSs to be determined, based on the use of the consensus mean, in terms of their relevance for mitigating a particular supply chain risk (SCR). Therefore, the relationship matrix developed in this study for defining the relationships between SCRs and RMSs is a useful tool for risk managers and other stakeholders in SCRM in the LNG industry in Australia. Thus, the study's relationship matrix is a primary source for finding RMSs for the mitigation of SCRs in the LNG industry in Australia.

A summary of the relationship scores between SCRs and RMSs derived from 50 simulations is presented in Table 9.3. The relationship score is the consensus mean from the simulations. The relationship scores from the simulations are similar to the relationship scores of the consensus mean based on primary data from the experts. The simulation scores are means of the simulation data randomly derived while considering the boundary conditions derived from the primary data from the experts. Therefore, the simulation scores are a general representation compared to the consensus mean based on the primary data from the experts. Hence, the relationships defined between SCRs and RMSs based on the simulations are expected to be superior compared to the relationships defined by consensus means based on primary data from the experts. No literature was found on the QFD-based simulation model for LNG SCRM, or for SCRM as a whole. However, to verify the findings from the QFD-based optimization, Dewan (2014) adopted a quantitative analysis using the partial least squares (PLS)-based structural equation modelling (SEM) technique (Chin, 1998). Therefore, with the current lack of studies on QFD-based simulation, the relationships defined between SCRs and RMSs, based on the simulation model, are expected to be an important source of information to risk managers and other stakeholders for selecting appropriate sets of RMSs for mitigating LNG supply chain risks (SCRs). This also demonstrates a significant step forward in the theoretical and methodological areas of the SCRM literature.

Table 9.3: Relationship matrix of QFD method derived from 50 simulations

	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR1	3.9	5.1	6.8	5.0	7.0	2.9	5.0	9.0	9.0	7.1	6.0	5.2	7.1	7.1	7.1	5.0	6.9	7.1	6.1	4.4	5.0	1.0	5.3	5.0		5.0	4.9	2.9	6.6	9.0
SCR2	5.0	9.0	5.5	1.0	5.5	3.7	5.0	5.0	5.0	5.0	5.0		6.9	5.0	8.0				1.0	5.0	9.0	9.0			5.5	1.0	5.0		5.0	9.0
SCR3	5.0				7.4		5.5	5.0	5.0		5.0	5.5			1.0		5.0	5.0	5.5	5.0	5.0			5.0		1.0		1.0		5.0
SCR4	5.2	1.0	1.0	2.9				7.2	7.0	6.7	7.0	1.0	3.5	2.7	5.0	1.0	5.0	1.0	5.0	5.0	5.0	9.0	9.0	5.0		3.0	7.1	5.8	9.0	9.0
SCR5	2.8	5.0	3.1	4.4	6.9		5.0	7.1	9.0	5.1	1.0	2.9	1.0	4.3		1.0	9.0	5.0	3.9	4.8	5.9	6.9	6.8	3.7		9.0	4.8	9.0	9.0	9.0
SCR6					1.0	3.8		5.0	5.0	4.6		9.0	9.0	9.0	9.0		9.0	9.0	5.2	6.9	2.9	5.0	9.0	9.0		6.7	5.0	9.0	9.0	9.0
SCR7	5.0				5.3			5.1	5.0	4.9	5.5	4.9		1.0			5.0		5.0	5.0	3.6	1.0	5.0	5.0		1.0			9.0	9.0
SCR8	1.0	5.1		1.0	5.4	7.3	9.0	5.0		3.1	7.4	9.0	1.0	5.0	5.5	1.0	7.0	1.0	1.0	5.0	6.9	3.0	2.9	3.2		5.0	1.0	9.0	5.0	9.0
SCR9	5.0				1.0	9.0					1.0	1.0	7.0	3.7	5.3					5.0	9.0				7.2					
SCR10	5.0				1.0	7.2					1.0		7.3		4.7				7.0	5.0	5.0				7.5					
SCR11	7.0	6.9	9.0	7.2	5.0	5.5				9.0	6.8	7.2	7.2		5.1			5.0	5.0	1.0	3.1	9.0					5.0		9.0	6.9
SCR12	4.4	4.8	2.8	9.0	9.0				5.5	7.1	7.1	9.0	7.2	5.0	1.0		6.5	1.0	4.3	4.2	7.2	9.0	9.0	9.0		9.0	5.0		7.4	9.0
SCR13	5.0	5.0	5.0	5.0	5.0		9.0	5.0		5.0	5.0	5.0	6.7	1.0	9.0					3.1	2.7	9.0	9.0	5.0		5.0			9.0	9.0
SCR14					6.9	7.3		6.8	6.9	5.1	7.1	5.0	9.0	3.0	9.0		9.0	6.9	3.3	5.0	8.1	5.0	5.0	5.0		1.0			6.9	9.0
SCR15	5.0	5.0			7.5	7.1	5.0	7.2	8.5	5.2	6.8	5.0		5.5	9.0		7.9	6.1	2.9	5.0	7.9	9.0	6.9	5.0					7.2	9.0
SCR16	5.0				6.9	6.7		6.9	7.0	3.0	5.0	3.3		3.5	5.0		8.0	7.0	5.0	5.0	7.9	9.0	7.3	6.9					9.0	9.0
SCR17					5.0	6.8		7.1	9.0	4.8	5.0	7.1	6.0	2.8	5.0		9.0	7.2	6.0	7.2	6.9	9.0	2.9	3.1					6.9	9.0
SCR18	5.0				3.0	5.0		9.0	9.0	5.0	3.2	7.2		2.9			9.0	5.0	3.2	7.1	5.0		2.7	3.1			5.0		5.1	9.0
SCR19	4.5	6.8	4.7	1.0	6.9	5.0	9.0	1.0	4.9	7.1	8.5	8.0	7.4	9.0	6.7		3.2		7.0	6.7	7.2	9.0							9.0	9.0
SCR20	1.0	5.0			3.0					3.1	5.0	5.0	5.0	5.0			7.4	5.0		5.0	5.3	9.0	7.0	6.9					5.5	3.2
SCR21	6.8	3.0	5.0	5.0	6.7			2.8	7.0	7.0	5.6	3.2	5.6	5.0	7.3		9.0	6.5	6.9	6.7	6.9	9.0	3.1	3.1			5.0	5.0	7.3	9.0
SCR22	9.0		9.0		2.9	3.2		3.0	2.9	3.0	7.1	4.8	9.0	7.0	9.0		4.9	6.9	9.0	9.0	6.9	9.0	5.0	5.0					7.1	9.0
SCR23	5.0		1.0					7.0	6.8	5.0	9.0	7.1	1.0	5.0							9.0		1.0	1.0					9.0	9.0
SCR24	3.0	1.0			7.0		9.0	3.1	3.0	9.0	6.8	5.0	5.0		1.0		7.2	6.9		5.0	6.8	9.0	4.3	5.1					9.0	9.0
SCR25	4.8	9.0	5.2	9.0	7.2		9.0	5.0	5.0	3.2	3.1	5.0					7.0	8.6			3.4	1.0	3.0	3.0					5.0	9.0
SCR26	5.0	3.2	1.0		3.5			9.0		9.0	5.0	5.0	9.0	5.0	7.0					5.0	9.0	9.0	5.0	5.0					9.0	9.0
SCR27	9.0	5.0	9.0		9.0			9.0	9.0	6.9	5.1	9.0		9.0					6.9	5.0	9.0	9.0					5.0		5.0	5.3
SCR28	1.0	9.0		5.0	6.9			7.0	6.8	7.0	5.0	1.0	5.0	1.0	9.0			4.9	9.0	6.9	4.8	5.0				9.0			9.0	9.0
SCR29	9.0	9.0	1.0		4.9			9.0	9.0	4.9	5.4		9.0	5.0	9.0		7.1	7.1		7.0	7.0	9.0	1.0	5.0		1.0	5.0		7.0	9.0
SCR30	7.9	7.1	7.2	9.0	4.9			9.0	9.0	4.9	9.0			1.0			9.0	7.1	5.6	4.3	7.1	9.0	5.1	9.0		5.0			9.0	9.0
SCR31	6.9	6.8	7.1	5.0				1.0	5.0	6.9	6.9			5.0		4.5	5.0			5.0	5.2	3.4	6.7	5.0					5.0	7.0
SCR32	4.2	6.0	7.0		9.0					7.0	3.9			5.0		7.1	5.0			5.0	4.5	4.1	6.0						5.0	7.1
SCR33	5.9	6.9	6.1		9.0					7.1	7.2			5.0		7.0	5.0			5.0	6.0	6.8	5.8						5.0	6.9

9.4 Exploring the Highly Important Strategies to Mitigate Risks

The prioritization of RMSs is of immense importance in SCRM in focusing on the important strategies. The selection of important RMSs allows risk managers to implement these strategies in a resource-constrained environment where sufficient resources are not available for the implementation of all risk mitigation strategies (RMSs). This study has endeavoured to prioritize RMSs to find those of greatest importance, while considering their cost and their relative importance in mitigating the supply chain risks (SCRs). This facilitates the efficient and effective allocation of limited resources to achieve greater benefit of the resources through the mitigation of the greater risks. A conventional QFD approach considering cost of implementation of RMSs was used for the prioritization.

Although prioritization of RMSs is critical in SCRM, very limited work has to date been carried out in this field. Cox (2012) reported that many risk management initiatives and software tools used around the world result in the estimated ratings of a few (typically, two or three) components of risk which are presented as “heat maps", scatter diagrams, bar diagrams or look-up tables. Hence, Cox (2012) proposed a method for selecting important risks using the simulation evaluation of methods, while considering a limited budget. Although Cox (2012) considered cost as a constraint in evaluating risks, the study has not been further extended (e.g. by finding RMSs to mitigate the risks).

In a review of the literature on SCRM, Sodhi et al. (2012) reported that many works had covered the first three aspects of SCRM, namely, risk identification, risk assessment and risk mitigation, whereas only a limited number of studies had extended to the responsiveness part. However, the majority of the papers reviewed by Sodhi et al. (2012) carried out the mitigation aspect of SCRM as a part of broad SCRM frameworks, with only a limited number of studies focused on empirical methods, either quantitative or qualitative. Limited numbers of studies, particularly those that have used the QFD method, have been conducted on prioritizing strategies to mitigate SCRs, while considering the cost of implementing these strategies. Citing Cohen (1995) along with Hauser and Clausing (1988), Han et al. (2001) reported that the majority of QFD applications concluded with the completion of the first matrix (defined as the relationship matrix in the current study). More recently, Chowdhury and Quaddus (2015) carried out a multiple objective optimization using QFD to find efficient resilient strategies for mitigating the supply chain vulnerabilities of the garment industry of Bangladesh. Dewan (2014) used QFD-based optimization to prioritize mitigation strategies associated with the risks to the banking industry of Bangladesh. These studies are based on the QFD-based optimization principle as depicted by Park and Kim (1998). However, no studies have been found on the prioritization of RMSs for LNG SCRM, both around the world and/or in the context of Australia. Therefore, this study, with its prioritization of RMSs, is expected to be a valuable resource in the SCRM literature. In addition, through this prioritization, risk managers will be able to find the important RMSs in order to allocate resources in a limited budget scenario to achieve a greater level of risk mitigation.

The RMSs to mitigate LNG SCRs have been prioritized following the QFD method's conventional approach with consideration of the cost of the implementation of risk mitigation strategies (RMSs). In the conventional QFD method, the absolute importance (AI) score of an RMS represents its importance, compared to that of other RMSs, in mitigating supply chain risks (SCRs). The relative absolute importance (RAI) score is also a measure of the importance of the RMS in mitigating SCRs compared to that of other RMSs, for which the sum of all RAI scores is equal to 1. This relative scale facilitates the comparison of a parameter (such as RAI) between the different experts. Another dimension of RMSs is the cost of their implementation. As with RAI, the costs of the implementation of RMSs are also converted into a relative scale for which the sum of all costs of the implementation of RMSs is equal to 1. Although an RMS could have a very high RAI score, it may not be very effective in mitigating SCRs if the cost of implementation is very high relative to that of other RMSs. Thus, the effectiveness of an RMS is measured based on its importance in mitigating SCRs per unit of cost. Hence, the relative effectiveness (RE) of an RMS is a measure of the RAI that can be achieved per unit of relative cost (RC). Therefore, the consideration of the cost of the implementation of RMSs is of great importance in their prioritization. Accordingly, the prioritization of RMSs based on the relative effectiveness (RE) of RMSs is a better representation of those RMSs of greater importance compared to the prioritization based on AI by following the conventional QFD method.

Based on relative effectiveness (RE) calculated from the primary data collected from the experts, the rankings of RMSs, considering the consensus mean (CM) and the ensemble mean (EM), are summarized in Table 9.4. Details of rankings based on the primary data collected from the experts are presented in Chapter 6. Table 9.4 also contains the relative effectiveness (RE) and corresponding ranking of the RMSs derived from the 50 simulations used in the simulation model (details in Chapter 8). These three methods of ranking highlight the importance of selecting an appropriate approach for analysing data collected in supply chain risk management (SCRM). Although, similarities exist among the three ranking methods, considerable variation is also found. For example, RMS1 was ranked with a position at 1 by all three ranking methods, thus RMS1 was depicted as the most effective RMS among all RMSs in LNG SCRM in Australia. However, the rankings of RMS2 were 7, 12 and 24 based on the consensus mean, the ensemble mean and the simulated ensemble mean of relative effectiveness (RE) (Table 9.4). As explained earlier in discussion on the optimization model (Chapter 7) and on the simulation model (Chapter 8), the ensemble mean is superior to the consensus mean and the simulation ensemble mean is superior to the ensemble mean. Thus, to select highly effective RMSs for mitigating SCRs, ranking based on the simulated ensemble mean is recommended. Therefore, the approach adopted in prioritizing the RMSs for LNG SCRM is quite comprehensive in nature. Hence, the ranking prepared for LNG SCRM in Australia is expected to be a useful resource for risk managers in selecting the RMSs of greater importance to mitigate SCRs and to allocate limited resources accordingly. In addition, the approach is expected to enhance the SCRM literature on the prioritization of risk mitigation strategies (RMSs).

Table 9.4: Summary of relative effectiveness and rank of risk mitigation strategies (RMSs) with optimization and simulation

Note: This is based on the consensus means of the risk probability score, the risk impact score and the risk indices along with rankings based on the consensus means from 50 simulations.

*	**Relative effectiveness and rank of risk mitigation strategies with optimization and simulation**																													
	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
CM	2.3	1.3	0.9	0.5	1.3	1.3	0.4	0.8	1.2	1.2	1.4	1.4	1.0	0.9	0.9	0.2	1.4	1.2	1.1	1.3	1.2	0.4	0.7	0.7	0.6	0.6	0.5	0.5	1.8	1.5
CR	1	7	19	27	9	8	29	20	14	12	5	4	16	18	17	30	6	13	15	10	11	28	22	21	24	23	26	25	2	3
EM	2.2	1.2	0.9	0.5	1.3	1.6	0.3	0.9	1.2	1.2	1.4	1.4	1.0	0.9	0.9	0.3	1.4	1.2	1.2	1.3	1.2	0.3	0.6	0.7	0.8	0.6	0.5	0.5	1.8	1.1
ER	1	12	20	27	7	3	28	18	9	11	6	5	16	17	19	30	4	13	14	8	10	29	23	22	21	24	25	26	2	15
EMS	2.8	0.7	0.8	0.5	1.0	1.1	0.7	0.7	0.9	0.9	1.2	1.4	0.9	0.8	1.1	0.2	1.6	1.3	1.0	1.8	1.1	1.3	1.0	0.9	0.4	0.7	0.5	0.4	1.4	1.6
ERS	1	24	20	27	14	10	23	22	19	17	9	5	16	21	11	30	4	7	13	2	12	8	15	18	29	25	26	28	6	3

*CM=consensus mean of relative effectiveness from optimization; CR=consensus rank based on mean of relative effectiveness from optimization; EM=ensemble mean of relative effectiveness from optimization; ER=ensemble rank based on mean of relative effectiveness from optimization; EMS=ensemble mean of relative effectiveness from simulation; ERS=ensemble rank based on mean of relative effectiveness from simulation.

9.5 Optimal Mitigation Strategies

In reality, it is impossible to implement all RMSs due to limited or reduced budgets. In addition, in practical terms, it is not necessary to mitigate all risks, with this dependent on the risk appetite of the risk manager and taking into consideration the budget and other policy measures. Therefore, the need to determine optimal sets of RMSs for limited budget scenarios is paramount in limited budget or limited cost scenarios. The literature suggests that interest has recently been growing in the optimization problem faced by supply chain risk management (SCRM). Reporting that multi-criteria considerations affect the performance of SCRM; Qu et al. (2014) applied proximal point algorithms in the convex multi-criteria optimization method. However, Qu et al. (2014) highlighted the difficulty, in the case of infinite Pareto solutions, in finding the entire solution set. Hahn and Kuhn (2012) indicated that stochastic programming (Pongsakdi et al., 2006; You et al., 2009) and robust optimization methods (Mulvey et al., 1995) are common in physical supply chain planning and risk management. However, current decision frameworks do not bestow a comprehensive robust approach on value-based performance and risk optimization (Hahn and Kuhn, 2012). Hence, Hahn and Kuhn (2012) extended their value-based approach (Hahn and Kuhn, 2011) into integrated performance risk management. However, their approach does not show the relationships between SCRs and RMSs and, in addition, RMSs are not optimized. Thus, optimal sets of RMSs for limited budget scenarios cannot be identified.

By adopting QFD-based optimization, the relationships between SCRs and RMSs can be defined; as a result, optimal sets of RMSs can be determined for limited budget or limited cost scenarios. A summary of the recent work on QFD-based optimization is presented in Appendix A (Table A2.2). Chowdhury and Quaddus (2015) have recently developed a 0–1 multi-objective optimization model based on QFD methodology to optimize resilient strategies following the principles outlined by Park and Kim (1998). In another study, Dewan (2014) adopted a similar approach to Park and Kim (1998) to optimize strategies for mitigating the risks of the banking industry. In the current study, the optimization model has been developed and solved to determine the optimal sets of RMSs for different cost scenarios following the principles delineated by Park and Kim (1998) on QFD-based optimization.

The optimization model was developed and solved based on (i) consensus means of the data from the six experts and (ii) data from an individual expert and then ensemble means of the derived results. The optimization model was solved for nine cost scenarios that varied depending on the availability of the budget. The cost scenarios were defined as S1, S2, …, S8 and S9 which were 90%, 80%, …, 20% and 10% of the total cost of implementation of all RMSs for a particular set of data. For each cost scenario, the level of risk mitigation and the corresponding set of selected RMSs were obtained from solving the optimization. A summary of the optimal sets of RMSs for different cost scenarios obtained by solving the optimization model is summarized in Table 7.6 in Chapter 7. From Table 7.6, a risk manager can select a particular cost scenario to obtain the level of risk mitigation that is achievable along with the optimal set of RMSs to be implemented. A summary of the optimal sets of RMSs for different cost scenarios based on the ensemble means of optimization that considered each expert's data individually is summarized in Table 7.5 (Chapter 7): the optimization results based on the individual experts are presented in Appendix E. It is important to note that the optimal set of RMSs for the ensemble mean does not provide a particular set of RMSs for a cost scenario; rather, it provides the importance of an RMS as a percentage (%) of the times it appeared (was selected) in the ensemble run. Thus, in the case of ensemble means of optimization (and simulation) results, the selected set of RMSs for a cost scenario should be prioritized based on the percentage (%) of times of each RMS's appearance in the ensemble run. Hence, the optimal set of selected RMSs for the ensemble run is the number of RMSs selected for a cost scenario which have appeared (been selected) a greater percentage (%) of times than other RMSs, provided the cost of the RMSs remains within the budget of the cost scenario. The findings from the optimization model provide information on the level of risk mitigation that can be achieved for different cost scenarios and the corresponding RMSs that need to be implemented for LNG supply chain risk management (SCRM). Therefore, this finding appears to be a useful resource for risk managers and other stakeholders in mitigating LNG SCRs in Australia when considering limited budget scenarios.

The simultaneous implementation of interrelated RMSs could result in cost savings. Thus, the optimization model was also solved for cost saving options. The findings that considered cost savings showed that a greater level of risk mitigation was achieved for a similar cost in comparison to the options without cost savings. As cost savings are likely from the simultaneous implementation of interrelated RMSs, findings showed optimization with the cost savings option is preferred over optimization without the cost saving option.

The simulation model was developed based on data from the experts and solved for 50 simulations: the ensemble means of the simulation results were then derived. A summary of the optimal sets of RMSs derived from the 50 simulations is presented in Table 8.5 (in Chapter 8). As explained in Section 9.4, the simulated ensemble mean is considered superior to the ensemble mean from optimization. Therefore, it is recommended that a simulated ensemble mean be used for selecting the optimal set of RMSs for a cost scenario with the desired level of risk mitigation.

The rationale of a simulation model is to generalize the findings from the optimization model based on primary data from the experts. In the current study, the findings from the solution of the optimization model based on the data from the six experts were six sets of results (on the level of risk mitigation, the cost and the optimal set of RMSs). However, a range of solutions is possible within the range of the boundary conditions of the SCR and RMS attributes based on the primary data from the experts. Furthermore, the addition or exclusion of a set from an expert could also influence the results of the optimization due to the relatively small size of the survey sample of experts. However, increasing the number of the sample size of the survey is quite difficult as there is a limited number of LNG experts across the world, with very few experts having a comprehensive understanding of the complex LNG supply chain. Hence, a simulation model with the boundary conditions of the SCR and RMS attributes determined based on primary data from the experts is the best possible way to generalize the findings of the optimization model. The review of the literature, including the literature on both SCRM and LNG, indicated that no work had been done on developing and solving a simulation model by extending the QFD-based optimization. As a result, the development and solution of the simulation model for LNG SCRM is quite unique in its nature. Thus, the simulation model is expected to augment the SCRM literature in terms of the methods used and the practical application.

9.6 Reliability and Validity of the Model

9.6.1 Model reliability

The model reliability was ensured and checked through the following five steps. Firstly, in step 1, in identifying a comprehensive list of SCRs to the LNG industry in Australia, it is important to ensure that all SCRs were identified. The SCRs were identified through a comprehensive review of the available literature including journals, reports, newspapers, company brochures, etc. Secondly, identifying the appropriate RMSs to mitigate the SCRs was of immense importance. A comprehensive list of LNG supply chain RMSs was compiled through reviewing the available literature on risk mitigation strategies (RMSs). Thirdly, the initial check of the availability of RMSs to mitigate all of the SCRs was carried out through preparation of the QFD method's relationship matrix. The relationship matrix demonstrates the relationships between SCRs and risk mitigation strategies (RMSs). Thus, the preliminary assessment of the QFD method's relationship matrix verified that the appropriate set of RMSs had been selected to mitigate all supply chain risks (SCRs).

In step 2, the identified sets of SCRs and RMSs were verified by an LNG expert from Australia. A meeting was organized to verify that the list of SCRs was comprehensive and that the identified RMSs were appropriate. After a discussion, the list of SCRs and RMSs along with the research objectives was shared with the expert for his review. Based on the expert's suggestions, a final list of SCRs and RMSs was prepared with minor changes made to the initial lists. Thus, the list of SCRs was considered comprehensive and the RMSs identified were treated as appropriate for mitigating the SCRs to the LNG industry in Australia.

In step 3, reliability was assessed through the quality of the survey data received from the LNG experts. In total, six sets of responses were received through the questionnaire. Although every effort was made in the attempt to make the questionnaire simple and succinct, it was impossible to achieve this outcome for reasons which included: (i) the study of LNG SCRM is very complex; (ii) the number of LNG SCRs and RMSs identified was relatively large (33 SCRs and 30 RMSs); (iii) the QFD-based analysis of SCRM requires primary data in two stages (firstly, to prioritize the SCRs and, secondly, to prioritize the RMSs); and (iv) the individual relationships between an SCR and an RMS needed to be defined for each case. In addition, the costs of implementation of the RMSs were needed to develop the optimization model and the subsequent simulation model. Considering the complexity of the questionnaire, very few errors were incurred in its completion with hardly any missing data (with the exception of two SCRs in one case). The three possible reasons for such a high quality survey response from the LNG experts could be: (i) the experts were leaders in their field with a huge amount of experience and great expertise; (ii) the questionnaire was self-explanatory although relatively long due to the large set of data needed; and (iii) the great professionalism as well as support from the experts assisted in carrying out such a complex study. Such a high quality of survey response from the experts indirectly verified that: (i) the LNG SCRs identified were comprehensive and the RMSs identified were appropriate; and (ii) the scales used to measure the SCR attributes, the RMS attributes and the costs were appropriate. The quality of the survey data established the correct foundation for studying LNG SCRM and also set the foundation for a reliable model for LNG supply chain risk management (SCRM).

In step 4, model reliability was evaluated based on the principles and assumptions of the model. Here, the optimization model based on the QFD method was set up following the principles adopted by Park and Kim (1998). More recently, Chowdhury and Quaddus (2015) and Dewan (2014) have carried out QFD-based optimization following the principles of Park and Kim (1998). Therefore, the QFD-based optimization model developed here for LNG SCRM was based on well-established principles. This demonstrates evidence of a credible optimization model.

In step 5, model reliability was appraised through analysis of the model output based on data from the six experts. Table 9.5 presents a summary of the correlation between the levels of risk mitigation achieved for the nine cost scenarios based on the data from the six experts. Analysis shows that the level of relationship was very high ($R^2 > 0.99$) between the experts in terms of the levels of risk mitigation achieved for the cost scenarios. Further analysis was carried out to assess the variability between the experts in terms of the levels of risk mitigation for the cost scenarios. Figure 9.1 presents a summary of the range of variation in the levels of risk mitigation among the experts along with the consensus means.

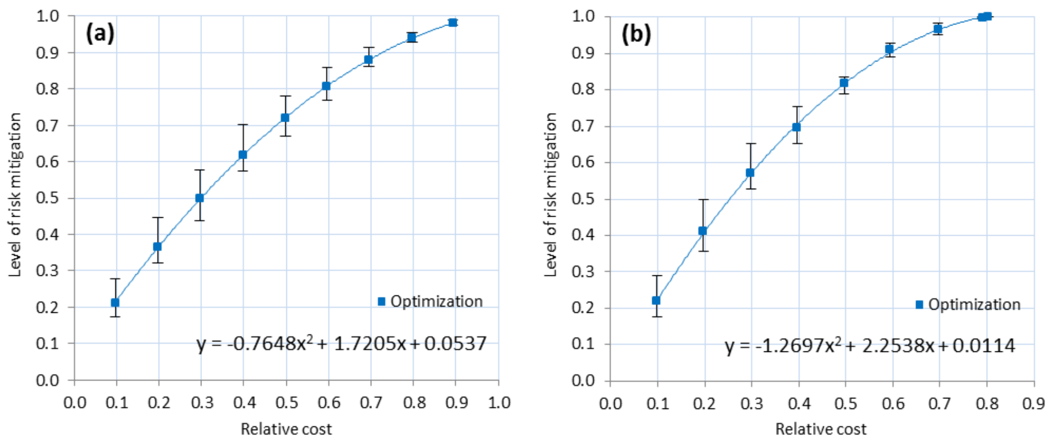


Figure 9.1: Level of risk mitigation obtained for different relative cost from optimization model constraint-based data from the six experts

Notes: The graph shows ensemble mean of level of risk mitigation and corresponding deviation range (error) as varied among the Experts for different relative cost; (a) considering linear cost constraint and (b) considering quadratic cost constraint.

Analysis shows that variations among the experts in the levels of risk mitigation were within ±10% for the cost scenarios with budgets 50% or higher, considering the linear cost constraint (without savings) (Figure 9.1[a]). Similarly, variations in the levels of risk mitigation among the experts were within ±10% for cost scenarios with budgets 40% or higher, considering the quadratic cost constraint (with savings) (Figure 9.1[b]). Although higher variations (in percentage [%]) in the levels of risk mitigation were observed for cost scenarios with budgets of less than 50%, the absolute variation range did not vary greatly compared to the variations in the 50% budget range. In addition, variations in the levels of risk mitigation diminished for cost scenarios with increasing budgets. Thus, the consensus among the experts in achieving the levels of risk mitigation for different cost scenarios demonstrates the model's promising results.

Table 9.5: Correlation matrix demonstrating relationship of level of risk mitigation among the experts achieved for different cost scenarios considering: (a) linear cost constraint and (b) quadratic cost constraint

(a)	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6
Expert 1	1.000	0.997	0.999	0.999	0.995	0.995
Expert 2	0.997	1.000	0.996	1.000	0.999	0.999
Expert 3	0.999	0.996	1.000	0.998	0.993	0.993
Expert 4	0.999	1.000	0.998	1.000	0.999	0.998
Expert 5	0.995	0.999	0.993	0.999	1.000	0.998
Expert 6	0.995	0.999	0.993	0.998	0.998	1.000

(b)	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6
Expert 1	1.000	0.998	0.999	0.998	0.998	0.996
Expert 2	0.998	1.000	0.997	0.998	0.998	0.998
Expert 3	0.999	0.997	1.000	0.996	0.996	0.994
Expert 4	0.998	0.998	0.996	1.000	0.999	0.999
Expert 5	0.998	0.998	0.996	0.999	1.000	0.999
Expert 6	0.996	0.998	0.994	0.999	0.999	1.000

9.6.2 Model validity

The validation of the optimization model was carried out through comparing the results from the optimization model with the results from the simulation model. The optimization model was developed and solved based on primary data collected from the six experts while the simulation model was developed within the boundary conditions based on data from the experts. The simulation model provided a better picture of the levels of risk mitigation and the selected sets of RMSs for the cost scenarios compared to what was achieved in the optimization results. As the simulation results brought other possible realizations of the levels of risk mitigation and selected sets of RMSs, the results were considered superior compared to the results from the optimization model. Thus, comparison of the optimization results with the simulation results is expected to critically evaluate the credibility of the optimization model.

A comparative analysis of the ensemble means of the level of risk mitigation from the optimization and simulation models depicts both results as being very close. A comparison of the ensemble means of the level of risk mitigation from both the optimization and simulation models for different cost scenarios (relative cost [RC]) shows that they closely follow each other for both linear and quadratic cost constraints (Figure 9.2[a] and [b]). A scatter plot of the ensemble means of the level of risk mitigation of the optimization model against the simulation model shows that all the points are closely aligned to the 1:1 line (Figure 9.2[c] and [d]). This means that the ensemble means of the level of risk mitigation from optimization and simulation models are in great agreement. The R2 values between the optimization results and simulation results show very high scores with 0.9994 for the linear cost constraint (without savings) and 0.9991 for the quadratic cost constraints (with savings). The very high R2 scores represent very strong relationships between the results from optimization and simulation. Therefore, the results from the optimization model are validated through the simulation model.

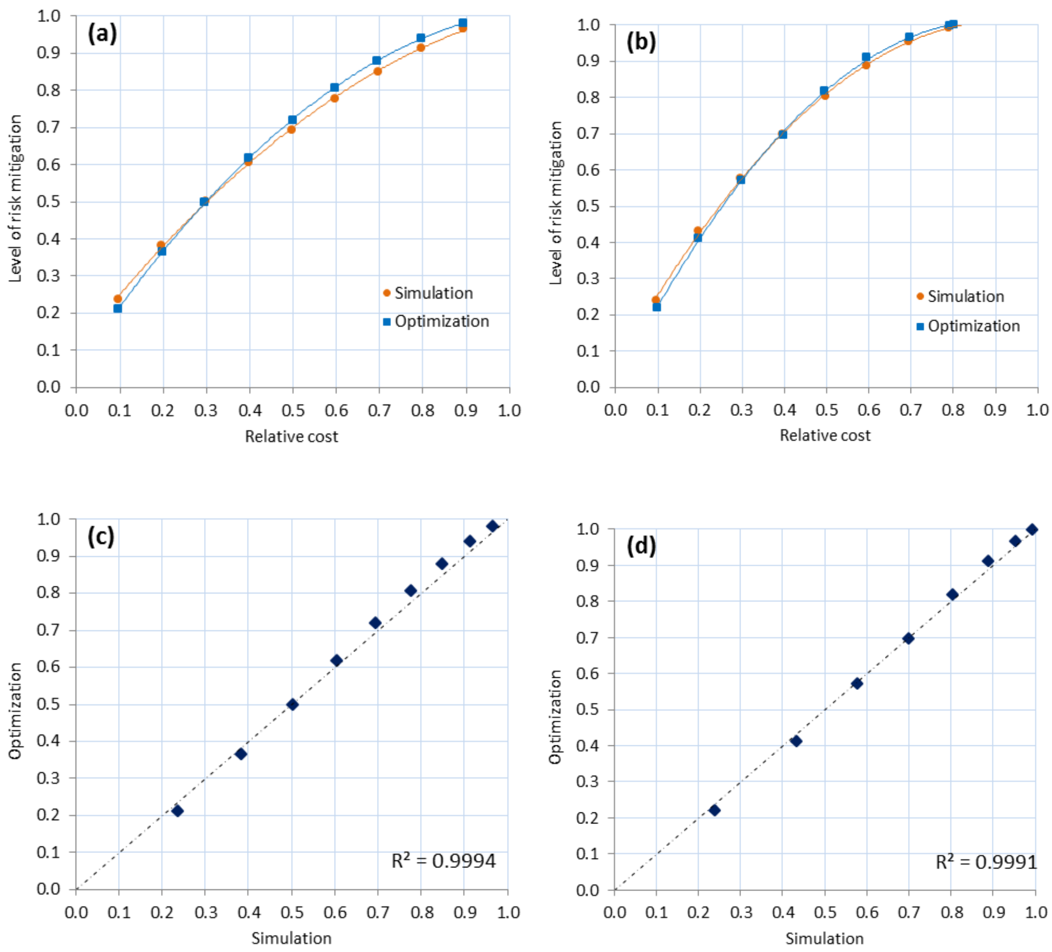


Figure 9.2: Comparison between the ensemble means of level of risk mitigation from optimization and simulation models for different relative costs

Notes: (a) considering linear cost constraint and (b) considering quadratic cost constraint. Scatter plot of ensemble means of levels of risk mitigation are presented in (c) and (d), considering linear and quadratic cost constraint, respectively.

9.7 Findings in View of Research Objectives

The findings from this research are summarized in this section in view of the research objectives (as outlined in Chapter 1). Research objective 1 sought the identification of SCRs and RMSs for the LNG supply chain in Australia and research objective 2 set out to develop a method for SCRM and to apply the method to LNG SCRM. Following objectives 1 and 2, objective 3 was to investigate the relationships between the SCRs and RMSs identified, followed by the prioritization of the SCRs and RMSs of the LNG supply chain in Australia. Objective 4 dealt with the development of an optimization model to find optimal sets of RMSs for different cost scenarios while objective 5 addressed the development of a simulation model to generalize the findings from the optimization model.

In relation to objectives 1 and 3, the identification and prioritization of SCRs and RMSs along with the relationships between the SCRs and RMSs for the LNG supply chain in Australia are discussed in Sections 9.2, 9.3 and 9.4. The optimization model development and findings from the optimization are discussed in Section 9.5. Findings from the simulation model (in light of objective 5) are discussed in the latter part of Section 9.5 and in Section 9.6.2. The development of the methods for SCRM (in view of objective 2) and its application in SCRM for the LNG industry in Australia is discussed below.

As an emerging area of research, methods for SCRM are evolving and in an early stage of development. For example, as reported by Sodhi et al. (2012), to date, the boundaries of SCRM research are unclear and the fields of SCRM are greatly diversified, based on the scope and domain of expertise which greatly influence the selection of a great variety of research tools. The scope of the research and the needs of the industry also act as important factors or determinants in selecting research tools. The nature of the industry and the areas of expertise are also important determinants in determining the scope of SCRM studies. The scope can be further constrained by many other factors, such as the accessibility of information, the availability of funding and the willingness of experts to participate in the research process. In addition, different aspects of SCRs, such as sources, identification, categorization, selection and definition of variables for measurement or assessment, vary to a great degree among the studies. In the current study, a method for LNG supply chain risk mitigation has been developed. The basic steps of the method are: (i) LNG supply chain risk and mitigation strategy identification; (ii) LNG supply chain risk prioritization; (iii) LNG supply chain risk mitigation strategy prioritization; (iv) development and solution of an optimization problem; and (v) development and solution of a simulation problem. Secondary data from the review of the literature were used as the basis for carrying out the identification of SCRs and risk mitigation strategies (RMSs). All other analysis was carried out using primary data. Considering the different steps from the start (e.g. identification of SCRs and RMSs) to the end (e.g. the simulation model), this method of SCRM is quite comprehensive and unique in its type. Therefore, this method can be adopted as a robust method of supply chain risk management (SCRM). In addition, this method can be applied to other similar industries for SCRM, thus demonstrating the method’s generic nature in supply chain risk management (SCRM).

Some new concepts have been introduced and applied in the methodology developed for SCRM which include: (i) the domain variability of SCR and RMS attributes (as explained in

Section 5.7 and 5.9); (ii) a weightage scale to capture variation as well as consensus among the experts (in Section 5.8); (iii) the concept of the risk flexibility index (RFI) (as explained in subsection 4.6.1.4 and Section 6.4.6); (iv) the ranking of SCRs and RMSs based on consensus means and ensemble means and the comparison between them (as summarized in Table 9.1 and Table 9.4); (v) the development of a simulation model to explain the domain variability of SCRs and RMSs (as presented in Chapter 8); and (vi) the ranking of SCRs and RMSs based on simulation data (as summarized in Table 9.1 and Table 9.4).

The domain variability of SCRs is explained in Section 5.9 which depicts that the SCR attributes (i.e. probability and impact) are not single point data; rather, they vary across a range depending on the boundary conditions defined by the experts. The same is true for RMS attributes (such as relationship scores and costs of implementation). The domain variability of SCRs and RMSs ultimately leads to the concept of the development of a simulation model for supply chain risk management (SCRM).

The concept of a weightage scale is explained in Section 5.8.1 which demonstrates the rationale of the scale and its mathematical formulation. The weightage scale captures the variation among the experts in scoring a particular SCR attribute and determines the appropriate weight for the attribute. Therefore, the ranking based on the weighted score of the SCR attribute is considered superior compared to the ranking without the weighting.

The risk flexibility index (RFI) of an SCR is a simple measure of the RMSs available to mitigate a particular SCR which discerns the number of RMSs suggested by the experts. This index value is useful as it provides more information about a risk and the RMSs available to mitigate the risk. If a risk has more RMSs assigned to mitigate it, then the risk is treated as a flexible risk, whereas if a risk has limited RMSs assigned to mitigate it, then the risk is treated as a rigid risk. A flexible risk (SCR) has more RMSs assigned to mitigate it which means it can be mitigated to a certain level with greater flexibility in the selection of RMSs. This is important as it may not always be possible to implement all RMSs selected for a particular risk due to cost or budget constraints. On the other hand, for a rigid risk, a limited number of RMSs is assigned to mitigate it and thus flexibility in the selection of RMSs is less. Therefore, the RFI is a useful index in understanding the nature of a risk with respect to the RMSs available to mitigate it.

Details of the development of the simulation model are explained in Chapter 8. The rankings of SCRs and RMSs based on simulated data are summarized in Sections 9.2 and 9.4 and the relationships between SCRs and RMSs are summarized in Section 9.3. Rankings based on simulated data are considered superior compared to those without simulation as simulation data consider other possible ranges of options of SCR and RMS attributes within the range of these attributes.

9.8 Chapter Summary

This chapter has discussed the findings from this research in the light of the study's objectives. The SCRs and RMSs are identified and the relationships between the SCRs and RMSs are defined. The SCRs and RMSs are prioritized and ranked based on SCR and RMS attributes. The highly probable and high impact risks are identified and ranked accordingly. The SCRs are also ranked based on risk indices. Different rankings are compared and a better approach is recommended. The RMSs for highly probable and high impact risks are identified and summarized based on 50 simulations. Optimal sets of RMSs for different cost scenarios are summarized from the solving the optimization model and the simulation model. Results from the simulation model were found to be superior compared to the optimization model's results. The optimization model was found to be reliable and valid; thus, the results demonstrate some credibility considering the variations. Based on the findings, the research objectives were addressed

CHAPTER 10

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

10.1 Chapter Introduction

In this chapter, the findings of this study, the implications of the findings and the contributions in the knowledge areas are explained. A summary of the research is presented. The contributions of this research in theory and practice are outlined. The development of a decision tool is explained. Implications of the findings from this research for the LNG industry in Australia are highlighted. The research limitations are indicated and the future research directions are outlined.

10.2 Summary of Research

Based on the review of the literature, a comprehensive list of LNG SCRs was prepared. To mitigate the SCRs, a comprehensive list of LNG supply chain RMSs was prepared. The SCRs and RMSs were then verified by an LNG industry expert. Some minor revisions of the SCR list and RMS list were carried out following this expert's review. Primary data were collected from six LNG experts. The SCRs were prioritized following a widely used supply chain risk formula (*risk = probability x impact* [Cox, 2012]). A weightage scale was developed to capture the consensus among the experts in scoring SCR attributes (i.e. probability and impact). The SCRs were also prioritized based on the weighted average of the SCR attributes. As the weighted average score considered consensus among the experts, the ranking based on the weighted average score was found superior compared to the ranking based on the average score. The experts' six sets of scores of an SCR are six realizations of a greater number of possible realizations of SCR attributes. With an increase in the survey sample (if possible), this could result in a much greater number of realizations of SCR attributes. Considering the challenges of the study of LNG SCRM, a simulation approach for SCR attributes was adopted and explained which ultimately translated into the development of a simulation model for LNG supply chain risk management (SCRM).

The LNG supply chain RMSs were prioritized following the conventional QFD method. The QFD method's relationship matrix method defined the relationships between SCRs and risk mitigation strategies (RMSs). A conventional QFD scale of 1-5-9 was used to define relationships between SCRs and risk mitigation strategies (RMS). From the SCR attributes and relationship scores between SCRs and RMSs, the absolute importance (AI) scores of RMSs were calculated. The AI score of an RMS represents the importance of an RMS in mitigating a supply chain risk (SCR). The RMSs were ranked based on the AI scores. The relative absolute importance (RAI) score was calculated for which the sum of all RAI scores is equal to 1. The relative scale of RAI facilitated the comparison between the experts.

The costs of implementing RMSs were estimated based on the data collected from the LNG experts. The costs were converted into a relative scale where the sum of the costs of implementation of all RMSs is equal to 1. The relative effectiveness (RE) of an RMS was calculated which represents the relative importance of an RMS that can be achieved per unit of relative cost (RC). The RMSs were ranked based on their relative effectiveness (RE).

An optimization model was developed and solved in order to find optimal sets of RMSs for different cost scenarios. Nine cost scenarios were defined based on availability of their budget. The objective function was developed and cost constraints were defined. The optimization model was developed and solved based on data from an individual expert and then ensemble means were derived. The optimization was also solved based on consensus mean data from the six experts. The results of the optimization from the consensus means and the ensemble means were compared.

The findings of the optimization model were extended and explained further through the development and solving of a simulation model. The boundary conditions of the simulation model were defined as the minimum and maximum scores of the SCR and RMS attributes collected from the six experts. The RAND() function of MS Excel was used to develop the simulation model. The simulation model was solved for 50 simulations. The results from the simulation model were compared with the results from the optimization model. The model reliability and validity were evaluated. The research questions were discussed based on the findings from the research. The findings of this study are useful for supply chain risk mitigation for the LNG industry in Australia.

10.3 Contributions of the Research

10.3.1 Theoretical contributions

Until recent times, LNG SCRs were generally seen as unavoidable and thus they have received little attention (Burr, 2005). Supply chain risk management (SCRM) is also a relatively new field of research, and it is currently chaotic and, to some extent, disorganized (Trkman and McCormack, 2009). Regarding the LNG supply chain, to date, very limited work has been carried out. Thus, the research methods for LNG SCRM are not well developed and the theoretical base is not well established. This study proposed a research framework consisting of prioritizing SCRs based on the widely used risk formula (*risk = probability x impact* [Cox, 2012]) and prioritizing RMSs following the conventional QFD method. An optimization model was then developed which was solved following quadratic integer programming. A simulation model was developed and solved following the principles of the optimization model. Hence, this research contributes to methodology and theory development in the area of LNG supply chain risk management (SCRM).

This study of LNG supply chain risk mitigation in Australia is quite unique and can be treated as a comprehensive effort in the field of supply chain risk mitigation. This study is also unique as a method for LNG supply chain risk mitigation has been developed under a newly formulated theoretical framework and the method has then been applied to mitigate LNG supply chain risk mitigation in Australia. The development of a method and its practical application in LNG supply chain risk mitigation are quite a significant contribution in the knowledge areas of supply chain risk mitigation for four main reasons. Firstly, supply chain risk mitigation is an emerging area of research, with the absence of well-defined methods and also the lack of a theoretical framework for carrying out such research. Secondly, LNG is a new form of energy in the international market and few, in any, studies have been carried out to date on LNG supply chain risk mitigation, in particular, for the Australian LNG industry. Thirdly, the LNG supply chain is very complex to study for reasons such as long-term investment; international ventures; geopolitics; cross-regional trade; the involvement of rapidly emerging technology; a changing energy market with the emergence of technology, etc. Fourthly, as a relatively new industry, a very limited number of experts is available globally who have a comprehensive understanding of the LNG supply chain. In addition, these experts are very busy with their commitments; thus, collecting primary data for supply chain risk mitigation is quite challenging. Therefore, this study has dealt with two emerging areas of research (supply chain risk mitigation and a new product, LNG), a complex supply chain and the limited availability of data. Considering these challenges, the development of a method for supply chain risk mitigation and its application in supply chain risk mitigation for the LNG industry of Australia is real progress in supply chain risk mitigation. Furthermore, the method developed in this study can be treated as a generalized method for supply chain risk mitigation and can be applied to study supply chain risk mitigation of other products or services. Hence, this study can be treated as a real step forward in the areas of supply chain research.

10.3.2 Practical contributions

The issue of energy security is crucial for Australia for its development and sustainability. Australia has limited crude oil with relatively greater reserves of natural gas and coal. With the development of technology in recent times, LNG has emerged as a global commodity with greater flexibility of its transportation, both by container and through pipeline. This has created a lucrative opportunity for Australian natural gas to be exported as LNG to the Asia-Pacific energy market where demand for energy is growing and is expected to continue in the future. However, recent figures from ABARE indicate that Australia is exporting more LNG for less value. In addition, as LNG is a form of natural gas, it is a relatively clean form of energy. Due to carbon tax, demand for clean energy in the domestic market will also increase. Thus, LNG exporters are demanding best value from their exports, hence sustainable exports. Australia will also face more competition from other LNG exporting countries in the region regarding price, investment, technology, operation challenges (e.g. cost, labour), policy changes, etc. To capitalize on the opportunity of the growing energy market in the Asia-Pacific region, Australia needs to have secure upstream investment in the LNG supply chain. This research has developed strategies for LNG SCRM in Australia for securing upstream investment and maintaining sustainable exports. For example, appropriate policy measure to ensure long term fiscal stability is likely to improve investment attractiveness for future LNG projects.

This study of LNG supply chain risk mitigation is quite comprehensive in nature. Most of the supply chain risk mitigation studies result in the identification of SCRs followed by prioritization of the risks and plotting the risks into a heat map. Only limited studies have extended to the identification of RMSs for supply chain risk mitigation and assigning these RMSs to mitigate the risks. Few, if any, studies have extended into estimating the costs of implementing RMSs; developing an optimization model to find optimal sets of RMSs for different cost scenarios; and developing a simulation model for generalization of the optimization results leading to the development of a decision model. In this respect, the method developed in this study is a comprehensive method for studying supply chain risk mitigation starting from the identification of the risks leading to a decision model for supply chain risk mitigation. Therefore, the LNG supply chain risk mitigation carried out in this study can be treated as a comprehensive study of its kind.

10.3.3 Development of a decision model for LNG SCRM

The optimization problem developed for LNG SCRM can be solved for any level of cost or budget constraint between 0% and 100% of the total cost of implementing all the risk mitigation strategies (RMSs). The optimization results provide a level or amount of risk mitigation and an optimal set of RMSs to be implemented within the cost or budget constraints. Through solving the optimization problem for a set of cost constraints (without cost savings), a corresponding set of levels of risk mitigation and a respective set of RMSs to be implemented would be available to managers or decision makers. By plotting the results of the level of risk mitigation against the corresponding cost or budget constraints, an *optimization diagram* (Figure 10.1) can be developed. An exponential or polynomial best fit curve can be fitted with the points representing the levels of risk mitigation for the corresponding cost or budget constraints. The same process can be repeated considering cost savings in the cost constraint function. The optimization diagram appears a useful tool for risk managers or decision makers responsible for SCRM decision making to gain an understanding of the level of risk mitigation that can be achieved with a certain level of cost or budget allocation. Once management has decided to achieve a certain level of risk mitigation, this will lead to certain budget constraints; however, for any level of budget constraint, the optimization problem can be solved to obtain an optimal set of RMSs to be implemented.

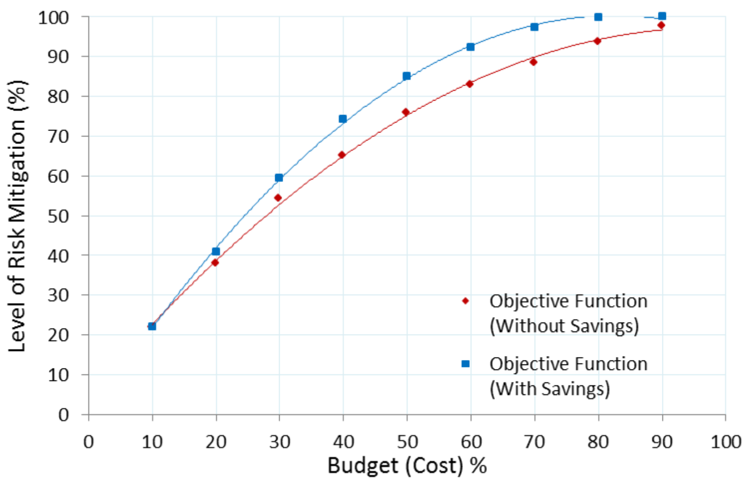


Figure 10.1: Example "*optimization diagram*" for supply chain risk mitigation showing level of risk mitigation with respect to budget constraints

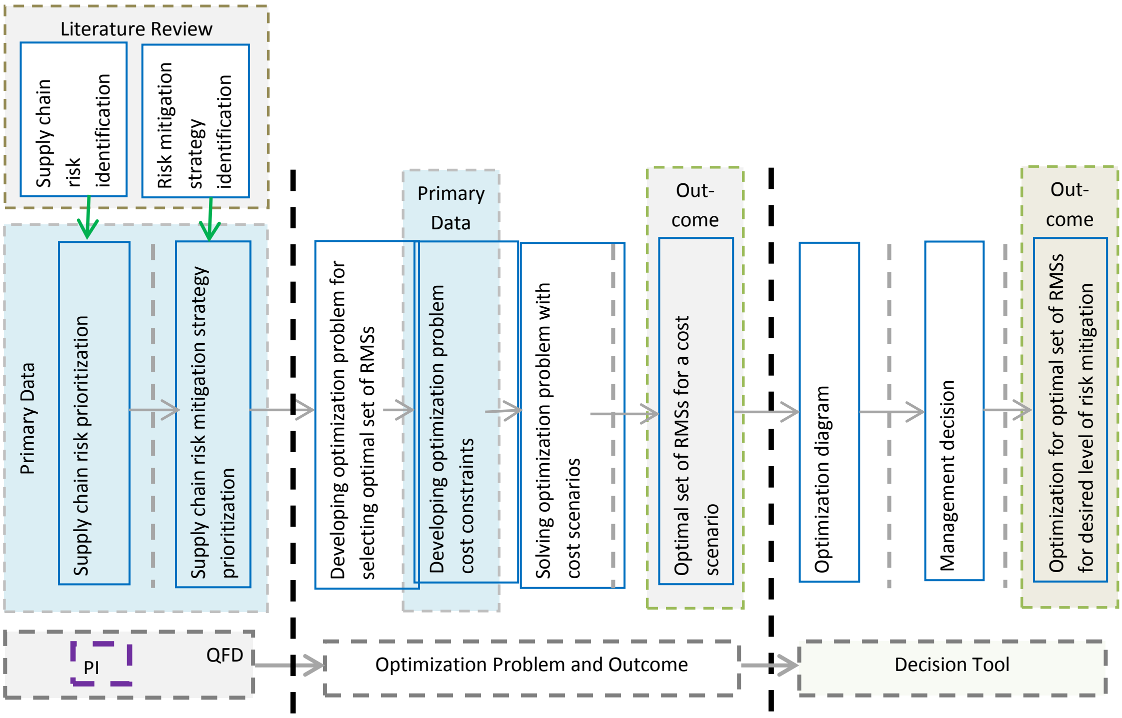


Figure 10.2: Decision model for supply chain risk management showing methods, processes and outcomes

A decision model for SCRM showing the methods, processes and outcomes is presented in Figure 10.2. The decision model appears a useful approach for SCRM as it incorporates all the different stages of SCRM from beginning to end. The model consists of three major components or stages: (i) integrated application of QFD method with probability impact method for SCR prioritization and RMS prioritization; (ii) developing and solving the optimization problem to obtain an optimal set of RMSs for a particular cost constraint; and (iii) developing a decision tool for risk managers or decision makers to make decisions on supply chain risk management (SCRM).

The model starts with the identification of SCRs followed by risk prioritization using the probability impact method. Most SCRM studies result in these two stages where, in some cases, the prioritized risks are presented in a matrix form, on charts or as a heat map. The decision model here identifies RMSs for mitigating the risks and then extends to RMS prioritization through the QFD method. It is quite useful for risk managers to have the risks identified and prioritized, and also to have the corresponding RMSs identified and prioritized for supply chain risk management (SCRM). The information developed in the first stage of the decision model is usually very useful for risk managers or decision makers responsible for decision making for SCRM as usually this information rarely becomes available during decision making. However, this information is not sufficient for efficient and effective decision making. For example, risk managers or decision makers need to know answers to questions like: where to allocate limited resources; what strategies need to be implemented to obtain the maximum level of risk mitigation; and whether the most important RMS is cost-effective. For effective and efficient decision making, in the second stage of the decision model, an optimization problem has been developed through maximizing the amount of risk mitigation that can be achieved with limited resources, that is, introducing cost as a constraint. Through solving the optimization problem, the risk manager or decision maker would then know the level of risk mitigation that could be achieved for a certain amount or level of cost. They would also obtain an optimal set of RMS that needs to be implemented to achieve the desired level of risk mitigation within the cost constraints. Thus, management would be able to make an informed decision on risk mitigation in supply chain risk management (SCRM). The third stage of the decision model for SCRM is the development of a decision tool for management decision making. Here, an optimization diagram has been developed through solving the optimization problem for different cost scenarios and plotting the level of risk mitigation achieved against the cost incurred (Figure 10.1). From this diagram, a risk manager or decision maker can easily make decisions about what level of risk mitigation can be achieved with limited resources. Once the decision is made either on the level of risk mitigation or on resource allocation, the optimization problem can be solved to obtain an optimal set of RMSs that need to be implemented to achieve the desired level of risk mitigation with limited cost or limited resources. Therefore, the decision model presented here is quite comprehensive for supply chain risk management (SCRM).

10.4 Implications for LNG Industry in Australia

This study is a practical work on supply chain risk mitigation for LNG industry in Australia. Here, the risks to the LNG supply chain are identified and prioritized. The risk mitigation strategies (RMSs) are identified and these RMSs are assigned to mitigate the risks. The costs of implementing the RMSs are estimated. An optimization model has been developed and solved for finding optimal sets of RMSs for different cost scenarios. A simulation model has been developed for generalization of the optimization results. Finally, using the results of the optimization model, a decision support system is developed which is a useful decision tool for mitigating LNG supply chain risks in Australia. The identified risks to the LNG supply chain in Australia and the associated RMSs were checked by a local LNG industry expert. In addition, the primary data collected to carry out the analysis in this study were sourced from local and global LNG industry experts. Therefore, the findings of this study of LNG supply chain risk mitigation in Australia warrant a great deal of credibility. Hence, despite a few limitations, this study has made a great contribution to the theory and method of supply chain risk mitigation and is a creditable practical work of LNG supply chain risk mitigation in Australia.

The LNG supply chain risks (SCRs) identified here are specific to Australian LNG industry. Similarly, the RMSs identified for mitigation of the SCRs are also specific to Australian context. In addition, the SCRs are dependent and influenced by many factors as explained in Chapter 3. Therefore, the SCRs are dynamic in nature and expected to change over period depending on the factors (such as changes in national and international policy). A particular risk for Australia could be an opportunity for other country. Hence, generalization of the SCRs and RMSs identified for Australian LNG industry are impossible in global context for other countries. Thus, the findings of this study are not externally valid, i.e. the findings are not transferable to other country context.

10.5 Research Limitations

While this study has explored many aspects of LNG supply chain risk and risk mitigation strategies, as with every other study, it is not without limitations. The LNG supply chain is very complex and studying LNG SCRs and RMSs is a multidimensional problem. The absence of a well-defined methodology for studying SCRM is another dimension of complexity in studying LNG supply chain risks (SCRs). Even the individual risk itself is multidimensional and influences or is influenced by many factors.

One limitation of this study is the limited set of primary data collected for LNG supply chain risk mitigation. As LNG is a relatively new industry, not many experts were available globally who were willing to participate in a survey. In addition, the LNG industry is highly technical and an understanding of the full supply chain is difficult to learn, with not many experts having this understanding. The experts were busy and completing the questionnaire needed a reasonable amount of time.

Another limitation of this study is defining the level of the interrelated risk mitigation strategies (RMSs). Here, the level of relationship was defined by the researcher based on consultation with two experts. The correlation matrix score could be collected through the survey. However, this could make the questionnaire a bit longer leading to difficulties in receiving responses as well as compromising the quality of collected data.

A weightage scale was developed and applied to measure consensus among the experts in scoring the SCR attributes. Then, the weighted average score of the SCR attributes was calculated and SCRs were prioritized based on the weighted average attributes. However, in calculating the absolute importance (AI) of RMSs, such weighted score of SCR attributes was not considered. Instead, the AI scores of RMSs were calculated following the conventional QFD method. Thus, the weighted attributes of SCR can be used in calculating the AI for RMSs which may improve the results of the prioritization of risk mitigation strategies (RMSs). Such a weightage scale can also be applied to the QFD method's relationship matrix to address the consensus among the experts, considering the variability.

Another limitation was observed in terms of the optimization algorithm based on quadratic integer programming. If the AI score of an RMS is assigned a value of 0, then that RMS should not be selected in the optimization process as these RMSs do not improve the level of optimization, instead increasing costs. However, it was found that RMSs with an AI score of 0 were sometimes selected during the optimization process.

10.6 Future Research Directions

This research can be extended through collecting a large set of primary data from the LNG experts. This would enhance the credibility of the study's findings towards generalization through generating a consensus set of risk mitigation strategies (RMSs).

The optimization and simulation model were solved using the Solver function of MS Excel. This process is tedious and time consuming for solving different cost scenarios based on different expert opinions and also when conducting a number of simulations. The optimization and simulation processes can be automated through developing a computer program. The computer program would allow the user to quickly solve the optimization problem for any cost scenario and to automatically prepare graphs and charts for decision making. Hence, automation could be extended to the decision model.

The method developed and applied for LNG supply chain risk mitigation in this study could be applied in other industries. This method can be tested as a general method of supply chain risk mitigation through applying this method to other industries. In the absence of a well-defined method, this method could be a generic method for studying supply chain risk mitigation.

The SCRs can be grouped into sub-groups depending on different criteria. These criteria could be based on different stages of the LNG supply chain (e.g. upstream, mid-stream and downstream). This may help in strategic decision making along the supply chain through identifying weaknesses along the chain. Another way of grouping could be based on the nature of risks (e.g. financial, capital, environmental, strategic, geopolitical, strategic, operational, etc.). This type of analysis would help to identify specific (such as financial, marketing, environmental and strategic) areas of management decision making. This type of grouping of SCRs could be carried out at different stages of analysis. A grouping at an initial stage of the study would provide more flexibility of analysis attributes of the groups. A grouping of SCRs could still be carried out post-analysis and some attributes of the groups could still be determined from the results. For example, the SCRs of this study can be grouped under broad categories of financial, strategic, environmental, Hazardous and operational and thereby SCRs and RMSs attributes of these broad categories can be estimated.

As with the grouping of SCRs, LNG supply chain RMSs could also be grouped based on different criteria. These criteria could be based on different stages of the LNG supply chain or on different strategic areas of risk management.

In defining and prioritizing SCRs, as widely used approach (*risk = probability x impact* [Cox, 2012]) of risk prioritization has been adopted in this study. Other approaches of risk prioritization (such as the use of the analytic hierarchy process [AHP]) could also be adopted. Risk attributes could then be incorporated in the QFD-based optimization and simulation model for prioritizing SCRs, determining the level of risk mitigation and the optimal sets of RMSs for different cost scenarios. There is no specific reason for not choosing other methods (such as AHP) of risk prioritization. However, emphasis has been provided to adopt such research methods which are simple and widely used, thereby, this research would be easily understood by greater community. Also, effort has been made to keep the methods for SCRM as general as possible so that it can be applied to most of the fields of SCRM.

One of the traditional scales (1-5-9) of the QFD method was used in this research to define relationships between SCRs and risk mitigation strategies (RMSs). The use of a continuous scale (for example 1–9) instead of a discrete scale could be considered in future research. This continuous scale may provide more flexibility for defining relationships between SCRs and RMSs in the QFD method's relationship matrix. For example, using the conventional QFD scale, measurement of the relationships between SCRs and RMSs was limited to three categories; weak, medium or strong. It was impossible to define any relationships that were in-between these three categories; for example, the strength of a relationship could lie somewhere between weak and medium or between medium and strong. The use of a continuous scale thus would provide opportunity to define the relationships in a flexible way, thus avoiding the limitations of a categorical (discrete) scale. It is understood that SCRM is an emerging area of research and there is a lack of well-established research methods. One of the objective of this research is to develop a method for SCRM. Therefore, emphasis has been provided to remain within well-established practices in selection of scale and methods to avoid controversy while outmost effort has been given to be pragmatic and innovative in terms of bringing new concepts and ideas (such as measuring consensus, developing weightage scale, exploring variability domain of SCR, developing optimization model and simulation model).

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Appendix A: LNG statistics and summary of QFD based optimization

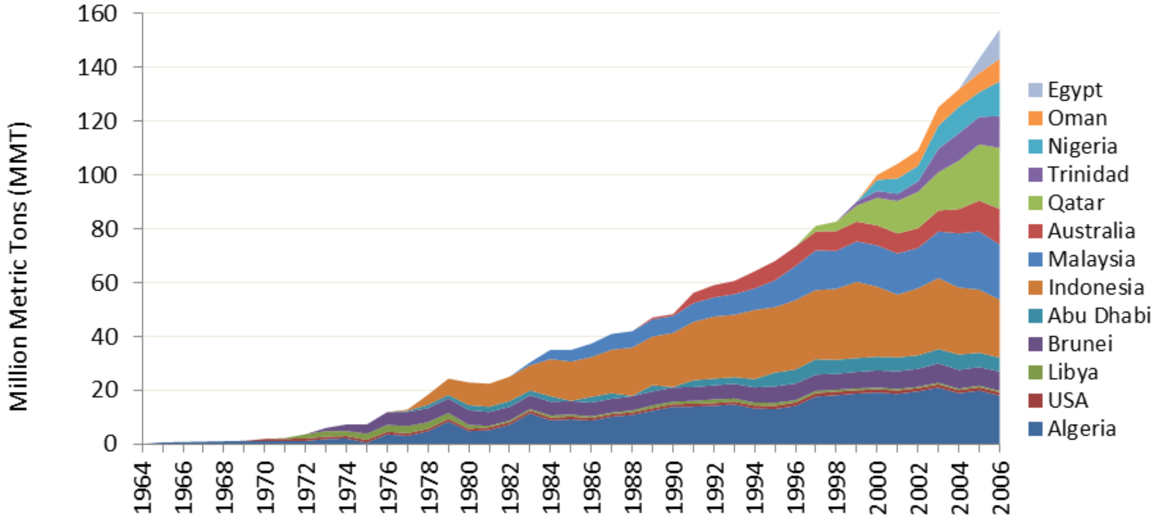


Figure A2.1: LNG production statistics by country from 1964

Data source: http://www.lngpedia.com/lng-statistics/

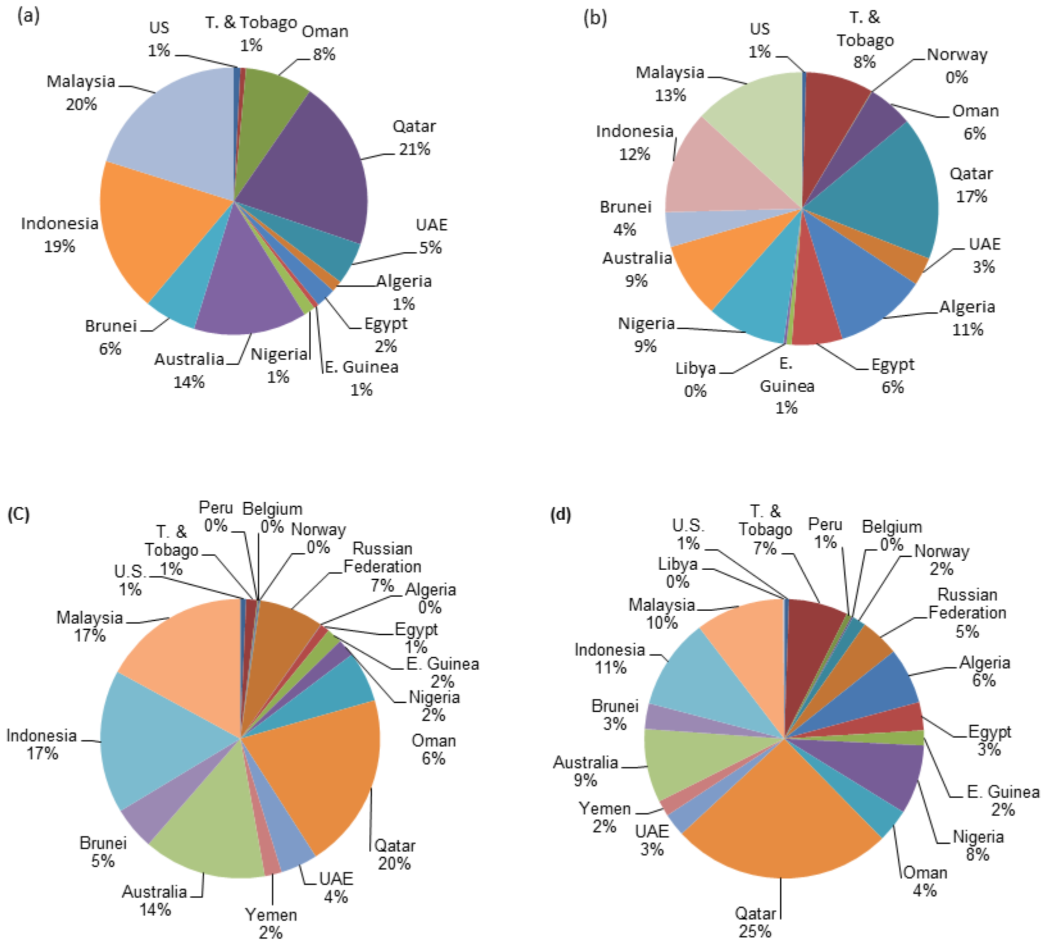
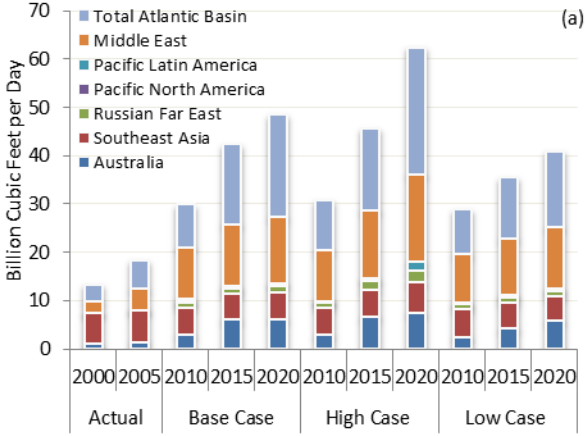


Figure A2.2: Country market share of LNG trade in 2007: (a) Asia-Pacific market; (b) global market and market share during 2010; (c) Asia-Pacific market; and (d) global market

Note: Data source for (a) and (b): Cedigaz. Data source for (c) and (d): BP Statistical Review of World Energy, June 2011).



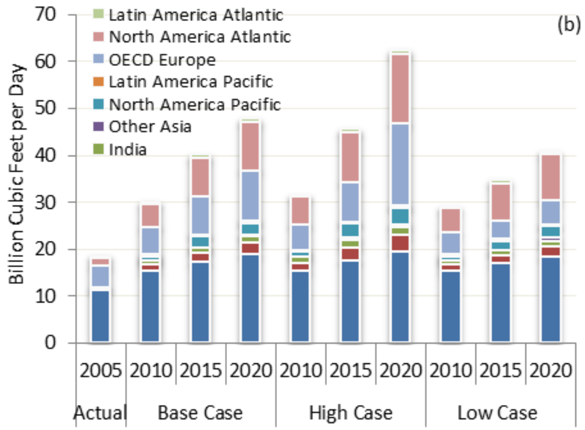


Figure A2.3: Projection of global LNG: (a) supply and (b) demand from different regions to 2020

(Data source: Jensen Associates, 2007)

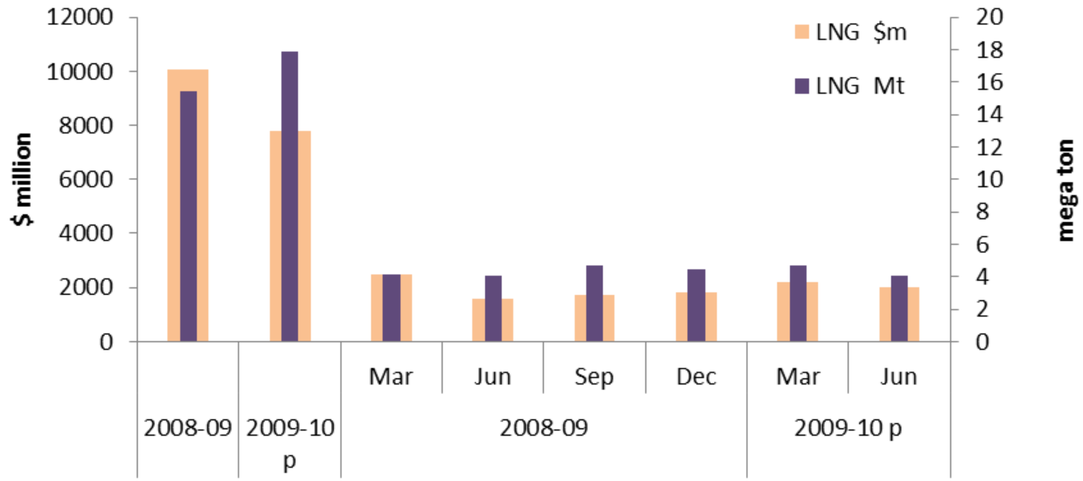


Figure A2.4: Export summary of LNG from Australia in recent times showing export quantity and value earned
(Data source: ABARE-BRS, June quarter, 2010)

Table A2.1: LNG Asia-Pacific market during 2010

(Data source: BP Statistical Review of World Energy June 2011).

Billion cubic metres	From																	
To	US.	T. & Tobago	Peru	Belgium	Norway	Russian Federation	Algeria	Egypt	E. Guinea	Nigeria	Oman	Qatar	UAE	Yemen	Australia	Brunei	Indonesia	Malaysia	**Total LNG**
Australia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
China	-	0.07	0.08	0.08	-	0.51	-	0.08	0.08	0.17	-	1.61	0.08	0.70	5.21	-	2.45	1.68	**12.80**
Hong Kong	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
India	-	0.66	-	-	-	-	-	0.09	0.17	0.33	-	10.53	-	0.37	-	-	-	-	**12.15**
Japan	0.85	0.15	-	0.08	-	8.23	0.08	0.57	0.72	0.84	3.80	10.15	6.86	0.16	17.66	7.78	17.00	18.55	**93.48**
Malaysia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
Singapore	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
South Korea	0.35	0.88	0.08	0.08	0.16	3.90	-	0.98	1.85	1.18	6.11	10.16	0.25	2.27	1.33	1.05	7.42	6.39	**44.44**
Taiwan	-	0.51	-	-	0.07	0.67	-	0.17	0.35	1.09	0.50	3.75	0.42	-	1.06		2.62	3.68	**14.90**
Thailand	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
Total (Asia-Pacific)	**1.20**	**2.27**	**0.16**	**0.24**	**0.23**	**13.31**	**0.08**	**1.89**	**3.17**	**3.61**	**10.41**	**36.20**	**7.61**	**3.50**	**25.27**	**8.83**	**29.49**	**30.31**	**177.77**
Total (Global)	**1.64**	**20.38**	**1.82**	**0.57**	**4.71**	**13.40**	**19.31**	**9.71**	**5.16**	**23.90**	**11.49**	**75.75**	**7.90**	**5.48**	**25.36**	**8.83**	**31.36**	**30.54**	**297.63**

Table A2.1A: Summary of two dimensions of risks as defined by various scholars.

Definition/ theme	Risk Component		References
	Likelihood	Impact	
Common definition or theme	likelihood of occurrence	consequences	Ritchie and Brindley, 2007
Two important dimension of risk	expectation of risk sources	outcome of risk impact	Tang and Musa, 2011
Is consequence of risk negative?		risk as being associated with negative consequences	Christopher and Lee, 2004; Paulsson, 2005; Spekman and Davis, 2004; Wagner and Bode, 2006
Debate on expectancy of risk	expectancy of an event and its measures (probability or frequency of occurrence) still remain a well-debated issue		Tang and Musa, 2011
Debate on expectancy of risk	Can risk be treated as an expected event such as quality deficiencies?		Wagner and Bode, 2006
Debate on expectancy of risk	Can risk be treated as an unexpected event such as terrorist attacks, wars, natural disasters, etc.?		Christopher and Lee, 2004; Kleindorfer and Saad, 2005; Quinn, 2006
Control over consequence		environmental disruptions (such as power failure, fire, flood etc.) which are beyond their control	Zsidisin et al., 2005

Table A2.1B: Summary of methods of SCRM as identified by various scholars.

Theme	Definition SCRM process and methods	References
SCRM is a process	Steps of SCRM vary widely among SCRM studies depending on the scope of the study, nature of the industry, expertise of researchers and other factors (such as accessibility of risk information, availability of funding, needs of the industry, etc).	Sodhi et al., 2012
a conceptual framework for analysing risk in supply networks	Stages of a supply network are: (i) define structure of the network; (ii) analyse the dynamics of risk; and (iii) assess the impact of risk.	Keow Cheng and Hon Kam, 2008
A framework for managing the risks of disruption in the supply chain	four main premises are: (i) specifying the nature of underlying hazards leading to risk; (ii) risk assessment through quantification; (iii) approach for managing risk; and (iv) appropriate management policies and actions aligned with the supply chain	Kleindorfer and Saad, 2005
Review of SCRM literature and grouping SCRM process	Reviewed the existing SCRM literature and identified the SCRM process, grouped the SCRM process into four elements: (i) risk identification; (ii) risk assessment; (iii) risk mitigation; and (iv) responsiveness to risk incidents.	Sodhi et al., 2012
Review of supply chain risks and risk management methods	reviewed supply chain risks and risk management methods focusing on risk identification, risk measures and risk management	Yu and Li, 2011
Methods for risk identification in SCRM	methods for risk identification are comprehensive analysis, classification and analysis of judgment (Haiyan, 2007); risk mapping technology (Souter, 2000); the statistical probability model and supply chain model (Zolkos, 2003); and the data mining method (Zhang and Huang, 2004)	Haiyan, 2007; Souter, 2000; Zolkos, 2003; Zhang and Huang, 2004
Methods for risk measurement in SCRM	The risk measurement methods that were found in Yu and Li's (2011) review are conditional value at risk (Wu and Wang, 2004); the supply chain operations model (Lin, 2005); a two-level programming model with expected loss (Wang et al., 2008); and the back propagation neural network model (Wang, 2010)	Yu and Li, 2011; Wu and Wang, 2004); Lin, 2005; Wang et al., 2008; Wang, 2010
Grouping of risk management methods	the risk management methods reviewed are grouped under five theoretical domains: (i) theory of operation; (ii) theory of cost; (iii) theory of elasticity; (iv) theory of options; and (v) the information coordination and theory mechanism	Yu and Li (2011)
Categorization of SCRM articles	categorized SCRM articles into three groups: (i) conceptual; (ii) quantitative empirical (statistical analysis of empirical data); and (iii) qualitative empirical (case studies)	Sodhi et al., 2012

Table A2.2: Summary of optimization works based on quality function deployment (QFD) method

Source	Study area/objective	Weight	Objective function (as presented by author/s)	Constraints/variables
Wasserman (1993)	A decision model for prioritizing design requirements during the QFD planning process	1-3-9	$Z = \max\{w_1.x_1 + w_2.x_2 + ... + w_n.x_n\}$ The objective function is a simple, linear weighting of the technical importance measures, w_j for the normalized relationship matrix, and the decision variables, x_j for j = 1,2, ..., n.	A linear cost constraint is proposed where the cost coefficients, c_1, c_2, ..., c_n represent the incremental increase in unit cost associated with a change in x_j. $c_1.x_1 + c_2,. x_2 + ..., c_n. x_n \leq B$, c_j: incremental change in unit cost when x_j = 1,2, ..., *n*, is varied. *B:* maximum incremental unit cost targeted.
Park and Kim (1998)	Determination of an optimal set of design requirements using House of Quality.	Rate swings of all other attributes on a 0–100 scale followed by normalization	An integer programming model for maximizing customer satisfaction by selecting appropriate DRs is formulated as follows: $$Max f(x) = \sum_{j=1}^{n} (AI_j) \times x_j$$ s.t. $g_k(x) \leq B$ for k = 1,..............., l $x \in X.$ where AI = absolute technical importance rating of DR_j, *x* = 0–1 decision variable for DRj (i.e., if DR_j is selected, *x =1*. Otherwise, it is 0), *x* = a decision variable vector, { x_j}, *j=1*, ..., *n*, $g_k(x)$ = *k*th organizational resource constraint, *l* = number of organizational resource constraints.	The cost constraint function in a quadratic form is as follows: s.t. $g_j(x) \leq B$ for *j* = 1,..............., n $$g_j(x) = \sum_{j=1}^{n} c_j \times x_j - \sum_{i=1}^{n} \sum_{j>i}^{n} s_{ij}\, x_i x_j$$ where s_{ij} is saving of resource (e.g. cost) usage associated with simultaneous implementation of *i* th and *j*th DRs. c_j is cost required to include DR_j, and B is a given total target cost.
Zhou (1998)	Fuzzy logic and optimization models for implementing QFD	A set of numbers from 1 to 9 is used as a scale for paired comparison	A mixed integer linear programming (MILP) model is proposed as: $$Max \sum_{i} a_i\, d_i^{-1} x_i$$	The objective function maximizes the sum of the utility values. Constraint (i) imposes that no improvement is made to an engineering characteristic that is not

Source	Study area/objective	Weight	Objective function (as presented by author/s)	Constraints/variables
			subject to $x_i \leq z_i P_i \quad \forall i \quad (i)$ $\sum_i (D_i z_i + c_i x_i) \leq B \quad (ii)$ $l_i \leq x_i \leq u_i \quad \forall i \quad (iii)$ $z_i \in \{0,1\} \quad \forall i \quad (iv)$	selected. P_i is any number that can make $z_i P_i \geq u_i$ when $z_i = 1$. Constraint (ii) ensures that the total cost of improvements does not exceed the given budget limit. Constraint (iii) enforces the competition requirement and technological feasibility. Constraint (iv) represents integer function.
Vairaktarakis (1999)	Optimization tools for design and marketing of new/improved products using the House of Quality		• An integer programming model for the identification of a parts mix for the new/ improved product. • An optimization model for the identification of a single "consensus" ranking of customer preferences for the product. • Shows how the information stored in the HoQ charts can be used to identify perceptual gaps (i.e. cases where one competitor is falsely perceived to perform better than another). The following model identifies a parts mix (if one exists) that maximizes product performance without exceeding the budget *W* for the materials. For $1 \leq k \leq n_0$ and $1 \leq l_k \leq n_k$, consider the binary variables: $x_{kl_k} = \begin{cases} 1 & if\, p_{kl_k}\ is\ selected\ among\ the\ alternatives\ for\ P_k \\ 0 & otherwise \end{cases}$ and the model:	The set (i) of constraints corresponds to the assignment of part options in the parts mix; constraint (ii) is the budget constraint; and equation (iii) corresponds to the integrality constraints.

<table>
<tr><th>Source</th><th>Study area/objective</th><th>Weight</th><th>Objective function (as presented by author/s)</th><th>Constraints/variables</th></tr>
<tr><td></td><td></td><td></td><td>$$(P)\ \max \sum_{k=1}^{n_0}\sum_{l=1}^{n_k} w_k\, p_k\,(c_{kl})x_{kl}$$
subject to
$$\sum_{l=1}^{n_k} x_{kl} = 1 \quad k = 1,2,\dots\dots\dots,n_0 \qquad (i)$$
$$\sum_{k=1}^{n_0} x_{kl}\sum_{l=1}^{n_k} c_{kl}\ x_{kl} \ \le\ W \qquad (ii)$$
$$x_{kl}\ \in \{\,0,1\}\ \ 1 \le k\ \le\ n_o, \quad 1\ \le l_k\ \le\ n_k \qquad (iii)$$</td><td></td></tr>
<tr><td>Fung et al. (2002)</td><td>Product design resources optimization using a non-linear fuzzy quality function deployment model</td><td></td><td>• The objective for determining the planned attainments for technical attributes (TAs) in QFD is usually to maximize the overall customer satisfaction. Taking into consideration the imprecision in primary cost, budget limitations and other technical constraints, a fuzzy QFD planning model (FP) was formulated (p. 591).</td><td>(i) the imprecision in primary cost
(ii) budget limitations
(iii) other technical constraints</td></tr>
<tr><td>Bai and Kwong (2003)</td><td>Inexact genetic algorithm approach to target values' setting of engineering requirements in QFD</td><td></td><td>• Instead of determining one set of exact optimal target values for engineering requirements, this approach can generate a family of inexact optimal solutions with the consideration of various design scenarios.
• Based on Kim et al. (2000), a more general fuzzy optimization model for target values' setting of engineering requirements in QFD is proposed with the objective function to maximize the degree of satisfaction of customers to customer requirements</td><td>Two sets of fuzzy relationship constraints and a set of cost constraints</td></tr>
</table>

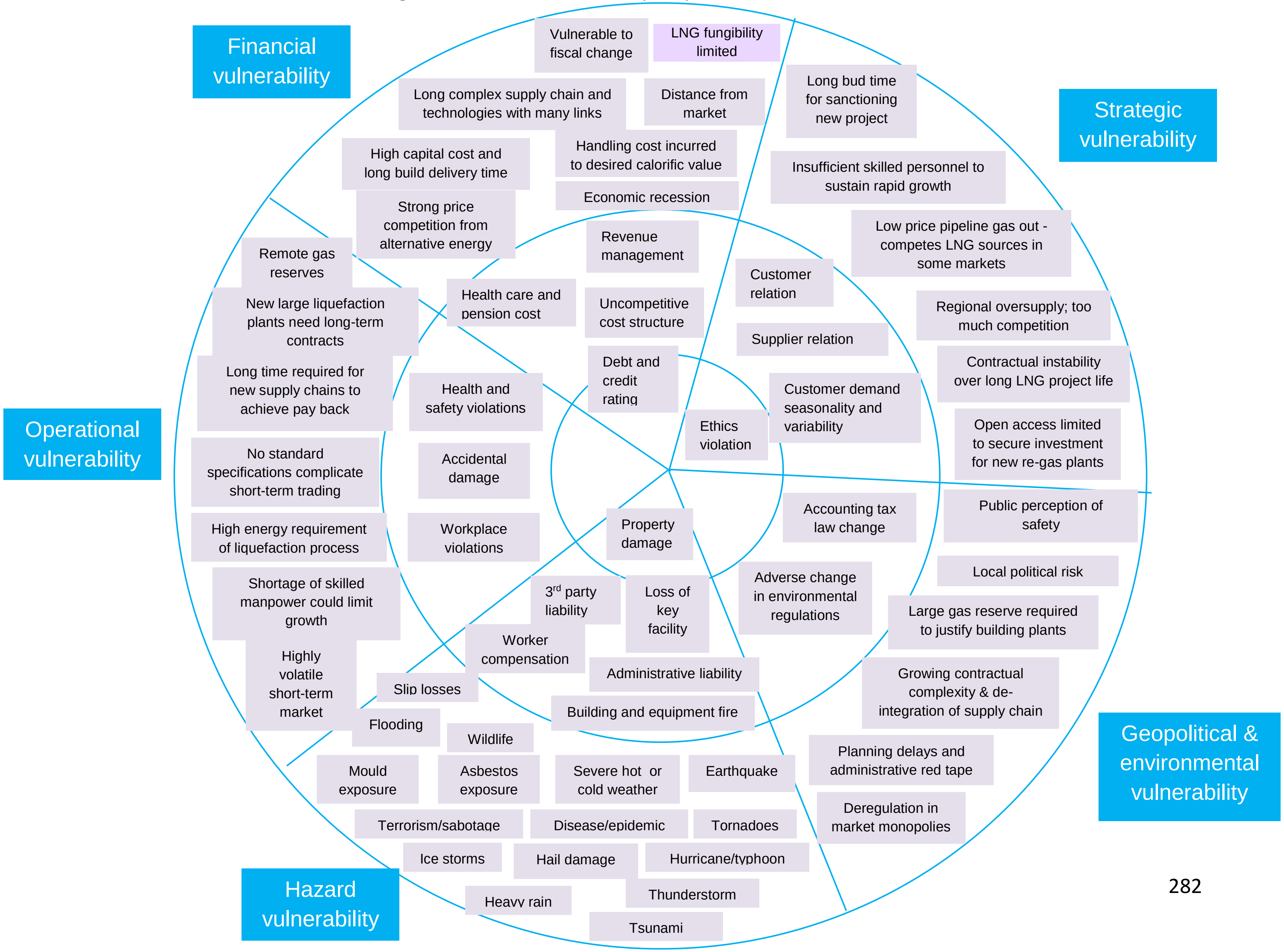
Source	Study area/objective	Weight	Objective function (as presented by author/s)	Constraints/variables
			• Zimmermann's (1996) tolerance approach was adopted to solve the fuzzy optimization model. • An inexact genetic algorithm (GA) (Wang and Fang 1997) is employed to generate a family of inexact satisfactory target values' setting for engineering requirements from the fuzzy optimization model	
Yang et al. (2003)	Quality function deployment-based optimization and exploration for ambiguity		• A customer-oriented optimization method that reflects the customer's preferences for making a trade-off between multiple objectives. • A set of target design objective levels to attain maximum overall customer satisfaction level is selected by generating part of the whole Pareto set, enabled by constructing an approximation model for a Pareto surface (p. 91).	Making trade-offs between multiple objectives (customer needs)
Lai et al. (2004)	Optimizing product design using the Kano model and QFD		• The optimization model's objective is to maximize the difference in customer satisfaction between the to-be-designed product and the benchmark product which can be achieved with the objective function of minimizing the weighted difference of the to-be designed product and the ideal situation (p. 1088)	(i) cost of unit improvement in engineering characteristics (ii) cost limit
Fehlmann (2005)	Impact of linear algebra on QFD		• This traditional way of calculating solution profiles from a QFD matrix is the first step but does not yield the optimum solution. • The convergence factor is the natural metric for optimization, measuring how well one's choice of solution profile matches the goal. • The formula for the convergence factor is the length of the profile difference between the	(i) add more solution components that better support the goal topics (e.g. the customer's needs) until the convergence factor decreases (ii) normalized "raw weight" using the normalization formula

Source	Study area/objective	Weight	Objective function (as presented by author/s)	Constraints/variables
			goal profile and the effective profile, divided by the number of profile coefficients (p. 89).	
Lai et al. (2005)	Dynamic programming for QFD optimization		The overall optimization model is as follows: $$Max\ CR = \sum_{j=1}^{n} (CR_j)\ (x_j)$$ subject to $$\sum_{j=1}^{n} (x_j)\ \leq C$$ j = 1,2,………………n where *C* is the total budget, $CR_j\ (x_j)$ is the overall customer satisfaction achieved when a budget of x_j has been allocated to a technical attribute *j*, and *n* is the number of technical attributes.	(i) Cost alternatives of technical attributes (ii) Total cost or budget
Kahraman et al. (2006)	A fuzzy optimization model for the QFD planning process using the analytic network approach		A fuzzy analytic network process (ANP) model is used for the prioritizing of product technical requirements (PTRs) in QFD. The results of the model, the evaluation algorithm steps for determining the overall priorities of the PTRs, are used for the estimation of the objective function's coefficients in an optimization model based on mixed-integer programming. A clear objective is to identify the best improvements so the total utility value is maximized and all constraints satisfied. The considered optimization model is as follows: $$Maximize \sum a_i\ d_i^{-1} x_i$$ subject to	(i) the first constraint represents that no improvement is made to a PTR that is not selected. (ii) The second constraint ensures that the total cost of improvements does not exceed the given budget limit. Due to limited resources, a budget constraint is often necessary to ensure that the total cost of improvements must not exceed the given budget. (iii) The third constraint enforces the competition requirement and technological feasibility. In other

Source	Study area/objective	Weight	Objective function (as presented by author/s)	Constraints/variables
			$x_i \leq z_i P_i \quad \forall i \quad (i)$ $\sum_i (D_i z_i + c_i x_i) \leq B \quad (ii)$ $l_i \leq x_i \leq u_i \quad \forall i \quad (iii)$ $z_i \in \{0,1\} \quad \forall i \quad (iv)$ The notations introduced are as follows: c_i = unit cost of improving PTRs; B = Budget limit, l_i = the lower bound of x_i and u_i = the upper bound of x_i.	words, to be competitive, a company usually sets its targets better or at least not worse than its competitors. Any improvement must be subjected to technological feasibility enforced by available resources.
Lai et al. (2006)	QFD optimization using linear physical programming		The aim of the design team is to attain the highest customer satisfaction level while meeting budget limitations. The linear programming (LP) mathematical expressions are formulated.	(i) only constraint is the budget (i) however, in practice, there may be other constraints which can be added.

Appendix B: LNG vulnerability map

Figure A3.1: LNG vulnerability map



Appendix C: Survey questionnaire

Survey Questionnaire

This survey questionnaire is for Supply Chain Risk Management for Liquefied natural gas industry in Australia. It consists of two sections: (i) Probability of occurrence and likely impact of an LNG risk and (ii) Risk mitigation strategies for the risks and cost of implementation risk mitigation strategy.

SECTION 1: Probability of occurrence and likely impact of an LNG risk

The supply chain of LNG industry in Australia are exposed to and influenced by multidimensional risk, both internal and external to the industry. A small change in business environment (for example national or international policy change) may influence LNG supply chain, hence, expose to risk. Through review of literature, LNG supply chain risks for Australia are identified. However, these risks are contextual and vary greatly in regard to their occurrence and likely impact to the supply chain. For each of the risks listed in this section, please circle the number or mark in different colour that best indicate the likely occurrence of a particular risk and its likely impact on the LNG supply chain for Australia. The sequence followed in presenting the risks does not represent any importance or priority of the risk over other in the supply chain.

Risk Probability	Risk Sl. No.	LNG Supply Chain Risk	Impact of Risk
Cannot occur / May or may not occur / Certain to occur 0 5 9 Probability scale			Low / Moderate / High 0 5 9 Impact scale
Please circle or mark with different colour as appropriate			Please circle or mark with different colour as appropriate
0 1 2 3 4 5 6 7 8 9	1	Downgrade of investment attractiveness for new plant	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	2	Occurrences of policy differences in state to state	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	3	Increasing international Pipe line Gas supply	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	4	Payment cost is higher of skill human resources than other competitors	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	5	Lower productivity for LNG production	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	6	Strong AU$ (local currency)	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	7	Different kind of reception terminal and storage facilities	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	8	Cost of energy Mix for securing energy security	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	9	Introduction of carbon tax	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	10	Adoption of new emissions trading scheme	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	11	Strong community concern regarding non-conventional gas exploration	0 1 2 3 4 5 6 7 8 9

0 1 2 3 4 5 6 7 8 9	12	Plant start-up delays	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	13	Supply of gas in domestic market at lower cost hence reduce LNG export	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	14	Competition from other exporter in Global LNG market	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	15	Emergence of new exporter in Global LNG market	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	16	Discovery of new reserve example East Africa	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	17	Emergence of US shale gas revolution	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	18	Extraction of natural gas from Methane hydrate in Japan	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	19	Multiple Regulatory risk	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	20	The emergence of LNG spot market and more short term contract	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	21	High cost due to remoteness of the projects	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	22	Increase competition from other fuels	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	23	Flexible capability of technology adaptation	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	24	Customer demand priority shift to other energy mix	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	25	Over proposed LNG project	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	26	Unstable Fiscal stability and fiscal credibility	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	27	Lack of skilled staff in LNG project	0 1 2 3 4 5 6 7 8 9

0 1 2 3 4 5 6 7 8 9	28	Lessen recovery of Global economic slowdown	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	29	Revision of long-term supply contract revision	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	30	Fluctuation of LNG price due to oil production	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	31	Severe weather (extreme hot, severe thunderstorm) causing low production	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	32	Emergency shutdown of the plant due to Flood	0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9	33	Emergency shutdown of the plant due to tropical cyclone	0 1 2 3 4 5 6 7 8 9

SECTION 2: LNG Supply Chain Risk Mitigation Strategies

A. Instructions to assess the relation between risks and risk mitigation strategies:

Risk mitigation strategies are actions that help industry to avoid or minimize impacts of risks and help to achieve business objectives. Through the review of literature, risk mitigation strategies for LNG supply chain risks are identified and presented in the following table with LNG supply chain risks. Not all strategies are relevant, appropriate or effective with same level of performance to mitigate a specific risk.

Please assess each strategy in relation to its relevance to a particular risk and score it based on the following scale.

1--- Little relevant
5---moderately relevant
9---Highly relevant

B. Assessment of relative cost of implementing risk mitigation strategies:

Relative cost of a risk mitigation strategy is the cost of implementation of strategy for risk mitigation. Assess the cost of implementing of an RMS based on the following scale:

I. Assess the largest cost of implementation a risk mitigation strategy; Score it as 100.
II. Assess the lowest cost of implementation a risk mitigation strategy; Score it as 10
III. Assess the remaining risk mitigation strategies compared to the highest and lowest cost strategies and score a number in between 10 and 100.

Note: An example of assessment matrix (partial) is provided in Appendix 1 for your convenience.

Risk Number	Strategy Number	1	2	3	4	5	6	7	8	9	10
	Risk Mitigation strategy / LNG Supply Chain Risk	Establish secure communication among stakeholders (public, private, community)	Involvement of stakeholders in different stages of project	To address community's threats (financial and environmental) from LNG projects (non-conventional)	Emphasising involvement of community (non-conventional)	Address end-user's confidence (reliability-of supply, competitive price, end-user requirement of quality)	Balanced Carbon tax policy formulation	Increase domestic use of LNG/ natural gas	Policy to increase likelihood of on schedule delivery (timely project completion)	Policy for addressing lack of skilled HR	Select appropriate location satisfying multidimensional requirements
1	Downgrade of investment attractiveness for new plant										
2	Occurrences of policy differences in state to state										
3	Increasing international Pipe line Gas supply										
4	Higher payment cost of skill human resources than other competitor										
5	Lower productivity for LNG production										
6	Strong AU$ (local currency)										
7	Different kind of reception terminal and storage facilities										
8	Occurrence of change energy Mix for securing energy security										
9	Introduction of carbon tax										
10	Adoption of new emissions trading scheme										
11	Strong community concern regarding non-conventional gas exploration										
12	Plant start-up delay										
13	Supply of gas in domestic market at lower cost hence reduce LNG export										
14	Competition from other exporter in global LNG market										
15	Emergence of new exporter in Global LNG market										
16	Discovery of new reserve e.g. East Africa										
17	Emergence of US shale Gas Revolution										
18	Extraction of natural gas from Methane hydrate in Japan										
19	Multiple regulatory risk										
20	The emergence of LNG spot market and more short term contract										
21	High cost due remoteness of the projects										
22	Increase competition from other fuels										
23	Flexible capability of technology adaptation										
24	Customer demand priority shift to other energy mix										
25	Over proposed LNG project										
26	Unstable Fiscal stability and fiscal credibility										
27	Lack of skilled staff in LNG project										
28	Lesson recovery of Global economic slowdown										
29	Revision of long-term supply contract										
30	Fluctuation of LNG price due to oil production										
31	severe Weather (extreme hot, severe thunderstorm) causing low production										
32	Emergency shutdown of the plant due to flood										
33	Emergency shutdown of the plant due to tropical cyclone										
	RELATIVE COST										

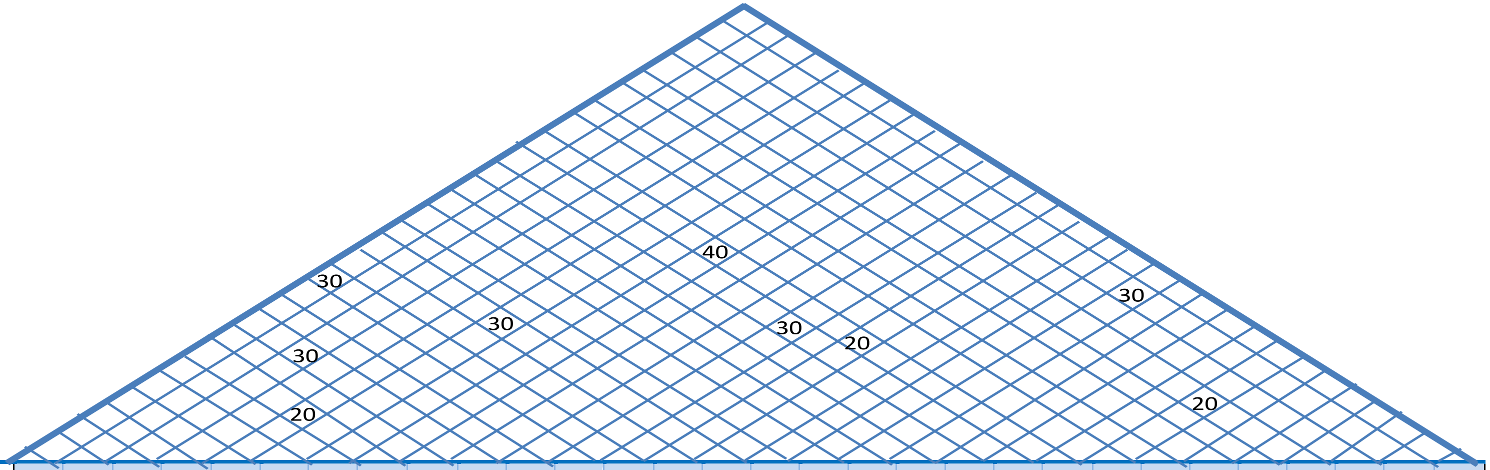
Risk Number	Strategy Number	11	12	13	14	15	16	17	18	19	20
	Risk Mitigation strategy / LNG Supply Chain Risk	Adopting RMS in different stages from planning to operation	Monitor global trends of technology development	Establish trust of relationship with state and federal govt. regarding fiscal policy	Multiple Facilities with Flexible/ Redundant resources	Consistency among local, state and federal govt. policy	Insurance coverage for hazard and unexpected risk	Signing long-term contract	Having redundant customer	Balancing cost by region	Balancing revenue flows by region
1	Downgrade of investment attractiveness for new plant										
2	Occurrences of policy differences in state to state										
3	Increasing international Pipe line Gas supply										
4	Higher payment cost of skill human resources than other competitor										
5	Lower productivity for LNG production										
6	Strong AU$ (local currency)										
7	Different kind of reception terminal and storage facilities										
8	Occurrence of change energy Mix for securing energy security										
9	Introduction of carbon tax										
10	Adoption of new emissions trading scheme										
11	Strong community concern regarding non-conventional gas exploration										
12	Plant start-up delay										
13	Supply of gas in domestic market at lower cost hence reduce LNG export										
14	Competition from other exporter in global LNG market										
15	Emergence of new exporter in Global LNG market										
16	Discovery of new reserve e.g. East Africa										
17	Emergence of US shale Gas Revolution										
18	Extraction of natural gas from Methane hydrate in Japan										
19	Multiple regulatory risk										
20	The emergence of LNG spot market and more short term contract										
21	High cost due remoteness of the projects										
22	Increase competition from other fuels										
23	Flexible capability of technology adaptation										
24	Customer demand priority shift to other energy mix										
25	Over proposed LNG project										
26	Unstable Fiscal stability and fiscal credibility										
27	Lack of skilled staff in LNG project										
28	Lesson recovery of Global economic slowdown										
29	Revision of long-term supply contract										
30	Fluctuation of LNG price due to oil production										
31	severe Weather (extreme hot, severe thunderstorm) causing low production										
32	Emergency shutdown of the plant due to flood										
33	Emergency shutdown of the plant due to tropical cyclone										
	RELATIVE COST										

Risk Number	Strategy Number	21	22	23	24	25	26	27	28	29	30
	Risk Mitigation strategy / LNG Supply Chain Risk	Building flexible global capacity	Robust back up system	Building responsive production	Building responsive delivery capacity	Balance emissions trading scheme policy formulation	Policy for Economic slowdown	Policy for Labour dispute	Policy for currency fluctuation	Monitor completion from existing and new competitor	Establish secure communication links within the company
1	Downgrade of investment attractiveness for new plant										
2	Occurrences of policy differences in state to state										
3	Increasing international Pipe line Gas supply										
4	Higher payment cost of skill human resources than other competitor										
5	Lower productivity for LNG production										
6	Strong AU$ (local currency)										
7	Different kind of reception terminal and storage facilities										
8	Occurrence of change energy Mix for securing energy security										
9	Introduction of carbon tax										
10	Adoption of new emissions trading scheme										
11	Strong community concern regarding non-conventional gas exploration										
12	Plant start-up delay										
13	Supply of gas in domestic market at lower cost hence reduce LNG export										
14	Competition from other exporter in global LNG market										
15	Emergence of new exporter in Global LNG market										
16	Discovery of new reserve e.g. East Africa										
17	Emergence of US shale Gas Revolution										
18	Extraction of natural gas from Methane hydrate in Japan										
19	Multiple regulatory risk										
20	The emergence of LNG spot market and more short term contract										
21	High cost due remoteness of the projects										
22	Increase competition from other fuels										
23	Flexible capability of technology adaptation										
24	Customer demand priority shift to other energy mix										
25	Over proposed LNG project										
26	Unstable Fiscal stability and fiscal credibility										
27	Lack of skilled staff in LNG project										
28	Lesson recovery of Global economic slowdown										
29	Revision of long-term supply contract										
30	Fluctuation of LNG price due to oil production										
31	severe Weather (extreme hot, severe thunderstorm) causing low production										
32	Emergency shutdown of the plant due to flood										
33	Emergency shutdown of the plant due to tropical cyclone										
	RELATIVE COST										

Appendix 1

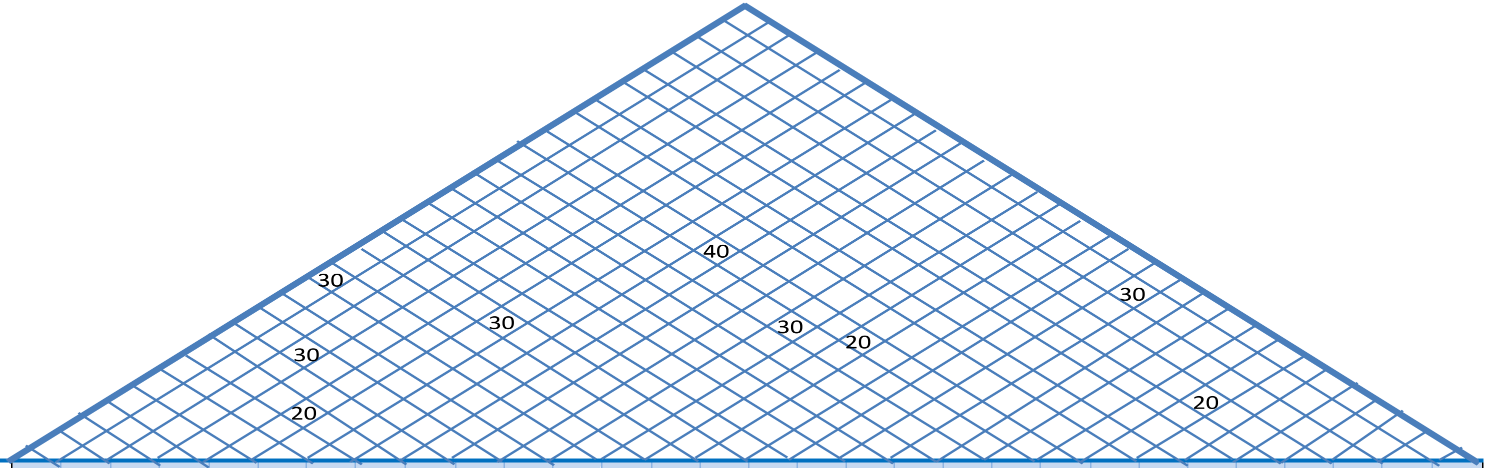
Risk Number	Strategy Number	1	2	3	4	5	6	7	8	9	10
	Risk Mitigation strategy / LNG Supply Chain Risk	Establish secure communication among stakeholders (public, private,	Involvement of stakeholders in different stages of project	To address community's threats (financial and environmental) from LNG projects (non-conventional)	Emphasising involvement of community (non-conventional)	Address end-user's confidence (reliability of supply, competitive price, end-user requirement of quality)	Balanced Carbon tax policy formulation	Increase domestic use of LNG/ natural gas	Policy to increase likelihood of on schedule delivery (timely project completion)	Policy for addressing lack of skilled HR	Select appropriate location satisfying multidimensional requirements
1	Downgrade of investment attractiveness for new plant	5	9	5		5	1		9	9	5
2	Occurrences of policy differences in state to state			5		5	5				
3	Increasing international Pipe line Gas supply							5			
4	Higher payment cost of skill human resources than other competitor				1				5	9	5
5	Lower productivity for LNG production	5	5	5	5	5			9	9	9
6	Strong AU$ (local currency)						5				5
7	Different kind of reception terminal and storage facilities	5				9			9	5	9
8	Occurrence of change energy Mix for securing energy security					9	5	9			5
9	Introduction of carbon tax						9				
10	Adoption of new emissions trading scheme						9				1
11	Strong community concern regarding non-conventional gas exploration	9	9	9	9	5	5				9
12	Plant start-up delay	5	9	5	9		5			9	9
13	Supply of gas in domestic market at lower cost hence reduce LNG export						5	9			
14	Competition from other exporter in global LNG market					9			5	5	9
15	Emergence of new exporter in Global LNG market							5	5	9	9
16	Discovery of new reserve e.g. East Africa					9			5	5	5
17	Emergence of US shale Gas Revolution						5		9	9	1
18	Extraction of natural gas from Methane hydrate in Japan						5		9	9	1
19	Multiple regulatory risk	9	9	5		9	5		1	9	1
20	The emergence of LNG spot market and more short term contract										
21	High cost due remoteness of the projects	5	5	5	5	9			5	9	9
22	Increase competition from other fuels					1	5		1	5	1
23	Flexible capability of technology adaptation								9	9	5
24	Customer demand priority shift to other energy mix					9		9	1	5	9
25	Over proposed LNG project	9	9	9	9	9		9	5	5	1
26	Unstable Fiscal stability and fiscal credibility					5			9		
27	Lack of skilled staff in LNG project									9	5
28	Lesson recovery of Global economic slowdown					9			9	9	9
29	Revision of long-term supply contract					9			9	9	
30	Fluctuation of LNG price due to oil production								9		
31	severe Weather (extreme hot, severe thunderstorm) cause low production										
32	Emergency shutdown of the plant due to flood										
33	Emergency shut down the plant due to tropical cyclone										
	RELATIVE COST	10	10	15	10	100	60	4o	80	90	70

Appendix D: LNG SCR and RMS attributes based on experts



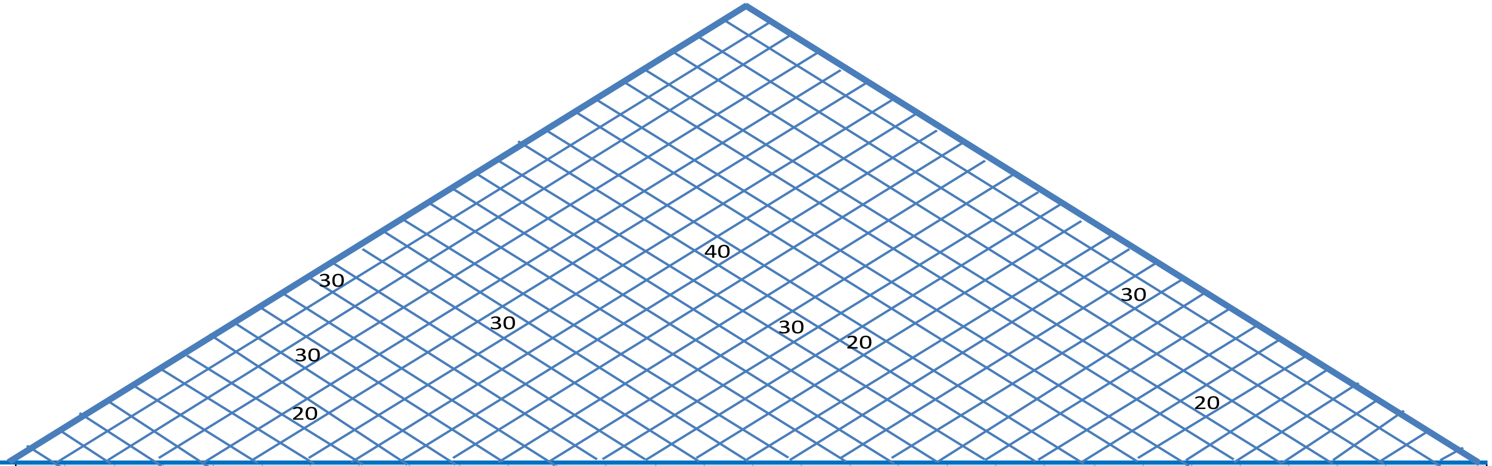
Expert (i)	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR1	5	6	0.023	5	5	5	5	9	1	5	9	9	9	5	9	9	9	9	5	5	9	5	1	5	1	9	5			9	5	9	9
SCR2	7	7	0.038	5	9	5	1	5	1	5	5	5	5	5										9	9				1	5		5	9
SCR3	5	6	0.023	5				5				5			5			1		5		5	5	5					1		1		5
SCR4	7	6	0.032	9			1					9	5	5	1	1	5	5	1	5	1	1	1	5	9	9	5		5	9	5	9	9
SCR5	3	7	0.016	1	5	1	1	5		5	5	9	1	1	5	1	1		1	9	5	1	1	5	9	9	9		9	9	9	9	9
SCR6	6	7	0.032								5	5	9		9	9	9	9		9	9	5		5	5	9	9		9	5	9	9	9
SCR7	3	4	0.009										1		1		1			5		5	5	1	1	5	5		1			9	9
SCR8	7	7	0.038		9		1							9	9	1	5	5	1	9	1	1	5	9	5	5	5		5	1	9	5	9
SCR9	3	6	0.014											1	1	9	1	5															
SCR10	3	5	0.011											1																			
SCR11	5	6	0.023		9	9	5	5						9	9	9		9			5	5	1		9					5		9	9
SCR12	7	7	0.038	9	9	1		9					5	9	9	9	1	1		5	1	1	1	9	9	9	9		9	5		9	9
SCR13	5	6	0.023	5	5	5	5	5					5	5	5	5	1						1	1	9	9	5		5			9	9
SCR14	7	6	0.032									5	9	9	9	9	1	9				1	5	9	5	5	5		1			9	9
SCR15	7	6	0.032	5				9					5	9	9			9				1		9	9	9	5					9	9
SCR16	8	7	0.043	5				5			5		5	5	5			5				5		9	9	9	9					9	9
SCR17	8	7	0.043					5			9		9	5	5			5				5		9	9	5	5					9	9
SCR18	6	8	0.037	5				1					5	1	5		5					5	9			5	5			5		9	9

Expert (i)	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR19	6	6	0.028	1				5		9		1	5	9	9		9			5		9	9	9	9							9	9
SCR20	7	6	0.032	1	5			5					1	5	5	5	5			5	5			5	9	9	9					9	5
SCR21	7	7	0.038	9	1	5	5					9	5	9	5			9			5		5	9	9	5	5					9	9
SCR22	8	8	0.049	9		9		5				1	5	9	9	9	9	9		9	9	9	9	9	9							9	9
SCR23	6	6	0.028	5		1					9		5	9	9	1								9								9	9
SCR24	7	7	0.038	5										5	5	5				5	5		5	9	9	9	9					9	9
SCR25	5	6	0.023	1		1		5					5	1										1	1	1	5					5	9
SCR26	6	7	0.032	5	1	1		1					9	5	5									9	9							9	9
SCR27	7	8	0.043	9	5	9		9			9	9	9	9	9		9						5	9	9							9	9
SCR28	6	6	0.028	1	9		5				5	5	5	5		5		9						9	5							9	9
SCR29	7	7	0.038	9	9	1		5			9		9	9		9		9					9	9	9				1	5		9	9
SCR30	6	7	0.032	9	9	9	9	9				9	9	9										9	9	9	9					9	9
SCR31	5	6	0.023	5	5	5	5				1	5	5	9						5			5	1	1	5	5					5	9
SCR32	5	7	0.027	1	5	5		9					5	1						5			5	1	1							5	5
SCR33	7	7	0.038	5	5	5		9					9	9						5			5	5	5							5	5
C				30	100	70	100	40	10	50	100	100	60	60	60	100	30	80	20	50	50	40	40	80	100	80	80	10	50	70	60	100	100
AI				4.5	3.3	2.5	1.2	4.0	0.1	0.6	2.4	2.6	5.3	6.1	5.0	2.9	2.4	3.6	0.2	2.8	1.8	2.0	3.0	6.6	6.5	4.2	3.8	0.0	1.4	1.7	1.1	7.8	8.3



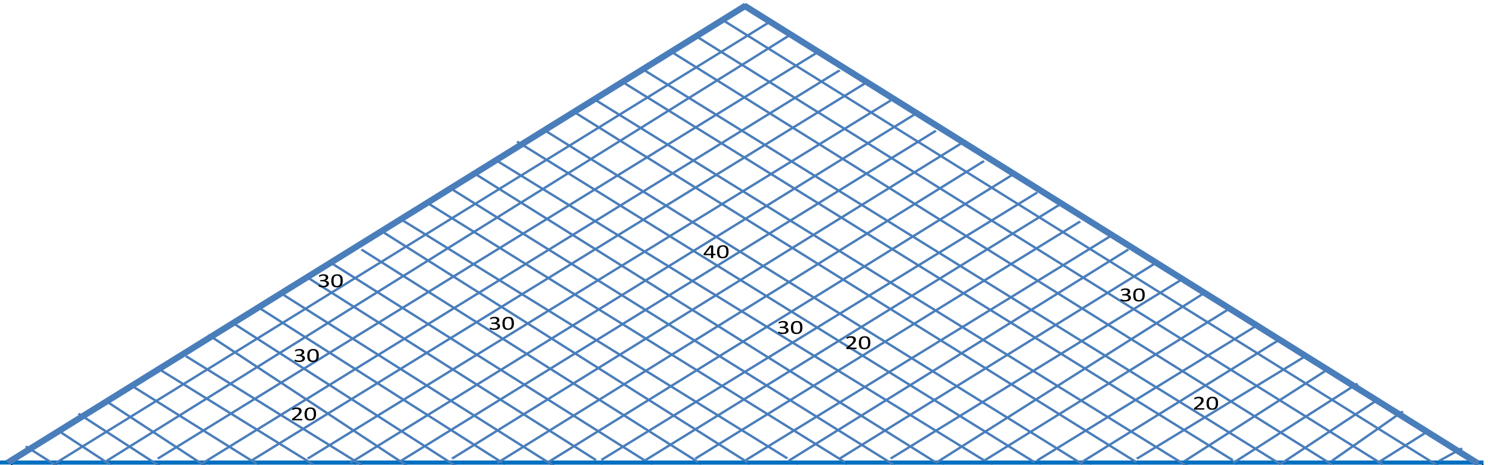
Expert (ii)	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR1	7	7	0.030	7	9	7		6			9	9	9	7	9	7	6	6		9		7	8						5		5		
SCR2	6	5	0.018			6		6	6							9		7										6					
SCR3	2	2	0.002							6					6							6											
SCR4	9	8	0.044								7	8	9	7		7						8	9								7		
SCR5	7	6	0.026	5	5	5	5	8			9	9	9				7					7	7	7	7	7	7						
SCR6	9	8	0.044						6				8									8	8						6		9		
SCR7	4	4	0.010	5				9			9	5	9	6										6									
SCR8	5	5	0.015					9	7	9			5					6		9			5	5									
SCR9	9	8	0.044						9								6	8										6					
SCR10	9	8	0.044						9									7				7						6					
SCR11	9	9	0.049	9	9	9	9	5	6				9	9	9	9		8						5									
SCR12	8	7	0.034	6	9	5	9					9	9	6		5	9			8		8	8	6								6	
SCR13	8	7	0.034							9														4									
SCR14	9	8	0.044					9			9	5	9							9	9			7									
SCR15	9	8	0.044	5	5					5	5	8	9		6		6			7	7			7									
SCR16	9	7	0.038					9			5	5	5		6		6			7	7			6									
SCR17	9	7	0.038						5		9	9			7	6				9	9	7	7	6									
SCR18	5	4	0.012						5		9	9			9																		

Expert (ii)	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR19	8	7	0.034	9	9	5		9	5		1	9	8	8	7	9		8						6									
SCR20	8	7	0.034																	9				7									
SCR21	9	8	0.044	5	5	5	5	9			5	9	9			6		6		9	8	8	8	7						5	5	6	
SCR22	6	5	0.018					1	5		1	5	1							9	8			5									
SCR23	6	5	0.018								9	9	5		7																		
SCR24	5	4	0.012					9		9	1	5	9							9	9			5									
SCR25	8	7	0.034	9	9	9	9	9		9	5	5	1							8	8			6									
SCR26	7	7	0.030					6			9					9		9															
SCR27	8	8	0.039									9	5	6								7											
SCR28	8	8	0.039					9			9	9	9					9			9	9	9	6									
SCR29	7	7	0.030					9			9	9								9	9												
SCR30	7	7	0.030	7	7	7					9		9							9	9	7	7										
SCR31	6	6	0.022	7	7	7							9	7					9					7	7	7							
SCR32	6	6	0.022	7	7	7							9	7					9					7	7	7							
SCR33	6	6	0.022	7	7	7							9	7					9					7	7	7							
C				20	20	50	60	100	50	30	80	60	80	80	50	50	50	50	60	60	60	60	60	100	70	70	20	20	20	20	20	20	10
AI				2.8	2.9	2.4	1.4	3.6	2.1	1.1	3.9	4.6	5.5	2.2	2.0	2.4	1.4	2.6	0.6	3.8	3.1	3.1	2.7	3.8	0.6	0.6	0.2	0.6	0.4	0.2	1.1	0.5	0.0



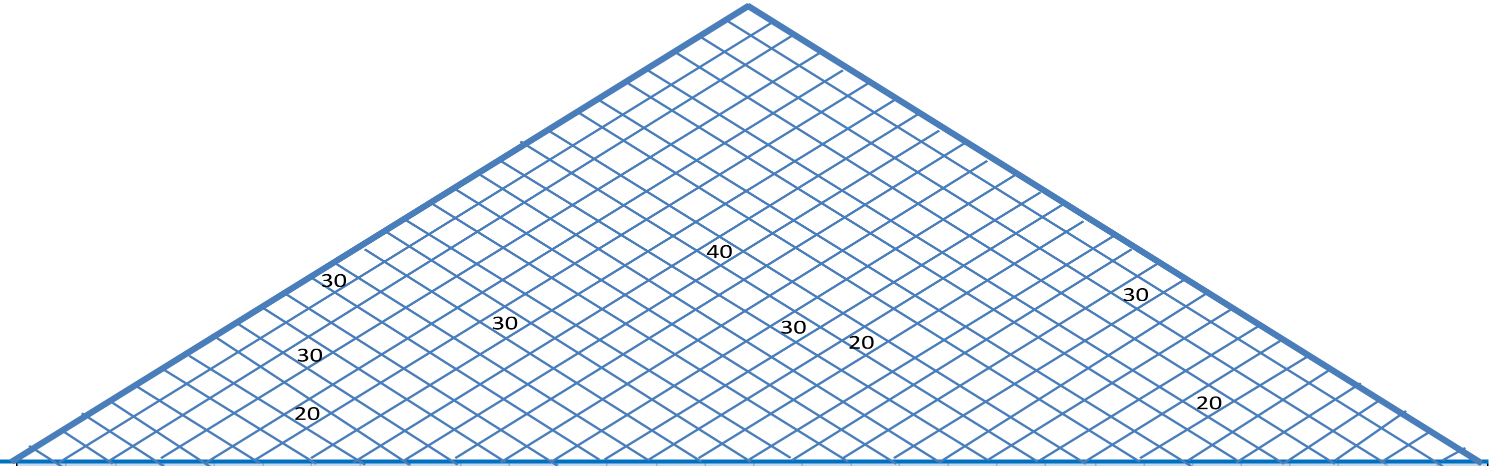
Expert (iii)	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR1	7	8	0.035					9	5				5	5	5	5	5	5		9	5	5		5		1	5		5	1	1	5	
SCR2	8	6	0.030						5	5		5					5	9					5					5		5			
SCR3	5	4	0.013					9			5			5							5			5			5						
SCR4	8	7	0.035	1	1							5					1												1	5			
SCR5	4	6	0.015										5	1	1		5						1	5	5	5	1			1			
SCR6	7	6	0.027										1									1		1							9		
SCR7	4	5	0.013								1		1		9		1										5						
SCR8	5	5	0.016										1	5			5							5		1	1					5	
SCR9	7	7	0.031						9							5		5					5	9				5					
SCR10	6	7	0.027						5							5		5					5	5				9					
SCR11	8	8	0.040	5	5	9	9									5																	5
SCR12	8	8	0.040	1	1							1					5							5						5			
SCR13	7	6	0.027			5	5	5					5			9		9						5									
SCR14	9	9	0.051					9			5			5	1		5			9	5	5	5	9		5	5					9	
SCR15	9	9	0.051					9			5			5	1		5			9	5	5	5	9		5	5					9	
SCR16	8	7	0.035					9			5			5	1		5			9	5	5	5	9		5	5					9	
SCR17	8	8	0.040					5			5				5		5			9	5	5	5	5		1	1					5	
SCR18	5	8	0.025												9		5			9	5	1	5	5		1	1					5	

Expert (iii)	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR19	7	8	0.035		5	5							5			5		5		1		5	5	9									
SCR20	7	6	0.027					1					5	5			5			5			5	9		5	5					5	
SCR21	9	8	0.045								1		5		1		5					5		5		1	1						
SCR22	7	7	0.031					5			5		1	5	1		5			9	5			5		5	5					5	
SCR23	7	8	0.035												5		5									1	1						
SCR24	5	8	0.025					5						5						9	5		5	5		1	1						
SCR25	8	8	0.040											5										5		5	1						
SCR26	7	8	0.035														5	5					5	9		5	5						
SCR27	5	6	0.019									9																		5		1	1
SCR28	6	7	0.027										5				1				1		5	1					9				
SCR29	8	9	0.045					1					1	1			5				5		5	5		1						5	
SCR30	7	8	0.035					1					1				1						5	5		1			5				
SCR31	5	4	0.013	5									5				5		1				5	5	5	5							5
SCR32	5	6	0.019	5									5				5		5				5	5	5	5							
SCR33	5	5	0.016	5									5				5		5				5	5	5	5							
C				10	10	30	10	20	30	50	70	30	90	20	10	20	100	20	30	20	20	30	50	100	60	50	50	30	10	20	20	10	10
AI				0.5	0.5	0.7	0.5	2.4	0.7	0.2	1.2	0.5	1.5	1.7	1.1	1.1	3.1	1.3	0.2	2.8	1.8	1.5	2.9	5.0	0.3	2.0	1.7	0.5	0.6	0.7	0.3	2.4	0.3



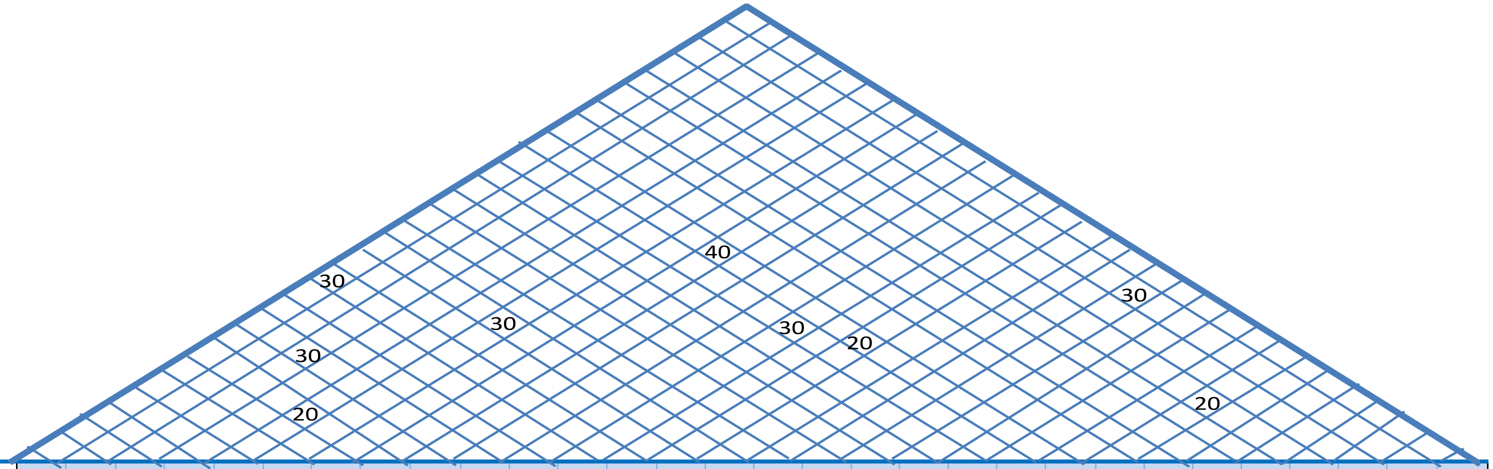
Expert (iv)	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR1	7	7	0.046	1	1	5	5		1	5	9	9	5	5	1	9		5	5	5										5			9
SCR2	5	5	0.023													5		9				1											
SCR3	7	8	0.052					5							5					5				5									
SCR4	5	5	0.023	5	1	1	5				5	5	5																	5			
SCR5	5	3	0.014																														
SCR6	6	6	0.034					1																							9		
SCR7	7	2	0.013					1							9																		
SCR8	8	5	0.037	1	1			1													1			5									
SCR9	8	6	0.045	5				1	9							9		1										9					
SCR10	4	6	0.022	5				1	9							9		1										9					
SCR11	7	7	0.046	9	9	9	9						9			5		1															
SCR12	8	7	0.052										5	5																5			9
SCR13			0.000																														
SCR14	5	5	0.023					5	9		9	9	1	5	5																	5	
SCR15	8	8	0.060					6	9		9	9	1	5	5																	5	
SCR16	8	8	0.060					5	9		9	9	1	5	5																	9	
SCR17	8	8	0.060					5	9		9	9	1	5	5																	9	
SCR18	4	7	0.026											1																		1	

Expert (iv)	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR19	5	5	0.023	5	5	1	1									5		5		1			5	5									
SCR20	8	5	0.037																	9				1								1	1
SCR21	7	6	0.039								5	5	9	1								5											
SCR22	4	4	0.015						1											1	5												
SCR23			0.000																														
SCR24	3	5	0.014	1	1													1			5												
SCR25	8	6	0.045								5	5	5	5	5					5												5	
SCR26	3	3	0.008	5	5			5										5															
SCR27	7	7	0.046									9	5	1																5			
SCR28	4	4	0.015												1									5					9				
SCR29	5	7	0.033					5												5							5						
SCR30	7	7	0.046																			1	1	5									
SCR31	4	4	0.015																5														5
SCR32	3	3	0.008																9						5	5							9
SCR33	4	4	0.015																9						5	5							9
C				10	10	10	15	40	15	10	50	50	40	25	15	15	10	20	15	60	10	10	10	25	15	15	20	15	10	25	10	40	25
AI				1.1	0.7	0.7	0.8	1.7	2.5	0.2	2.8	3.2	2.0	1.8	1.7	1.5	0.0	0.7	0.5	1.3	0.2	0.3	0.2	0.9	0.1	0.1	0.2	0.6	0.1	0.8	0.3	1.8	1.2



Expert (v)	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR1	6	7	0.030	5	1	5		5		5	9	9	5	5	9	9	5	5		9	5	5							5		5	9	9
SCR2	8	5	0.029			5			1	5		5				5	5	9				1	5					5		5			
SCR3	6	3	0.013					9			5			5	5					5	5			5			5						
SCR4	7	8	0.041			1	1				9	9	9	5		5						9							5	5			
SCR5	3	5	0.011			5	9	5			5	9	5		5		5					5	9	5	9	9	9			9			
SCR6	9	8	0.052						1				5									9	5	5					5		9		
SCR7	4	4	0.012					9			5		9	5	9									5			5						
SCR8	8	5	0.029		5			9	5		5		1	5		1	5			5				9	1		5					5	
SCR9	4	8	0.023	5					9								5	5					5	9				5					
SCR10	7	8	0.041	5					9							5		9				5	5					9					
SCR11	6	8	0.035	5	9	9	5		5				9	5	5	9		9						1									5
SCR12	6	8	0.035	5	5							5	5	9		5	5							5						5			9
SCR13	6	7	0.030			5	5				5		5			5		9						5									
SCR14	6	6	0.026					5	9		5	9	5	9	5					9	9		5	9								9	
SCR15	9	8	0.052		5				9		9	9	5		9		5			9	5	1	5	9		5	5					9	
SCR16	8	8	0.046					9	9		9	5	5				5			9	9	5		9		5	9					9	
SCR17	8	7	0.041					5	9		5	9	1	5	5		5			9	9	5	9	9		1	1					5	
SCR18	6	7	0.030											1	9		5			9	5	1	9	5		1	1					5	

Expert (v)	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR19	7	6	0.030	5	5	9	1		5				9			9		5				9	9	5									
SCR20	7	6	0.030											5			5			9			5	5		9	5					5	1
SCR21	7	7	0.036	5		5		5			1	9	5	1			5					9		9			5						
SCR22	7	4	0.020					1	5		1		5	9	5		9			9	9			9			5					9	
SCR23	5	8	0.029								5	5			5		5									1	1						
SCR24	6	6	0.026					9			5	1		9				1		9	9		5	5		9	1						
SCR25	8	8	0.046								5	5	5	1	5					5				1		1	5					5	
SCR26	6	7	0.030	5	4			1									5	8					5	9		5	5						
SCR27	7	8	0.041									9	9	9								5								5		5	5
SCR28	5	4	0.014					5			5	5	9		1						5		9	9					9				
SCR29	7	8	0.041					9			9		1	5			5				9		9	9		1						9	
SCR30	7	7	0.036		5	5							9				1			9	5	9	5	5		1			5				
SCR31	4	6	0.017	5	5	5							9	5			5		1				5	5	1	9							9
SCR32	3	7	0.015	5	5	5							9	5			5		9				5	1	5	5							9
SCR33	4	4	0.012	5	5	5							9	5			5		9				5	5	5	5							9
C				20	30	40	50	60	30	50	90	60	80	40	40	40	40	50	30	40	40	40	60	100	80	70	50	10	30	35	30	40	30
AI				1.5	1.6	1.7	0.5	2.3	2.7	0.3	3.3	3.5	4.3	3.0	2.2	1.8	2.9	1.9	0.3	3.5	2.7	2.9	3.5	5.0	0.3	1.8	2.0	0.6	0.9	0.8	0.6	3.0	1.4



Expert (vi)	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR1	6	8	0.034	1	5	9		5	1		9	9	9	5	5	5		9		9	5					1			5	1		9	
SCR2	8	7	0.039			5			5	5		5				9		9				1	5					5		5			
SCR3	2	8	0.011					9		5				5	5						5			5									
SCR4	6	6	0.025	5	1						5	9	9	9		1													1	5	5		
SCR5	3	4	0.008	1	5		5	9				9	1	1	5		5						9	5	5	5	1			1			
SCR6	9	8	0.051						5				5									9	9	1					9		9		
SCR7	5	4	0.014	5				5					9		9		1							5			5						
SCR8	6	7	0.030					1	9	9			5	9			5	5		9				9								5	
SCR9	8	8	0.045	5				1	9							9	5	9					5	9				9					
SCR10	9	6	0.038	5				1	9							5		5				9	5					9					
SCR11	7	8	0.039	9	9	9	9		5				9	9	9	5		1						5									9
SCR12	8	7	0.039			5	9						9	5		9	1			5		5		9								9	
SCR13	7	6	0.030			5	5	5		9			5			9		9					5										
SCR14	9	8	0.051					5	5		9	9	5	9	9		1				9			9		5	5					9	
SCR15	7	8	0.039					9	5		9	9	1	9	5		5			9	5			9		9	5					9	
SCR16	8	7	0.039					9	5		5	9	5	5	5		1			9	9			9		9	9					9	
SCR17	9	8	0.051					5	5		9	9	5	5	9		1			9	9	5	5	9		5	1					9	
SCR18	5	8	0.028					5	5		9	9	5	5	9		1			9	5	1	5	5		5	5					9	

Expert (vi)	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR19	5	5	0.018	1	9	5	1	9	5		1	1	9	9	9	5		5					5	9									
SCR20	8	7	0.039										5	5			5			9				1		5	5					5	
SCR21	8	8	0.045								1	9	9		1	5	5	5				5	9	9		1	1			5	5	9	
SCR22	5	8	0.028								5	5	5	5	5					1	9			9		5	5					9	
SCR23	5	6	0.021								9	9	5		9		5									1	1						
SCR24	3	6	0.013					9		9		5	9	5						9	9		5	9		5	9						
SCR25	6	8	0.034	9	9	9	9	5		9	5	5	5	1						9	9			1								5	
SCR26	5	4	0.014	5	5			5			9					9	5	9					5	9									
SCR27	6	7	0.030									9	9	1								9								5		1	9
SCR28	8	5	0.028								5	9	5				1				5	9	5	9					9				
SCR29	5	8	0.028					5			9	9	9	1			5			9	5		9	9		1						5	
SCR30	7	7	0.035	9	9	9		1			9						1			9	9	5		5		9			5				
SCR31	4	6	0.017	9	9	9							9	9			5		1				5	9	5	9							5
SCR32	3	6	0.013		5	9							5	5			5		5				5	9	5	5							
SCR33	5	7	0.025	5	9	5							9	9			5		5				5	5	9	5							
C				30	20	60	35	45	50	40	70	70	90	70	60	50	60	80	50	60	60	50	40	85	100	90	70	30	40	60	40	30	25
AI				2.0	1.9	2.3	1.2	2.7	2.8	1.2	3.5	4.4	5.2	3.8	2.8	2.4	1.9	2.2	0.2	3.6	3.1	2.2	3.0	5.4	0.4	2.6	1.6	0.9	1.1	0.7	0.8	3.9	0.7

Appendix E: Summary of optimization results

Table A7.3(a): Summary of optimization results for different cost scenarios without savings calculated based on Expert 1's opinion

Cost scenario and budget			Risk mitigation without savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used																																
(i)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1728	89.6	1720.0	0.974	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0	1	1
S2	80	1536	79.7	1530.0	0.929	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	0	1	0	1	1
S3	70	1344	68.8	1320.0	0.872	1	1	1	0	1	0	0	0	0	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	0	1	0	1	1
S4	60	1152	59.9	1150.0	0.813	1	1	0	0	1	0	0	0	0	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	0	0	0	0	1	1
S5	50	960	50.0	960.0	0.741	1	0	0	0	1	1	0	0	0	1	1	1	0	1	0	0	1	0	1	1	1	1	1	1	0	0	0	0	1	1
S6	40	768	39.6	760.0	0.638	1	0	0	0	1	1	0	0	0	1	1	1	0	1	0	0	1	0	0	1	1	1	0	0	0	0	0	0	1	1
S7	30	576	29.7	570.0	0.518	1	0	0	0	1	0	0	0	0	1	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1
S8	20	384	19.8	380.0	0.354	1	0	0	0	1	1	0	0	0	1	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
S9	10	192	9.9	190.0	0.200	1	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

*Total average cost is 1920. 0=RMS is not selected and 1=RMS is selected

Table A7.3(b): Summary of optimization results for different cost scenarios with savings calculated based on Expert 1's opinion

Cost scenario and budget			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used																																
(i)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	
S1	90	1728	80.94	1554.0	1.000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
S2	80	1536	79.90	1534.0	0.998	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1
S3	70	1344	70.00	1344.0	0.970	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1
S4	60	1152	59.58	1144.0	0.910	1	1	1	0	1	1	0	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	0	0	0	1	1
S5	50	960	49.69	954.0	0.834	1	0	1	0	1	1	0	1	0	1	1	1	1	1	1	0	1	1	0	1	1	1	1	0	0	0	1	0	1	1
S6	40	768	39.74	763.0	0.726	1	0	1	0	1	1	0	1	0	1	1	1	0	1	1	0	0	1	0	0	1	1	1	0	0	0	0	0	1	1
S7	30	576	29.90	574.0	0.582	1	0	0	0	1	0	0	1	0	1	1	1	0	1	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	1
S8	20	384	19.79	380.0	0.413	1	0	0	0	1	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
S9	10	192	9.90	190.0	0.203	1	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

*Total average cost is 1920. 0=RMS is not selected and 1=RMS is selected

Table A7.3(c): Summary of optimization results for different cost scenarios without and with savings calculated based on Expert 1's opinion

Cost scenario and budget			Risk mitigation without savings			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used			Budget used																																
(i)	%	Actual	%	Actual	$Rf(x)$	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1728	89.6	1720.0	0.974	80.94	1554.0	1.000	☑	☑	☑	✓	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑		☑	☑	✓	☑	☑
S2	80	1536	79.7	1530.0	0.929	79.90	1534.0	0.998	☑	☑	☑	✓	☑	✓	✓	✓	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑	☑	☐	✓	☑	✓	☑	☑
S3	70	1344	68.8	1320.0	0.872	70.00	1344.0	0.970	☑	☑	☑		☑	✓		✓	✓	☑	☑	☑	✓	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑		✓	☑		☑	☑
S4	60	1152	59.9	1150.0	0.813	59.58	1144.0	0.910	☑	☑	✓		☑	✓		✓		☑	☑	☑	✓	☑	☑	☐	☑	✓	☑	☑	☑	☑	☑	☑	✓				☑	☑
S5	50	960	50.0	960.0	0.741	49.69	954.0	0.834	☑		✓		☑	☑		✓		☑	☑	☑	✓	☑	✓		☑	✓	☐	☑	☑	☑	☑	☐			✓		☑	☑
S6	40	768	39.6	760.0	0.638	39.74	763.0	0.726	☑		✓		☑	☑		✓		☑	☑	☑		☑	✓		☐	✓		☐	☑	☑	✓						☑	☑
S7	30	576	29.7	570.0	0.518	29.90	574.0	0.582	☑				☑			✓		☑	☑	☑		✓			✓			☑	☑	✓							☐	☑
S8	20	384	19.8	380.0	0.354	19.79	380.0	0.413	☑				☑	☐		✓		☑	☑	☑								☐	☑	✓								
S9	10	192	9.9	190.0	0.200	9.90	190.0	0.203	☑				☑					✓	☑	☐																		

☐=RMS selected considering linear cost constraint and ✓=RMS selected considering quadratic cost constraint

Table A7.4(a): Summary of optimization results for different cost scenarios without savings calculated based on Expert 2's opinion

Cost scenario and budget		Risk mitigation without savings			Selected RMSs under different cost scenarios																														
Scenario	Budget available*	Budget used																																	
(ii)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1350	90.0	1350.0	0.977	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1
S2	80	1200	80.0	1200.0	0.941	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	0	1	1	0	1	1	1
S3	70	1050	70.0	1050.0	0.876	1	1	1	0	1	1	1	1	1	1	0	1	1	0	1	0	1	1	1	1	1	0	0	0	1	0	0	1	1	1
S4	60	900	60.0	900.0	0.800	1	1	1	0	0	1	1	1	1	1	0	1	1	0	1	0	1	1	1	1	1	0	0	0	0	0	0	1	0	0
S5	50	750	50.0	750.0	0.707	1	1	1	0	0	1	1	1	1	1	0	0	1	0	1	0	1	1	1	1	0	0	0	0	0	0	0	1	0	0
S6	40	600	40.0	600.0	0.596	1	1	1	0	0	0	0	1	1	1	0	0	1	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1
S7	30	450	30.0	450.0	0.483	1	1	1	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0
S8	20	300	20.0	300.0	0.363	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
S9	10	150	10.0	150.0	0.196	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1

*Total average cost is 1500. 0=RMS is not selected and 1=RMS is selected

Table A7.4(b): Summary of optimization results for different cost scenarios with savings calculated based on Expert 2's opinion

Cost scenario and budget		Risk mitigation with savings			Selected RMSs under different cost scenarios																														
Scenario	Budget available*	Budget used																																	
(ii)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1350	80.20	1203.0	1.000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S2	80	1200	79.53	1193.0	1.000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
S3	70	1050	69.40	1041.0	0.974	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	0	1	1	0
S4	60	900	58.73	881.0	0.909	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	0	0	1	0	0	1	1	0
S5	50	750	49.67	745.0	0.815	1	1	1	0	1	1	0	1	1	1	0	1	1	0	1	0	1	1	1	0	1	1	0	0	0	0	0	1	1	0
S6	40	600	39.67	595.0	0.669	1	1	1	0	0	1	0	0	1	1	0	1	1	0	1	0	1	0	1	1	1	0	0	0	0	0	0	1	0	0
S7	30	450	29.73	446.0	0.531	1	1	1	0	0	0	0	1	1	1	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	0	0	0	1	0
S8	20	300	20.00	300.0	0.408	1	1	1	0	0	0	0	0	1	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0
S9	10	150	10.00	150.0	0.177	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

*Total average cost is 1500. 0=RMS is not selected and 1=RMS is selected

Table A7.4(c): Summary of optimization results for different cost scenarios without and with savings calculated based on Expert 2's opinion.

Cost scenario and budget			Risk mitigation without savings			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used			Budget used																																
(ii)	%	Actual	%	Actual	$f(x)$	%	Actual	$f(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1350	90.0	1350.0	0.977	80.20	1203.0	1.000	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	✓	✓	☑	☑	☑	☑	☑	☑
S2	80	1200	80.0	1200.0	0.941	79.53	1193.0	1.000	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	✓	✓	✓	☑	☑	✓	☑	☑	☐
S3	70	1050	70.0	1050.0	0.876	69.40	1041.0	0.974	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	✓	☑	☑	✓	☑		☑	☑	☑	☑	☑	✓			☑	✓		☑	☑	☐
S4	60	900	60.0	900.0	0.800	58.73	881.0	0.909	☑	☑	☑		✓	☑	☑	☑	☑	☑		☑	☑	✓	☑		☑	☑	☑	☑	☑	✓			✓			☑	✓	
S5	50	750	50.0	750.0	0.707	49.67	745.0	0.815	☑	☑	☑		✓	☑	☐	☑	☑	☑		✓	☑		☑		☑	☑	☑	☐	✓	✓						☑	✓	
S6	40	600	40.0	600.0	0.596	39.67	595.0	0.669	☑	☑	☑			✓		☐	☑	☑		✓	☑		☑		☑	☐	☑	✓	✓							✓		☐
S7	30	450	30.0	450.0	0.483	29.73	446.0	0.531	☑	☑	☑					☑	☑	☑			✓				☑	✓	☐			✓			✓			☐	✓	
S8	20	300	20.0	300.0	0.363	20.00	300.0	0.408	☑	☑	✓						☑	☑			✓				☑	☐										✓		
S9	10	150	10.0	150.0	0.196	10.00	150.0	0.177	☑	☑					✓			☐							✓											☐	✓	☐

☐=RMS selected considering linear cost constraint and ✓=RMS selected considering quadratic cost constraint

Table A7.5(a): Summary of optimization results for different cost scenarios without savings calculated based on Expert 3's opinion

Cost scenario and budget			Risk mitigation without savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used																																
(iii)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	927	89.3	920.0	0.988	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
S2	80	824	79.6	820.0	0.954	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1
S3	70	721	69.9	720.0	0.913	1	1	1	1	1	1	0	1	0	0	1	1	1	1	1	0	1	1	1	1	1	0	1	1	0	1	1	0	1	1
S4	60	618	59.2	610.0	0.860	1	1	0	1	1	1	0	0	0	0	1	1	1	1	1	0	1	1	1	1	1	0	1	1	0	1	1	0	1	0
S5	50	515	49.5	510.0	0.782	1	1	0	1	1	0	0	0	0	0	1	1	1	1	1	0	1	1	1	1	1	0	1	0	0	1	0	0	1	0
S6	40	412	39.8	410.0	0.703	1	1	0	1	1	0	0	0	0	0	1	1	1	0	1	0	1	1	1	1	1	0	1	0	0	1	0	0	1	0
S7	30	309	29.1	300.0	0.578	0	0	0	0	1	0	0	0	0	0	1	1	1	0	1	0	1	1	0	1	1	0	0	0	0	1	0	0	1	0
S8	20	206	19.4	200.0	0.445	1	0	0	1	1	0	0	0	0	0	1	1	1	0	1	0	1	1	1	0	0	0	0	0	0	1	0	0	1	0
S9	10	103	9.7	100.0	0.279	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0

*Total average cost is 1030. 0=RMS is not selected and 1=RMS is selected

Table A7.5(b): Summary of optimization results for different cost scenarios with savings calculated based on Expert 3's opinion

Cost scenario and budget			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used																																
(iii)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	927	78.8	812.0	1.000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S2	80	824	78.8	812.0	1.000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S3	70	721	69.1	712.0	0.985	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1
S4	60	618	60.0	618.0	0.928	1	1	1	1	1	1	0	1	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1
S5	50	515	49.5	510.0	0.834	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	0	1	1	1	1	1	0	1	0	0	1	1	0	1	0
S6	40	412	39.8	410.0	0.755	1	1	1	1	1	1	0	0	0	0	1	1	1	0	1	0	1	1	1	1	1	0	1	0	0	1	1	0	1	0
S7	30	309	30.0	309.0	0.653	1	1	0	1	1	0	0	0	0	0	1	1	1	0	1	0	1	1	1	1	1	0	0	0	0	1	0	0	1	0
S8	20	206	19.3	199.0	0.499	1	0	0	1	1	0	0	0	0	0	1	1	1	0	0	0	1	1	0	0	1	0	0	0	0	1	0	0	1	0
S9	10	103	9.9	102.0	0.290	1	0	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0

*Total average cost is 1030. 0=RMS is not selected and 1=RMS is selected

Table A7.5(c): Summary of optimization results for different cost scenarios without and with savings calculated based on Expert 3's opinion

Cost scenario and budget			Risk mitigation without savings			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used			Budget used																																
(iii)	%	Actual	%	Actual	$Rf(x)$	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	927	89.3	920.0	0.988	78.8	812.0	1.000	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑
S2	80	824	79.6	820.0	0.954	78.8	812.0	1.000	☑	☑	☑	☑	☑	☑	✓	✓	☑	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑
S3	70	721	69.9	720.0	0.913	69.1	712.0	0.985	☑	☑	☑	☑	☑	☑		☑	✓	✓	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	✓	☑	☑	✓	☑	☑		☑	☑
S4	60	618	59.2	610.0	0.860	60.0	618.0	0.928	☑	☑	✓	☑	☑	☑		✓			☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	✓	☑	☑		☑	☑	✓	☑	✓
S5	50	515	49.5	510.0	0.782	49.5	510.0	0.834	☑	☑	✓	☑	☑	✓					☑	☑	☑	☑	☑		☑	☑	☑	☑	☑		☑			☑	✓		☑	
S6	40	412	39.8	410.0	0.703	39.8	410.0	0.755	☑	☑	✓	☑	☑	✓					☑	☑	☑		☑		☑	☑	☑	☑	☑		☑			☑	✓		☑	
S7	30	309	29.1	300.0	0.578	30.0	309.0	0.653	✓	✓		✓	☑						☑	☑	☑		☑		☑	☑	✓	☑	☑					☑			☑	
S8	20	206	19.4	200.0	0.445	19.3	199.0	0.499	☑			☑	☑						☑	☑	☑		☐		☑	☑	☐		✓					☑			☑	
S9	10	103	9.7	100.0	0.279	9.9	102.0	0.290	✓				✓						☑	☑	✓		☐		☐	☑								✓			☑	

☐=RMS selected considering linear cost constraint and ✓=RMS selected considering quadratic cost constraint

Table A7.6(a): Summary of optimization results for different cost scenarios without savings calculated based on Expert 4's opinion

Cost scenario and budget		Risk mitigation without savings			Selected RMSs under different cost scenarios																														
Scenario	Budget available*	Budget used																																	
(iv)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	576.0	89.1	570.0	0.979	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1
S2	80	512.0	79.7	510.0	0.940	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	0	0	0	1	0	1	1	1	1
S3	70	448.0	69.5	445.0	0.885	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1
S4	60	384.0	59.4	380.0	0.807	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
S5	50	320.0	50.0	320.0	0.726	1	1	1	1	0	1	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
S6	40	256.0	39.8	255.0	0.626	1	1	1	1	0	1	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S7	30	192.0	29.7	190.0	0.509	1	0	1	0	0	1	0	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S8	20	128.0	19.5	125.0	0.378	1	1	1	0	0	1	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S9	10	64.0	8.6	55.0	0.226	1	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

*Total average cost is 640. 0=RMS is not selected and 1=RMS is selected

Table A7.6(b): Summary of optimization results for different cost scenarios with savings calculated based on Expert 4's opinion

Cost scenario and budget		Risk mitigation with savings			Selected RMSs under different cost scenarios																														
Scenario	Budget available*	Budget used																																	
(iv)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	576.0	81.7	523.0	1.000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S2	80	512.0	79.8	511.0	0.996	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
S3	70	448.0	70.0	448.0	0.954	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1
S4	60	384.0	59.5	381.0	0.912	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	0	1	0	0	1	1	0	0	1	0	1	0	1	1
S5	50	320.0	49.4	316.0	0.824	1	0	1	1	1	1	0	1	1	1	1	1	1	0	1	0	0	1	0	0	1	1	0	0	0	0	0	0	1	1
S6	40	256.0	39.2	251.0	0.700	1	1	1	1	1	1	0	1	0	1	1	1	1	0	1	0	0	1	0	0	1	1	0	0	0	0	0	0	1	0
S7	30	192.0	29.8	191.0	0.586	1	0	1	0	1	1	0	1	0	1	1	1	1	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
S8	20	128.0	19.9	127.5	0.409	1	1	1	0	0	1	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S9	10	64.0	9.5	60.5	0.256	1	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0

*Total average cost is 640. 0=RMS is not selected and 1=RMS is selected

Table A7.6(c): Summary of optimization results for different cost scenarios without and with savings calculated based on Expert 4's opinion

Cost scenario and budget			Risk mitigation without savings			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used			Budget used																																
(iv)	%	Actual	%	Actual	$Rf(x)$	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	576.0	89.1	570.0	0.979	81.7	523.0	1.000	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	✓	✓	✓	☑	☑	☑	☑	☑	☑
S2	80	512.0	79.7	510.0	0.940	79.8	511.0	0.996	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑		☑	☑	✓	☑	☑	☑	☑	✓		✓	☑	✓	☑	☑	☑	☑
S3	70	448.0	69.5	445.0	0.885	70.0	448.0	0.954	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑		☑	✓		✓	✓	✓	☑	✓	✓	✓	☑		☑	✓	☑	☑
S4	60	384.0	59.4	380.0	0.807	59.5	381.0	0.912	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑		☑	✓		✓			✓	✓			✓		✓		☑	☑
S5	50	320.0	50.0	320.0	0.726	49.4	316.0	0.824	☑	☐	☑	☑	✓	☑		☑	☑	☑	☑	☑	☑		✓			✓			✓	✓							☑	☑
S6	40	256.0	39.8	255.0	0.626	39.2	251.0	0.700	☑	☑	☑	☑	✓	☑		☑	☐	☑	☑	☑	☑		✓			✓			✓	✓							✓	
S7	30	192.0	29.7	190.0	0.509	29.8	191.0	0.586	☑		☑		✓	☑		☑	☐	✓	☑	☑	☑		✓						✓	✓								
S8	20	128.0	19.5	125.0	0.378	19.9	127.5	0.409	☑	☑	☑			☑	✓		☐	✓	✓	☑	☑																	
S9	10	64.0	8.6	55.0	0.226	9.5	60.5	0.256	☑					☑						☑	☑								✓									

☐=RMS selected considering linear cost constraint and ✓=RMS selected considering quadratic cost constraint

Table A7.7(a): Summary of optimization results for different cost scenarios without savings calculated based on Expert 5's opinion

Cost scenario and budget			Risk mitigation without savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used																																
(v)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1264.5	88.6	1245.0	0.987	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1
S2	80	1124.0	79.7	1120.0	0.939	1	1	0	0	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	0	1	1	1
S3	70	983.5	69.0	970.0	0.861	1	1	0	0	1	1	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	0	0	0	1	1
S4	60	843.0	59.8	840.0	0.767	1	0	0	0	1	1	0	0	1	1	1	1	0	1	0	0	1	1	1	1	1	0	1	1	0	0	0	0	1	1
S5	50	702.5	49.8	700.0	0.671	1	0	0	0	1	1	0	0	1	1	1	1	0	1	0	0	1	1	0	1	1	0	0	1	0	0	0	0	1	0
S6	40	562.0	39.9	560.0	0.577	1	0	0	0	0	1	0	0	1	1	1	0	0	1	0	0	1	1	0	1	1	0	0	0	1	0	0	0	1	0
S7	30	421.5	29.9	420.0	0.464	1	0	0	0	0	1	0	0	1	0	1	1	0	1	0	0	1	1	0	1	0	0	0	0	1	0	0	0	1	0
S8	20	281.0	19.9	280.0	0.331	1	0	0	0	0	1	0	0	1	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0
S9	10	140.5	10.0	140.0	0.174	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0

*Total average cost is 1405. 0=RMS is not selected and 1=RMS is selected

Table A7.7(b): Summary of optimization results for different cost scenarios with savings calculated based on Expert 5's opinion

Cost scenario and budget			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used																																
(v)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1264.5	79.6	1118.0	1.000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S2	80	1124.0	79.6	1118.0	1.000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S3	70	983.5	69.6	978.0	0.967	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	0	1	1
S4	60	843.0	59.4	834.0	0.908	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	0	0	0	0	1	1
S5	50	702.5	49.5	696.0	0.788	1	0	1	0	0	1	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	1	0	0	0	0	1	1
S6	40	562.0	39.9	560.0	0.667	1	0	1	0	0	1	0	0	1	1	1	1	1	1	0	0	1	1	0	1	1	0	0	0	1	0	0	0	1	0
S7	30	421.5	29.8	418.0	0.528	1	0	1	0	0	1	0	0	0	1	1	1	0	1	0	0	1	1	0	0	1	0	0	0	1	0	0	0	1	0
S8	20	281.0	19.5	274.0	0.356	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0
S9	10	140.5	10.0	140.0	0.176	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0

*Total average cost is 1405. 0=RMS is not selected and 1=RMS is selected

Table A7.7(c): Summary of optimization results for different cost scenarios without and with savings calculated based on Expert 5's opinion

Cost scenario and budget			Risk mitigation without savings			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used			Budget used																																
(v)	%	Actual	%	Actual	$Rf(x)$	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1264.5	88.6	1245.0	0.987	79.6	1118.0	1.000	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑
S2	80	1124.0	79.7	1120.0	0.939	79.6	1118.0	1.000	☑	☑	✓	✓	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	✓	☑	☑	☑
S3	70	983.5	69.0	970.0	0.861	69.6	978.0	0.967	☑	☑	✓	✓	☑	☑		✓	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	✓	☑	☑	☑		✓		☑	☑
S4	60	843.0	59.8	840.0	0.767	59.4	834.0	0.908	☑	✓	✓		☑	☑		✓	☑	☑	☑	☑	✓	☑	✓		☑	☑	☑	☑	☑	✓	☐	☑					☑	☑
S5	50	702.5	49.8	700.0	0.671	49.5	696.0	0.788	☑		✓		☐	☑			☑	☑	☑	☑	✓	☑	✓		☑	☑	✓	☑	☑			☑					☑	✓
S6	40	562.0	39.9	560.0	0.577	39.9	560.0	0.667	☑		✓			☑			☑	☑	☑	✓	✓	☑			☑	☑		☑	☑				☑				☑	
S7	30	421.5	29.9	420.0	0.464	29.8	418.0	0.528	☑		✓			☑			☐	✓	☑	☑		☑			☑	☑		☐	✓				☑				☑	
S8	20	281.0	19.9	280.0	0.331	19.5	274.0	0.356	☐					☐			☐		☑	✓		☑			☑	✓			✓				☐				☑	
S9	10	140.5	10.0	140.0	0.174	10.0	140.0	0.176	☑										☑			☐			☑												✓	

☐=RMS selected considering linear cost constraint and ✓=RMS selected considering quadratic cost constraint

Table A7.8(a): Summary of optimization results for different cost scenarios without savings calculated based on Expert 6’s opinion

Cost scenario and budget			Risk mitigation without savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used																																
(vi)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1494.0	89.5	1485.0	0.981	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	0
S2	80	1328.0	79.2	1315.0	0.931	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	0	0	0	0	1	0
S3	70	1162.0	69.6	1155.0	0.872	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	0	0	0	0	0	1	0
S4	60	996.0	59.6	990.0	0.784	1	1	1	0	1	0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	0
S5	50	830.0	50.0	830.0	0.694	1	1	0	0	1	0	0	1	1	1	1	0	1	1	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	0
S6	40	664.0	39.8	660.0	0.575	1	1	0	0	1	0	0	1	1	1	0	0	0	1	0	0	1	1	0	1	1	0	0	0	0	0	0	0	1	0
S7	30	498.0	29.5	490.0	0.439	1	1	0	0	1	0	0	0	1	0	0	0	0	1	0	0	1	0	1	1	1	0	0	0	0	0	0	0	1	0
S8	20	332.0	19.9	330.0	0.321	1	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0
S9	10	166.0	9.9	165.0	0.190	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0

*Total average cost is 1660. 0=RMS is not selected and 1=RMS is selected

Table A7.8(b): Summary of optimization results for different cost scenarios with savings calculated based on Expert 6’s opinion

Cost scenario and budget			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used																																
(vi)	%	Actual	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1494.0	80.0	1328.5	1.000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S2	80	1328.0	77.0	1278.5	0.997	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S3	70	1162.0	69.5	1153.5	0.952	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	0	0	1	0
S4	60	996.0	59.2	983.5	0.891	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	0	0	0	1	0
S5	50	830.0	49.9	828.5	0.811	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	0	0	0	0	0	0	1	0
S6	40	664.0	39.9	662.5	0.653	1	1	0	0	1	1	0	1	1	0	0	1	1	1	0	0	1	1	1	1	1	1	0	0	0	0	0	0	1	0
S7	30	498.0	29.5	490.5	0.542	1	1	1	0	1	0	0	0	0	1	0	1	1	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	1	0
S8	20	332.0	19.6	325.5	0.385	1	1	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	1	0
S9	10	166.0	9.9	164.5	0.216	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0

*Total average cost is 1660. 0=RMS is not selected and 1=RMS is selected

Table A7.8(c): Summary of optimization results for different cost scenarios without and with savings calculated based on Expert 6's opinion

Cost scenario and budget			Risk mitigation without savings			Risk mitigation with savings			Selected RMSs under different cost scenarios																													
Scenario	Budget available*		Budget used			Budget used																																
(vi)	%	Actual	%	Actual	$Rf(x)$	%	Actual	$Rf(x)$	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
S1	90	1494.0	89.5	1485.0	0.981	80.0	1328.5	1.000	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	✓	☑	☑	☑	☑	☑	☑	☑	✓
S2	80	1328.0	79.2	1315.0	0.931	77.0	1278.5	0.997	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	✓	☑	☑	✓	✓	✓	✓	☑	✓
S3	70	1162.0	69.6	1155.0	0.872	69.5	1153.5	0.952	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	✓	✓	✓		✓			☑	
S4	60	996.0	59.6	990.0	0.784	59.2	983.5	0.891	☑	☑	☑	✓	☑	✓	☑	☑	☑	☑	☑	☑	☑	☑	✓		☑	☑	☑	☑	☑	✓			✓				☑	
S5	50	830.0	50.0	830.0	0.694	49.9	828.5	0.811	☑	☑	✓		☑	✓		☑	☑	☑	☑	✓	☑	☑	✓		☑	☑	□	☑	☑	✓							☑	
S6	40	664.0	39.8	660.0	0.575	39.9	662.5	0.653	☑	☑			☑	✓		☑	☑	□		✓	✓	☑			☑	☑	✓	☑	☑	✓							☑	
S7	30	498.0	29.5	490.0	0.439	29.5	490.5	0.542	☑	☑	✓		☑				□	✓		✓	✓	□			☑	✓	□	☑	☑								☑	
S8	20	332.0	19.9	330.0	0.321	19.6	325.5	0.385	☑	☑		□	☑				□			✓	✓				□	✓		☑	✓								☑	
S9	10	166.0	9.9	165.0	0.190	9.9	164.5	0.216	□	□			□							✓						✓		□	✓								☑	

□=RMS selected considering linear cost constraint and ✓=RMS selected considering quadratic cost constraint

Table A7.9: summary of comparison between optimization based on consensus mean and ensemble mean for SCRM.

Attribute or theme	Consensus mean		Ensemble mean	
	Advantage	Limitations	Advantage	Limitations
General understanding	Standard process of analysing consensus		Advanced process of analysing consensus	
Analysis process	Measure of central tendency (e.g. mean) of the data of primary attributes are determined prior to further analysis such as optimization			Does not consider measure of central tendency (e.g. mean) of the data of primary attributes in further analysis such as optimization
Further analysis of primary data		Attributes of individual set of primary data is lost in the subsequent analysis	Attributes of individual set of primary data prevails in the subsequent analysis	
Scale of measurement of attributes		Scale of measurement of primary attributes shortens after analysis of central tendency (such as mean) which affects results of further analysis such as optimization	Scale of measurement of primary attributes does not affect further analysis such as optimization as central tendency (such as mean) is measured after further analysis	
Nature of results	Further analysis based on primary attributes provides a deterministic result	Further analysis based on primary attributes does not capture variability in the results based on primary data	Further analysis based on primary attributes provides a deterministic as well as probabilistic range of the results capturing variability in the results based on primary data	
Scale of results and score objective function of optimization		Scale of further analysis (such as optimization) of results becomes shorten resulting into lower level score of optimization	Scale of further analysis (such as optimization) of results does not shorten resulting into higher level score of optimization	
Additional information from further analysis (optimization)		Provides no additional information except deterministic results	Provides additional information such as preferential order of implementation of MRS which are not selected full (100%) in consensus based on all the experts.	

Appendix F: Limits of SCR and RMS attributes for simulation model

Table A8.1: Minimum limit of SCR attributes and RMS attributes for simulation model

	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR1	5	6		1	1	5	5	5	1	5	9	9	5	5	1	5	5	5	5	5	5	5	1	5	1	1	5		5	1	1	5	9
SCR2	5	5		5	9	5	1	5	1	5	5	5	5	5		5	5	7				1	5	9	9			5	1	5		5	9
SCR3	2	2		5				5		5	5	5		5	5			1		5	5	5	5	5			5		1		1		5
SCR4	5	5		1	1	1	1				5	5	5	5	1	1	1	5	1	5	1	1	1	5	9	9	5		1	5	5	9	9
SCR5	3	3		1	5	1	1	5		5	5	9	1	1	1	1	1		1	9	5	1	1	5	5	5	1		9	1	9	9	9
SCR6	6	6						1	1		5	5	1		9	9	9	9		9	9	1	5	1	5	9	9		5	5	9	9	9
SCR7	3	2		5				1			1	5	1	5	1		1			5		5	5	1	1	5	5		1			9	9
SCR8	5	5		1	1		1	1	5	9	5		1	5	9	1	5	5	1	5	1	1	5	5	1	1	1		5	1	9	5	9
SCR9	3	6		5				1	9					1	1	5	1	1					5	9				5					
SCR10	3	5		5				1	5					1		5		1				5	5	5				6					
SCR11	5	6		5	5	9	5	5	5				9	5	5	5		1			5	5	1	1	9					5		9	5
SCR12	6	7		1	1	1	9	9				1	5	5	9	5	1	1		5	1	1	1	5	9	9	9		9	5		6	9
SCR13	5	6		5	5	5	5	5		9	5		5	5	5	5	1	9					1	1	9	9	5		5			9	9
SCR14	5	5						5	5		5	5	1	5	1	9	1	9		9	5	1	5	7	5	5	5		1			5	9
SCR15	7	6		5	5			6	5	5	5	8	1	5	1		5	9		7	5	1	5	7	9	5	5					5	9
SCR16	8	7		5				5	5		5	5	1	5	1		1	5		7	5	5	5	6	9	5	5					9	9
SCR17	8	7						5	5		5	9	1	5	5	6	1	5		9	5	5	5	5	9	1	1					5	9
SCR18	4	4		5				1	5		9	9	5	1	5		1			9	5	1	5	5		1	1			5		1	9
SCR19	5	5		1	5	1	1	5	5	9	1	1	5	8	7	5	9	5		1		5	5	5	9							9	9
SCR20	7	5		1	5			1					1	5	5	5	5			5	5		5	1	9	5	5					1	1
SCR21	7	6		5	1	5	5	5			1	5	5	1	1	5	5	5		9	5	5	5	5	9	1	1			5	5	6	9
SCR22	4	4		9		9		1	1		1	1	1	5	1	9	5	9		1	5	9	9	5	9	5	5					5	9
SCR23	5	5		5		1					5	5	5	9	5	1	5							9		1	1					9	9
SCR24	3	4		1	1			5		9	1	1	9	5	5	5		1		5	5		5	5	9	1	1					9	9
SCR25	5	6		1	9	1	9	5		9	5	5	1	1	5					5	8			1	1	1	1					5	9
SCR26	3	3		5	1	1		1			9		9	5	5	9	5	5					5	9	9	5	5					9	9
SCR27	5	6		9	5	9		9			9	9	5	1	9		9					5	5	9	9					5		1	1
SCR28	4	4		1	9		5	5			5	5	5	5	1	5	1	9			1	9	5	1	5				9			9	9
SCR29	5	7		9	9	1		1			9	9	1	1		9	5	9		5	5		5	5	9	1	5		1	5		5	9
SCR30	6	7		7	5	5	9	1			9	9	1	9			1			9	5	1	1	5	9	1	9		5			9	9
SCR31	4	4		5	5	5	5				1	5	5	5			5		1	5			5	1	1	5	5					5	5
SCR32	3	3		1	5	5		9					5	1			5		5	5			5	1	1	5						5	5
SCR33	4	4		5	5	5		9					5	5			5		5	5			5	5	5	5						5	5
C				10	10	10	10	20	10	10	50	30	40	20	10	15	10	20	15	20	10	10	10	25	15	15	20	10	10	20	10	10	10

Table A8.2: Maximum limit of SCR attributes and RMS attributes for simulation model

	P	I	W	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SCR1	7	8		7	9	9	5	9	5	5	9	9	9	7	9	9	9	9	5	9	9	7	8	5	1	9	5		5	9	5	9	9
SCR2	8	7		5	9	6	1	6	6	5	5	5	5	5		9	5	9				1	5	9	9			6	1	5		5	9
SCR3	7	8		5				9		6	5	5		5	6			1		5	5	6	5	5			5		1		1		5
SCR4	9	8		9	1	1	5				9	9	9	9	1	7	5	5	1	5	1	9	9	5	9	9	5		5	9	7	9	9
SCR5	7	7		5	5	5	9	9		5	9	9	9	1	5	1	7		1	9	5	7	9	7	9	9	9		9	9	9	9	9
SCR6	9	8						1	6		5	5	9		9	9	9	9		9	9	9	9	5	5	9	9		9	5	9	9	9
SCR7	7	5		5				9			9	5	9	6	9		1			5		5	5	6	1	5	5		1			9	9
SCR8	8	7		1	9		1	9	9	9	5		5	9	9	1	5	6	1	9	1	1	5	9	5	5	5		5	1	9	5	9
SCR9	9	8		5				1	9					1	1	9	6	9					5	9				9					
SCR10	9	8		5				1	9					1		9		9				9	5	5				9					
SCR11	9	9		9	9	9	9	5	6				9	9	9	9		9			5	5	1	5	9					5		9	9
SCR12	8	8		9	9	5	9	9				9	9	9	9	9	9	1		8	1	8	8	9	9	9	9		9	5		9	9
SCR13	8	7		5	5	5	5	5		9	5		5	5	5	9	1	9					5	5	9	9	5		5			9	9
SCR14	9	9						9	9		9	9	9	9	9	9	5	9		9	9	5	5	9	5	5	5		1			9	9
SCR15	9	9		5	5			9	9	5	9	9	9	9	9		6	9		9	7	5	5	9	9	9	5					9	9
SCR16	9	8		5				9	9		9	9	5	5	6		6	5		9	9	5	5	9	9	9	9					9	9
SCR17	9	8						5	9		9	9	9	5	9	6	5	5		9	9	7	9	9	9	5	5					9	9
SCR18	6	8		5				5	5		9	9	5	5	9		5			9	5	5	9	5		5	5			5		9	9
SCR19	8	8		9	9	9	1	9	5	9	1	9	9	9	9	9	9	8		5		9	9	9	9							9	9
SCR20	8	7		1	5			5					5	5	5	5	5			9	5		5	9	9	9	9					9	5
SCR21	9	8		9	5	5	5	9			5	9	9	9	5	6	5	9		9	8	9	9	9	9	5	5			5	5	9	9
SCR22	8	8		9		9		5	5		5	5	5	9	9	9	9	9		9	9	9	9	9	9	5	5					9	9
SCR23	7	8		5		1					9	9	5	9	9	1	5							9		1	1					9	9
SCR24	7	8		5	1			9		9	5	5	9	9	5	5		1		9	9		5	9	9	9	9					9	9
SCR25	8	8		9	9	9	9	9		9	5	5	5	5	5					9	9			6	1	5	5					5	9
SCR26	7	8		5	5	1		6			9		9	5	5	9	5	9					5	9	9	5	5					9	9
SCR27	8	8		9	5	9		9			9	9	9	9	9		9					9	5	9	9					5		9	9
SCR28	8	8		1	9		5	9			9	9	9	5	1	5	1	9			9	9	9	9	5				9			9	9
SCR29	8	9		9	9	1		9			9	9	9	9		9	5	9		9	9		9	9	9	1	5		1	5		9	9
SCR30	7	8		9	9	9	9	9			9	9	9	9			1			9	9	9	7	9	9	9	9		5			9	9
SCR31	6	6		9	9	9	5				1	5	9	9			5		9	5			5	9	7	9	5					5	9
SCR32	6	7		7	7	9		9					9	7			5		9	5			5	9	7	7						5	9
SCR33	7	7		7	9	7		9					9	9			5		9	5			5	7	9	7						5	9
C				30	100	70	100	100	50	50	100	100	90	80	60	100	100	80	60	60	60	60	60	100	100	90	80	30	50	70	60	100	100

Appendix G: Summary of RAI and cost of RMS for 50 simulations

Table A8.2a: Summary of the scores of RAI and the cost of the implementation of RMSs for 50 simulations

	P	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SIM1	Cost	10.08	36.38	45.44	13.07	86.39	33.41	32.17	52.96	95.26	53.18	64.83	25.24	41.01	45.87	63.64	37.71	27.46	23.26	38.21	23.61	95.67	17.77	71.39	48.70	21.61	30.24	34.55	56.16	19.86	74.75
	RAI	0.038	0.032	0.024	0.020	0.044	0.023	0.016	0.040	0.045	0.038	0.043	0.037	0.035	0.034	0.038	0.005	0.043	0.035	0.031	0.040	0.053	0.052	0.033	0.031	0.006	0.016	0.015	0.011	0.055	0.064
SIM2	Cost	18.56	33.93	39.24	18.90	69.94	18.83	46.56	82.12	43.94	71.38	30.84	56.31	60.96	94.49	57.83	40.70	35.14	21.63	16.35	58.12	74.75	41.98	69.57	33.04	29.16	13.57	21.37	11.53	61.74	71.67
	RAI	0.039	0.031	0.023	0.017	0.043	0.021	0.017	0.043	0.044	0.043	0.046	0.036	0.035	0.033	0.037	0.004	0.043	0.034	0.031	0.045	0.052	0.052	0.032	0.033	0.004	0.015	0.016	0.011	0.056	0.062
SIM3	Cost	29.38	61.15	53.74	77.89	30.34	44.42	13.58	76.82	78.86	51.87	51.44	40.69	31.79	50.34	69.34	19.54	35.01	56.81	27.68	13.40	44.97	85.36	50.04	23.31	16.68	27.96	49.14	33.76	52.66	62.06
	RAI	0.038	0.030	0.023	0.018	0.044	0.023	0.016	0.042	0.044	0.043	0.045	0.039	0.037	0.034	0.038	0.005	0.044	0.032	0.029	0.040	0.049	0.054	0.033	0.030	0.005	0.016	0.016	0.009	0.059	0.063
SIM4	Cost	12.43	62.81	63.22	42.38	69.63	39.06	46.24	54.40	76.01	86.12	71.52	23.42	24.23	37.20	69.10	57.72	50.50	47.34	47.38	58.34	93.80	84.06	59.90	24.08	17.47	11.66	70.00	30.13	99.49	41.56
	RAI	0.041	0.031	0.024	0.020	0.043	0.020	0.016	0.039	0.043	0.040	0.042	0.036	0.036	0.033	0.038	0.004	0.045	0.034	0.034	0.039	0.051	0.052	0.035	0.033	0.005	0.018	0.015	0.012	0.057	0.064
SIM5	Cost	16.46	14.65	47.81	87.16	38.13	19.12	46.95	73.92	67.06	60.89	34.84	52.39	25.25	17.82	44.92	39.29	44.41	18.28	51.48	27.32	89.45	81.53	82.59	60.14	29.78	32.85	20.43	55.01	39.20	11.03
	RAI	0.039	0.032	0.025	0.019	0.042	0.025	0.017	0.039	0.042	0.046	0.043	0.036	0.038	0.030	0.040	0.005	0.041	0.032	0.028	0.041	0.052	0.055	0.034	0.032	0.004	0.016	0.017	0.011	0.057	0.063
SIM6	Cost	10.83	83.84	13.47	91.79	33.09	16.73	21.38	96.64	60.10	75.88	28.74	50.37	49.46	51.28	66.69	39.20	56.93	21.63	58.45	35.71	92.92	58.93	39.24	78.54	10.15	28.47	68.78	44.13	46.78	67.84
	RAI	0.037	0.032	0.022	0.018	0.044	0.025	0.016	0.040	0.043	0.041	0.043	0.035	0.037	0.034	0.038	0.005	0.044	0.034	0.032	0.042	0.052	0.052	0.033	0.032	0.007	0.017	0.014	0.011	0.056	0.062
SIM7	Cost	10.08	68.16	37.22	69.77	70.63	18.15	49.16	65.11	53.40	58.94	70.12	56.04	58.56	98.20	44.09	41.78	34.04	11.31	31.59	53.14	47.24	83.15	29.89	53.45	27.45	43.85	24.14	10.95	26.35	38.05
	RAI	0.035	0.033	0.026	0.018	0.042	0.025	0.016	0.041	0.043	0.045	0.044	0.037	0.036	0.033	0.039	0.005	0.041	0.034	0.030	0.043	0.051	0.052	0.033	0.032	0.005	0.015	0.015	0.010	0.056	0.064
SIM8	Cost	19.56	25.63	30.52	71.18	83.81	38.47	11.70	89.67	31.08	64.21	53.21	20.55	53.10	12.85	57.62	48.93	43.78	34.77	16.05	49.11	42.38	40.23	45.89	78.71	21.62	21.85	51.28	28.84	14.35	92.09
	RAI	0.035	0.031	0.023	0.019	0.043	0.024	0.016	0.042	0.044	0.042	0.046	0.034	0.036	0.031	0.040	0.005	0.042	0.032	0.029	0.045	0.056	0.051	0.034	0.031	0.004	0.018	0.017	0.011	0.054	0.063
SIM9	Cost	16.09	50.59	23.84	35.04	45.71	35.66	35.40	81.69	86.36	58.15	74.42	53.58	56.00	60.09	41.13	27.10	34.60	13.98	46.49	58.42	82.23	61.28	86.14	65.26	16.24	21.32	68.13	58.55	12.56	87.03
	RAI	0.038	0.032	0.025	0.019	0.043	0.024	0.017	0.037	0.043	0.041	0.045	0.036	0.037	0.034	0.040	0.005	0.044	0.035	0.028	0.041	0.053	0.054	0.033	0.030	0.006	0.015	0.016	0.011	0.056	0.062
SIM10	Cost	11.54	68.60	27.58	35.33	81.90	37.25	25.32	93.71	97.18	50.21	51.72	24.96	24.26	59.30	24.01	18.12	22.01	46.86	58.53	45.23	86.16	97.60	53.62	33.77	20.92	35.22	34.94	19.89	16.89	51.22
	RAI	0.039	0.031	0.026	0.020	0.048	0.023	0.017	0.040	0.040	0.042	0.044	0.036	0.037	0.030	0.036	0.004	0.044	0.032	0.030	0.039	0.053	0.054	0.033	0.032	0.005	0.015	0.017	0.010	0.057	0.065
SIM11	Cost	26.72	90.95	38.92	66.75	21.37	26.86	35.55	56.55	34.44	88.40	75.65	31.03	87.68	94.42	61.60	54.89	30.87	38.07	24.37	43.37	54.42	38.18	40.51	74.94	20.62	34.32	68.89	34.56	23.66	28.80
	RAI	0.038	0.033	0.023	0.019	0.044	0.023	0.017	0.040	0.042	0.042	0.044	0.038	0.037	0.031	0.038	0.004	0.042	0.035	0.027	0.041	0.051	0.053	0.035	0.031	0.005	0.016	0.015	0.010	0.059	0.064
SIM12	Cost	14.13	34.21	56.48	91.47	87.76	16.81	48.49	77.84	88.41	53.87	58.03	47.58	29.68	78.10	65.03	48.18	56.69	27.22	36.66	56.21	32.62	46.65	25.46	52.35	21.75	36.16	53.15	21.53	50.99	92.58
	RAI	0.038	0.031	0.025	0.020	0.040	0.023	0.016	0.039	0.045	0.042	0.046	0.036	0.039	0.030	0.038	0.004	0.042	0.031	0.030	0.043	0.052	0.053	0.035	0.031	0.005	0.017	0.016	0.011	0.058	0.063
SIM13	Cost	29.75	96.86	63.09	29.87	74.72	19.40	11.81	78.80	75.64	87.58	74.27	27.87	40.52	70.09	29.20	35.99	28.25	34.66	28.32	20.83	84.51	77.00	48.29	75.30	12.10	46.23	63.04	24.37	81.03	72.28
	RAI	0.039	0.029	0.024	0.021	0.044	0.027	0.018	0.039	0.042	0.042	0.045	0.037	0.038	0.029	0.037	0.003	0.042	0.033	0.032	0.039	0.054	0.053	0.033	0.031	0.006	0.015	0.017	0.009	0.058	0.063
SIM14	Cost	22.98	88.08	25.09	35.30	26.40	27.91	23.99	72.56	79.85	54.80	31.28	58.30	55.43	16.23	47.98	33.94	30.26	24.48	36.77	30.32	50.02	86.61	16.12	35.23	13.18	32.94	59.83	48.87	53.90	60.04
	RAI	0.042	0.033	0.022	0.019	0.039	0.022	0.017	0.040	0.043	0.046	0.045	0.036	0.038	0.032	0.038	0.005	0.041	0.032	0.030	0.039	0.052	0.055	0.036	0.033	0.006	0.016	0.015	0.010	0.055	0.064
SIM15	Cost	10.07	44.54	31.29	99.46	35.18	40.59	26.50	81.93	76.16	66.68	75.45	44.59	40.60	78.01	44.87	43.94	56.96	28.20	54.45	12.73	62.71	28.97	27.60	64.72	22.24	13.46	57.13	20.70	93.96	48.56

	P	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
	RAI	0.040	0.032	0.023	0.017	0.041	0.022	0.016	0.041	0.041	0.044	0.046	0.036	0.035	0.033	0.038	0.005	0.045	0.031	0.029	0.042	0.056	0.055	0.033	0.031	0.005	0.015	0.016	0.011	0.057	0.064
SIM16	Cost	23.24	65.68	38.96	92.71	78.79	12.16	18.54	71.72	55.95	70.02	66.14	14.10	82.50	43.64	32.98	36.18	32.68	17.61	59.08	56.19	31.94	27.15	42.88	33.87	13.06	46.23	41.51	32.60	85.57	28.04
	RAI	0.041	0.032	0.023	0.020	0.044	0.022	0.016	0.039	0.041	0.043	0.045	0.035	0.036	0.035	0.037	0.006	0.044	0.031	0.030	0.040	0.053	0.055	0.036	0.030	0.005	0.015	0.015	0.010	0.057	0.064
SIM17	Cost	20.42	65.13	69.88	92.54	52.88	45.17	11.52	96.26	55.53	71.98	28.46	37.27	80.37	42.14	57.14	16.46	43.89	15.77	15.91	10.58	59.46	64.57	44.44	24.73	10.98	20.17	40.93	26.74	29.15	26.20
	RAI	0.037	0.032	0.024	0.018	0.044	0.026	0.017	0.041	0.042	0.040	0.043	0.036	0.035	0.034	0.040	0.005	0.044	0.034	0.032	0.038	0.054	0.053	0.036	0.031	0.006	0.015	0.016	0.009	0.057	0.062
SIM18	Cost	18.60	10.89	27.25	16.91	83.25	13.11	46.38	97.54	31.80	59.38	52.59	18.84	81.10	70.96	34.38	29.06	24.16	35.11	36.32	12.31	80.95	52.77	75.86	28.07	15.10	20.90	46.87	35.89	83.44	13.68
	RAI	0.042	0.032	0.022	0.019	0.045	0.024	0.017	0.041	0.044	0.042	0.045	0.040	0.037	0.033	0.040	0.003	0.042	0.032	0.031	0.041	0.052	0.053	0.032	0.030	0.005	0.015	0.015	0.010	0.056	0.061
SIM19	Cost	29.60	53.18	16.72	80.64	58.37	35.43	29.67	79.75	74.48	41.76	77.36	58.20	76.42	57.94	56.31	54.56	27.95	31.94	53.39	47.36	77.50	92.91	33.16	60.43	24.69	46.31	45.29	56.84	16.89	25.62
	RAI	0.037	0.032	0.023	0.020	0.043	0.025	0.016	0.040	0.044	0.040	0.043	0.036	0.034	0.033	0.039	0.005	0.045	0.032	0.033	0.043	0.050	0.053	0.036	0.032	0.003	0.016	0.018	0.012	0.057	0.062
SIM20	Cost	28.57	71.13	64.21	43.00	70.03	45.64	32.69	67.54	92.68	83.12	66.48	51.66	27.11	64.35	67.81	24.47	49.40	25.25	33.68	11.38	54.77	72.36	16.69	47.93	22.53	37.14	69.36	37.82	61.12	21.88
	RAI	0.037	0.033	0.024	0.018	0.046	0.024	0.017	0.039	0.043	0.044	0.045	0.036	0.037	0.034	0.040	0.005	0.043	0.032	0.031	0.042	0.051	0.054	0.034	0.030	0.005	0.014	0.015	0.009	0.054	0.065
SIM21	Cost	22.77	67.35	69.61	45.77	45.93	14.70	16.41	72.47	30.19	64.14	69.86	22.29	51.50	59.37	29.46	57.27	20.37	51.08	10.51	22.86	59.21	78.70	36.42	22.24	21.10	42.64	52.96	16.00	53.74	27.02
	RAI	0.039	0.031	0.024	0.018	0.043	0.025	0.017	0.039	0.039	0.042	0.044	0.041	0.037	0.033	0.040	0.005	0.045	0.034	0.030	0.039	0.051	0.052	0.036	0.032	0.005	0.014	0.015	0.009	0.055	0.063
SIM22	Cost	18.71	48.65	38.55	36.57	55.67	27.29	13.60	98.44	48.57	55.02	29.60	32.99	19.29	65.47	61.31	48.47	37.58	45.62	49.93	16.46	30.54	94.30	24.71	36.48	26.35	41.36	67.15	53.67	46.66	14.71
	RAI	0.037	0.031	0.026	0.018	0.041	0.026	0.016	0.037	0.045	0.047	0.046	0.037	0.035	0.033	0.039	0.005	0.042	0.031	0.026	0.042	0.054	0.055	0.034	0.030	0.004	0.015	0.016	0.009	0.058	0.064
SIM23	Cost	12.01	93.42	53.46	23.06	54.15	15.02	45.94	82.09	35.36	83.51	76.33	27.37	76.64	86.34	38.70	46.96	51.59	40.57	16.41	31.27	81.85	33.01	60.49	55.45	29.71	25.10	56.61	31.53	72.40	20.72
	RAI	0.041	0.031	0.024	0.017	0.042	0.024	0.018	0.038	0.040	0.043	0.045	0.036	0.036	0.031	0.038	0.005	0.042	0.032	0.028	0.042	0.054	0.054	0.034	0.033	0.006	0.014	0.017	0.011	0.058	0.063
SIM24	Cost	15.07	38.96	30.51	40.31	23.09	33.27	45.09	51.44	95.03	61.63	53.65	31.40	56.10	86.15	27.80	17.11	44.28	46.61	24.86	10.15	48.48	15.38	54.98	35.57	17.98	27.26	20.89	38.36	31.50	85.76
	RAI	0.038	0.029	0.024	0.018	0.043	0.021	0.016	0.040	0.042	0.045	0.044	0.038	0.039	0.035	0.037	0.004	0.044	0.034	0.031	0.042	0.054	0.052	0.034	0.032	0.005	0.015	0.014	0.011	0.056	0.062
SIM25	Cost	20.84	23.10	31.66	85.19	64.27	39.84	26.11	63.64	96.81	53.21	27.07	50.47	95.08	52.52	39.60	48.64	22.00	28.01	54.64	18.78	33.71	29.04	59.01	50.26	25.78	47.25	36.07	52.90	79.39	98.66
	RAI	0.040	0.031	0.026	0.018	0.045	0.024	0.016	0.040	0.042	0.043	0.044	0.035	0.035	0.034	0.037	0.005	0.042	0.033	0.029	0.042	0.054	0.054	0.035	0.031	0.006	0.015	0.016	0.010	0.055	0.063
SIM26	Cost	18.84	82.63	49.49	65.67	68.68	32.27	35.41	91.81	63.62	47.85	56.30	23.28	78.05	93.88	35.05	38.59	38.26	12.36	55.78	42.53	74.33	75.96	38.35	49.97	22.96	22.52	57.03	40.85	32.68	71.12
	RAI	0.036	0.031	0.023	0.019	0.045	0.021	0.015	0.042	0.044	0.047	0.045	0.040	0.035	0.033	0.038	0.005	0.043	0.031	0.032	0.039	0.051	0.054	0.033	0.032	0.004	0.015	0.016	0.011	0.055	0.064
SIM27	Cost	23.56	12.02	62.49	28.15	74.71	45.68	32.39	54.41	78.10	67.94	62.64	55.62	62.28	37.00	24.20	29.46	58.56	50.64	47.84	54.94	49.00	18.70	19.93	76.83	24.71	25.82	65.24	34.97	99.75	49.82
	RAI	0.041	0.031	0.022	0.019	0.043	0.024	0.017	0.040	0.044	0.042	0.043	0.034	0.035	0.032	0.038	0.005	0.045	0.032	0.033	0.043	0.050	0.052	0.033	0.033	0.006	0.015	0.015	0.012	0.057	0.064
SIM11	Cost	14.43	65.77	40.26	32.46	98.28	13.06	35.22	65.09	68.18	78.67	25.82	58.62	20.62	79.29	50.63	32.59	29.67	53.83	55.62	41.47	83.54	33.11	29.59	37.30	14.31	13.02	28.95	13.35	55.80	86.26
	RAI	0.038	0.033	0.026	0.019	0.046	0.023	0.018	0.039	0.041	0.042	0.045	0.035	0.036	0.035	0.039	0.004	0.043	0.032	0.030	0.039	0.055	0.053	0.032	0.030	0.006	0.015	0.016	0.011	0.057	0.063
SIM12	Cost	21.60	91.95	50.22	48.51	61.14	22.83	26.97	83.10	81.96	42.64	68.36	24.73	60.83	89.58	57.88	19.36	49.93	56.67	53.29	35.56	45.46	66.03	83.99	28.35	13.20	23.94	45.11	13.80	29.89	78.92
	RAI	0.039	0.033	0.023	0.018	0.044	0.023	0.017	0.038	0.042	0.042	0.044	0.038	0.035	0.035	0.038	0.004	0.044	0.034	0.029	0.045	0.051	0.054	0.031	0.032	0.005	0.015	0.016	0.011	0.057	0.064
SIM13	Cost	26.39	62.58	41.16	69.20	28.59	33.26	21.97	90.61	92.22	87.13	37.74	22.66	77.70	59.24	27.96	57.54	49.03	30.21	48.90	21.70	95.28	50.02	47.01	70.15	22.36	25.53	64.64	32.05	54.32	71.32
	RAI	0.040	0.032	0.025	0.019	0.045	0.021	0.017	0.037	0.041	0.041	0.043	0.038	0.036	0.034	0.038	0.005	0.042	0.032	0.030	0.040	0.057	0.056	0.033	0.033	0.004	0.015	0.016	0.011	0.055	0.064
SIM14	Cost	24.67	89.05	52.12	83.75	67.14	18.57	47.43	98.96	95.21	64.76	74.72	56.65	99.28	68.61	68.34	29.02	48.27	52.29	47.78	19.74	66.88	56.43	81.57	47.73	25.80	42.82	41.79	54.71	79.33	18.74
	RAI	0.040	0.032	0.026	0.020	0.044	0.025	0.018	0.036	0.043	0.043	0.041	0.038	0.037	0.033	0.038	0.005	0.044	0.032	0.024	0.041	0.051	0.053	0.035	0.032	0.005	0.016	0.016	0.011	0.058	0.063

	P	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
SIM15	Cost	20.46	74.91	38.32	61.91	76.66	29.59	29.13	52.81	88.23	86.07	72.72	25.48	18.71	15.64	50.74	44.09	56.88	16.18	51.11	15.10	84.61	70.98	24.48	49.88	24.87	28.46	62.10	39.43	99.64	87.74
	RAI	0.039	0.035	0.026	0.017	0.044	0.023	0.017	0.038	0.044	0.041	0.044	0.034	0.036	0.034	0.039	0.006	0.044	0.032	0.030	0.040	0.052	0.053	0.035	0.031	0.004	0.016	0.017	0.010	0.054	0.062
SIM16	Cost	12.67	60.32	57.11	45.63	26.61	32.10	24.37	86.74	70.17	57.24	69.41	48.52	88.51	78.11	62.97	36.36	41.72	58.12	47.93	56.99	82.02	70.08	74.61	60.50	29.80	30.49	47.61	21.56	99.29	97.20
	RAI	0.036	0.033	0.026	0.019	0.046	0.020	0.018	0.040	0.046	0.046	0.045	0.033	0.034	0.030	0.039	0.005	0.045	0.035	0.029	0.040	0.051	0.052	0.036	0.032	0.004	0.016	0.016	0.011	0.054	0.062
SIM17	Cost	25.27	94.24	17.63	76.46	79.49	14.95	48.33	52.99	89.92	80.32	35.05	14.44	44.01	13.30	23.73	38.88	25.07	54.41	29.44	13.12	85.21	50.42	79.28	35.29	16.13	27.17	45.45	12.99	74.65	68.83
	RAI	0.038	0.030	0.022	0.020	0.042	0.024	0.017	0.040	0.044	0.044	0.043	0.034	0.038	0.035	0.038	0.004	0.042	0.038	0.033	0.042	0.050	0.054	0.030	0.031	0.006	0.015	0.017	0.009	0.056	0.062
SIM28	Cost	20.24	90.70	64.78	37.15	25.57	26.44	34.47	82.40	58.39	47.22	32.64	30.92	40.99	41.47	47.42	50.79	27.35	45.58	52.39	19.46	80.04	77.21	52.50	50.33	11.29	12.30	34.65	33.39	95.68	68.78
	RAI	0.040	0.031	0.021	0.017	0.045	0.021	0.018	0.040	0.041	0.042	0.046	0.038	0.038	0.031	0.040	0.005	0.044	0.032	0.029	0.042	0.050	0.053	0.036	0.032	0.005	0.016	0.015	0.011	0.056	0.064
SIM29	Cost	15.04	57.78	54.74	87.27	38.52	14.07	48.89	82.21	76.78	88.09	39.85	59.13	18.05	57.53	26.46	40.73	50.14	59.73	55.70	32.42	81.67	94.28	66.45	61.69	25.18	20.18	41.99	32.89	33.87	42.85
	RAI	0.039	0.034	0.026	0.019	0.043	0.022	0.015	0.038	0.044	0.043	0.046	0.037	0.036	0.035	0.037	0.005	0.044	0.032	0.027	0.042	0.052	0.054	0.033	0.031	0.005	0.015	0.016	0.009	0.058	0.063
SIM30	Cost	26.99	70.74	45.27	33.00	55.79	33.64	19.80	96.79	67.85	86.47	34.92	38.33	56.04	40.28	37.51	34.89	41.50	27.56	23.30	15.62	39.16	25.94	59.84	60.60	11.74	14.22	60.45	57.56	96.78	24.71
	RAI	0.037	0.031	0.025	0.020	0.042	0.022	0.017	0.041	0.043	0.042	0.043	0.036	0.033	0.034	0.039	0.005	0.045	0.034	0.030	0.043	0.052	0.053	0.035	0.032	0.004	0.016	0.015	0.011	0.054	0.064
SIM31	Cost	22.69	94.20	43.48	17.70	59.55	31.47	45.95	51.44	58.94	48.00	58.97	24.20	28.91	32.85	47.41	39.02	27.45	58.61	57.30	42.60	36.01	47.36	23.45	54.64	27.94	39.70	39.91	49.50	94.69	34.11
	RAI	0.039	0.032	0.027	0.019	0.042	0.024	0.017	0.038	0.044	0.038	0.045	0.037	0.035	0.033	0.039	0.005	0.044	0.030	0.034	0.041	0.050	0.052	0.032	0.034	0.007	0.016	0.016	0.011	0.056	0.063
SIM32	Cost	26.81	33.99	35.32	73.29	45.23	13.30	21.66	52.15	33.32	56.77	62.94	18.71	70.75	35.38	31.53	51.51	42.61	22.25	48.56	19.16	44.44	68.29	36.61	61.97	24.46	44.72	21.76	23.34	82.47	11.32
	RAI	0.037	0.032	0.024	0.019	0.043	0.022	0.018	0.039	0.042	0.043	0.045	0.035	0.036	0.032	0.040	0.006	0.044	0.035	0.032	0.040	0.048	0.055	0.034	0.032	0.004	0.016	0.014	0.011	0.057	0.064
SIM33	Cost	16.70	20.85	23.59	90.09	42.98	21.25	40.40	69.00	54.65	44.19	56.97	52.82	89.29	67.89	71.42	17.87	58.61	18.44	51.25	59.37	44.40	94.79	58.78	20.51	18.74	42.70	68.07	33.57	28.16	74.35
	RAI	0.042	0.031	0.023	0.019	0.042	0.023	0.017	0.039	0.044	0.045	0.045	0.040	0.034	0.031	0.036	0.004	0.046	0.035	0.030	0.038	0.051	0.052	0.036	0.034	0.004	0.015	0.015	0.010	0.056	0.063
SIM34	Cost	21.78	75.71	37.16	60.11	25.64	27.36	36.10	63.01	66.49	80.95	21.73	17.47	82.84	71.93	61.68	28.95	47.89	26.48	53.17	24.50	31.72	25.34	21.77	56.79	28.17	15.82	27.58	38.20	23.27	22.24
	RAI	0.040	0.032	0.023	0.019	0.044	0.024	0.019	0.038	0.041	0.045	0.046	0.039	0.037	0.032	0.038	0.005	0.044	0.035	0.027	0.039	0.051	0.053	0.032	0.031	0.006	0.015	0.016	0.010	0.054	0.064
SIM35	Cost	19.34	43.97	55.97	87.43	53.18	38.57	44.74	70.88	64.33	58.53	34.22	13.58	84.87	76.93	53.71	44.94	23.67	35.45	25.48	53.08	56.72	35.20	60.37	53.29	28.04	27.50	29.45	52.74	87.76	39.74
	RAI	0.039	0.034	0.025	0.019	0.042	0.021	0.016	0.039	0.042	0.040	0.047	0.039	0.038	0.034	0.038	0.005	0.042	0.032	0.028	0.040	0.052	0.054	0.035	0.032	0.004	0.015	0.016	0.011	0.058	0.063
SIM36	Cost	10.26	79.02	17.70	11.99	75.03	14.55	21.30	62.28	44.88	74.08	47.69	32.07	93.04	43.52	51.20	20.12	43.63	12.74	45.63	13.65	97.17	96.72	60.13	49.08	23.47	40.73	55.62	26.17	20.49	73.70
	RAI	0.039	0.031	0.024	0.019	0.044	0.022	0.017	0.041	0.043	0.041	0.042	0.038	0.037	0.035	0.037	0.004	0.044	0.034	0.034	0.041	0.050	0.053	0.035	0.032	0.005	0.015	0.017	0.013	0.054	0.061
SIM37	Cost	20.88	96.22	53.20	49.09	31.33	32.27	11.12	98.45	45.16	87.40	52.40	28.67	33.50	37.54	67.72	31.36	42.43	34.52	37.72	55.12	95.54	39.37	26.65	25.49	18.92	37.59	48.51	39.94	42.18	76.17
	RAI	0.037	0.032	0.023	0.018	0.043	0.023	0.018	0.039	0.041	0.041	0.047	0.036	0.038	0.033	0.039	0.004	0.045	0.034	0.029	0.042	0.053	0.052	0.033	0.033	0.005	0.016	0.015	0.011	0.054	0.064
SIM38	Cost	18.24	41.64	17.73	33.86	75.92	23.52	34.30	61.27	73.51	44.39	57.16	25.50	16.74	48.68	56.98	40.02	51.64	43.32	33.87	50.61	91.61	62.47	55.46	58.68	22.75	35.75	42.05	32.22	57.78	85.98
	RAI	0.037	0.032	0.025	0.020	0.044	0.020	0.016	0.039	0.041	0.042	0.042	0.036	0.035	0.034	0.038	0.006	0.045	0.034	0.031	0.041	0.051	0.053	0.036	0.033	0.005	0.015	0.016	0.011	0.055	0.064
SIM39	Cost	14.73	92.33	27.18	36.95	75.79	46.90	31.35	54.51	97.63	53.34	60.60	43.42	41.24	92.21	57.29	15.19	36.89	45.95	17.28	15.60	62.76	17.69	40.57	39.28	27.34	19.12	62.89	54.44	90.70	27.41
	RAI	0.037	0.029	0.019	0.018	0.043	0.023	0.017	0.043	0.042	0.045	0.044	0.038	0.035	0.032	0.037	0.004	0.045	0.036	0.030	0.046	0.052	0.051	0.033	0.034	0.006	0.017	0.014	0.011	0.056	0.064
SIM40	Cost	20.76	68.59	55.44	93.70	98.55	19.40	48.21	99.98	85.45	88.56	48.47	31.21	60.71	52.03	58.73	16.77	27.00	42.77	47.91	39.91	26.12	37.21	15.63	69.33	12.55	40.52	26.81	47.96	40.54	95.41
	RAI	0.039	0.035	0.023	0.020	0.039	0.025	0.016	0.040	0.041	0.043	0.045	0.038	0.034	0.036	0.038	0.005	0.044	0.031	0.032	0.039	0.053	0.051	0.036	0.033	0.004	0.017	0.015	0.011	0.055	0.065
SIM41	Cost	18.02	29.67	10.05	68.23	97.72	40.86	29.37	89.62	88.48	47.97	70.72	52.83	21.89	70.19	41.03	42.78	53.90	17.13	55.35	20.62	80.72	17.44	41.56	43.90	18.27	25.62	63.03	44.19	55.07	85.13

	P	RMS1	RMS2	RMS3	RMS4	RMS5	RMS6	RMS7	RMS8	RMS9	RMS10	RMS11	RMS12	RMS13	RMS14	RMS15	RMS16	RMS17	RMS18	RMS19	RMS20	RMS21	RMS22	RMS23	RMS24	RMS25	RMS26	RMS27	RMS28	RMS29	RMS30
	RAI	0.039	0.033	0.027	0.019	0.044	0.021	0.016	0.038	0.042	0.038	0.047	0.034	0.037	0.035	0.036	0.007	0.041	0.032	0.031	0.043	0.055	0.052	0.034	0.032	0.005	0.015	0.017	0.011	0.055	0.062
SIM42	Cost	15.05	65.51	31.66	97.88	92.42	47.41	47.82	68.42	88.34	53.94	43.20	41.59	67.15	19.23	38.36	47.94	42.58	19.36	50.88	36.57	95.59	25.52	74.41	41.27	10.90	20.02	32.48	15.10	44.52	50.57
	RAI	0.040	0.031	0.021	0.019	0.040	0.021	0.015	0.041	0.043	0.041	0.042	0.038	0.039	0.034	0.038	0.004	0.044	0.034	0.030	0.044	0.053	0.052	0.033	0.033	0.006	0.016	0.017	0.012	0.058	0.062
SIM43	Cost	25.11	36.42	27.52	74.60	57.52	30.62	33.59	57.90	86.50	46.82	46.67	34.11	45.70	99.37	39.29	53.80	21.25	46.06	37.08	49.69	88.51	97.79	69.01	40.25	22.25	28.57	26.91	55.92	43.32	55.85
	RAI	0.035	0.031	0.021	0.017	0.041	0.023	0.017	0.041	0.043	0.042	0.046	0.040	0.037	0.033	0.037	0.004	0.044	0.031	0.031	0.044	0.052	0.054	0.034	0.033	0.005	0.016	0.018	0.012	0.054	0.064
SIM44	Cost	18.56	33.93	39.24	18.90	69.94	18.83	46.56	82.12	43.94	71.38	30.84	56.31	60.96	94.49	57.83	40.70	35.14	21.63	16.35	58.12	74.75	41.98	69.57	33.04	29.16	13.57	21.37	11.53	61.74	71.67
	RAI	0.039	0.031	0.023	0.017	0.043	0.021	0.017	0.043	0.044	0.043	0.046	0.036	0.035	0.033	0.037	0.004	0.043	0.034	0.031	0.045	0.052	0.052	0.032	0.033	0.004	0.015	0.016	0.011	0.056	0.062
SIM45	Cost	29.38	61.15	53.74	77.89	30.34	44.42	13.58	76.82	78.86	51.87	51.44	40.69	31.79	50.34	69.34	19.54	35.01	56.81	27.68	13.40	44.97	85.36	50.04	23.31	16.68	27.96	49.14	33.76	52.66	62.06
	RAI	0.038	0.030	0.023	0.018	0.044	0.023	0.016	0.042	0.044	0.043	0.045	0.039	0.037	0.034	0.038	0.005	0.044	0.032	0.029	0.040	0.049	0.054	0.033	0.030	0.005	0.016	0.016	0.009	0.059	0.063
SIM46	Cost	12.43	62.81	63.22	42.38	69.63	39.06	46.24	54.40	76.01	86.12	71.52	23.42	24.23	37.20	69.10	57.72	50.50	47.34	47.38	58.34	93.80	84.06	59.90	24.08	17.47	11.66	70.00	30.13	99.49	41.56
	RAI	0.041	0.031	0.024	0.020	0.043	0.020	0.016	0.039	0.043	0.040	0.042	0.036	0.036	0.033	0.038	0.004	0.045	0.034	0.034	0.039	0.051	0.052	0.035	0.033	0.005	0.018	0.015	0.012	0.057	0.064
SIM47	Cost	16.46	14.65	47.81	87.16	38.13	19.12	46.95	73.92	67.06	60.89	34.84	52.39	25.25	17.82	44.92	39.29	44.41	18.28	51.48	27.32	89.45	81.53	82.59	60.14	29.78	32.85	20.43	55.01	39.20	11.03
	RAI	0.039	0.032	0.025	0.019	0.042	0.025	0.017	0.039	0.042	0.046	0.043	0.036	0.038	0.030	0.040	0.005	0.041	0.032	0.028	0.041	0.052	0.055	0.034	0.032	0.004	0.016	0.017	0.011	0.057	0.063
SIM48	Cost	10.83	83.84	13.47	91.79	33.09	16.73	21.38	96.64	60.10	75.88	28.74	50.37	49.46	51.28	66.69	39.20	56.93	21.63	58.45	35.71	92.92	58.93	39.24	78.54	10.15	28.47	68.78	44.13	46.78	67.84
	RAI	0.037	0.032	0.022	0.018	0.044	0.025	0.016	0.040	0.043	0.041	0.043	0.035	0.037	0.034	0.038	0.005	0.044	0.034	0.032	0.042	0.052	0.052	0.033	0.032	0.007	0.017	0.014	0.011	0.056	0.062
SIM49	Cost	10.08	68.16	37.22	69.77	70.63	18.15	49.16	65.11	53.40	58.94	70.12	56.04	58.56	98.20	44.09	41.78	34.04	11.31	31.59	53.14	47.24	83.15	29.89	53.45	27.45	43.85	24.14	10.95	26.35	38.05
	RAI	0.035	0.033	0.026	0.018	0.042	0.025	0.016	0.041	0.043	0.045	0.044	0.037	0.036	0.033	0.039	0.005	0.041	0.034	0.030	0.043	0.051	0.052	0.033	0.032	0.005	0.015	0.015	0.010	0.056	0.064
SIM50	Cost	19.56	25.63	30.52	71.18	83.81	38.47	11.70	89.67	31.08	64.21	53.21	20.55	53.10	12.85	57.62	48.93	43.78	34.77	16.05	49.11	42.38	40.23	45.89	78.71	21.62	21.85	51.28	28.84	14.35	92.09
	RAI	0.035	0.031	0.023	0.019	0.043	0.024	0.016	0.042	0.044	0.042	0.046	0.034	0.036	0.031	0.040	0.005	0.042	0.032	0.029	0.045	0.056	0.051	0.034	0.031	0.004	0.018	0.017	0.011	0.054	0.063

Appendix H: Summary of variability in LNG SCR attributes

Table A9.2: Summary of variability in risk probability score, risk impact score and risk indices

Note: This shows the average value, standard deviation, weightage, weighted average and ranking of LNG SCR based on 50 simulations.

	Probability								Impact								Risk Indices							
Risk Id. No.	Min	Max	Avg.	Std. Dev.	Weightage	Weighted average	Rank (AS)	Rank (WAS)	Min	Max	Avg.	Std. Dev.	Weightage	Weighted average	Rank (AS)	Rank (WAS)	Min	Max	Avg.	Std. Dev.	Weightage	Weighted average	Rank (AS)	Rank (WAS)
SCR1	5	7	6.1	0.7	1.3	7.8	22	12	6	8	7.0	0.6	1.4	9.5	10	11	30	56	42.5	5.3	1.4	59.9	15	10
SCR2	5	8	6.6	0.9	1.2	7.8	12	13	5	7	5.9	0.6	1.4	8.1	25	17	25	56	38.8	5.6	1.4	53.3	22	16
SCR3	2	7	4.3	1.4	1.1	4.5	33	33	2	8	5.2	1.7	1.0	5.2	29	31	4	56	21.8	9.9	1.1	23.9	32	33
SCR4	5	9	7.2	1.2	1.1	7.8	7	14	5	8	6.5	0.9	1.2	7.7	17	21	25	72	46.8	10.2	1.1	50.9	12	19
SCR5	3	7	5.2	1.2	1.1	5.7	26	28	3	7	4.9	1.2	1.1	5.3	32	30	12	42	26.2	9.9	1.1	28.9	29	30
SCR6	6	9	7.5	0.8	1.2	9.0	5	8	6	8	7.0	0.6	1.4	9.6	9	8	36	72	52.9	6.4	1.3	68.2	7	8
SCR7	3	7	4.9	1.0	1.1	5.6	31	29	2	5	3.5	0.9	1.2	4.2	33	33	12	20	16.9	4.7	1.5	25.3	33	32
SCR8	5	8	6.4	0.9	1.2	7.4	17	20	5	7	6.1	0.6	1.3	8.1	20	16	25	49	39.0	7.1	1.2	48.4	21	20
SCR9	3	9	6.0	1.9	1.0	6.0	24	27	6	8	6.9	0.5	1.4	9.6	14	10	18	72	41.4	13.8	1.0	41.4	18	22
SCR10	3	9	6.2	1.8	1.0	6.2	20	26	5	8	6.5	0.8	1.2	7.8	16	20	15	72	40.3	13.0	1.0	40.9	19	23
SCR11	5	9	6.9	1.3	1.1	7.5	10	19	6	9	7.6	0.9	1.2	8.9	2	13	30	81	53.0	11.7	1.0	55.3	6	14
SCR12	6	8	7.1	0.6	1.4	9.7	9	7	7	8	7.5	0.3	1.8	13.6	6	4	48	64	53.2	4.7	1.5	79.2	5	4
SCR13	5	8	6.4	0.9	1.2	7.6	18	16	6	7	6.5	0.3	1.9	12.1	18	5	30	56	41.4	6.3	1.3	53.9	17	15
SCR14	5	9	7.1	1.3	1.1	7.5	8	17	5	9	7.1	1.3	1.1	7.6	8	22	25	81	50.4	13.0	1.0	51.2	9	18
SCR15	7	9	7.9	0.6	1.4	10.8	4	5	6	9	7.5	0.9	1.2	8.6	7	14	42	81	59.0	8.3	1.2	68.9	3	7
SCR16	8	9	8.5	0.3	1.9	16.3	2	2	7	8	7.5	0.3	2.0	15.0	4	1	56	64	63.8	2.8	2.0	127.7	2	1
SCR17	8	9	8.5	0.3	2.0	16.8	1	1	7	8	7.5	0.3	2.0	15.0	5	2	56	72	63.9	3.0	1.9	121.5	1	2
SCR18	4	6	5.0	0.6	1.3	6.7	28	24	4	8	6.0	1.2	1.1	6.5	21	26	20	48	30.2	7.4	1.2	36.8	26	27
SCR19	5	8	6.5	0.7	1.2	8.0	14	10	5	8	6.5	0.8	1.2	8.0	19	19	25	56	41.9	7.3	1.2	51.3	16	17

	Probability								Impact								Risk Indices							
Risk Id. No.	Min	Max	Avg.	Std. Dev.	Weightage	Weighted average	Rank (AS)	Rank (WAS)	Min	Max	Avg.	Std. Dev.	Weightage	Weighted average	Rank (AS)	Rank (WAS)	Min	Max	Avg.	Std. Dev.	Weightage	Weighted average	Rank (AS)	Rank (WAS)
SCR20	7	8	7.5	0.3	1.7	13.1	6	3	5	7	6.0	0.5	1.4	8.4	23	15	40	56	45.0	4.3	1.6	70.1	13	6
SCR21	7	9	8.1	0.6	1.3	10.5	3	6	6	8	7.0	0.6	1.4	9.6	12	9	42	72	56.6	6.7	1.3	71.7	4	5
SCR22	4	8	6.2	1.0	1.1	7.0	19	21	4	8	5.9	1.2	1.1	6.3	26	28	16	64	36.7	10.5	1.1	39.6	23	24
SCR23	5	7	6.1	0.6	1.3	8.1	21	9	5	8	6.6	0.8	1.2	8.1	15	18	30	56	39.9	5.0	1.5	57.9	20	13
SCR24	3	7	5.0	1.2	1.1	5.5	27	31	4	8	6.0	1.2	1.1	6.5	22	25	15	49	29.9	8.3	1.2	34.9	27	28
SCR25	5	8	6.8	0.9	1.2	8.0	11	11	6	8	7.0	0.6	1.4	9.7	11	7	30	64	47.4	6.6	1.3	60.4	11	9
SCR26	3	7	4.9	1.1	1.1	5.5	30	30	3	8	5.5	1.2	1.1	6.0	28	29	9	56	27.0	7.4	1.2	32.9	28	29
SCR27	5	8	6.4	0.9	1.2	7.6	16	15	6	8	6.9	0.6	1.4	9.4	13	12	30	64	44.4	6.2	1.3	58.1	14	12
SCR28	4	8	6.0	1.2	1.1	6.5	23	25	4	8	5.9	1.2	1.1	6.4	24	27	16	64	36.0	10.9	1.1	38.4	24	26
SCR29	5	8	6.4	0.9	1.2	7.5	15	18	7	9	8.1	0.6	1.4	11.0	1	6	35	72	52.1	9.3	1.1	58.4	8	11
SCR30	6	7	6.5	0.3	2.0	13.0	13	4	7	8	7.5	0.3	1.8	13.7	3	3	42	56	49.1	2.9	1.9	95.7	10	3
SCR31	4	6	5.0	0.6	1.4	6.8	29	23	4	6	5.0	0.5	1.4	7.2	30	23	16	36	24.9	3.6	1.7	43.0	30	21
SCR32	3	6	4.5	0.9	1.2	5.3	32	32	3	7	4.9	1.4	1.0	5.2	31	32	9	36	22.6	8.4	1.2	26.3	31	31
SCR33	4	7	5.7	0.8	1.2	6.9	25	22	4	7	5.6	0.9	1.2	6.7	27	24	16	49	32.4	7.4	1.2	39.5	25	25