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Department of Management Science

Supply Chain Risk Management: Exploring an Integrated Process for Managing Interdependent Risks and Risk Mitigation Strategies

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Signed Statement

This statement is intended clearly to define the extent of my contribution to previously published work for which I have been jointly responsible.

Following papers (including articles, book chapters and conference proceedings) have resulted from the work included in the thesis. I developed the ideas and papers under the able guidance of my supervisors (Professor John Quigley and Dr Alex Dickson). The contribution of other academics is limited to providing feedback on the draft version of the manuscripts and facilitating empirical research.

Chapter 2:

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Chapter 6:

Qazi, A., Quigley, J., & Dickson, A. Supply chain risk network management: A paradigm shift towards modelling systemic risks and risk appetite. Annual Meeting of the Decision Sciences Institute, Austin, 2016.

Chapter 7:

Qazi, A., Gaudenzi, B., Quigley, J., & Dickson, A. Supply chain risk network management: A Bayesian Belief Network and Expected Utility based approach for managing supply chain risks (under revision).

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Abstract

The goal of this research is to investigate interdependency modelling of supply chain risks, and to develop and empirically evaluate a supply chain risk management process that not only integrates all stages of the process but also captures interdependencies between risks and risk mitigation strategies. The proposed process is tailored to the risk management needs of both conventional and project driven supply chains. Project driven supply chains necessitate experimenting untested (unique) strategies depending on the level of project complexity whereas in the case of conventional supply chains, there is generally a consensus in establishing interdependencies between risks and the efficacy of strategies.

A systematic literature review methodology was employed to identify research gaps and establish the research agenda. In order to gain an insight into industrial practice, empirical research was conducted in South Australia involving semi-structured interviews with experts in project risk management that resulted in the development of a project complexity and risk management (ProCRiM) process. The research gaps identified and the findings of the empirical research helped in developing dependency based probabilistic supply chain risk measures that can be readily used for assessing and managing risks associated with global supply chains.

In order to capture interdependencies between supply chain risks, strategies and performance measures, two case studies were conducted in reputed supply chains involving semi-structured interviews and focus group sessions that resulted in the development of two risk management frameworks: an adapted version of ProCRiM applicable to project driven supply chains and a framework specific to conventional supply chains. The research also focused on investigating the merits and challenges associated with implementing the proposed process. In order to capture the risk appetite of a decision maker, a process namely supply chain risk network management is developed and illustrated through a simulation study.

Contents

Chapter 1

Introduction

1.1 Introduction

This thesis explores developing an integrated supply chain risk management (SCRM) process within an interdependent setting of interacting risks and risk mitigation strategies. With the main aim of presenting the context of this research, the chapter provides the rationale for undertaking the research, delineates the research objectives and questions, introduces the approach adopted, highlights the contributions to the literature, and finally presents the structure of the thesis.

1.2 Rationale for Research

Supply chains have become more complex due to the globalisation and outsourcing in manufacturing industries. Global sourcing and lean operations are the main drivers of supply chain disruptions (Son & Orchard, 2013). In addition to the network configuration based complexity, non-linear interactions between complex chains of risks categorised as 'systemicity' of risks (Ackermann et al., 2014) make it a daunting task to understand and manage these dynamics. SCRM is an active area of research that deals with the overall management of risks ranging across the entire spectrum of a supply chain including external risk factors. Besides an increase in the frequency of disruptions, supply chains are more susceptible because of the increasing interdependency between supply chain actors and the substantial impacts of cascading events.

Supply chain risks can be viewed with respect to three broad perspectives: a 'butterfly' concept that segregates the causes, risk events and the ultimate impact; the categorisation of risks with respect to the resulting impact in terms of delays and disruptions; and the network based classification in terms of local-and-global causes and local-and-global effects (Sodhi & Tang, 2012). *"Global SCRM is the identification and evaluation of risks and consequent losses in the global supply chain, and implementation of appropriate strategies through a coordinated approach among supply chain members with the objective of reducing one or more of the following –losses, probability, speed of event, speed of losses, the time for detection of the events, frequency, or exposure –for supply chain outcomes that in turn lead to close matching of actual cost savings and profitability with those desired"* (Manuj & Mentzer, 2008b, p. 205).

Risk management comprises different stages including risk identification, risk analysis, risk evaluation, risk treatment and risk monitoring (SA, 2009). A number of risk management frameworks have been proposed for managing supply chain risks (Chopra & Sodhi, 2004; Sinha et al., 2004; Manuj & Mentzer, 2008a; Knemeyer et al., 2009; Trkman & McCormack, 2009; Tummala & Schoenherr, 2011), however, there are two main limitations about these studies. The first and most significant limitation of these frameworks is their consideration of risks as independent factors. Given the inter-connectedness of supply chain risks it is unlikely that treating risks as independent will accurately capture risks, so that when such a risk management process is adopted incorrect conclusions may be drawn about the efficacy and cost-effectiveness of risk mitigation strategies. Classification of risks has been explored comprehensively resulting in identification of independent categories of risks for aiding the risk identification stage of the SCRM process (Juttner et al., 2003; Chopra & Sodhi, 2004; Kleindorfer & Saad, 2005; Bogataj & Bogataj, 2007; Manuj & Mentzer, 2008a; Tang & Tomlin, 2008; Oke & Gopalakrishnan, 2009). However, risk identification must involve different stakeholders and capture the interdependent interaction between risks ranging across the entire supply network (Ackermann et al., 2014; Badurdeen et al., 2014). Limited studies have assessed risks within an interdependent setting, however, the proposed frameworks generally follow the process flow of a supply chain (Leerojanaprapa et al., 2013; Garvey et al., 2015) which is not feasible when considering substantial supply chain networks.

The second limitation of the analysed frameworks relates to their main focus on the risk identification and risk analysis stages whereas risk treatment has not been explored in detail (Colicchia & Strozzi, 2012). Although probabilistic risk measures have been introduced for prioritising interdependent supply chain risks (Garvey et al., 2015), it is not always viable (cost-effective) to mitigate the critical risks identified. Therefore, there is a need to explore interdependency between risks and risk mitigation strategies within a probabilistic network setting. These gaps that are found in the literature have led to the main research aim that drives this research which is: How can we design a SCRM process capturing systemic interactions between risks and risk mitigation strategies across the integrated stages of the risk management process?

Supply chains operate within an integrated setting of interdependent firms and even within a single firm, entities and risks are not isolated; rather, there are complex chains of interaction. Current risk classifications and methods investigating optimal treatment of these individual risks can prove to be sub-optimal if there are correlations between risks and strategies (Garvey et al., 2015). According to Ho et al. (2015): *"Investigating the joint impact of such risks can lead to better management of supply chains than treating each risk type in isolation. ...*

However, there is lack of research measuring the correlations between risk factors and corresponding risk types, or the probability of occurrence of particular risk types associated with their factors" (Ho et al., 2015, p. 5060).

Colicchia & Strozzi (2012) argue that *"the validity and usefulness of the practices and tools proposed is not strongly supported by empirical evidence and widely acknowledged in the current literature"* (Colicchia & Strozzi, 2012, p. 412) and *" ... the key challenge for an effective disruption management is developing structured and systematic tools for risk identification and assessment that explicitly consider the dynamic interactions among supply chain partners and among risk sources. ... Furthermore, mostly the studies focus on minimising cost or maximising profit as a single objective"* (Colicchia & Strozzi, 2012, p. 412). Similarly, Ho et al. (2015) corroborate the same finding and reiterate that *"Although there is an increasing amount of research in the area of SCRM, most of them are theoretical in nature. For instance, a wide variety of SCRM management methods and conceptual frameworks have emerged, however, they have not been validated empirically. To fill this gap, scholars could use primary data to investigate the applicability and effectiveness of those SCRM models in practical situations"* (Ho et al., 2015, p. 5060).

Another important theme of the research is to establish a risk management process for a project driven supply chain. Long-term projects involving new product development (NPD) often result in major delays and cost overruns and therefore, bearing in mind the complexity of such projects, it is extremely important to consider interdependency between risks and involve different stakeholders in identifying key risks (Ackermann et al. 2006; Ackermann et al. 2014). Despite Boeing adopting an unconventional supply chain by introducing loss-sharing partnerships in the development project of the 787 Dreamliner in order to reduce financial risks and development time, the project was delayed incurring major financial penalties because the project team did not realise the importance of assessing and managing risks before commencement of the project (Tang et al., 2009). Conventional supply chains (involving routine processes) and project driven supply chains (involving unique processes specific to NPD) are reported to have different characteristics and therefore, there is a need to tailor the risk management process in accordance with the characteristics and objectives of the supply chain (Leerojanaprapa, 2014).

Complexity in projects relates to structural elements, dynamic elements and interaction of these elements across the broad categories of technical, organisational and environmental domains (Baccarini, 1996; Kardes et al., 2013; Botchkarev & Finnigan, 2015). Technical elements focus on the technical aspects of a project, organisational elements capture a softer perspective, while environmental elements influence the project and stakeholders from outside the project scope (Bosch-Rekveldt et al., 2011). There are two schools of thought with regard to whether risk is an element of complexity (Bosch-Rekveldt et al., 2011; Geraldi et al., 2011) or the two are distinct concepts (Vidal & Marle 2008; Saunders et al. 2015; Saunders et al. 2016). Such distinction is of prime importance as the methods aimed at evaluating project complexity would yield significantly different results. Different methods have been proposed for evaluating project complexity (Vidal et al. 2011a; Vidal et al. 2011b; Xia & Chan 2012; He et al. 2015; Lu et al. 2015; Nguyen et al. 2015) that mainly isolate complexity from risk. Adopting such a disintegrated approach of evaluating complexity and risk in silos results in undermining the synergistic effect of interacting complexity attributes (drivers) and complexity-induced risks and raises the possibility of selecting sub-optimal risk mitigation strategies.

It is not only important to understand and evaluate project complexity but also to visualise the complex interaction between project complexity and complexity induced risks in order to prioritise critical risks and select optimal risk mitigation strategies. Moreover, these risks must also be linked to the project objectives which in turn will influence the utility of a decision maker concerning the relative importance of each project objective. Although the standard risk management process (SA, 2009) comprising different stages –namely: risk identification; risk analysis; risk evaluation; risk treatment; and risk monitoring –is generally adopted in the literature on project risk management as it presents a systematic approach of modelling risks (Schieg, 2006), the interdependency between risks and complexity is not reflected in the framework.

Project complexity attributes (drivers) pose vulnerabilities to the successful conclusion of major projects involving NPD, resulting in cost and time overruns. An important aspect of establishing a link between the knowns (represented by complexity attributes or drivers) at the commencement stage of a project and the 'known unknowns' (Ramasesh & Browning, 2014) (termed as risks in this research) that may potentially materialise within the life cycle of a project has not been given due consideration. As we are focusing on the commencement stage of a project, the risks and strength of interaction between risks included in the model represent the belief of experts developed through learning from past experiences. However, unexpected emerging risks introduced during the life-cycle of a project and not envisioned at the commencement stage can have significant impact on the project objectives and therefore, besides establishing an effective risk management process, there is a need to cultivate a culture of alertness to deal with such risks categorized as 'unknown unknowns' (Ramasesh & Browning, 2014).

The risk appetite of a decision maker drives the tolerance level with respect to the acceptance of risks. *"The decision maker's degree of acceptance with respect to the deterioration of target-values defines his attitude towards supply chain risk. Risk-averse supply chain managers only accept a minor deterioration of target values of an efficiency- (or effectiveness-) based supply chain goal in exchange for the adherence or increase of an effectiveness- (or efficiency-) based supply* *chain goal. Risk-seeking decision makers, however, accept higher degrees of value deterioration of a specific goal in exchange for the adherence or increase of an opposite one. Risk-neutral supply chain managers prefer neither of the two objective types"* (Heckmann et al., 2015, p. 127). Very few frameworks in SCRM have captured the risk appetite of a decision maker (Knemeyer et al., 2009; Lavastre et al., 2012), however, to the best of our knowledge, no existing study has ever investigated designing a SCRM framework within a network setting of interacting risks driven by the risk appetite of a decision maker.

Integration of indifference curves representing risk managers preferences within the risk matrix has been recently introduced in the literature on risk management that results in discretising the risk matrix into five risk zones: Negligible-no need for further concern; Acceptable-need for monitoring the risks with no investment; Controllable-need for adopting emergency plans; Critical-need for mitigating risks as long as the benefits exceed the costs; and Unacceptable-need for bringing the risks down to the critical level at any cost (Ruan et al., 2015). This study leads to an interesting question: Whether the concept of introducing preferences represented by indifference curves in a risk matrix for assessing independent risks can be developed further to account for interdependent supply chain risks? Recently, few studies have focused on proposing probabilistic supply chain risk measures for assessing and managing interdependent risks (Garvey et al., 2015; Qazi et al., 2017). Selection of optimal risk mitigation strategies has also gained limited attention in the literature on SCRM (Tuncel & Alpan, 2010; Micheli et al., 2014; Aqlan & Lam, 2015) but the main challenge is to develop these studies further to capture the risk appetite of a decision maker.

Interdependency modelling has been extensively explored in other research areas especially the reliability and safety of engineering systems and also, well-established techniques like Bayesian Belief Networks (BBNs) and Expected Utility Theory (EUT) are commonly used in capturing interdependency between risks and modelling the risk appetite of a decision maker, respectively (Aven & Kristensen, 2005; Aven, 2015). However, these methods and risk management frameworks are not readily (directly) applicable to modelling and managing supply chain risks mainly because of the complex and unique features of supply chain risks: unlike risks associated with engineering (physical) systems, supply chain risks involve soft factors like strategic (opportunistic) behaviour of stakeholders; the layout (qualitative causal structure) of a physical system is generally known whereas it is very difficult (not viable) to accurately model a supply network and corresponding risks because of a number of suppliers and entities involved; components within a physical system can readily be monitored for any malfunction whereas it might not be possible to detect a risk occurring within a supply chain where not all stakeholders are incentivised to share any private information with regard to the realisation of a risk or their reliability; engineering systems are maintained and improved through the use of established interdependency based models and maintenance (and accident) data recorded whereas such data is not available in the case of supply chain risks as practitioners rely on risk matrix based tools and interdependency modelling is generally ignored (Leerojanaprapa, 2014). Therefore, there is a need to adapt the interdependency based tools commonly used in other areas to the context of SCRM such that the complexity associated with supply chain risks is managed effectively and the tools developed fit well with the requirements and competence of practitioners who prefer to use simple risk matrix based tools.

Heckmann et al. (2015) conducted a critical review of quantitative approaches for managing supply chain risks focusing on the definitions, measures and modelling of risk. According to them: *"Standard deviation, mean-variance approaches, value-at-risk, conditional-value-at-risk or premiums are risk measures that aim at describing the interaction of uncertainty and the extent of its related harm or benefit. Owing to the lack of quantitative measures that capture the more complex* *realities of supply chains, these measures –developed in finance and insurance contexts –are applied for supply chain risk, too"* (Heckmann et al., 2015, p. 127). Their emphasis on the need for developing risk measures capable of reflecting the complex realities of supply chains corroborates the fact that a straight forward carry over of risk measures and risk management frameworks from another application area will not work.

A very few researchers have comprehensively explored BBNs in modelling interdependent supply chain risks (Leerojanaprapa, 2014; Garvey et al., 2015). Leerojanaprapa (2014) proposed a generic BBN modelling process to support supply chain risk analysis based on expert knowledge and demonstrated the soft benefits that participants can gain from being involved in the modelling process. The empirical evaluation of the proposed process through a case study conducted in the medical supply chain demonstrates the efficacy of BBNs in supporting the decision making process of prioritising risks. Developing on the proposed framework and following the guidelines mentioned with regard to the future research agenda, this thesis explores utilising BBNs as a framework for developing a comprehensive SCRM process including the risk treatment stage where the efficacy and cost of strategies are exclusively modelled within the framework. Furthermore, the risk appetite of a decision maker is captured to account for the preferences with regard to balancing the network expected loss and the cost of strategies.

Garvey et al. (2015) introduced a framework for modelling supply chain risks as a BBN keeping in view the process flow of a supply chain. They have also introduced new probabilistic supply chain risk measures for identification of critical entities within a supply network. Their proposed modelling framework differs from the existing BBN based studies in SCRM (Dogan & Aydin, 2011; Badurdeen et al., 2014; Lockamy, 2014) in terms of exploring the propagation impact of risks across the network of interconnected risks and supply network elements, but their proposed risk measures only consider the impact of risks on the descendant nodes and ignore capturing the diagnostic effect. Also, the proposed framework does not focus on modelling and evaluating risk mitigation strategies (risk treatment). However, their framework and proposed supply chain risk measures establish the context for developing an integrated process to manage supply chain risks and introducing effective risk measures suitable for the complex supply networks.

1.3 Research Objectives

With the context already established, it is logical to present the overarching objectives of the research which are:

Objective I: To identify the future agenda in SCRM

Objective II: To develop a SCRM process integrating all stages of the risk management process and capturing interdependencies between risks and risk mitigation strategies

1.4 Research Questions

Following are the research questions investigated:

RQ1: What are the limitations of existing studies in the literature on SCRM?

RQ2: How can we design a SCRM process capturing systemic interactions between risks and mitigation strategies across the integrated stages of the risk management process; and subsequently, how can the potential mitigation strategies be evaluated within the network of interdependent risks and strategies in relation to different resource and budget constraints?

RQ3: How can we develop a risk management process and an effective modelling approach for capturing interdependency between complexity and risk in order to facilitate the decision making process of prioritising risks and risk mitigation strategies at the commencement stage of a project?

RQ4: How is the interdependency between risks managed in industry?

RQ5: How can we design a SCRM process integrating the systemic interaction between risks and the risk appetite of a decision maker?

RQ6: What are the merits and challenges of implementing the proposed SCRM process that captures interdependency between risks, multiple (potentially conflicting) objectives and risk mitigation strategies?

1.5 Summary of Research Approach

Several research methods have been adopted to address the research questions. As there has been a significant development in the literature on SCRM over the past decade, a systematic literature review (SLR) was conducted to establish research gaps. Because of limited evidence of empirical research on interdependency modelling of supply chain risks, semi-structured interviews were conducted with experts from construction industry that led to the development of a project complexity driven risk management process. The findings of the interviews provided an impetus to explore dependency based supply chain risk measures that could easily be used in practice.

Because of the efficacy of BBNs in capturing interdependency between uncertain variables, an integrated process was developed to capture interdependencies between supply chain risks, risk mitigation strategies and all stages of the risk management process. The process was enhanced through introducing the risk appetite of a decision maker within the modelling framework.

In order to empirically evaluate the theoretical models and ascertain the merits and challenges associated with the implementation of such interdependency based frameworks, two case studies were conducted at global manufacturing supply chains involving focus group sessions and semi-structured interviews. The case studies helped in demonstrating the proposed approach and testing its efficacy.

The interview data was analysed through a thematic analysis that resulted in the development of propositions specific to the difference between the risk matrix based silo approach and the proposed approach.

1.6 Contribution to Knowledge

There are several contributions of the thesis. First, the research contributes to the literature on SCRM through conducting a comprehensive SLR of selected articles published over a period of last 15 years and provides some new insights for future research endeavours. Focusing on the interface of project complexity and complexity induced risks, a project complexity and risk management (ProCRiM) process and modelling approach are proposed that are theoretically grounded in the framework of EUT and BBNs presenting a very useful tool not only for capturing causal relationships between uncertain variables but also for establishing the strength of these interdependencies.

With focus on methodological contribution to the literature on SCRM, the thesis introduces a comprehensive integrated process of SCRM integrating all stages of the risk management process and capturing interdependencies between risks and strategies. Dependency based probabilistic supply chain risk measures are proposed for capturing network wide impact of risks that help in prioritising risks both in the risk assessment and risk monitoring stages.

With focus on integrating the risk appetite of a decision maker within a probabilistic network of interacting supply chain risks, the main contribution is to introduce a new risk management process namely Supply Chain Risk Network Management (SCRNM). The conventional risk matrix is transformed in order to make it compatible for assessing interdependent supply chain risks in relation to the utility indifference curves specific to a decision maker.

Finally, a SCRM process integrating interdependent risks, risk mitigation strategies and multiple (potentially conflicting) objectives is proposed with contributions across multiple facets. First, the process is adapted from the theoretically grounded frameworks within the literature on SCRM (Garvey et al., 2015; Sherwin et al., 2016) and project risk management (Qazi et al., 2016). Second, the process is demonstrated through conducting two case studies in reputed global supply chains resulting in two different models of risk networks specific to a conventional and a project driven supply chain. Third, merits and challenges associated with the implementation of such interdependency based frameworks are explored. Fourth, propositions are developed to elucidate the importance of accounting for interdependence of supply chain risks by comparing the proposed process to a standard risk matrix-based approach.

1.7 Thesis Structure

The research aim, objectives, methods and questions are linked to the chapters as shown in Figure 1.1.

Chapter 2: Supply Chain Risk Management Literature Review. This chapter provides the findings of the SLR conducted and presents important research themes that have gained limited attention in the literature. These gaps establish the context of the research.

Chapter 3: Research Methodology. This chapter presents the philosophical underpinnings of the study and delineates the research methods and modelling approach adopted to address the research questions.

Chapter 4: Project Complexity and Risk Management. This chapter explicates the findings of the semi-structured interviews conducted with the experts in construction industry and introduces a process for modelling project

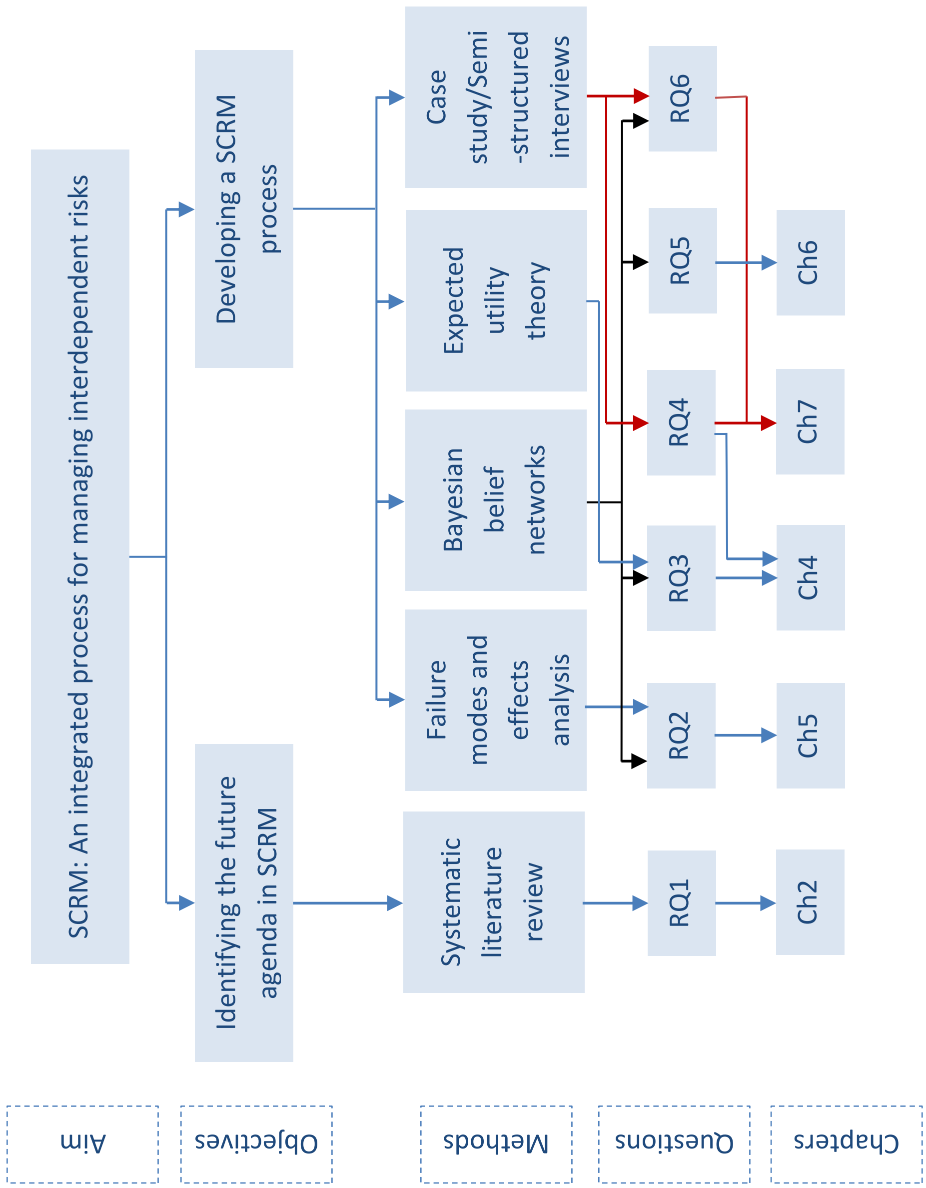

Figure 1.1: Research aim, objectives, methods and questions.

and supply chain risks keeping into account the project characteristics (project complexity attributes). Interdependency between project complexity and risk is established within the theoretically grounded framework of BBNs and EUT.

Chapter 5: Exploring Dependency Based Probabilistic Supply Chain Risk Measures for Prioritising Interdependent Risks and Strategies. This chapter introduces dependency based probabilistic supply chain risk measures and proposes a new SCRM process that utilises the concept of Shapley value from the field of Cooperative Game Theory and makes use of Failure Modes and Effects Analysis (FMEA) which is widely used in the industry.

Chapter 6: Supply Chain Risk Network Management: A Paradigm Shift towards Modelling Systemic Risks and Risk Appetite. Risk matrix is widely used in the industry for prioritising risks. Although EUT provides a systematic approach of assessing risks and risk mitigation strategies, it might not be feasible to model even a simple network comprising limited number of interconnected risks and strategies as the size of required data grows exponentially. In this chapter, algorithms are presented to capture the risk appetite of a decision maker in prioritising interdependent risks and risk mitigation strategies and a modified risk matrix is proposed to account for interdependencies between risks.

Chapter 7: Empirical Investigation of Modelling Interdependent Supply Chain Risks. This chapter presents the findings of two case studies that were conducted in leading manufacturing supply chains. The main aim of this chapter is to describe the merits and challenges associated with introducing the proposed interdependency based modelling process in the industry. Finally a refined process is presented after consulting the practitioners and realising the limitations of the proposed framework.

Chapter 8: Conclusions. This chapter concludes the thesis by presenting the main findings and the approach adopted. The original contribution of the research is delineated and practical implications and limitations are discussed. Finally, areas for future research are proposed.

Chapter 2

Supply Chain Risk Management Literature Review

2.1 Introduction

SCRM is gaining increasing interest from researchers (Khan & Burnes, 2007; Sodhi et al., 2012; Colicchia & Strozzi, 2012). A number of researchers have reviewed the literature and consolidated important research findings (Juttner et al., 2003; Khan & Burnes, 2007; Vanany et al., 2009; Rao & Goldsby, 2009; Bellamy & Basole, 2013) but few studies have adopted the procedure of SLR (Colicchia & Strozzi, 2012; Ghadge et al., 2012). SLR presents an effective technique to discover research gaps through a methodological process. Following the process adopted by Tranfield et al. (2003), this chapter presents the findings of SLR conducted with the main aim of establishing research gaps. SLR differs from narrative review in terms of providing transparent and replicable results through evidence-based knowledge management (Tranfield et al., 2003; Ghadge et al., 2012).

The scope of SLR is limited to reviewing peer-reviewed articles published over a period of last 15 years. NVivo 10 (qualitative data analysis software) is used for validating the results of SLR. Based on the findings of the review, important research gaps are identified and a risk management framework is proposed for managing supply chain risks that can capture interdependency between supply chain risks across different domains of a supply network. This chapter is structured as follows. Basic concepts related to the field of SCRM are discussed in Section 2.2. Findings resulting from the descriptive and thematic analysis of the SLR are described in Section 2.3. Moreover, identified research gaps are also discussed in detail. A conceptual framework for modelling interdependency between supply chain risks is developed and presented in Section 2.4 to help researchers model global supply chain risks in a holistic manner.

2.2 Supply Chain Risk Management

Risk has been defined as a chance of danger, damage, loss, injury or any other undesired consequences (Harland et al., 2003). According to Knight (1921), risk is something measurable in a way that probabilities of the outcomes can be estimated whereas, uncertainty is not quantifiable and probabilities of the possible outcomes are not known. After analysing concept of risk in different disciplines, Manuj & Mentzer (2008a) found the presence of following three components in all conceptualisations of risk:

- probability (likelihood) of the occurrence of an event that leads to the realisation of a risk,
- potential losses once the risk is realised,
- significance of the consequences of losses.

Supply chain risk is characterised by both the probability of an event and its severity given that an event occurs (Handfield et al., 2011). Juttner et al. (2003) define supply chain risk as a *"variation in the distribution of possible* *supply chain outcomes, their likelihood, and their subjective value"*. Lee (2014) identifies elements of loss, significance of loss, uncertainty associated with the loss and probability of loss as four key dimensions of supply chain risk. Zsidisin (2003) defines supply risk as *"the potential occurrence of an incident associated with inbound supply from individual supplier failures or the supply market, in which its outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety"*.

According to Tang (2006a): *"SCRM is the management of supply chain risks through coordination or collaboration among the supply chain partners so as to ensure profitability and continuity"*. According to Juttner et al. (2003): *"SCRM aims to identify the potential sources of supply chain risk and implement appropriate actions to avoid or contain supply chain vulnerability"*. Vulnerability is defined as an exposure to serious disturbances from risks within a supply chain as well as risks external to the supply chain (Christopher & Peck, 2004).

Manuj & Mentzer (2008b) conducted an extensive literature review and a qualitative study comprising interviews and focus group meeting in order to develop a grounded theory for understanding global supply chain risks. According to them: *"Global SCRM is the identification and evaluation of risks and consequent losses in the global supply chain, and implementation of appropriate strategies through a coordinated approach among supply chain members with the objective of reducing one or more of the following –losses, probability, speed of event, speed of losses, the time for detection of the events, frequency, or exposure –for supply chain outcomes that in turn lead to close matching of actual cost savings and profitability with those desired"*.

Recently, there has been a shift in the interest of researchers towards exploring the impact of disruptions on global supply chains. Global sourcing and lean operations are the main drivers of supply chain disruptions (Son & Orchard, 2013). Risk management is an established field in some areas of organisational life like finance but it is still a developing theme within the realm of supply chain management (Khan & Burnes, 2007). Although there is an ongoing debate on the objective and subjective nature of risk, there is a consensus among researchers on treating risk management as a process comprising three stages including risk identification, risk estimation and risk evaluation (White, 1995).

2.3 Systematic Literature Review

In contrast to the traditional narrative review, SLR adopts a replicable and transparent process that minimises the bias by providing an audit trail of the reviewers' plan of action (Cook et al., 1997). The systematic review and its associated procedure, meta-analysis, play an important role in evidence-based practices. Systematic review is conducted for identifying major contributions to a research field whereas meta-analysis provides a statistical procedure for synthesising key findings (Tranfield et al., 2003). A systematic review differs from the narrative review in terms of following a comprehensive and an unbiased search. Though SLR necessitates investing plethora of time and great deal of commitment, the results are deemed as of high quality and most efficient (Mulrow, 1994). The complete process of conducting SLR is shown in Figure 2.1.

2.3.1 Identification of Research

The first step in conducting SLR is to identify keywords and search terms that are deduced from the scope of research, literature and discussion within the review team. One key aspect is to report the search terms in detail for replication in future. The searches should not only be confined to the published journals rather unpublished reports, conference papers and other working papers must also be taken into consideration. The search phase results in identification of a detailed listing of articles and papers for further consideration.

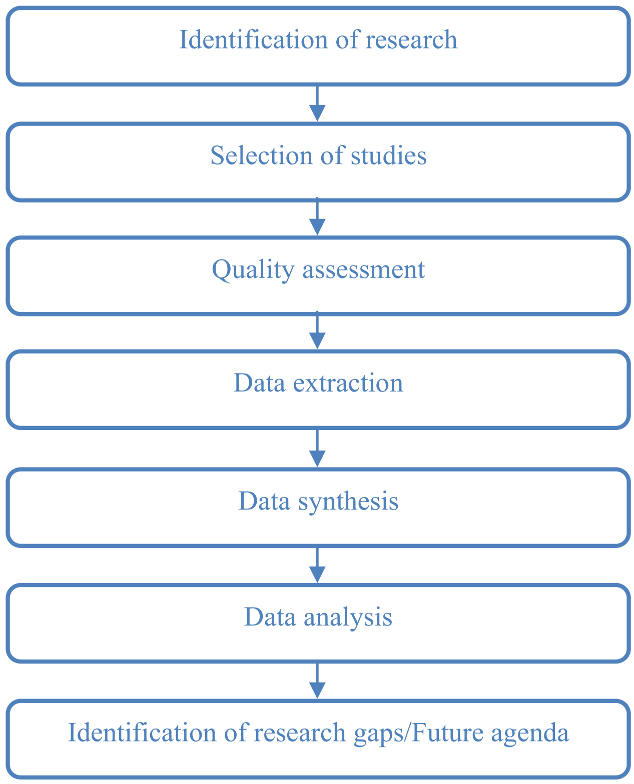

Figure 2.1: Systematic literature review process (adapted from Tranfield et al. 2003).

Following the guidelines of SLR process (Tranfield et al., 2003), science direct, web of science, emerald and ABI-inform (Proquest) were utilised for researching the existing literature. Google scholar was also used for supporting this activity. Over 200 peer-reviewed articles were collected using search strings including 'supply chain risk management', 'supply network risk', 'supply risk', 'supply chain disruption', and 'supply chain vulnerability'. Different combinations of these search strings were also used to validate the findings.

2.3.2 Selection of Studies and Quality Assessment

Studies that meet the inclusion criteria and strictly violate the exclusion criteria are selected for the review process. The criteria are based on an important aspect of selecting high quality studies. However, this stage is quite subjective and therefore, more than one reviewer must be involved in conducting this stage of the review process. Disagreements need to be resolved through discussions following a systematic approach. A preliminary review of all potentially relevant citations is conducted followed by further selection for a more detailed evaluation. The number of sources selected at each stage needs to be recorded and the reasons for exclusion annotated. A quality assessment should include following criteria (Popay et al., 1998):

- Does the research explore subjective meanings that relate to the experiences of other people?
- Does the research design enable flexibility to the changes occurring during the study?
- Is the study sample selected in a systematic manner governed by theory?
- Does the sample include different sources of knowledge about the issues being compared?

- Does the researcher explicitly mention the process of transformation from data to interpretation?
- Do the claims made to generalisability follow a logical/theoretical process from the data?

The inclusion criterion concerning the year of publication spanned across 15 years (from 2000 to June, 2014). The starting year of 2000 was selected on the basis of preliminary review that revealed growing interest of researchers in the field after the 9/11 attacks in the USA. It was decided to gauge the quality of selected articles through the lens of the Association of Business Schools (ABS) that publishes quality ratings of academic journals. Besides the quality criterion being the leading factor for selection, we manually scrutinised the articles for their relevance to the specific field of SCRM and finally, 145 peer-reviewed articles were selected for conducting the SLR. The distribution of articles with respect to the journals and corresponding ABS rating are shown in Table 2.1. Majority of articles were published in the International Journal of Physical Distribution & Logistics Management, and Supply Chain Management: An International Journal. The distribution of articles with respect to the ABS rating is depicted in Figure 2.2. Almost half of the selected articles were published in high ranking journals (rating of three or four).

Journal	**No. of articles**	**ABS rating/(Impact Factor)**
Benchmarking: An International Journal	3	1
Business Process Management Journal	2	1
California Management Review	1	3
Chemical Engineering Science	1	(2.613)
Computers & Industrial Engineering	2	2
Computers in Industry	2	(1.457)
Decision Sciences	2	3
Decision Support Systems	1	3
European Journal of Operational Research	4	3
		Continued on next page

Table 2.1 – continued from previous page

Journal	No. of articles	ABS rating/(Impact Factor)
Expert Systems with Applications	2	3
Industrial Management & Data Systems	4	1
International Journal of Information Systems and Supply Chain Management	1	
International Journal of Logistics Research and Applications	2	2
International Journal of Operations & Production Management	2	3
International Journal of Physical Distribution & Logistics Management	21	2
International Journal of Production Economics	14	3
International Journal of Production Research	6	3
International Journal of Productivity and Performance Management	1	1
Journal of Business Logistics	2	2
Journal of Enterprise Information Management	2	
Journal of Manufacturing Technology Management	5	2
Journal of Marketing Channels	1	
Journal of Modelling in Management	1	
Journal of Operations Management	10	4
Journal of Purchasing & Supply Management	4	2
Journal of Supply Chain Management	3	1
Journal of the Operational Research Society	1	3
Kybernetes	1	(0.416)
Management Decision	1	1
Management Science	1	4
MIT Sloan Management Review	1	3
Omega	1	3
Performance Improvement	1	
Production and Operations Management	4	3
Production Planning & Control	1	3
Strategy & Leadership	1	
Supply Chain Forum: An International Journal	1	

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Table 2.1 – continued from previous page

Journal	**No. of articles**	**ABS rating/(Impact Factor)**
Supply Chain Management: An International Journal	19	3
Team Performance Management: An International Journal	1	
The International Journal of Logistics Management	11	2
Transportation Research Part E: Logistics and Transportation Review	1	3

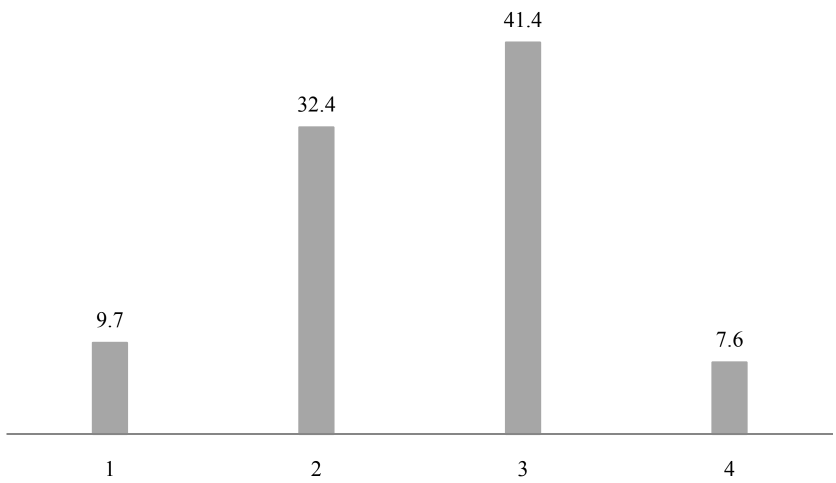
Table 2.1: Distribution of articles with respect to journals and corresponding ABS rating (Source: 2010 ABS Academic Journal Quality Guide, Thomson Reuters Journal Citation Reports 2014).

2.3.3 Data Extraction

Selection and quality assessment stages are followed by data extraction that requires documentation of all steps involved. Data extraction can involve following either a paper-based or computer assisted method. Data extraction forms can be used to record details of information source (title, authors, and publication data) and other pertinent details including context of the study and qualitative evaluation of methodological underpinning. In order to utilise the computational power of text mining methods, all the selected articles were imported in NVivo 10 which is a useful software developed by QSR International for conducting qualitative data analysis.

2.3.4 Data Synthesis

Research synthesis is a process of consolidating findings of different studies on a research topic. Narrative review is the simplest and well-known form of research synthesis but this type of review fails to seek generalisation from the reviewed literature (Greenhalgh, 1997). This shortcoming can be overcome by conducting



Source: 2010 ABS Academic Journal Quality Guide

Figure 2.2: Percentage distribution of articles with respect to the ABS rating of journals.

meta-analysis that enables pooling of data through statistical techniques.

The 'word frequency' query was run in NVivo 10 in order to determine the extent of research in various themes. The resulting themes with corresponding statistics are shown in Table 2.2. Word count and percentage count represent the frequency and frequency ratio of a word to the total word count, respectively. The main inclusion criterion was aimed at selecting studies pertaining to risk management in supply chains and the results of the text mining validate the fulfilment of this criterion. Most of the studies relate to supplier risks as suppliers are considered to be the main source of disruptions. Table 2.2 also reveals an important fact that certain themes are underexplored having lower values of relative frequency and need further research including but not limited to global supply chains, customer risks, quality risks, disruptions and risks related to new design (product development). The tabular results are also presented in the shape of a word cluster as shown in Figure 2.3. The size of each word represents its relative frequency.

Word	Count	Percentage count
Supply	21,060	2.28
Risk	17,842	1.93
Chain	14,313	1.55
Management	11,636	1.26
Supplier	4,905	0.53
Research	4,318	0.47
Information	2,841	0.31
Performance	2,780	0.30
International	2,691	0.29
Business	2,469	0.27
Network	2,383	0.26
Production	2,371	0.26
Model	2,361	0.26
Process	2,343	0.25
Product	2,319	0.25
Logistics	2,225	0.24
Analysis	2,212	0.24
Study	2,167	0.23
Demand	2,027	0.22
Cost	2,006	0.22
Operations	1,994	0.22
Case	1,980	0.21
Time	1,894	0.20
Impact	1,842	0.20
Level	1,750	0.19
Disruption	1,737	0.19
Company	1,697	0.18
Approach	1,592	0.17
Global	1,523	0.16
Review	1,511	0.16
Value	1,511	0.16
Customer	1,481	0.16
System	1,412	0.15
Quality	1,401	0.15
Literature	1,384	0.15
Decision	1,368	0.15
Data	1,361	0.15
Factors	1,347	0.15
Inventory	1,345	0.15
Design	1,337	0.14

Table 2.2: Word frequency analysis of database.

Figure 2.3: Word cluster diagram.

2.3.5 Data Analysis

The main purpose of SLR is to help researchers and practitioners understand the development within a specific research field and therefore, an effective reporting style is mandatory for achieving this goal. The report may comprise two stages focusing on the descriptive and thematic analyses. The first stage provides a descriptive analysis of the field that is extracted from the earlier recorded forms. This part of the report may include classification of articles with respect to the origin of authors, yearly volume of publications, epochs of research field and so forth. The researcher must also present a thematic analysis to report on the extent to which consensus is shared across various research themes within the field. Furthermore, research gaps need to be established for identifying future research themes.

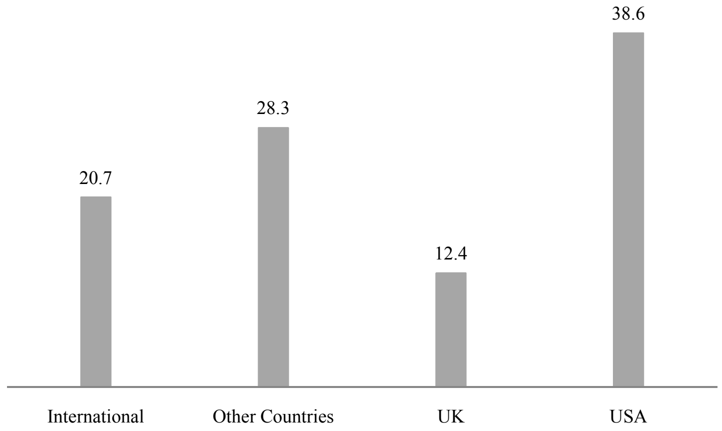


Figure 2.4: Percentage distribution of articles with respect to the contributing country.

Descriptive Analysis

Contributing Country

The selected articles were classified with respect to the country of contribution as shown in Figure 2.4. If the authors belonged to different countries, the contribution was categorised as 'international' and in the case of all authors hailing from the same country but other than UK or USA, the contribution was classified as 'other countries'. A major contribution has been made by the USA based authors keeping in view the presence of global supply chains in the region. Most of the contributions categorised as 'other countries' are from authors of Australia, Canada, Germany, Sweden and Italy.

Year of Publication

The articles were also analysed with respect to the year of publication as shown in Figure 2.5 that clearly reveals that the field of SCRM started gaining the attention of researchers in 2000 and since 2004, there has been an accelerated progress in the research field. Maximum articles were published in 2009 and if the timeline is segregated into two halves, the number of articles published in the second half is almost twice that of the first half. It manifests the growing interest

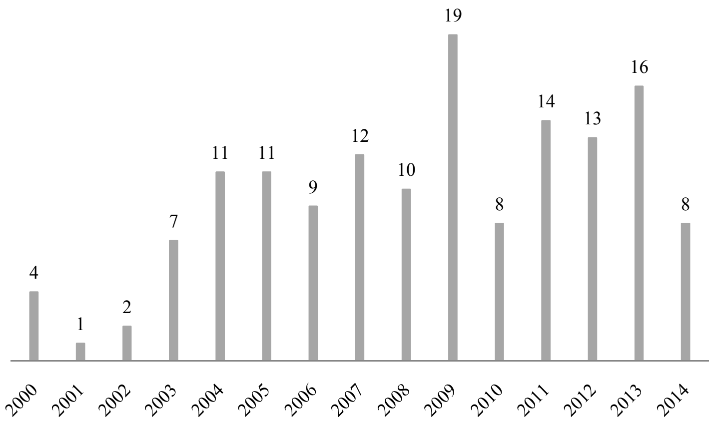


Figure 2.5: Distribution of articles with respect to the year of publication.

of researchers and practitioners in the field and its potential for further growth in research.

Industry of Application

The main aim of classifying articles with respect to industrial application was to ascertain the extent to which different models/frameworks proposed have been empirically evaluated. The classification of articles with respect to industrial application is shown in Figure 2.6. Most of the studies have been conducted in the automotive industry. Almost 38% of the articles did not involve industrial application of the research that clearly necessitates conducting more industry focused research in future. 'Multiple' indicates a mix of different industries and the corresponding articles either reported multiple case studies or presented interviews/surveys in various industries. Only 3% of the selected articles were focused on small and medium enterprises whereas 59% of the articles were aimed at companies with global footprint. The analysis indicates lack of research in the realm of small companies and keeping in view the major impact of disrupted bottleneck small firms on the entire supply network, there is a need for conducting extensive research in order to explore risk management techniques followed by small companies and the impact of these practices on global supply chains.

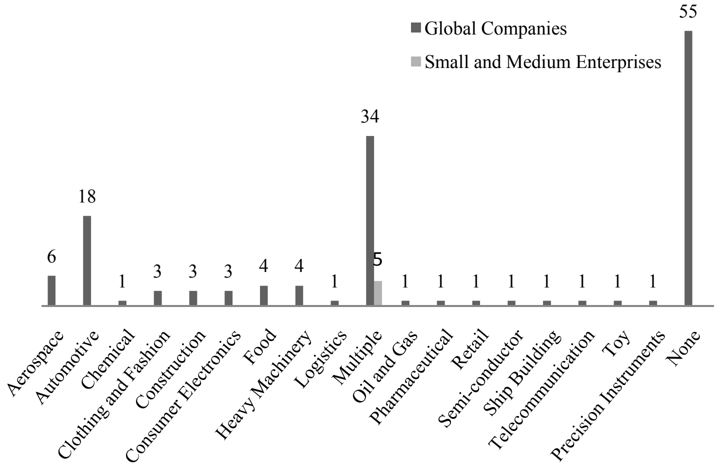


Figure 2.6: Distribution of articles with respect to the industrial application.

Application in New Product Development

We also categorised articles on the basis of their application in NPD (see Figure 2.7) mainly because these long-term NPD projects often result in major delays and cost overruns and therefore, bearing in mind the complexity and importance of such projects, it is necessary to focus on these projects and to develop effective models capturing interdependency between risks and involving different stakeholders in the risk management process (Ackermann et al. 2006; Ackermann et al. 2014). Also, conventional supply chains (involving routine processes) and project driven supply chains (involving unique processes specific to NPD) are reported to have different characteristics and therefore, there is a need to tailor the risk management process in accordance with the characteristics and objectives of the supply chain (Leerojanaprapa, 2014). The SLR revealed that project driven supply chain risks have gained limited attention from the researchers. Studies categorised as 'other' did not focus on the important aspect of design change or NPD. The results clearly necessitate conducting extensive research in order to explore risks associated with NPD and plan effective strategies to treat such critical risks. A summary of articles focusing on the management of supply chain risks concerning NPD is given in Table 2.3.

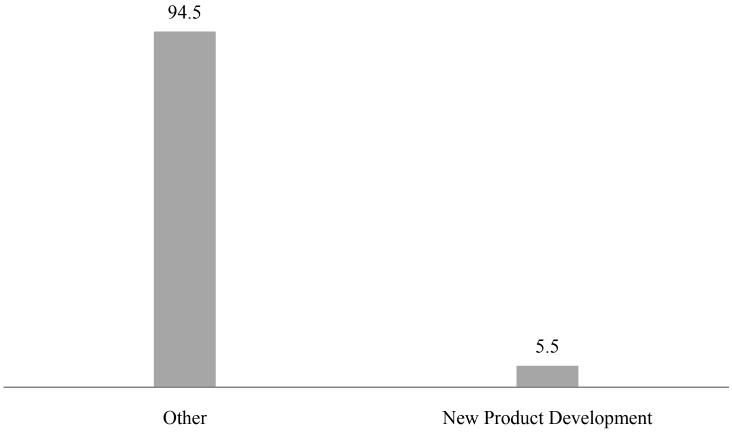


Figure 2.7: Percentage distribution of articles with respect to the application in new product development.

Authors	Purpose/methodology	Findings
Zsidisin & Smith (2005)	To explore if early supplier involvement may be a useful tool for managing supply risk; Analysis of risk reduction factors in the context of agency theory; Development of theory through presentation of research propositions; A case study conducted in an aerospace industry	Agency theory provides an effective lens for assessing the practical implications of supply management initiatives; Purchasing organisations can achieve higher level of performance through strategic implementation of early supplier involvement in concurrent engineering
Kayis et al. (2007)	Development of a risk management tool (knowledge ware) for collaborative multi-partner, multi-site NPD projects; Validation of the tool in two large scale engineering development projects	The tool provides a systematic approach for managing concurrent product and process development based on risk management standards; Efficacy of the tool depends on the quality and amount of data fed into the knowledge ware

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Table 2.3 – continued from previous page

Authors	Purpose/methodology	Findings
Khan et al. (2008)	To explore impact of product design on SCRM in an era of global supply arrangements; In-depth longitudinal case study of a UK clothing manufacturing and fashion retail industry	Design-led risk management is a novel approach to mitigating supply chain risks; Need for exploring the impact of design changes on supply chain risks through a holistic approach; Requirement of conducting research in various industries for exploring ways and means of integrating design and SCRM
Lee et al. (2009)	Development of a model for assessing large engineering project risks in ship building industry; Interviews and surveys for collecting data; Development of BBN models for small and medium scale industries through a data driven approach	BBNs can model the risks associated with large engineering projects; The limitation of this method relates to the increased reliance on expert survey in populating the BBN model
Tang et al. (2009)	Analysis of Boeing‘s rationale for the unconventional supply chain of Boeing 787 Aircraft; In-depth analysis of reports, statistics and secondary data	The project failure is attributed to the drastic changes in design, development process and supply chain and lack of management expertise in managing supply chain risks; The Boeing case study can help managers in other industries learn from the mistakes before engaging in similar unconventional supply chains
Lee & Johnson (2010)	Interviews and surveys for collecting data from high-tech firms engaged in new product alliances; To study the impact of governance mechanisms on the risks associated with inter-firm alliances	In contrast to the previous studies, the research is focused on examining the inter-firm relationships as a means of managing risks; Analysis of three types of risks (performance, relational and knowledge appropriation) in relation to the context of inter-firm NPD

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Table 2.3 – continued from previous page

Authors	Purpose/methodology	Findings
Lin & Zhou (2011)	To identify supply chain risk dimensions in special purpose vehicle industry in the context of product design change; A case study is conducted and a cause-effect diagram is used to model supply chain risks	Identification of risk dimensions and development of a cause-effect diagram to help managers recognise their supply chain risks; Need of conducting case studies in other industries for identifying pertinent supply chain risks and effective risk management practices
Ghadge et al. (2013)	Development of a holistic, systematic and quantitative risk assessment process for managing supply chain risks using systems approach; A case study conducted in an aerospace industry	The system model is a working tool for providing perspective of future disruptive events; Systems thinking provides the ability to capture dynamic interaction of risk behaviours

Table 2.3: Summary of articles on SCRM concerning NPD projects.

Thematic Analysis

The articles have been analysed on the basis of following significant themes:

- Research method: qualitative, quantitative or a combination of these methods are used to study the field of SCRM,
- Type of risk: there are a number of risk classifications, however, we classified articles on the basis of organisational, network (supply or demand) and external risks,
- Risk management process: risk management process can be segregated into three stages including risk identification, assessment and mitigation/control.

We considered it important to investigate different types of research methods and techniques used in the realm of SCRM in order to identify the prominent methods/techniques used and ascertain the need for investigating unexplored

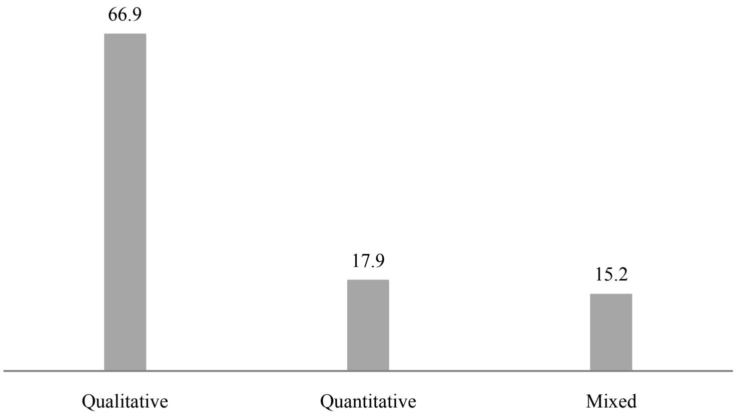

Figure 2.8: Percentage distribution of articles with respect to the research methodology.

promising techniques. As supply chain risks have mainly been classified into independent categories in the literature, we analysed the articles on the basis of risk type in order to identify the risk types needing more attention. The main aim of classifying articles with respect to each stage of the risk management process was to establish whether all stages of the process are considered equally important and the entire process is explored holistically.

Research Method

The distribution of articles with respect to the type of research method is shown in Figure 2.8. Most of the articles have followed a qualitative methodology while a very limited research is focused on utilising quantitative methods. Few studies have even employed mixed techniques. Adopting a mixed methods approach is beneficial to research in terms of integrating unique features of the two methodological streams.

Qualitative methods were classified on the basis of research approaches like conceptual theory, literature review and empirical study as shown in Figure 2.9. Empirical studies can be further classified as case studies, surveys, interviews, focus group and secondary data analysis. Many researchers have preferred conducting case studies. Blackhurst et al. (2005) used a multi-methodology empirical

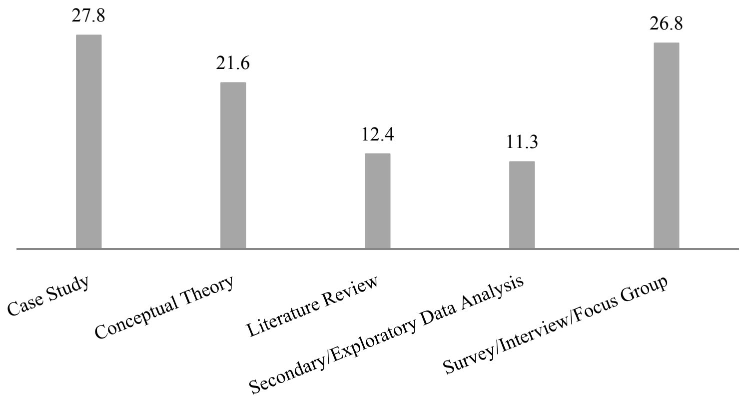

Figure 2.9: Percentage distribution of qualitative methodology based articles with respect to the sub-methods.

study combining case study, semi-structured phone interviews and focus group to study supply chain disruptions. Capo-Vicedo et al. (2011) presented a social network perspective of a supply chain and conducted an exploratory case study in construction industry. Christopher et al. (2011) conducted a multiple case study to explore the methods used by practitioners in assessing and mitigating global sourcing risks.

Khan et al. (2008) conducted an in-depth longitudinal case study of a major UK clothing and fashion retailer to investigate the impact of product design on SCRM. Leat & Revoredo-Giha (2013) conducted a case study in one of Scotland's major pork supply chains for identifying key risks and challenges involved in developing a resilient agri-food supply system. Researchers have also used surveys, semi-structured interviews and focus groups for collecting data to validate propositions and hypotheses (Jonsson, 2000; Hallikas et al., 2005; Perry, 2007; Autry & Bobbitt, 2008; Ellegaard, 2008; Manuj & Mentzer, 2008b; Jiang et al., 2009; Skipper & Hanna, 2009; Ellis et al., 2010; Lee & Johnson, 2010; Thun & Hoenig, 2011; Kern et al., 2012; Sodhi et al., 2012; Lavastre et al., 2012; Swierczek, 2014; Selviaridis & Norrman, 2014).

As the field of SCRM is still developing (Khan & Burnes, 2007; Ghadge et al., 2012; Sodhi et al., 2012), a number of studies have focused on developing conceptual theories and frameworks. These conceptual theories are important in terms of establishing a framework for advancing the current state of knowledge. However, these conceptual frameworks have not been extensively evaluated through empirical research and therefore, future research might be directed towards exploring the viability and limitations of such frameworks. A summary of selected conceptual theory based articles is presented in Table 2.4.

Authors	**Conceptual theory/framework**
Sinha et al. (2004)	Development of a generic prescriptive methodology for mitigating risks in an aerospace supply chain
Giunipero & Eltantawy (2004)	The level of risk management in a supply chain depends on situational factors: degree of product technology; security needs; relative importance of a supplier; and the purchaser's prior experience with the situation
Chopra & Sodhi (2004)	Managers can create a shared, organisation wide understanding of supply chain risks through stress testing and adapt the general risk mitigation strategy to the specific circumstances of the company through tailoring
Cheng & Kam (2008)	Development of a conceptual framework for analysing differential risks in alternative network configurations, ranging from single-principal, single-agent to the complex multi-principal, multi-agent scenarios
Manuj & Mentzer (2008a)	Development of a comprehensive risk management and mitigation model for global supply chains through synthesis of concepts, frameworks and insights from several disciplines
Richey (2009)	Integration of four existing theoretical perspectives (resource-based view of the firm, communication theory, competing values theory and relationship management theory) to develop a disaster recovery pyramid
Neiger et al. (2009)	Proposition of a novel value-focused process engineering methodology for process-based supply chain risk identification
Ponomarov & Holcomb (2009)	An integrated perspective on supply chain resilience through an extensive review of the literature from diversified fields including developmental psychology and ecosystems

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Table 2.4 – continued from previous page

Authors	Conceptual theory/framework
Knemeyer et al. (2009)	Development of a process to proactively plan for catastrophic risk events through an integration of diverse research streams
Trkman & McCormack (2009)	A new conceptual framework for the assessment and classification of suppliers based on their characteristics, performances and environment of the industry
Jia & Rutherford (2010)	Development of a conceptual process for mitigating supply chain relational risks that describes a relationship building process incorporating cultural adaptation for fostering a mutually beneficial partnership
Tse et al. (2011)	Development of a conceptual SCRM framework for mitigating quality risks
Tummala & Schoenherr (2011)	Development of a conceptual framework for a structured and ready-to-use approach in managing supply chain risks
Kim et al. (2011)	Development of a theoretical framework for relating key social network analysis metrics to supply network constructs
Kumar & Havey (2013)	Development of a decision support risk assessment and mitigation framework for a disaster relief supply chain
Braziotis et al. (2013)	Development of an outline for the distinction between supply chains and supply networks
Vilko et al. (2014)	A novel framework for linking established theories of uncertainty to the management of supply chain risks

Table 2.4: Summary of selected articles based on conceptual frameworks.

Literature reviews are fundamental to conducting research in any field. A number of researchers have conducted literature reviews mainly focusing on narrative reviews. Majority of the findings necessitate exploring the holistic nature of supply chain risks and conducting empirical-based research including case studies. A summary of literature reviews is presented in Table 2.5 describing the research methodology adopted and key findings.

Authors	Research Methodology	Findings
Juttner et al. (2003)	Literature on supply chain vulnerability and risk management is reviewed and compared with results obtained through the interviews with practitioners	Need for defining the concept of risk and adverse consequences, assessing the risk sources and investigating mitigation strategies in the context of supply chain; Requirement of conducting empirically grounded research
Tang (2006a)	A review of the literature is conducted on quantitative methods of managing supply chain risks and the methods are compared with actual practices	Plenty of new research areas to explore including: Strategies for managing supply chain disruption risks; Impact of radio-frequency identification (RFID) technology and government policies on supply chain management
Khan & Burnes (2007)	A thorough review of the general literature on risk and the specific literature on supply chain risk is conducted	Requirement of three pronged research agenda: Locate the research of supply chain risk within the broader study of risk; Conduct empirically-based research through case studies in order to investigate the management of risk in supply chains; Devise well-grounded models of SCRM incorporating risk management tools and techniques from other disciplines of research
Williams et al. (2008)	Literature on supply chain security is reviewed including academic publications, white papers and practitioner periodicals	Need for: Conducting research in the field of supply chain security using primary data; Developing quantitative methods to assess security risks; Linking supply chain security with the organisational performance; Exploring various strategies firms use in order to manage supply chain security risks

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Table 2.5 – continued from previous page

Authors	Research Methodology	Findings
Vanany et al. (2009)	Review of papers published from 2000 to 2007 is conducted through classification into different typologies	Need for: Conducting research concerning utility of information technology in mitigating supply chain risks; Exploring managerial perceptions towards supply chain risks from different perspectives; Designing a framework for collaboration between stakeholders in managing supply chain risks; Comparing various risk mitigation strategies across different sectors; Designing a decision making framework in selecting the best course of action for mitigating risks
Rao & Goldsby (2009)	Review of the literature on SCRM is conducted and a typology of risks is developed	Lack of an organised structure for the sources of supply chain risk; Provides typology of risk sources based on environmental, industrial, organisational, problem-specific and decision-maker related factors; Need for conducting substantive investigation in the field of SCRM
Olson & Wu (2010)	Review of the literature on identification and classification of supply chain risks is conducted and supply chain cases involving China have been studied	Identification of a generic framework with comparison of supply chain risk categories; Specific aspects of supply chain risks related to China are addressed; Supply chains are critical to contemporary business and therefore, SCRM is critical

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Table 2.5 – continued from previous page

Authors	Research Methodology	Findings
Tang & Nurmaya Musa (2011)	Literature survey and citation/co-citation analysis are conducted in order to investigate development in the field from 1995 to 2009	Existing literature mainly includes descriptive and conceptual models rather than quantitative models; Pressing need of studying risk management issues from the lens of industrial practice; A research gap of developing quantitative techniques for managing risks; Potential of research in the themes of robust planning, revenue management, agency theory, option theory, system dynamics and revenue logistics
Aloini et al. (2012)	Review of 140 articles is conducted in construction industry spanning a period of 11 years focusing on the risk identification stage	Classification and analysis of risk factors according to the responsibility and decision level; Contractor being placed at the planning decisional level is mainly responsible for identification and control of risk factors
Colicchia & Strozzi (2012)	A new methodology of 'systematic literature network analysis' is introduced that combines SLR with the citation network analysis approach for unfolding dynamics of the research filed	Need for: Conducting a structured study of supply chain complexity; Modelling supply chains considering the increased value of robustness and resilience; Assessing and managing disruption risks; Investigating mitigation strategies considering a supply network as an open system

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Table 2.5 – continued from previous page

Authors	Research Methodology	Findings
Ghadge et al. (2012)	SLR of quality articles published over a time period of 10 years is conducted and the results are validated through the findings of a text mining activity	Need for conducting research in following focused areas: Behavioural perceptions in risk management; Sustainability factors; Risk mitigation through collaboration contracts; Visibility and traceability; Risk propagation and recovery planning; Industry impact; Holistic approach to SCRM

Table 2.5: Summary of literature reviews on SCRM.

Limited articles are focused on quantitative modelling of supply chain risks. Many researchers have used a simulation technique for analysing supply chain risks as shown in Figure 2.10. Lutz et al. (2012) used game theory to demonstrate the practical impact of a multi-tier supply chain agreement. Interpretive structural modelling (ISM) has been used to analyse supply chain risks in food industry (Diabat et al., 2011) and to model mutual relationship among the enablers of supply chain risk mitigation (Faisal et al., 2006b).

Lo Nigro & Abbate (2011) used the concept of Shapley value to devise a mechanism of profit sharing among supply chain partners. Wieland (2013) developed mathematical models for determining an optimal solution and break-even points in the realm of four strategies including agility, robustness, resilience and rigidity. Multi-criteria decision making (Ravindran et al., 2009; Soni & Kodali, 2013) and stochastic programming (Guillen et al., 2005; Sodhi, 2005; Goh et al., 2007; Tang & Tomlin, 2008) have also been utilised for assessing supply chain risks.

Simulation provides a systematic approach for understanding the interactive impact of factors across different scenarios (Ghadge et al., 2012). The simulation techniques used in the realm of SCRM include Agent-based modelling (Breuer et al., 2013), Monte Carlo simulation (Ermoliev et al., 2000; Lee et al., 2012),

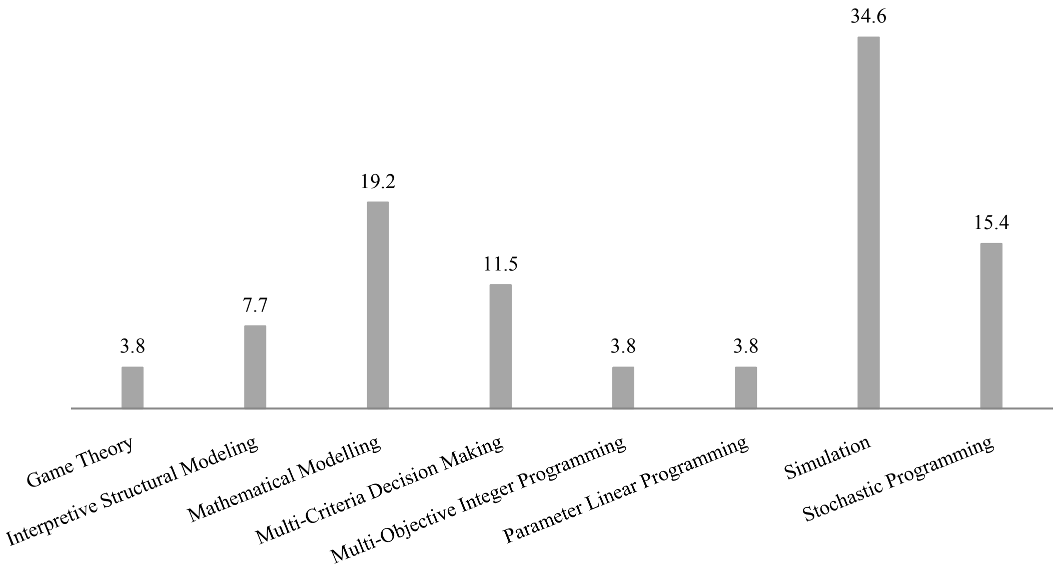

Figure 2.10: Percentage distribution of quantitative methodology based articles with respect to sub-methods.

Discrete event simulation (Durowoju et al., 2012), System dynamics modelling (Wilson, 2007) and Petri-Net modelling (Wu et al., 2007).

Researchers have also used mixed methods in their research. Analytical hierarchy process (AHP) modelling (Wu et al., 2006; Gaudenzi & Borghesi, 2006; Levary, 2007; Chen & Wu, 2013; Ganguly, 2014) and ISM (Faisal et al., 2007; Pfohl et al., 2011) have been used to develop models that were validated through case studies. It was revealed through the SLR that BBNs have recently started gaining the interest from researchers in modelling supply chain risks (Badurdeen et al., 2014). BBNs offer a unique feature of modelling risks combining both the statistical data and subjective judgement in the case of non-availability of data (Sigurdsson et al., 2001; Kelangath et al., 2011; Qazi et al., 2014). Although BBNs have been extensively used in the field of risk management, their application to the field of SCRM is mainly focused on addressing specific problems involving supplier selection, supplier assessment and ranking of suppliers. Therefore, the technique can be explored further to model risks across a supply network. A summary of such articles is shown in Table 2.6.

Authors	Methodology	Findings
Lockamy & McCormack (2009); Lockamy (2011); Lockamy & McCormack (2012); Lockamy (2014)	Development of a model for benchmarking supplier risks involving risk events related to supplier network, internal operations and external factors; Use of surveys and interviews for collection of data from both the internal and external company sources; Application on a group of 15 automotive casting suppliers for a major automotive company in the USA	BBNs serve as a very useful tool in assessing the risk exposure of a company to its suppliers; Model can be used to assess the risks of potential suppliers for an outsourcing strategy
Kayis et al. (2007)	Development of a comprehensive risk management tool (combining BBNs, AHP and knowledge warehouse) to help managers take control of concurrent engineering risks; Application of tool in two large scale NPD projects	The inclusion of expert judgement in risk analysis is beneficial since existing techniques are incapable of capturing several risk factors; Quality of results achieved through the tool will depend mainly on the commitment and awareness of future users in populating the warehouse
Dogan & Aydin (2011)	Development of a supplier selection model combining total cost of ownership and BBN methods; Application of the model in automotive industry to aid Tier-1 suppliers in selecting their own suppliers	The method is well suited to deal with incomplete or uncertain information of buyers about the suppliers; The model captures both the qualitative and quantitative criteria in supplier selection
Dogan (2012)	Development of a model for selection of an international manufacturing plant, combining total cost of ownership and BBN methods	The model relates factors to each other by parental representation in a graph facilitating transparency in reasoning; The proposed method allows exploring judgement of managers by following a systematic approach while globally considering all the relations among factors and between the factors and objectives

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Table 2.6 – continued from previous page

Authors	Methodology	Findings
Badurdeen et al. (2014)	Development of a supply chain risk taxonomy and a risk network map that capture interdependencies between risks; Application of the model on the Boeing company and its Tier-1 suppliers	The model presents an effective tool to capture the interaction of risk factors and helps in identifying key suppliers and mitigation strategies; Risk propagation across multiple tiers is not explored and is deemed as a future research agenda

Table 2.6: Summary of articles on the application of BBNs in SCRM.

Risk Classification

The articles were classified on the basis of organisational, network and external risks as shown in Figure 2.11. The articles categorised as 'Holistic' have focused on all types of risks. Organisational risks are the risks directly associated with the main focal firm and comprise inventory, operational, quality and management risks. The results clearly justify the need for conducting research focusing on organisational risks. Inventory risk arises from stock out inventories or buffer resulting into a corresponding loss of opportunity or handling costs (Juttner et al., 2003; Chopra & Sodhi, 2004). Operational or process risks can be initiated with events disrupting processing and manufacturing activities within an organisation (Lewis, 2003; Christopher & Peck, 2004; Cavinato, 2004).

Quality risks arise from the problems associated with a manufacturing plant or suppliers. Global outsourcing is considered as an important driver of quality risk (Zsidisin et al., 2004; Chopra & Sodhi, 2004; Zsidisin & Smith, 2005). Management risk is related to the lack of management expertise in dealing with supply chain risks. Management risks have been categorised as a major factor in the failure of major development projects (Tang et al., 2009; Zhao, 2013). The literature is lacking in identifying the organisational based characteristics of a

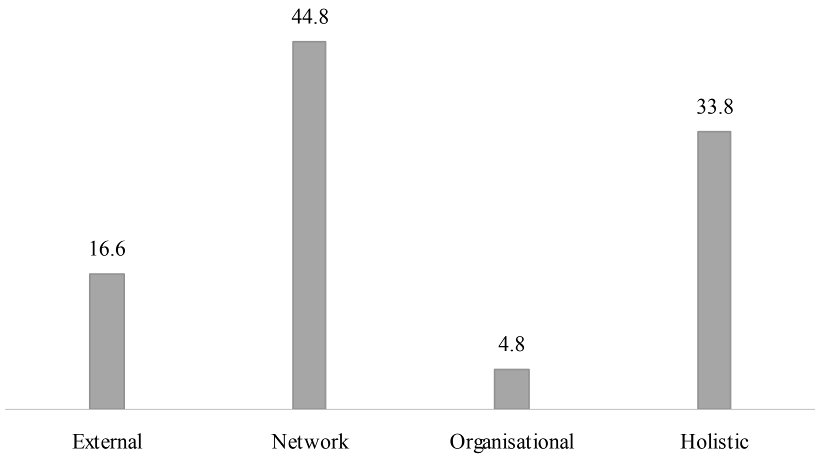

Figure 2.11: Percentage distribution of articles with respect to the classification of risks.

mature firm in dealing with supply chain risks and disruptions.

Network risks arise from interactions between a firm and its suppliers and customers. Network risks are found to be the most researched category of risks in the field of SCRM. However, most of the articles deal with the supplier risks and therefore, customer related risks need further investigation (Faisal et al., 2006a). Various studies have focused on assessing supplier risks and evaluating their performance (Blackhurst et al., 2008; Matook et al., 2009; Lockamy, 2011; Lockamy & McCormack, 2012; Chen & Wu, 2013).

External risks are driven by external events like extreme weather, earthquakes, political and market instability (Wagner & Bode, 2006). There has been an increase in the articles focusing on disruption risks (Hale & Moberg, 2005; Blackhurst et al., 2005; Kleindorfer & Saad, 2005; Craighead et al., 2007; Wu et al., 2007; Wilson, 2007; Ellis et al., 2010; Durowoju et al., 2012). A summary of articles on the classification of risks is shown in Table 2.7.

Authors	**Classification of risks**
Juttner et al. (2003)	Environmental, network and organisational risk sources

Continued on next page

Table 2.7 – continued from previous page

Authors	Classification of risks
Spekman & Davis (2004)	Inbound supply, information flow, financial flow, security of a firm's internal information flow, relationship with partners and corporate social responsibility risks
Cavinato (2004)	Physical, financial, informational, relational and innovational risks
Chopra & Sodhi (2004)	Systems, forecast, intellectual property, receivable, inventory and capacity risks
Christopher & Peck (2004)	Process, control, demand, supply and environmental risks
Kleindorfer & Saad (2005)	Operational contingencies, natural hazards, terrorism and political instability risks
Peck (2005)	Environmental, network and organisational risk sources
Bogataj & Bogataj (2007)	Supply, process, demand and control risks
Sodhi & Lee (2007)	Supply, demand and contextual risks
Tang & Tomlin (2008)	Supply, process, demand, intellectual property, behavioural and political/social risks
Manuj & Mentzer (2008a)	Supply, operations, demand, other risks including security and currency risks
Manuj & Mentzer (2008b)	Supply, operational, demand, security, macro, policy, competitive and resource risks
Oke & Gopalakrishnan (2009)	Low-impact high-frequency and high-impact low-frequency risks in the categories of supply, demand and miscellaneous
Rao & Goldsby (2009)	Framework, problem specific and decision making risks

Table 2.7: Summary of selected articles on classification of risks.

The major limitation of these classification schemes is their lack of capturing interdependency between risks. Existing classifications treating risks as independent factors are not suitable for the purpose of developing effective risk management techniques. There has been a very limited focus on exploring causal chains of vulnerabilities, sources, risks and resulting losses. Badurdeen et al. (2014) have developed a causal map capturing interdependency between risks, however, it is rudimentary and there is still a need for developing a new taxonomy of risks within a setting of causal risk paths. Risks need to be classified on the basis of such interacting paths instead of treating these as independent factors. It is considered as a vital research gap and future research must be directed towards establishing a well-grounded taxonomy focusing on risk paths and interactions. Despite there being numerous studies in other risk management contexts that study interdependent risks and indeed highlight the importance of accounting for interdependence (Aven, 2015), the same effective techniques and tools have not been exclusively adapted to the realm of SCRM. In supply chains, it is clear there is interdependency of risks (Lockamy, 2014) and therefore risk management methods should account for this.

Stage of Risk Management Process

Articles were also classified on the basis of risk management process as shown in Figure 2.12. Few studies have focused on risk identification exclusively while there is an equal distribution of articles corresponding to risk assessment and mitigation stages. Almost 28% of the articles have analysed the risk management process in its totality. Many researchers have proposed proactive mitigation strategies while limited studies have focused on analysing reactive strategies (Perry, 2007; Richey, 2009; Hopp et al., 2012; Kumar & Havey, 2013). A summary of risk mitigation strategies proposed in the literature is presented in Table 2.8.

Authors	Mitigation strategies
Johnson (2001)	Reducing capacity risks by outsourcing and building a flexible web of partners; Using information, air freight and warehouse consolidation to improve supply/demand matching; Reducing currency and political risks through operational hedging
Chopra & Sodhi (2004)	Add capacity and/or inventory; Have redundant suppliers; Increase responsiveness/flexibility/capability; Aggregate or pool demand; Have more customer accounts

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Table 2.8 – continued from previous page

Authors	Mitigation strategies
Christopher & Peck (2004)	Information accuracy, visibility and accessibility; Alerts for out of control conditions; Responsive corrective actions
Giunipero & Eltantawy (2004)	Extent of risk management depends on following four dimensions: Degree of product technology involved in the item purchased (high-tech vs. low-tech products); Need for security in handling, packaging and transporting the product (high vs. low); Importance of the supplier (regular vs. critical suppliers); Purchasers' prior experience with the situation whether it is a new item, new supplier or both (limited vs. significant experience)
Norrman & Jansson (2004)	A comprehensive study of Ericsson that has introduced a step for risk monitoring in the conventional risk management process and structured the entire process around central themes of incident handling and contingency planning
Spekman & Davis (2004)	Supplier selection process, certification or development programs; Building trust and to evaluate the trustworthiness of a potential partner; Need for a plan to develop an atmosphere of trust; Ensure open lines of communication; Requirement of an appropriate governance structure
Zsidisin et al. (2004)	Supplier improvement through communication and developing and certification programs; Mitigation of supply disruptions through creating business interruption plans, developing demand forecasts and modelling supply processes
Blackhurst et al. (2005)	Real-time sharing of correct information from every node in the supply chain; Prediction of capacity bottlenecks in global transportation networks
Kleindorfer & Saad (2005)	Approaches used to mitigate disruption risks must fit the characteristics and needs of the underlying environment of the focal supply chain; Need for continuous coordination, collaboration and information sharing between partners
Tang (2006b)	Forming a supply alliance network as a safety net against any disruption; Lead time reduction through redesigning the supply network; Establishing recovery planning systems for expediting recovery from a major disruption

Continued on next page

Table 2.8 – continued from previous page

Authors	Mitigation strategies
Sodhi & Lee (2007)	Keeping low inventories and flexible capacity; Having redundant suppliers for a bulk of non-core components; Using information technology to keep the supply chain responsive and informed
Manuj & Mentzer (2008b)	Postponement; Speculation; Hedging; Control, share or transfer risks through vertical integration, contracts and agreements; Security; Avoidance
Tang & Tomlin (2008)	Flexible supply strategy through multiple suppliers and flexible supply contracts; Flexible process strategy through flexible manufacturing process; Flexible product strategy through postponement; Flexible pricing strategy through responsive pricing
Braunscheidel & Suresh (2009)	Internal integration, external integration and adoption of external flexible practices are the direct antecedents of a firm's supply chain agility
Jiang et al. (2009)	Suppliers to adopt new enterprise level Human Resource Management practices such as performance-based compensation, training emphasising commitment towards the organisation and work; International buying firms from developed countries to cooperate with suppliers in improving the labour conditions in developing countries
Knemeyer et al. (2009)	Countermeasures for catastrophic events: Expand to alternate locations; Build protective wall; Buy insurance; Increase security
Oke & Gopalakrishnan (2009)	'One-fits all' approach for high-likelihood and low-impact risks while specific strategies for low-likelihood and high-impact risks; Better planning and co-ordination of supply and demand; Identifying supply chain vulnerability points and having contingency plans; Multiple sourcing strategy; Promotions and incentives for customers; Cost reduction in operations

Table 2.8: Summary of selected articles on mitigation of risks.

2.3.6 Future Research Agenda

SLR is a useful method to identify research gaps for exploring future research. The detailed and comprehensive analysis has revealed following important research

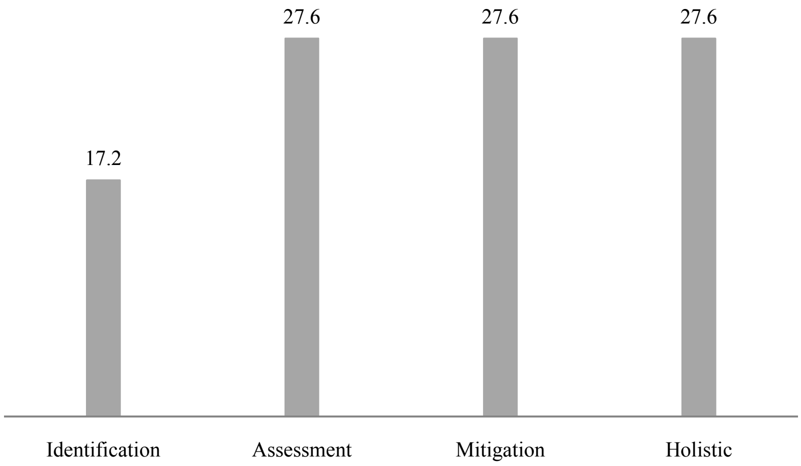

Figure 2.12: Percentage distribution of articles with respect to the risk management process.

areas:

Holistic Methods for Capturing Interdependency between Risks

Most of the reviewed studies have assumed risks as independent and/or focused on modelling specific domain in a supply chain and addressing a particular problem. Therefore, the proposed models and resulting solutions might not be realistic and globally optimal keeping in view the complex interaction of interdependent supply chain risks and actors (Dogan & Aydin, 2011; Badurdeen et al., 2014). There is a need for considering the holistic nature of supply chain risks and modelling a supply network as an open system (Colicchia & Strozzi, 2012; Ghadge et al., 2013). As there are numerous studies in other risk management contexts that study interdependent risks and indeed highlight the importance of accounting for interdependence (Aven, 2015), the same effective techniques and tools must be adapted to the context of SCRM. In supply chains, it is clear there is interdependency of risks (Lockamy, 2014) and therefore risk management methods should account for this.

Risk Taxonomy Exploring Causal Chains

Existing classifications of risks assign risks to independent categories and fail to capture the interdependency between risks. Risk identification is an important stage of risk management and treating risks as independent in the first stage makes it impossible for the subsequent stages to capture an important aspect of interdependency between risks. Therefore, these classifications are detrimental to the main theme of developing effective techniques of managing supply chain risks. There is a major research gap of developing a new taxonomy of risks within a setting of causal risk paths and future research must focus on exploring causal chains of vulnerabilities, risk sources, risk events and resulting losses.

Organisational Level Studies for Gauging Maturity Level

Based on the categorisation of articles with respect to risk classification, the results necessitate conducting extensive research in exploring organisational risks. Specifically, there is a need for assessing management related risks as management expertise can help improve planning and mitigate supply chain risks (Tang et al., 2009). Furthermore, some organisations are able to sustain disruptions while others succumb to the devastating impact and therefore, future research must also focus on exploring the factors that differentiate firms on the basis of their ability or maturity in recovering from major disruptions (Hittle & Leonard, 2011).

Disruption Propagation and Reliability of the Supply Network

Disruptions are unpredictable and in order to safeguard supply chain from the adverse effects of these disruptions, managers need to have complete visibility across the entire network (Colicchia & Strozzi, 2012; Ghadge et al., 2012). Recently, researchers have started studying the impact of disruptions on supply chains (Durowoju et al., 2012; Hopp et al., 2012; Son & Orchard, 2013; Marley et al., 2014). We propose modelling a supply network as an engineering system network and applying the techniques of system reliability in assessing reliability of supply networks. Though research has been conducted in assessing the reliability of a supply network, more research is needed to capture the complexity of a supply chain network through application of robust techniques.

Synergy of SCRM and Project Risk Management in New Product Development

Long-term projects involving NPD often result in major delays and cost overruns. Development of a new product demands integration of capabilities in managing supply chain risks and project risks. Limited studies have focused on investigating supply chain risks associated with NPD and as ignoring project driven supply chain risks can jeopardise the success of a project (Tang et al., 2009), it is very important to explore risks in such projects. Also conventional supply chains (involving routine processes) and project driven supply chains (involving unique processes specific to NPD) are reported to have different characteristics and therefore, there is a need to tailor the risk management process in accordance with the characteristics and objectives of the supply chain (Leerojanaprapa, 2014). There is also a need for conducting case studies in various industries for exploring means and methods of managing such risks (Khan et al., 2008).

Mechanism Design for Mitigating Strategic Risks

Strategic risks can result between supply chain stakeholders based on conflicting incentives of the individuals (Wakolbinger & Cruz, 2010; Lutz et al., 2012; Zhao et al., 2012; Zhao, 2013; Xin & Zhao, 2013). Game theory is an effective technique in mitigating such risks (Osborne, 2003). Risk sharing-based contracts can be designed for aligning conflicting incentives that will not only help in maintaining the high reliability of a supply network but also in materialising maximum profitability of the entire supply chain. The findings of the SLR revealed that strategic risks have not been fully explored in the literature and therefore, there is a need to model opportunistic behaviour of stakeholders while modelling and assessing supply chain risks.

SCRM practices in Small and Medium Enterprises

Supply chains are served raw material by a number of suppliers that are directly linked with multiple suppliers at higher echelon. Based on the findings of the SLR, research in SCRM has mainly focused on companies having global footprint whereas small and medium enterprises can have a significant impact on the entire network in case of the occurrence of any disruption. There is a need for conducting research in small and medium enterprises to explore their practices in managing supply chain risks (Ellegaard, 2008). Keeping in view the critical nature of dependency, the impact of disrupted small firms must be evaluated on the entire supply network for identifying critical firms and implementing proactive strategies (Hopp et al., 2012).

2.4 Conceptual Framework

Keeping in view the need for presenting a holistic approach of modelling interdependent supply chain risks and promising results achieved through the application of BBNs in the realm of SCRM (Leerojanaprapa, 2014), we present a conceptual framework based on the well-established AS/NZS ISO 31000:2009 risk management standard (SA, 2009) (see Figure 2.13). Risk assessment stage of the standard can be effectively modelled through BBNs. We propose developing causal maps for each category of risks including external, upstream, downstream and process risks. We adopt the notion of representing a risk by its constituents of trigger, risk event and resulting consequence (Sodhi & Tang, 2012). After developing these causal maps, all the risks across these maps can be linked together corresponding to common triggers, risk events and consequences.

This framework is unique in terms of capturing complex interactions between risks ranging across different domains of a supply network. The framework implies significance of treating risks as interdependent factors and emphasises the need for exploring causal chains of risks instead of focusing on independent categories of risks. The triggers across different domains of a supply network can interact together and a risk realising at one end of a supply network might propagate across the entire network representing 'systemicity' of risks (Ackermann et al., 2014). An external risk event might have detrimental effects on all segments of the supply network and therefore, it is important to model propagation across such causal paths instead of treating risks as independent factors.

BBNs can be used for modelling supply chain risks encompassing all three stages of risk assessment including risk identification, risk analysis and risk evaluation. Modelling the qualitative structure of BBNs involves identification of variables (nodes) and connecting the arcs across different nodes representing causal relationships. It reflects the same process of identifying risk sources, risks and consequences within the risk identification stage of the risk management process. Once the structure of a BBN is developed, the strength of relationships is established through populating the network with conditional probability values. This stage covers the risk analysis part of the risk management process where the probability and impact values of different risks are ascertained. However, BBNs capture the interdependent nature of interacting risks and therefore, the technique helps in assessing risks within a setting of interdependent environment. Risk evaluation necessitates identification of effective strategies in mitigating risks. Key risks can be identified through propagating evidence across the BBN in relation to different scenarios resulting in the selection of appropriate strategies for implementation.

The proposed framework is also beneficial in the risk monitoring stage where

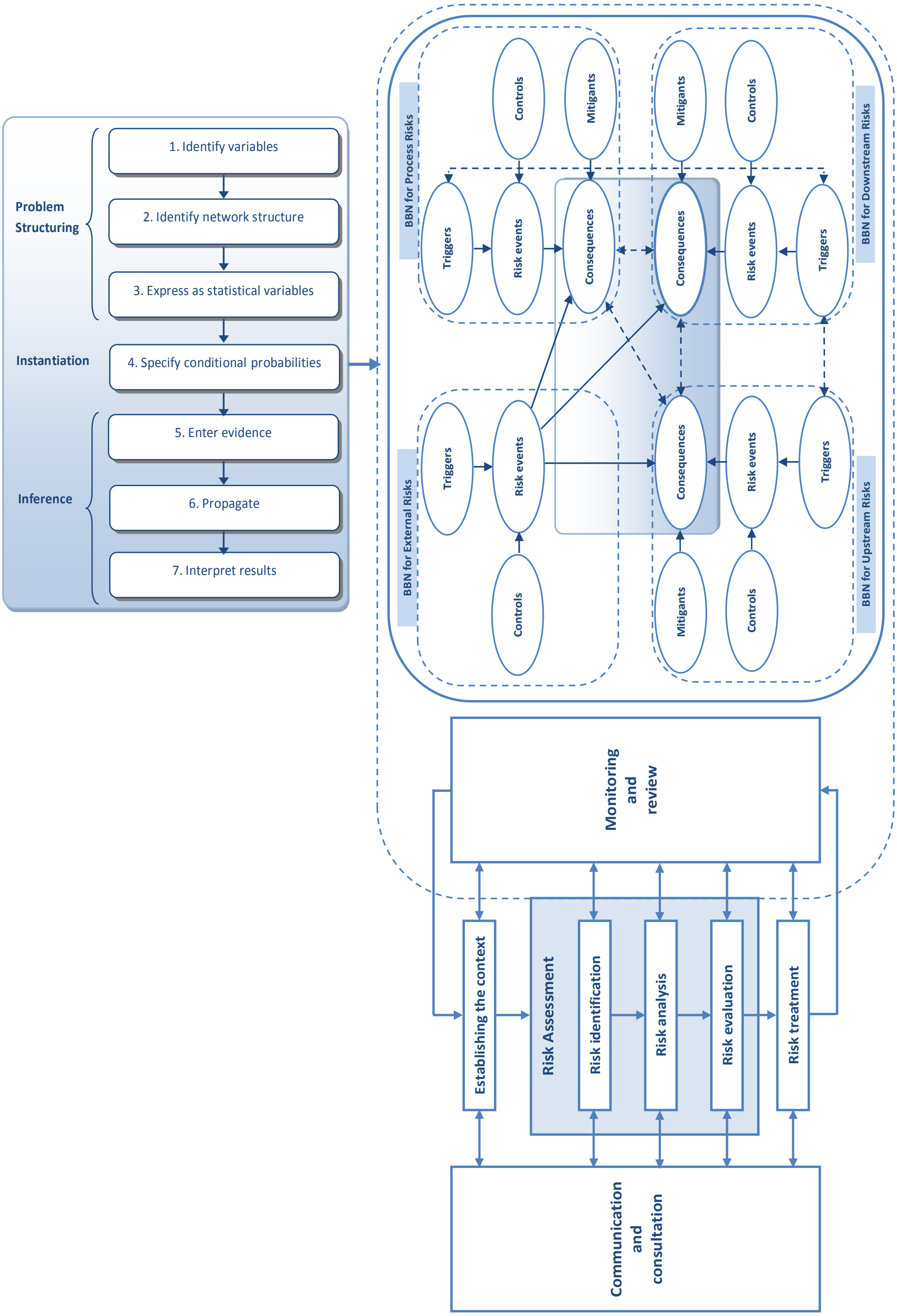

Figure 2.13: A conceptual framework for capturing interdependency between risks.

the key risks identified can be monitored and new risks added to the existing network without incorporating major changes in the model itself. The framework also presents an important feature of evaluating efficacy of mitigation strategies (preventive and reactive) within a setting of interconnected risks and mitigation strategies. As mitigation strategies can only be implemented at the cost of financial and human resources, such an evaluation is mandatory for selecting cost-effective strategies. The proposed framework can serve as an important paradigm shift from classifying independent categories of risks to exploring supply chain risks as causal chains of vulnerabilities, risk sources, risk events and consequences.

2.5 Summary

This chapter presents the findings of SLR conducted where 145 peer-reviewed articles published over a period of last 15 years were reviewed with the help of a text mining software. The methodology provided a systematic approach to gain an insight into the development of the field through different stages. Findings of the review were validated through the results of text mining analysis. Such an integration of SLR and knowledge management technique allows identification of distinct patterns that may not be observed through conventional narrative reviewing methods.

The analysis revealed major research gaps that have not been explored in detail. As supply chains are becoming complex, existing conventional classification of risks and methods relying on unrealistic assumption of independent risks are not appropriate for coping with the complexity. There is a need for shifting the focus from such simplified tools and classification schemes to more realistic and effective methods that can capture the holistic account of complex interactions. A new risk taxonomy representing causal chains of interacting vulnerabilities, risk sources, risk events and consequences can serve as a major contribution to the existing literature. The proposed risk management framework can be used to model interdependency between supply chain risks. BBNs have recently gained interest from researchers in modelling supplier risks; however, keeping in view the efficacy of technique, it can be further explored for modelling interaction of risks across the entire spectrum of a supply network. The next chapter describes the research methodology adopted.

Chapter 3

Research Methodology

3.1 Introduction

This chapter explicates the research methodology used to address the research questions. The chapter establishes the philosophical position of the thesis with regard to distinct paradigms including positivism, critical realism and pragmatism, describes the case study based method involving semi-structured interviews and presents a brief overview of BBNs.

3.2 Research Paradigm

Research paradigm is a perspective that is based on a set of presuppositions, concepts and values (Johnson & Christensen, 2008). Social science researchers shape their research designs on the basis of inherent philosophical preferences (James & Vinnicombe, 2002). It is extremely important to understand philosophical assumptions underlying a research process as *"The way we think the world is (ontology) influences: what we think can be known about it (epistemology); how we think it can be investigated (methodology and research techniques); the kind of theories we think can be constructed about it; and the political and policy stances we are prepared to take"* (Fleetwood, 2005, p. 197). Three distinct paradigms including positivism, critical realism and pragmatism will be analysed in the context of this research in order to explore the fit between the prominent paradigm and the research aim.

3.2.1 Positivism

Like the popularity of 'positivism' in the research field of traditional management science (Jackson, 1987), most of the research being conducted in the field of SCRM is governed by the same paradigm. Positivists believe that there is a reality out there and this ontological belief: how they *"(implicitly or explicitly) presume the world is"* (Ackroyd & Fleetwood, 2000, p. 10) informs their epistemological stance of 'Objectivism'- viewing existence of things as meaningful entities independent of consciousness and experience. Careful scientific research is deemed to attain the objective truth and underlying meaning (Crotty, 1998, pp. 5-6). Similarly, many researchers in SCRM consider supply chain risks as true reality and based on the assumption of objectivism, they devise models representing the dynamics of these risks. Furthermore, these researchers claim the theory as being positivist in a way that causal processes are conceived of as operating deterministically involving objective forces influencing the organisations (Donaldson, 1997). In SCRM, many researchers follow the viewpoint that *"universe may not be knowable ... (but) objective phenomenon (reality) ... is certainly knowable to a degree so far beyond our actual powers ... (and therefore) any limitation of knowledge due to lack of real consistency (i.e., ergodicity) in the cosmos may be ignored"* (Knight, 1921, p. 210).

We share the ontological assumption of the positivists on the basis of our belief that supply chain risks are happening in reality. However, these risks can not be measured accurately using the simplified and misleading assumption of risks being independent factors. Furthermore, as supply chain risks are complex because of the interdependency between supply chain entities and network wide interactions between risks, 'objectivism' is an inappropriate epistemology to deal with such complexity. As opposed to the positivist doctrine of finding simple cause-effect relationships (Powell, 2002), we are interested in exploring the underlying complex dynamics between risks and developing a process for managing these risks within a network setting.

According to Lupton (1999), risk is viewed as ranging between the technico-scientific perspective, which considers risks as objective and measurable, and the social constructivist perspective, which considers the influence of social, political and historical factors of those involved in managing risks (Khan & Burnes, 2007). Positivists considering risks being measured objectively, adopt the 'Objectivism' epistemology and mostly use different statistical methods for evaluating measures of risk. In contrast to this epistemological stance, we agree with the viewpoint of Yates & Stone (1992) considering 'risk as a subjective feature of a decision alternative'. The Society (1992) clearly mentions that *"... a particular risk or hazard means different things to different people in different contexts ... [risk] is socially constructed"*. Considering this notion of risk, even the 'objective' ontological reality of the world may be contested, and may necessitate viewing world as composed of multiple truths or realities. However, we consider this subjectivism at the epistemological level and believe that once supply chain risks are considered for effective management, researchers and practitioners view risks as negative events as opposed to opportunities and somehow ontologically, they perceive the nature of the world as 'objective'. Therefore, we strongly view 'subjectivism' to be *"the nature of knowledge, its possibility, scope and general basis"* (Honderich, 2005).

3.2.2 Critical Realism

In management science, critical realists seek to *"re-emphasize a realist view of being in the ontological domain while accepting the relativism of knowledge as so-*

cially and historically conditioned in the epistemological domain" (Mingers, 2006, p. 204). Ontologically, they believe in the existence of a domain of structures, mechanism, events and experiences (the real). These structures have causal relationships and the interplay gives rise to events (the actual). The structures may be physical, conceptual or unobservable entities. Furthermore, not all resulting events are observable and therefore, few of them can actually be experienced. Epistemologically, researchers do not have observer-independent access to the world because of the fact that our knowledge is always provisional and culturally dependent. But at the same time, keeping into account the judgemental relativity, not all theories are valid. Methodologically, science is not all about finding the governing laws, forecasting or describing events rather it is centrally concerned with *"explanation, understanding and interpretation"* (Mingers, 2006, p. 204). The experienced phenomenon is mapped to the underlying causal structure or mechanism and this process of postulating a plausible explanation is governed by abduction.

The critical realism notion of combining the objective reality of world and a social constructivist consideration of the interplay across complex systems is termed as *"analytical dualism"* (Archer & Bhaskar, 1998, p. 370). Very few researchers embrace this philosophical standpoint in SCRM. We find ourselves inclined towards this paradigm as the research is concerned with designing an integrated risk management process for assessing and managing complex interactions between supply chain risks. It is inappropriate to generalise the dynamics of these chaotic and random processes through relying on the abstraction of reality. Not only the inherent nature of these structures and processes contribute to this complexity but the strategic behaviours of stakeholders demand comprehending the underlying mechanisms. Critical realists argue that researchers must acknowledge limitations of conducting research in the positivist paradigm and therefore, concentrate on gaining a better understanding of underlying social, economic, physical and psychological processes (Mingers, 2006, p. 216).

Methodology is the strategy or plan of action lying behind the choice of particular methods and links use of methods to the desired outcome whereas methods are the techniques used to gather and analyse data related to the research question (Crotty, 1998, p. 3). Critical realism advocates using a multi-methodological approach. The researchers in this paradigm view research methods as tools for solving problems. It is very important to understand the problem and its context and once the problem structuring is performed comprehensively, it may lead to adopting specific types of methods. We think that conducting multiple case studies can help us understand the dynamics of interacting complex supply chain risks. The findings of case studies are *"likely to have important strengths like novelty, testability and empirical validity"* (Eisenhardt, 1989, p. 548). Although the literature review reveals a number of case studies already performed in SCRM, these generally fail to capture a holistic view of the complex interplay between supply chain risks (Colicchia & Strozzi, 2012; Ghadge et al., 2012). Keeping in view the prospect of BBNs as a *"way of operationalising critical realism's retroductive methodology"* (Mingers, 2006, p. 213), we intend to use this technique for developing models during the case studies. BBNs are effective in capturing dynamics underlying complex processes (Nadkarni & Shenoy, 2004).

The critical realist approach has been further advanced by Orlikowski (1992) advocating that *"reformulation of the technology concept and the structurational model of technology allow a deeper and more dialectical understanding of the interaction between technology and organisations"*. We consider that the practices of SCRM can be better understood through exploring the *"dialectic interplay between technocratic and social factors"* (Tinker & Lowe, 1984). Furthermore, this concept can be coupled with the behavioural aspect of people under consideration. The main purpose of this research is to understand the underlying complex dynamics of interaction between risk factors. This theme is in commensurate with the critical realist theory of describing the (largely hidden) *"causal mechanisms responsible for the overt behaviour"* (Bhaskar, 1975, p. 160) of systems. The main aim of our research is not to determine absolute processes or mechanisms underlying supply chain risks, rather, the findings of this research will generate *"plausible theories of the mechanisms responsible for identified ... patterns of phenomena"* (Archer & Bhaskar, 1998, p. 164) and help practitioners understand the complexity of these interactions in order to manage risks in a better way.

3.2.3 Pragmatism

Pragmatism rejects the ontological viewpoint of critical realism that there is an absolute reality and advocates presence of multiple subjective realities in the context of multiple actors. Therefore, pragmatists hold a subjectivist ontological belief. Researchers in this paradigm might consider bringing the best elements from apparently opposing strands on the criterion of what works in practice (Jackson, 1987). Pragmatism is posited to be a better paradigm for management science as it helps in the advancement of field through good practice rather than relying on an abstract theory (Jackson, 1987). We believe that there can be multiple realities and in the context of this research, such an ontological assumption would necessitate following a completely different theoretical approach. However, in management science, we develop projects on the strong foundation of established theories. Therefore, the relative neglect of theoretical underpinning in this paradigm is perplexing and also *"... in a complex world where facts are messy and disrespectful of our theories about them ... Our truth is not correspondent, but instrumental- the better theory is the one that stimulates better research, better teaching, better learning, better practice"* (Powell, 2002, p. 879). We oppose the pragmatic viewpoint in a way that it is possible to understand the underlying complex processes and true reality through analysing the subjective and diversified perspectives of individual actors or groups.

3.2.4 Summary

The research field of SCRM in general and our research project in particular have been explored through the lens of three divergent paradigms including positivism, critical realism and pragmatism. Many researchers have conducted research following the positivism stance. However, based on our assumptions about the reality of world and valid knowledge concerning this reality, we feel inclined towards selecting critical realism as a suitable paradigm for the research. It is important to understand the dynamics of complex processes and mechanisms underlying supply chain risks. Furthermore, the notion of 'analytical dualism' captures the interplay between actors and the structures being explored in this research project. Under the aegis of this paradigm, it is worth exploring the multi-methodology approach in order to understand the complex mechanisms involved in a better and effective manner.

3.3 Case Study Research and Semi-Structured Interviews

3.3.1 Case Study

A case is (Gillham, 2000, p. 1):

- a unit of human activity embedded in the real world,
- which can only be studied or understood in context,
- which exists in the here and now,
- that merges in with its context so that precise boundaries are difficult to draw.

A case study investigates a case to answer specific research questions and seeks a range of different kinds of evidence to support the analysis. No one kind or source of evidence is likely to be sufficient (or sufficiently valid) on its own and therefore, multiple sources of evidence are used with corresponding strengths and weaknesses (Gillham, 2000, pp. 1-2). *"Case studies are the preferred method when 'how' or 'why' questions are being investigated, the investigator has little control over events, and the focus is on a contemporary phenomenon in a real-life context"* (Yin, 2009, p. 2). *"Case studies have a distinctive place in evaluation research; the most important is to explain the presumed causal links in real-life interventions that are too complex for the survey or experimental strategies"* (Yin, 2009, p. 19). One of the guiding principles of defining the case and unit of analysis is to review the previous literature (Yin, 2009, p. 33).

Case study being a main method can comprise a number of sub-methods including but not limited to interviews, observations, document and record analysis, and work samples. Although the multi-method approach results in the collection of data from different methods, the data relates to the same issue under investigation. With the inherent strengths and weaknesses associated with each method, convergence of the results implies reliability of the analysis; however, any divergence does not necessarily mean that one set of data is wrong rather the underlying mechanism of the system under investigation is complicated than expected. The (non-)convergence of multiple sources of evidence is depicted in Figure 3.1. Adopting a multi-methodological approach is known as triangulation (Gillham, 2000, p. 13). Triangulation is *"using multiple sources of evidence- to collect information from multiple sources but aimed at corroborating the same fact or phenomenon"* (Yin, 2009, p. 114). Four types of triangulation are relevant while doing evaluation (Yin, 2009, p. 116):

- of data sources (data triangulation),
- among different evaluators (investigator triangulation),

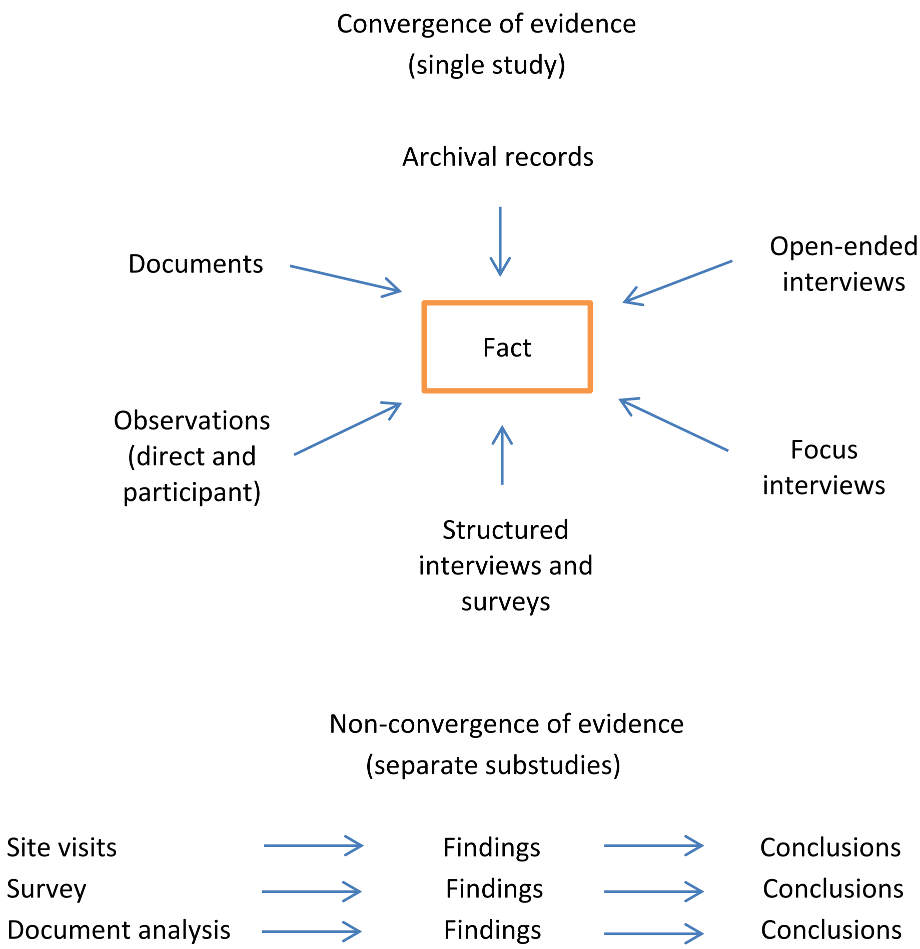

Figure 3.1: Convergence and non-convergence of multiple sources of evidence (source: Yin 2009, p. 117).

- of perspectives to the same data set (theory triangulation),
- of methods (methodological triangulation).

Benefits of the Case Study Approach

The main benefit of using qualitative method is to be able to (Gillham, 2000, p. 11):

- carry out an investigation where other methods are not viable,
- investigate situations where little is known about the case at hand,

- explore complexities that are beyond the scope of more 'controlled' approaches,
- 'get under the skin' of a group or organisation to find out the informal reality,
- view the case from the perspective of those involved,
- explore the underlying processes leading to results.

Critique about the Case Study Approach

There are some major concerns about the case study approach. First, the rigor of case study research is often questioned as there is a chance that the investigator has not followed a systematic approach and has influenced the direction of findings through biased views. A second concern relates to the case studies providing limited scope for scientific generalisation; however, the goal of conducting a case study is to *"expand and generalise theories (analytic generalisation) and not to enumerate frequencies (statistical generalisation)"* (Yin, 2009, p. 15). A third complaint is that case studies take too long resulting in massive documents.

The Case Study Protocol

"The protocol is a major way of increasing the reliability of case study research and is intended to guide the investigator in carrying out the data collection from a single case (again, even if the single case is one of several in a multiple-case study)" (Yin, 2009, p. 79). For case studies, the main purpose of using documents is to corroborate evidence from other sources. The strengths and weaknesses of different sources of evidence are given in Table 3.1.

Source of evidence	Strengths	Weaknesses
Documentation	Stable- can be viewed repeatedly	Retrievability-can be difficult to find
	Unobtrusive-not created as a result of the case study	Biased selectivity, if collection is incomplete
	Exact-contains exact names, references, and details of an event	Reporting bias- reflects (unknown) bias of author
	Broad coverage-long span of time, many events, and many settings	Access-may be deliberately withheld
Archival records	Same as those for documentation	Same as those for documentation
	Precise and usually quantitative	Accessibility due to privacy reasons
Interviews	Targeted-focuses directly on case study topics	Bias due to poorly articulated questions
	Insightful-provides perceived causal inferences and explanations	Response bias
		Inaccuracies due to poor recall
		Reflexivity-interviewee gives what interviewer wants to hear
Direct observations	Reality-covers events in real time	Time consuming
	Contextual-covers contest of 'case'	Selectivity-broad coverage difficult without a team of observers
		Reflexivity-event may proceed differently because it is being observed
		Cost-hours needed by human observers
Participant observation	Same as those for direct observation	Same as those for direct observation
	Insightful into interpersonal behavior and motives	Bias due to participant observer's manipulations of events
Physical artefacts	Insightful into cultural features	Selectivity
	Insightful into technical operations	Availability

Table 3.1: Six sources of evidence: strengths and weaknesses (source: Yin 2009, p. 102).

Tests	Case Study Tactic	Phase of research in which tactic occurs
Construct validity	Use multiple sources of evidence	Data collection
	Establish chain of evidence	Data collection
	Have key informants review draft case study report	Composition
Internal validity	Do pattern matching	Data analysis
	Do explanation building	Data analysis
	Address rival explanations	Data analysis
	Use logic models	Data analysis
External validity	Use theory in single-case studies	Research design
	Use replication logic in multiple-case studies	Research design
Reliability	Use case study protocol	Data collection
	Develop case study database	Data collection

Table 3.2: Case Study tactics for four design tests (source: Yin 2009, p. 41).

Criteria for Judging the Quality of a Research Design

The quality of a research design in general and case study in particular can be judged through following tests (Yin, 2009, p. 40) with details provided in Table 3.2:

- Construct validity: identifying correct operational measures for the concepts being studied,
- Internal validity (for explanatory or causal studies only and not for descriptive or exploratory studies): seeking to establish a causal relationship,
- External validity: defining the domain to which the findings can be generalised,
- Reliability: demonstrating the replication of the same results subject to certain conditions.

3.3.2 Interviews

A survey method usually involves both questionnaire and research interviews, but interviews of one kind or another are extremely important in the case study approach (Gillham, 2000, pp. 59-61). Interviewing, on any scale, is enormously time-consuming; however, in the case of highly structured interviews, the same is not true. The 'time cost' is a major factor in deciding the number of interviews and the venue (Gillham, 2000, p. 61). Different forms of interviews are classified with regard to the verbal data dimension as shown in Table 3.3.

The greatest strength of the face-to-face interview is the 'richness' of the communication that is possible. However, the richness comes at a price as it is not just the time associated with conducting the interview itself rather the time involved in transcription and analysis also. The use of interview technique is recommended when (Gillham, 2000, p. 62):

- small numbers of people are involved,
- they are accessible,
- they are 'key' and there is no possibility to lose any,
- the questions are mainly 'open' and require an extended response with prompts and probes for clarification,
- in the case of sensitive material, people will disclose things in a face-to-face interview rather than responding to an anonymous questionnaire.

"A semi-structured interview is the most important form of interviewing in case study research and it can be the richest single source of data" (Gillham, 2000, p. 63). It is highly recommended to record the interviews as (Gillham, 2000, p. 69):

- it is impossible to get a complete account any other way and there is no chance to miss anything,

Unstructured					Structured
Listening to other people's conversation; a kind of verbal observation	Using 'natural' conversation to ask research questions	'Open-ended' interviews; just a few key open questions, e.g. 'elite-interviewing'	Semi-structured interviews, i.e. open and closed questions	Recording schedules: in effect, verbally administered questionnaires	Semi-structured questionnaires: multiple choice and open questions	Structured questionnaires: simple, specific, closed questions

Table 3.3: The verbal data dimension (source: Gillham 2000, p. 60).

- writing down during the interview results in distraction and interrupts the flow,
- it is possible to listen to the interview several times in order to discern more each time.

3.3.3 Transcription and Content Analysis

Conducting an interview and recording is one stage of the process while transcribing and analysing the data is the other major step. It is always recommended to transcribe a recording at the earliest after the actual interview as the interview would still be fresh in the memory. The main purpose of content analysis is to *"identify substantive statements-statements that really say something"* (Gillham, 2000, p. 71). A content analysis necessitates performing following steps (Gillham, 2000, pp. 71-76):

- Take each transcript in turn.
- Go through each one highlighting substantive statements and ignore repetitions and other irrelevant material.
- Derive a set of categories for the responses to each question by means of the highlighted statements.
- Enter the categories on an analysis grid across the codes of respondents. As the category headings are simply a way of classifying the statements people have made, it is important to include important statements as well.
- Go through the transcripts, assigning each substantive statement (where possible) to a category. Statements that are not possible to be assigned must be dealt with separately. On the analysis grid, either tick the relevant box (this person made a statement which fits this category) or include the

actual statement or do both on separate sheets: one for a count analysis and one for a meaning analysis.

3.3.4 Description of the Semi-Structured Interviews Conducted

A total of 13 semi-structured interviews were conducted with experts in the construction industry in order to understand the current practices of managing project complexity and the associated risks. Furthermore, the respondents' opinion was sought on the viability of ProCRiM and proposed modelling approach. All the respondents were selected on the basis of their experience in project risk management within the construction industry. Initial contact with the interviewees was established through an academic and industrial network of researchers and afterwards, the snowballing process (Sadler et al., 2010) was utilised to select suitable respondents. The qualifications and work experience of the respondents are shown in Figure 3.2. The research was approved by the University of South Australia's Human Research Ethics Committee and all the interviews were conducted during June and August of 2015. In order to obviate the chance of misrepresentation and loss of data, all the interviews were audio-taped with the permission of respondents. After the completion of interviews, data was internally validated and content analysis (Udawatta et al., 2015) was performed for data reduction and concept identification. Subsequently, the transcripts and deduced themes were shared with the interviewees for validation.

3.3.5 Description of the Case Studies Conducted

An important aim of this study was to validate the proposed process through case studies in order to evaluate the benefits and challenges associated with its implementation. The validation of the process involved establishing the context

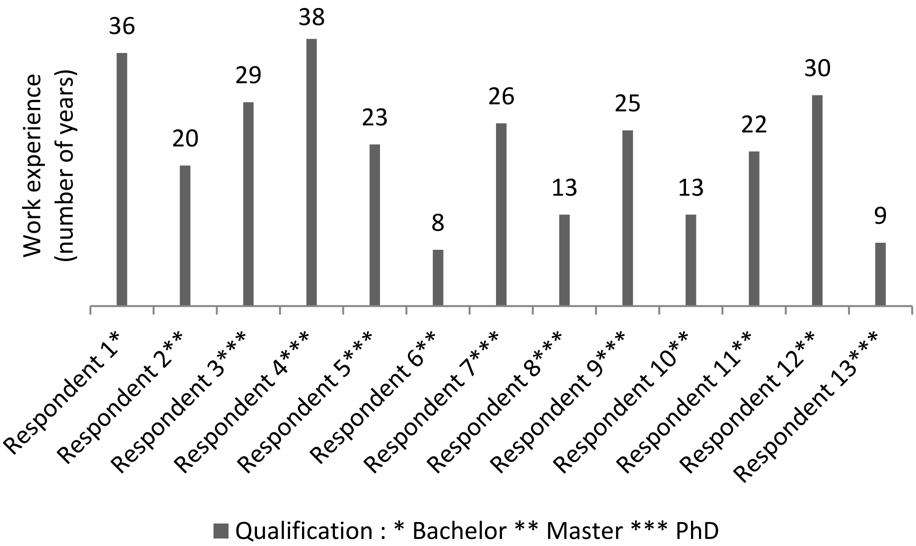

Figure 3.2: Profile of respondents.

of a *specific organisation* (case) and developing a model based on *how the decision makers perceived the interdependencies between risks and why certain risks and performance measures were given due importance* (study). In this context, the case study method was *"an appropriate choice for investigating 'how' and 'why' questions"* (Yin, 2009, p. 27).

Based on the professional contacts of academics working in the same research area, different companies including but not limited to SKF, Prysmian, Nokia Siemens Network, Autostrade per Italia, Barilla, Manni Group and Zanardi were approached through an email. The companies were selected on the basis of their established risk management process and exclusive focus on dealing with supply chain risks. Finally, Aero (a leading global technology provider) and Cell (an innovative leader in the telecommunication industry) were selected for conducting the case studies as their risk managers were keen on improving risk management process within the company and assessing the merits and challenges associated with the proposed process. Two case studies were considered sufficient to validate the proposed process and infer important findings as there are no existing studies focusing on the same theme and also, there were limited resources to conduct

Designation	Work experience (no. of years)	Respondent ID
Risk Manager	19	Resp#1
Purchasing and Supply Chain Manager	25	Resp#2
Loss Prevention Analyst	5	Resp#3
Insurance Manager	13	Resp#4
Project Manager	20	Resp#5
Project Risk Manager	15	Resp#6
Project Risk Manager	16	Resp#7

Table 3.4: Profile of respondents (semi-structured interviews).

additional case studies. The initial interview protocol was piloted with Zanardi (a manufacturing company specialising in the heat treatment of Iron and its alloys) that helped in revising the questions to clarify the terms and adopting a well-structured method to develop the risk networks in the two case studies.

The main data collection method was semi-structured interviews as *"the overwhelming strength of the face-to-face interview is the 'richness' of the communication that is possible"* (Gillham, 2000, p. 62) and *"the semi-structured interview is the most important form of interviewing in case study research and it can be the richest single source of data"* (Gillham, 2000, p. 63). As the research involved developing risk networks, the case study design utilised a mix of quantitative and qualitative evidence. Focus group sessions were also conducted to validate the model developed during each case study. The respondents were selected on the basis of their expertise in risk management in general and project risk management/SCRM in particular. A total of seven semi-structured interviews were conducted with details of the experts given in Table 3.4. Each interview lasted for 90 minutes on average (with the minimum and maximum time of 70 and 120 minutes, respectively). A total of six focus group sessions were held involving the development and validation of two models and communication of the results with each session lasting for 2 hours on average. The research was approved by the University of Strathclyde Human Research Ethics Committee.

In order to obviate the chance of misrepresentation and loss of data, all the interviews were audio-taped with the permission of respondents. Also, two researchers were engaged in conducting each case study in order to ensure the validity of research and the guidelines provided by Nadkarni & Shenoy (2004) and Pitchforth & Mengersen (2013) were strictly followed to validate the models developed. Following the interviews, the recordings were transcribed and the data was validated internally. Subsequently, content analysis was performed for data reduction and concept identification.

Afterwards, the transcripts and deduced themes were shared with the interviewees for validation. Besides interviews, secondary data including publicly available corporate reports, case studies and annual performance reports were collected and analysed in order to triangulate the data collected through interviews and focus group sessions. Finally, a case study report was prepared and shared with the respective company to validate the authenticity of results and help the participants identify any issues.

3.4 Bayesian Belief Networks

3.4.1 Introduction

BBNs provide a framework for modelling uncertainty. BBNs have their background in statistics and artificial intelligence and were first introduced in the 1980*s* for dealing with uncertainty in knowledge-based systems (Sigurdsson et al., 2001). They have been successfully used in addressing problems related to a number of diverse specialties including reliability modelling, medical diagnosis, geographical information systems, and aviation safety management. For understanding the mechanics and modelling of BBNs, interested readers may consult Sigurdsson et al. (2001), Nadkarni & Shenoy (2001), Nadkarni & Shenoy (2004), Jensen & Nielsen (2007), and Kjaerulff & Anders (2008). We consider BBNs as the best choice of modelling technique as it facilitates capturing interdependency between uncertain variables and a number of studies specific to SCRM have substantiated the efficacy of BBNs in modelling supply chain risks (Leerojanaprapa et al., 2013; Lockamy, 2014; Badurdeen et al., 2014; Garvey et al., 2015).

A BBN comprises following elements:

- A set of variables (each having a finite set of mutually exclusive events) and a set of directed edges between variables forming an acyclic directed graph; a directed graph is acyclic if there is no directed path $A_1 \rightarrow ... \rightarrow A_n$ so that $A_1 = A_n$, furthermore, the directed edges represent statistical relations if the BBN is constructed from the data whereas they represent causal relations if they have been gathered from experts' opinion,
- A conditional probability table $P(X|Y_1, ...Y_n)$ attached to each variable X with parents $Y_1, ..., Y_n$.

3.4.2 Chain Rule for Bayesian Belief Networks

Let a Bayesian Network be specified over $A = A_1, ..., A_n$, the chain rule of probability theory allows factoring joint probabilities resulting in the calculations made under certain probability states. The structure of a BBN implies that the value of a particular node is conditional only on the values of its parent nodes. Therefore, the unique joint probability distribution $P(A)$ representing the product of all conditional probability tables is given as follows:

$$P(A) = \prod_{i=1}^{n} P(A_i|pa(A_i)) \tag{3.1}$$

where $pa(A_i)$ are the parents of A_i.

3.4.3 Illustrative Example

Let us assume a very simple BBN comprising three risks; A, B and C as shown in Figure 3.3. Each variable is assumed to have two states: True (T) and False

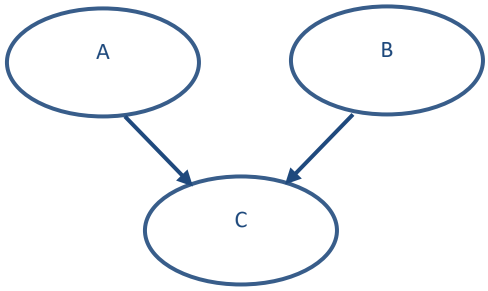

Figure 3.3: A BBN comprising three variables.

Parents		*P(Risk|Parents)*					
		A		B		C	
A	B	T	F	T	F	T	F
		0.4	0.6				
				0.7	0.3		
T	T					0.95	0.05
T	F					0.7	0.3
F	T					0.5	0.5
F	F					0.05	0.95

Table 3.5: (Conditional) probability values for the three nodes.

(F). A and B are the root nodes influencing their child node 'C' which is the leaf node having no child or descendant. The prior probability values of A and B and conditional probability values of C are given in Table 3.5.

The updated probability value of variable C can be calculated using Equation 3.2. One of the benefits of BBNs relates to the revision of beliefs once any evidence is propagated across a variable or set of variables using Bayes' Theorem. This feature of BBNs is particularly useful once there is a need to seek information about the probability of nodes that are not directly observable. The posterior beliefs about variables A and B can be calculated using Equations 3.3 and 3.4 once an evidence is instantiated at variable C. The calculation of updated probability of variable C results in the value of 0.57 as shown in Equation 3.5. The posterior probabilities of variables A and B are 0.61 and 0.84 in comparison with the prior probabilities of 0.4 and 0.7, respectively as shown in Equations 3.6 and 3.7. The increase in the revised probability of variable A is more than that of variable B because of its relatively stronger interdependency with the variable C.

$$
\begin{aligned}
P(C=T) =& P(C=T|A=T,B=T)*P(A=T)*P(B=T)+ \\
& P(C=T|A=T,B=F)*P(A=T)*P(B=F)+ \\
& P(C=T|A=F,B=T)*P(A=F)*P(B=T)+ \\
& P(C=T|A=F,B=F)*P(A=F)*P(B=F)
\end{aligned} \tag{3.2}
$$

$$
\begin{aligned}
P(A=T|C=T) &= \frac{P(A=T,C=T)}{P(C=T)} \\
&= P(C=T|A=T)*P(A=T)/P(C=T)
\end{aligned} \tag{3.3}
$$

$$
\begin{aligned}
P(B=T|C=T) &= \frac{P(B=T,C=T)}{P(C=T)} \\
&= P(C=T|B=T)*P(B=T)/P(C=T)
\end{aligned} \tag{3.4}
$$

$$
\begin{aligned}
P(C=T) &= (0.95*0.4*0.7)+(0.7*0.4*0.3)+(0.5*0.6*0.7)+(0.05*0.6*0.3) \\
&= 0.266+0.084+0.21+0.009 \\
&= 0.57
\end{aligned} \tag{3.5}
$$

$$
\begin{aligned}
P(A=T|C=T) &= \frac{(0.95*0.4*0.7)+(0.7*0.4*0.3)}{0.57} \\
&= \frac{0.266+0.084}{0.57} \\
&= 0.61
\end{aligned} \tag{3.6}
$$

$$
\begin{aligned}
P(B = T|C = T) &= \frac{(0.95 * 0.4 * 0.7) + (0.5 * 0.6 * 0.7)}{0.57} \\
&= \frac{0.266 + 0.21}{0.57} \\
&= 0.84
\end{aligned}
\tag{3.7}
$$

3.4.4 Main Features of BBNs

Following are the main advantages of using BBNs:

- BBNs provide a graphical representation of the problem that can help stakeholders visualise the interaction between a number of variables.
- Probabilistic reasoning is easily captured and propagated through powerful software.
- Prior beliefs about uncertain variables can be easily updated after providing evidence against separate sources in the network.
- Uncertainty in reasoning is taken into account and the (in)dependence between variables can be recognised.
- One can model BBNs even in the case of limited empirical data.

Following are the limitations of BBNs:

- Elicitation of expert judgment in both developing and populating the network is challenging in the case of non-availability of data.
- Available software have limited capability in dealing with continuous variables as the variables have to be discretised and this can lead to a limited ability to capture the original distribution of the variable (Weber et al., 2012).

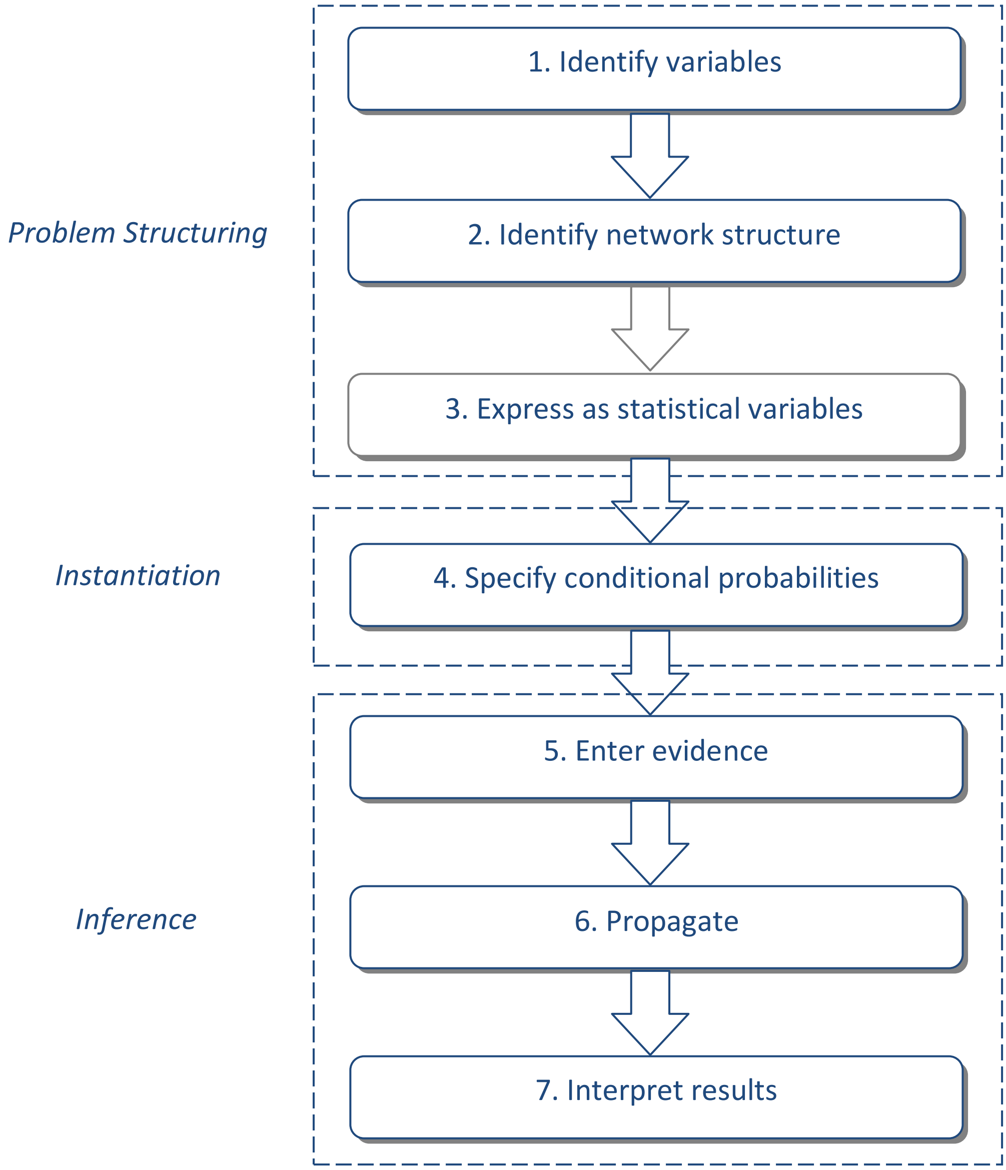

Figure 3.4: Building and using a BBN (source: Sigurdsson et al. 2001).

- The 'acyclic graph' requirement, which is needed to carry out probability calculus, is another limitation. It results in feedback effects not being included in the network (Barton et al., 2012).

3.4.5 Building and Using a BBN

There are three stages involved in developing and using a BBN (Sigurdsson et al., 2001) as shown in Figure 3.4.

Problem Structuring

This stage comprises three steps including the identification of variables, developing the network structure and defining the variables in terms of statistical values. The variables can either be discrete or continuous. Furthermore, the second and third steps are interchangeable as various iterations are necessitated before establishing a model for statistical inferential analysis. The problem owner needs to ensure that the model is developed to represent the real problem. Furthermore, the model builder can assist in structuring the model keeping in view the mechanics of BBNs.

Instantiation

This stage involves evaluation of conditional probabilities either through elicitation from the experts or extraction from the data. Probability elicitation is the most difficult part of the modelling process as experts find it very difficult to describe conditional probabilities. Furthermore, the values grow exponentially with the increase in number of parents of a node. There are various methods to aid elicitation of these probabilities (Norrington et al., 2008; Bolt & van der Gaag, 2010).

Inference

In this stage, knowledge about the variables is entered into the network and marginal probabilities for other variables are updated resulting in determination of the probabilities of variables of interest. There are various algorithms that make use of the conditional independence property inherent in the Bayesian Network structure. Simple networks can be solved through exact values while the complicated networks and the ones containing continuous variables are solved through approximation algorithms. The development of robust algorithms is a relevant research area within the domain of BBNs. Various evidences can be entered into the developed model and scenario analysis can be conducted for determining major causes impacting the consequence variable of interest.

3.5 Summary

This chapter presents the philosophical position of the research comparing distinct paradigms including positivism, critical realism and pragmatism. Case study approach and semi-structured interviews are described with the details of these methods conducted during the course of the research. Finally a brief overview of BBNs is provided as these are utilised as the main modelling technique. The next chapter introduces a project complexity driven risk management process and presents findings of the semi-structured interviews conducted with experts from the construction industry.

Chapter 4

Project Complexity and Risk Management

4.1 Introduction

BBNs offer an effective modelling technique for capturing interdependency between risks (Badurdeen et al., 2014; Lee et al., 2009) whereas EUT is widely used in decision making under uncertainty (Ruan et al., 2015). Within the theoretically grounded framework of EUT and BBNs, this chapter proposes a new process namely ProCRiM integrating all stages of the standard risk management process (SA, 2009) and establishing causal paths across project complexity attributes, risks and their consequences affecting the project objectives. EUT is mainly used to capture the preferences of a decision maker with regard to different possible outcomes of the project objectives and to prioritise strategies yielding the maximum value of expected utility subject to a budget constraint.

The main merit of ProCRiM is its focus on the holistic interaction between project complexity and risks without taking the extreme stance of either school of thought and therefore, the results do not depend on whether complexity and risk are treated as distinct concepts or not. Rather, we contend that it is the interdependency that must be given due consideration. Project complexity attributes (known at the project commencement stage) are represented as deterministic nodes, and risks and project objectives as chance nodes. The preferences of a decision maker with regard to the project objectives are characterised by means of a utility function. The chapter demonstrates the application of ProCRiM through an illustrative simulation study and presents the findings from 13 semi-structured interviews conducted with construction industry experts from South Australia. The empirical research helped in assessing the current techniques/tools used in the industry and evaluating the viability of ProCRiM.

4.2 Literature Review

As the focus of research lies at the interface of project complexity and interdependency modelling of risks in NPD in general and construction projects in particular, a brief overview of the literature specific to each domain is presented in the following sections.

4.2.1 Project Complexity

Project complexity has been extensively explored within the literature on project management and a number of definitions have been proposed focusing on different dimensions including structural complexity, uncertainty, dynamics, pace and socio-political (Geraldi et al., 2011). For this study, we follow the definition proposed by Vidal & Marle (2008): *"Project complexity is the property of a project which makes it difficult to understand, foresee and keep under control its overall behaviour, even when given reasonably complete information about the project system"*. In order to gain an insight into the emerging themes of project complexity, the studies were classified into three streams of conceptual frameworks/models, complexity measurement models and empirical studies investigating the constructs of complexity within different industries.

Conceptual Frameworks/Models

A number of frameworks have been proposed to conceptualise project complexity. The notion of project complexity as 'consisting of many varied interrelated parts' and its operationalisation in terms of 'differentiation and interdependency' (Baccarini, 1996) is replicated in most of the frameworks (Geraldi et al., 2011). There is a general consensus among researchers that complexity must encompass different facets of the project context including technical, organisational, environmental and socio-technical dimensions. Furthermore, project complexity is a function of time that necessitates exploring the dynamic nature of complexity. However, there are two different schools of thought in regard to the concept of complexity and uncertainty (Padalkar & Gopinath, 2016). Although the frameworks considering risk as a constituent of complexity emphasise the need for integrating these together (Bosch-Rekveldt et al., 2011; Geraldi et al., 2011), this is not followed in most of the models adopted for measuring complexity (Qureshi & Kang, 2015).

Building on the work of Baccarini (1996), Williams (1999) characterised the overall project complexity by two dimensions; Structural Complexity (number of elements and interdependence of elements) and Uncertainty (uncertainty in goals and methods). According to him, the structural complexity of projects is linked with the structural complexity of the product and complexity is directly affected by the tightening project deadlines. Furthermore, classical project management techniques are unable to address the structural complexity as well as the uncertainty associated with complex projects as these methods fail to capture the systemic and holistic interaction of factors contributing to uncertainty (Cicmil et al., 2006).

Advocating the need for adopting systems thinking modelling, Williams (2005) reported that systems modelling provides an effective approach of investigating the contribution of systemic effects of project characteristics towards the time and cost overruns. He emphasised the need for defining a metric for the attributes of complex projects and formulating an optimal mix of the two philosophies of project management ('maintaining the project plan' and 'constant re-planning') in relation to the specific complexity of a project.

In contrast to the concept of considering uncertainty as a vital part of complexity (Williams, 1999; Bosch-Rekveldt et al., 2011), Little (2005) considers complexity and uncertainty as two separate concepts. He proposed a concept of ranking projects across the four quadrants of project complexity (team size, mission criticality, team location, team maturity, domain knowledge gaps and interdependencies) and uncertainty (market uncertainty, technical uncertainty, project duration and dependencies within projects and scope flexibility). Similarly, Vidal & Marle (2008) also distinguished between project complexity and the risks originating from complexity. Advocating the same theme and need for understanding dynamics between risks in complex projects, Thamhain (2013) classified the dimensions of risk management into the degree of uncertainty, project complexity and impact, and introduced the risk-impact-on-performance model for describing the dynamics and cumulative nature of risks affecting performance.

Danilovic & Browning (2007) compared two complementary matrix based approaches for representing, analysing and managing crucial information regarding project domains and interactions. Their proposed approach helps in understanding the interdependency between different domains not only within a project but also across a portfolio of projects and furthermore, it reduces the uncertainty and ambiguity involved in product development projects.

Following an in-depth literature review, Vidal & Marle (2008) proposed an integrated project complexity framework comprising four categories of project size, variety, interdependence and project context specific to organisational and technological aspects, whereas Whitty & Maylor (2009) proposed viewing complexity as a matrix across structural, dynamic, independent and interacting entities and emphasised the need for investigating the main reasons for failure in major projects, measuring the complexity in a robust manner considering structural, dynamic and interaction elements, and establishing the conditions of complexity when the current tools are effective in managing projects. Similarly, through conducting a SLR, Geraldi et al. (2011) synthesised an integrated framework for assessing the project complexity comprising five dimensions of complexity –structural, uncertainty, dynamics, pace and socio-political, while Botchkarev & Finnigan (2015) developed a 'complexity taxonomy' with respect to three levels of product, project and external environment. Using the secondary data from existing literature and primary data from interviews conducted in process engineering projects, Bosch-Rekveldt et al. (2011) presented a comprehensive framework for characterising project complexity in large engineering projects comprising technical, organisational and environmental facets of an interconnected network of organisations.

In contrast to the studies focusing on country specific projects, Kardes et al. (2013) explored the structure of mega projects involving multi-country collaborations, challenges encountered during the execution and risk management techniques for dealing with the complexity. They categorised mega projects into infrastructure (dams, ports, railroads), extraction (minerals, oil and gas), production (massive military products such as fighter aircraft, chemical plants) and consumption (tourist installations, theme parks, malls) projects.

There are a number of studies establishing links between project complexity, risks and project performance. Wallace et al. (2004) used Structural Equation Modelling (SEM) to establish relationships between project risks and project performance related to software development projects. de Camprieu et al. (2007) presented a conceptual framework capturing the impact of project characteristics on different categories of risks that in turn influenced the project performance. They investigated the differences between the project managers from China and Canada in perceiving different categories of risks. Carvalho et al. (2015) introduced a conceptual model linking risk management to the project success considering the moderating effect of project complexity and validated the model using SEM.

Using tertiary and bibliometric analysis, Thome et al. (2015) synthesised the concepts of complexity, uncertainty, risk and resilience within the literatures on supply chain management and project management. They introduced a framework that links complexity and uncertainty to risk, establishing the indirect impact of risk management on complexity via resilience. Floricel et al. (2016) investigated the impact of complexity on project performance and confirmed their hypothesis through empirical research that there is an increase in the project performance in the presence of high levels of particular types of complexity if high levels of respective planning is present. Their results establish the link between complexity and project performance indicating the significant impact of strategies on the risks relative to different performance indicators.

Theoretical Models for Evaluating Project Complexity

Owing to the importance of evaluating project complexity, there has been significant progress in developing robust tools and techniques to measure complexity. Earlier models made use of simple matrix-based tools for scoring different characteristics of a project and calculating the average complexity value (Santana, 1990). Vidal et al. (2011a) and Vidal et al. (2011b) introduced a multi-criteria approach for evaluating project complexity through the use of AHP considering project size, project variety, project interdependence, and elements of context corresponding to organisational and technological facets. They validated their framework through a case study conducted in the entertainment industry. Using the similar hierarchy based modelling approach, He et al. (2015) developed a complexity measurement model based on the Shanghai Expo construction project in China using Fuzzy AHP, categorising complexity factors into technological, organisational, goal, environmental, cultural and informational facets. They conducted a two-round Delphi survey and found cultural complexity to be the most significant complexity followed by organisational, technological and informational complexity. They emphasised the need for evaluating complexity at earlier phases of a project and critically reviewing it afterwards.

Using a similar modelling approach, Nguyen et al. (2015) developed a hierarchy of complexity factors and parameters in transportation projects within Vietnam in order to measure project complexity and prioritise projects within a portfolio of projects in order to allocate resources to relatively complex projects. They considered different aspects of complexity including socio-political, environmental, organisational, infrastructural, technological and project scope. Xia & Chan (2012) identified complexity measures for building projects in China through conducting a Delphi questionnaire survey. They considered six measures of complexity: building structure and function; construction method; urgency of project schedule; project size/scale; geological condition; and neighbouring environment.

Qureshi & Kang (2015) developed their work on the conceptual frameworks of Bosch-Rekveldt et al. (2011) and Vidal & Marle (2008), and utilised SEM for understanding the influence of different organisational factors on project complexity rather than evaluating complexity index. They chose project size, project variety, interdependencies within the project, and elements of context as the main variables within the model and validated it in different industries including Construction, Information Technology, Textile, Automobile, and Research and Development through survey questionnaire. They found project variety and interdependence within the project as having a major influence on project complexity whereas project size implicitly affected complexity through influencing the project variety and interdependence.

Empirical Studies

Tatikonda & Rosenthal (2000) conducted a survey of 120 'high tech' NPD projects to study the impact of project characteristics –namely technology novelty (product and process) and project complexity (technology interdependence, objectives novelty and project difficulty) –on project objectives (technical performance, unit cost, time to market and combination of objectives). According to them, project size only captures part of the project complexity. Based on their findings, technology novelty is strongly associated with poor unit cost and time to market results whereas project complexity results in cost overruns. Furthermore, process technology novelty is more problematic than product technology novelty. Similarly, novelty of project objectives to the company has major implications on the project objectives.

Case studies have been conducted to understand different dimensions of project complexity and their implications on project objectives. Edkins et al. (2007) conducted multiple case studies in the construction industry and explored qualitative methods of computer-aided content analysis and causal mappings drawn from the area of managerial and organisational cognition to understand the issues related to the management of projects. Antoniadis et al. (2011) conducted five case studies in the construction industry in order to investigate the socio-organisational aspect of complexity of interactions and effects on project schedule performance and established an inverse relationship between the complexity of interactions and project performance. In order to integrate the static structural concept of complexity with emergent behaviours and link these to project performance, Lessard et al. (2014) introduced the 'House of Project Complexity' encompassing both technical and institutional (structural and process) elements.

Focusing on a single case study of successful projects, Koppenjan et al. (2011) investigated an upgrading project of a rail system in the Netherlands. They distinguished between two different approaches of managing projects: Predict-and-control (type I), where the risks and uncertainties are managed at the front end; and prepare-and-commit (type II), where flexibility is the norm for adapting the system with respect to changes in scope. A type I approach was adopted for achieving hard values like time and cost whereas a type II approach was implemented in case of soft values like safety and scope. The project did not experience major problems because uncertainty and complexity were managed through a type I approach. The study necessitates bridging the gap between two distinct fields of literature through empirical studies and theory development. Similarly, Giezen (2012) investigated how the project complexity was managed in the metro extension project of Rotterdam. The project used existing techniques and the staff were well trained in using similar technology, therefore, the technological complexity was immensely reduced. Focusing on the London Olympics 2012 Construction Program, Davies & Mackenzie (2014) classified it as a system of systems project and examined the organisational structure and process to coordinate the overall project, each individual system and interdependencies between them.

4.2.2 Interdependency Modelling of Risks

Researchers have been using different techniques for capturing interdependency between project/supply chain risks. Well-cited techniques include BBNs (Pai et al., 2003; Lockamy & McCormack, 2009; Luu et al., 2009; Dogan & Aydin, 2011; Lockamy, 2011; Lockamy & McCormack, 2012; Badurdeen et al., 2014; Lockamy, 2014; Garvey et al., 2015; Nepal & Yadav, 2015; Qazi et al., 2015); FMEA (Sinha et al., 2004; Chaudhuri et al., 2012); Network Theory (Squire, 2010; Kim et al., 2011; Fang et al., 2012); Monte Carlo Simulation (Lee et al., 2012); AHP (Gaudenzi & Borghesi, 2006; Wu et al., 2006; Kayis et al., 2007); Analytical Network Process (ANP) (Boateng et al., 2015); Causal Mapping (Ackermann et al. 2006; Edkins et al. 2007; Ackermann et al. 2014); Systems Thinking (Williams, 2005; Oehmen et al., 2009; Ghadge et al., 2013); Petri Net Simulation (Tuncel & Alpan, 2010); Graph Theory (Wagner & Neshat, 2010); ISM (Faisal et al., 2006b; Pfohl et al., 2011); and Fuzzy AHP (Zeng et al., 2007; Nieto-Morote & Ruz-Vila, 2011).

Fidan et al. (2011) introduced an ontology for linking risk and vulnerability to cost overrun in international construction projects. They attributed poor definition of risk and patterns of risk propagation as the major limitation of existing techniques in modelling and evaluating project risks. Following the same ontology, Yildiz et al. (2014) developed a knowledge-based risk mapping tool for cost estimation of international construction projects and Eybpoosh et al. (2011) introduced the concept of identifying risk paths in international construction projects using SEM. They emphasised the need for treating risks as an interconnected web of interacting vulnerabilities, sources, risks and resulting losses. Using the same approach, Liu et al. (2016) explored risk paths in the international construction projects performed by Chinese contractors and evaluated the impact of risks on project objectives. A similar risk taxonomy was introduced by Badurdeen et al. (2014) who applied their modelling approach to Boeing's development project of a product used in guidance systems for military applications.

Fang et al. (2012) proposed an approach of capturing the interaction between project risks using network theory. They conducted a topological analysis of the proposed network of interacting risks and introduced a new idea of identifying key risk factors. Hwang et al. (2016) used the same technique and explored the interdependencies between risks across distinct phases of the university information system development project in Taiwan. Using the similar approach of causal mapping, Ackermann et al. (2014) developed a modelling process to help project managers appreciate the impact of interactions between project risks through explicitly engaging a wide stakeholder base using a group support system and causal mapping process whereas Lin & Zhou (2011) utilised the technique of fishbone diagrams for investigating major supply chain risks faced by a focal company in relation to design changes proposed by the customers. Augmenting causal mapping with quantitative modelling of the relationship strengths through BBNs, Chin et al. (2009) identified critical risk factors involved in NPD projects and proposed a systematic probability generation approach of populating the BBN comprising risk factors. Similarly, BBNs have been used in capturing interdependency between risks within the construction industry (Luu et al., 2009; Lee et al., 2009).

4.2.3 Limitations of Existing Models on Project Complexity and Project Risk Management

AHP, Fuzzy Set Theory (FST) and hybrid methods integrating the two techniques have been extensively used in modelling project complexity due to their prominence in the literature on project risk management (Taroun, 2014). AHP is widely used in the academic community because of its ease of applicability and the intuitive hierarchical structure (Ananda & Herath, 2009). However, its main limitation is the underlying assumption of treating criteria as independent factors. Although this limitation has been overcome with the introduction of ANP, there is still a major concern of eliciting a number of preferences with regard to pairwise comparison of different criteria and alternatives (Ishizaka & Labib, 2009). FST has also been widely used in modelling risk and control systems. The main criticism of FST is its inability to provide the operational definition of the membership of a fuzzy set whereas subjective probabilities have operational definitions (Cooke, 2004). Furthermore, *"an apparently reasonable version of Fuzzy logic collapses mathematically to two-valued logic"* (Elkan et al., 1994).

Although interdependency modelling of project risks has been demonstrated using different techniques like ANP, SEM and network theory, these models fail to account for the propagation of risks and updating of beliefs upon receiving new information. SEM has its limitation in ensuring that necessary causal conditions have been met and therefore, the results might not guarantee causal relationships between the variables and associated strength (Bollen & Pearl, 2013).

Existing models have mainly focused on a specific stage of the risk management process like risk identification and/or risk analysis whereas to the best of our knowledge, an integrated project complexity and risk management process has not been presented. The mentioned techniques fail to assess risks within a probabilistic setting of interacting risks and do not focus on the risk treatment and risk monitoring stages that involve selection of optimal risk mitigation strategies and addition of new risks to the network, respectively. Although some studies like Zhang & Fan (2014) and Fan et al. (2015) have focused on evaluating risk response strategies, these have the drawback that risks and strategies are treated as independent factors.

To fill this gap, an integrated process namely ProCRiM is proposed that is grounded in the theoretical framework of EUT and BBNs. As BBNs manifest both the causal map of interdependent variables and strength of relationship between interconnected variables, these can overcome the limitations of other causal mapping tools by providing the visualisation of propagation patterns. Furthermore, as there are a number of uncertainties at the commencement stage of a project, BBNs present a unique tool to model these uncertainties and cope with incomplete information (Badurdeen et al., 2014).

EUT is a well-established tool in decision making under uncertainty (Ruan et al., 2015), however, its application to the literature on project risk management and practice is quite limited (Kutsch & Hall, 2005). Lu & Yan (2013) investigated two main types of measurement of perceived risk in the construction projects; direct measurement and expected-utility based measurement. Their results indicate that managers use the direct measurement method and the ranking of independent risks is quite different for the two methods. However, in real scenarios, risks are not independent but interact within a network setting. Advocating the need for modelling the risk attitude of a decision maker, Wang & Yuan (2011) investigated the critical factors affecting contractors' risk attitudes in construction projects in China and grouped these into four categories: knowledge and experience, contractor's character, personal perception, and economic environment.

4.3 ProCRiM and Modelling Approach

Understanding the complexity of a project before the commencement stage is of significant importance (Bosch-Rekveldt et al., 2011; Thamhain, 2013). However, in order to identify critical risks and select optimal risk mitigation strategies, the complexity attributes need to be linked to complexity induced risks. We adapt the established risk management framework (SA, 2009) as it is used widely both by researchers and practitioners (Ahmed et al., 2007). Although the description of terms and concepts used in the framework is controversial (Aven, 2011), our focus is limited to the stages involved in the process.

4.3.1 Project Complexity and Risk Management (ProCRiM)

The proposed process is shown in Figure 4.1 manifesting its exclusive focus on the 'systemicity' of complexity drivers and risks. Instead of treating complexity and risk in isolation, the concept of complexity and risk network is introduced. The process starts with the specification of project context in terms of defining the scope of the risk management process and identifying stakeholders involved

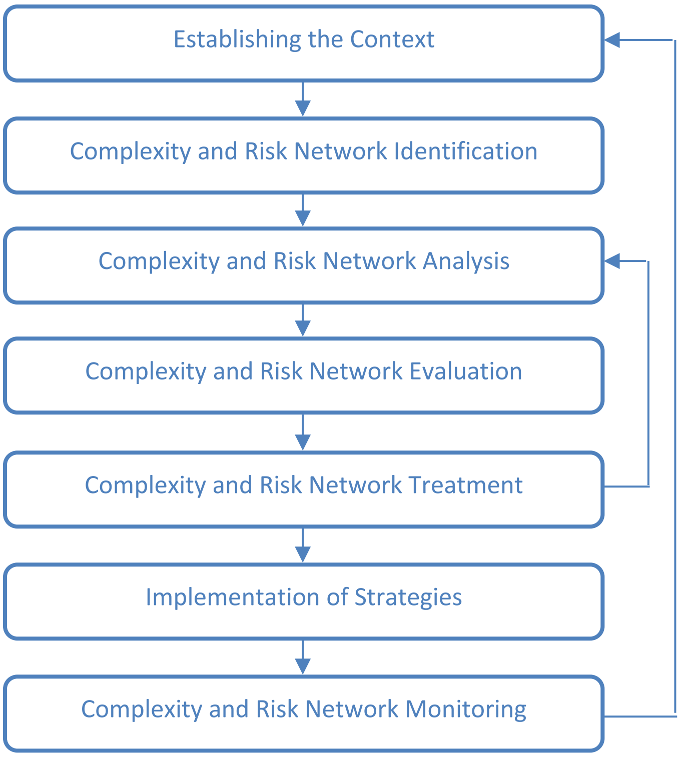

Figure 4.1: Project complexity and risk management.

in the process.

Complexity and risk network identification is a critical stage where there is a need for bringing a paradigm shift as the existing literature is rife with conventional tools and techniques of identifying risk and complexity categories without focusing on the network of interacting factors. Complexity and risk network analysis involves determining the strength of interactions between complexity drivers and risks. Instead of calculating the probability and impact values for individual risks, this stage is meant to capture the importance of each risk and complexity driver within the network setting. In the risk evaluation stage, the decision maker assigns a utility function to the project objectives and critical risks are identified through propagating evidence across the network. This stage must be able to provide a visual aid to the decision maker in appreciating the propagation impact of risk(s). Depending on the importance of specific project objectives, the decision maker should be able to identify critical risks.

Complexity and risk network treatment deals with the evaluation of different combinations of complexity and risk management strategies within the network setting. Sometimes, certain project complexity drivers can be adapted to manage the complexity and complexity driven risks. The proposed process flow is in contrast with the one established in the extant literature as instead of following unidirectional flow, it is an iterative process where evaluation of each combination of strategies necessitates re-assessing and re-evaluating the complexity and risk network. The iterative process results in the selection of an optimal combination of strategies that not only considers the network wide holistic effect of these strategies but also yields an acceptable configuration of risks represented by the maximum expected utility value corresponding to the specific budget constraint. After determining the optimal combination of strategies, these are implemented and as complexity and risk management is a continuous process, there is a need for continuously monitoring the network and updating it on regular basis.

This process presents a unique feature of complementing two different schools of thought on the concept of complexity and risk; one considering risk as an element of complexity (Williams, 1999; Geraldi et al., 2011; Bosch-Rekveldt et al., 2011) and the other distinguishing the two (Baccarini, 1996; Little, 2005; Vidal & Marle, 2008). Majority of the existing complexity evaluation models follow the latter philosophical stance (Vidal et al., 2011b; He et al., 2015) thereby failing to account for the risks that are considered important in the former epistemological framework. However, considering risk as an integral part of the complexity does not suffice as categorisation of complexity attributes and risks fails to account for the complex interaction between complexity drivers and resulting risks.

4.3.2 Inputs and Outputs of the ProCRiM based Models

The main difference of the proposed process with the established process (SA, 2009) is its focus on the network of interacting project complexity drivers and project risks as shown in Figure 4.2. As an input to any model governed by the proposed process, the decision maker needs to identify not only the complexity drivers, risks and project objective but also to establish interdependencies between these factors and the associated strength of relationships.

Considering the generic nature of project complexity elements introduced by Bosch-Rekveldt et al. (2011), we propose using these elements for establishing the complexity level of a project. However, instead of segregating these elements into distinct groups and categorising risks, we propose investigating the synergistic effect of multiple complexity elements and risks. These complexity elements are represented by rectangular nodes. We do not aim to evaluate the complexity by itself as it fails to identify the critical risks. Instead, we link the complexity elements (except the ones categorised as risks) proposed by Bosch-Rekveldt et al. (2011) to different associated risks which in turn affect the project objectives like the delivery time, cost, quality and so on. Both the risks and project objectives are represented by oval shaped nodes. Finally, the overall utility (diamond shaped node) is defined by the decision maker according to the relative importance of each project objective. All the chance nodes (risks and objectives) and complexity elements are assumed as binary variables.

As an input, the decision maker also needs to identify potential risk mitigation strategies, corresponding cost and impact across different risks. A strategy or combination of strategies can have a positive correlation with a risk or multiple risks. The output of models following ProCRiM helps in identifying critical risks and optimal risk mitigation strategies. Furthermore, emerging risks can easily be added to the established network of interacting factors. The inputs and outputs of the ProCRiM are shown in Figure 4.3.

The developed network can help the decision maker understand complex dynamics across the project complexity and complexity induced risks, and identify critical risks for implementing mitigation strategies. The BBNs are utilised as

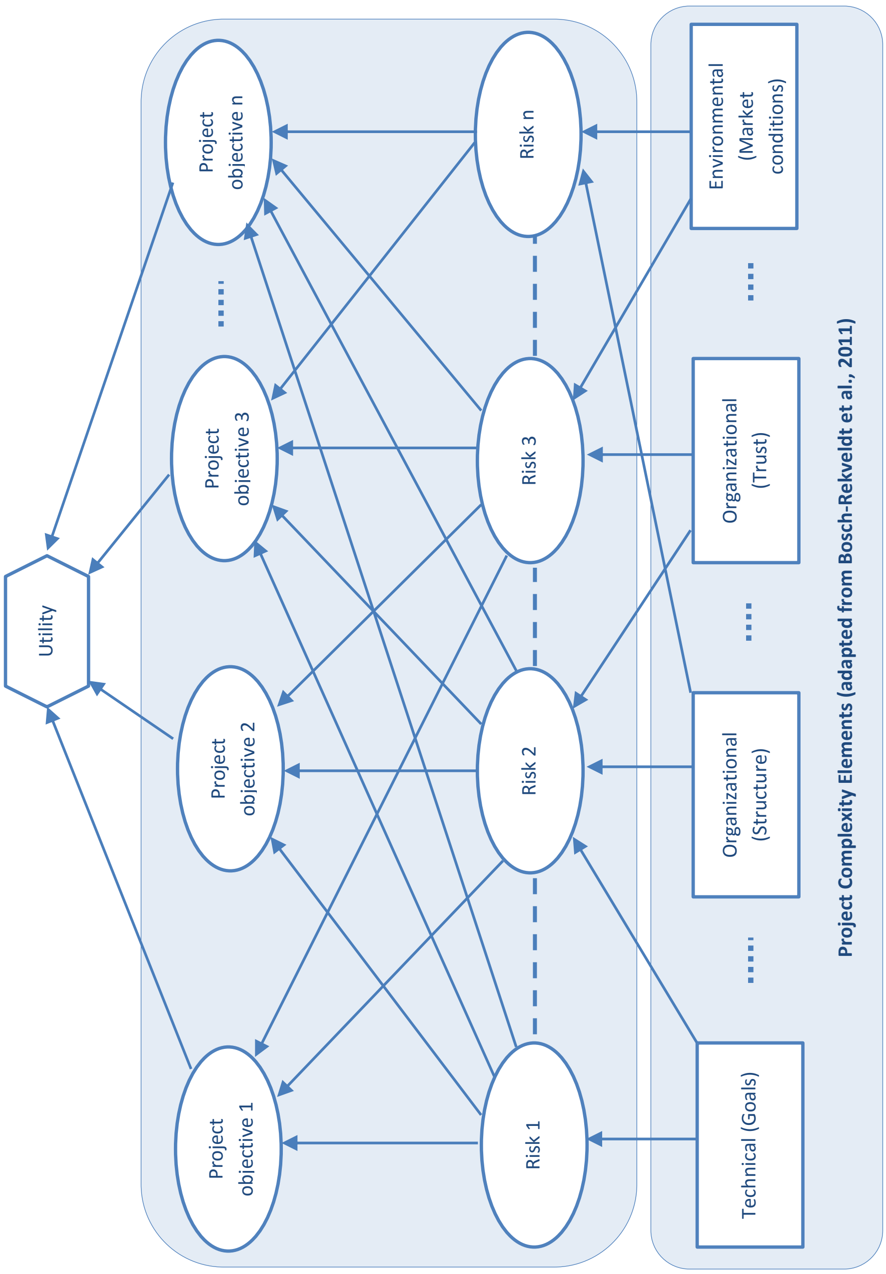

Figure 4.2: Project complexity driven network of risk paths as an input to the ProCRiM.

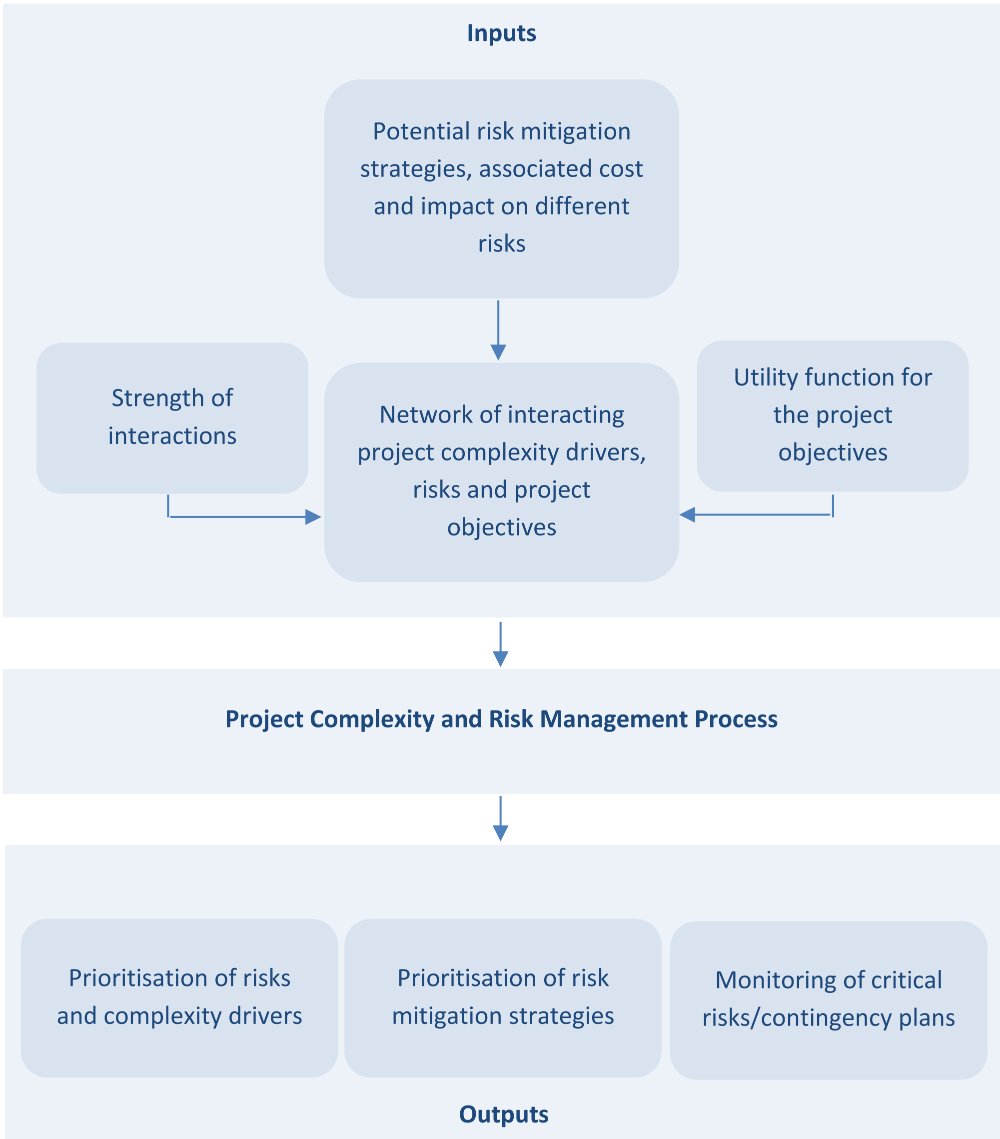

Figure 4.3: Inputs and outputs of the models according to ProCRiM.

the modelling technique in the proposed approach. The network fits well with the conflicting theories on the conceptualisation of complexity and risk: for the proponents of 'risk as an element of complexity', the entire framework presents a way of evaluating complexity; whereas for researchers advocating the need for differentiating risk from complexity, it seems viable to treat these two concepts as distinct within the network. However, adopting either perspective yields the same results as the aim is to capture the interdependency rather than taking the extreme position.

4.3.3 Modelling Approach

The process for the development of our proposed framework is shown in Figure 4.4. The first stage of Problem Structuring involves identification of project complexity attributes (known at the project commencement stage) and objectives, risks, and development of the network structure followed by representing these as statistical variables. In the second stage of Instantiation, conditional probability values and utility values are specified for respective nodes. Conditional probability values represent the strength of interdependency between risks and corresponding influence on the objectives whereas utility values capture the preference of a decision maker with respect to different possible outcomes of the objectives identified. In the final stage of Inference, evidence in the form of project characteristics and risks is fed into the model and propagated in order to conduct sensitivity analysis. Finally, key risk factors are identified on the basis of detailed analysis and optimal mitigation strategies are planned at the commencement stage of the project.

The opinion of experts (profiles shown in Figure 3.2) was sought on the potential efficacy of adopting ProCRiM to manage project complexity and project risks. Empirical research undertaken explored the current state of risk management practices within the construction industry, investigated the proposed mod-

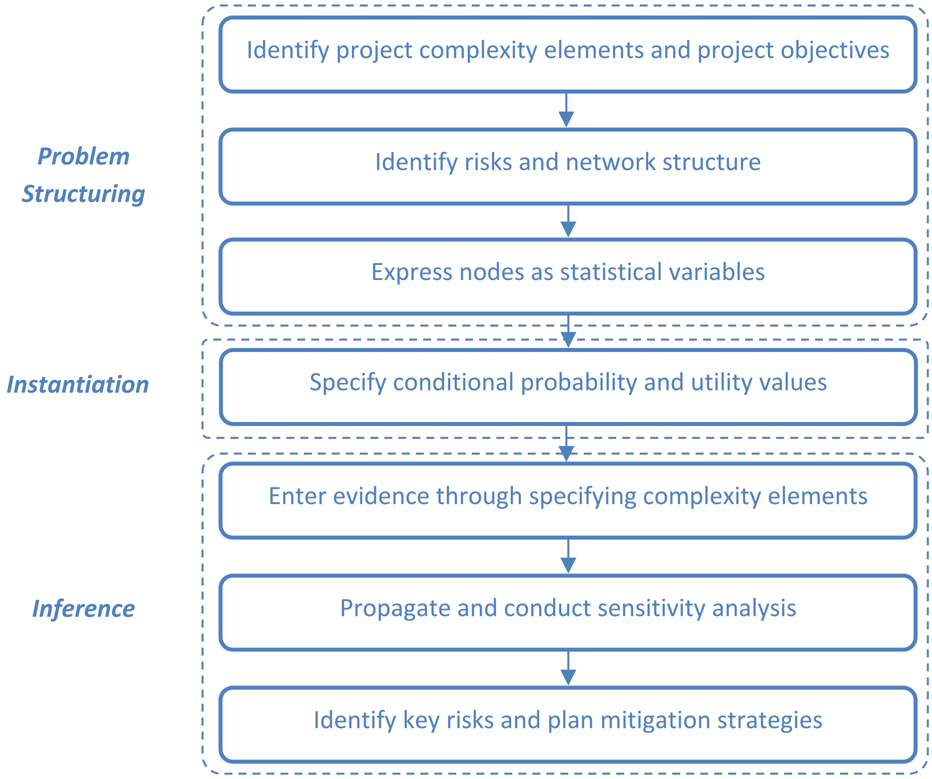

Figure 4.4: Flowchart for implementing the ProCRiM using EUT and BBNs (adapted from Sigurdsson et al. 2001).

elling approach and attempted to identify the interdependencies between relevant project complexity elements (Bosch-Rekveldt et al., 2011) and risks (Zou et al., 2007) within construction projects.

4.4 Findings of Empirical Research

In general, all the respondents agreed that risks are treated as independent factors within the construction industry and risk registers are used for identifying important risks where probability and impact values are associated with individual risks. Systemic interaction of risks is never considered either at the commencement stage of a project or within the life-cycle of a project. According to Respondent 10: *"No, we do not see the link of interdependency between risks in the risk management process. ... When you come to the industry, it is still challenging to implement the basic steps even in case of risk registers. The value* *of conducting comprehensive risk management process is not tangible and it is really difficult to gain the support from senior management"*.

As the risk identification is based on the unrealistic assumption of risks being independent, there is no possibility of assessing the systemicity of risks and therefore, risk mitigation strategies are not evaluated within an interdependent setting of risks and strategies. According to Respondent 9: *"No, the current risk management techniques don't capture the interdependency between risks. In most cases, risk management is very casually done and solutions are proposed and implemented on ad hoc basis. In the prevailing situation where risks are analysed in isolation and their response strategies are proposed independently, the interdependency between them is mostly disregarded"*.

It was confirmed by a number of respondents that project managers rely on their intuition and past experience in managing risks. Furthermore, the level and sophistication of risk management process varies with project complexity itself. However, even the highly complex projects executed in developed countries are not managed through the lens of interdependency modelling techniques. According to Respondent 5: *"Project managers take decisions on the basis of their gut feeling and experience. It is all firefighting. However, there is a marked difference between the techniques adopted in developed countries with those implemented in developing countries. But still, even in the case of projects undertaken in developed countries, interdependency modelling is not considered at all"*.

Most of the respondents confirmed that project complexity is evaluated at the commencement stage of projects. However, it was revealed that the project complexity is merely confined to technical aspects whereas organisational and environmental constructs of complexity are ignored. According to Respondent 4: *"The business as usual in project management narrows down the description, implication and effect of complexity into mere structural complication. The other aspects of complexity such as pace of construction, uniqueness of design/construction* *technique or material, uncertainty of decision making, socio-political scenario of host country/location of project, etc. are very conveniently overlooked".*

The current techniques/tools are not capable of providing a visual representation of interacting risks and propagation patterns across the network of interdependent risks. The proposed process can help project managers understand the complex dynamics and identify critical risks taking into account the systemic interaction of risks. According to Respondent 3: *"The current tools, however smart, have yet to develop further in order to provide holistic and clear visual (or other) representation of dynamics across different project and supply chain risks. The dynamic nature of projects and risk propagation trends during various life-cycle phases renders it challenging to manifest propagation of a materialised risk across the web of interdependency".*

The ProCRiM and proposed modelling approach were considered as an important tool for understanding the dynamic behaviour of risk. However, the main limitation of the proposed approach is the requirement of substantial data that might not be readily available and would be difficult to elicit. Regarding the efficacy of our proposed approach, Respondent 2 responded: *"If this model is able to identify critical risks specific to the industry, it will give great insight to the project manager in terms of identifying the source of critical risks and considering control actions. We do focus on past projects in terms of identifying key risks but those risks are considered in isolation".*

The major reasons for lack of interest in using interdependency modelling are limited knowledge/expertise of managers in using sophisticated tools, limited support from senior management and the difficulty in populating these models in the case of limited data. According to Respondent 7: *"... It's partly because of higher data demand for such techniques and lack of awareness/training on the part of practitioners. These gaps can be bridged but lack of serious efforts in this direction stands out to be a major issue".*

We had also included project complexity elements except risks (Bosch-Rekveldt et al., 2011) and construction project risks (Zou et al., 2007) within the research tool that were presented to the respondents in the form of a matrix. Based on their responses, key complexity elements and project risks (selected by at least 7 respondents), and interdependencies (represented by shaded cells) were identified as shown in Table 4.1 and Table 4.2, respectively. Although the responses varied in relation to past experiences and general understanding of respondents, some common themes could be found emerging from the matrices. The main purpose of this exercise was not to identify a comprehensive list of key complexity elements and risks but to explore if the experts considered such interdependency to be important. It was revealed that there were certain complexity elements influencing a number of risks and similarly, key risks could be identified that were being influenced by a number of complexity elements. As the respondents were located in South Australia, they did not consider market condition and country related complexity elements to be relevant. Similarly, project size and cost were only considered important by two respondents as projects having higher cost and bigger size might not necessarily be classified as complex projects.

4.5 Application of ProCRiM and Modelling Approach

4.5.1 Application Setting

In this section, the application of ProCRiM and the proposed modelling approach is demonstrated through an illustrative simulation study as shown in Figure 4.5. The model representing critical risks specific to a construction project is adapted from an existing model proposed by Eybpoosh et al. (2011) who used SEM for evaluating cost overruns. However, their model considered a single node for the

ID	Project Complexity Element	Category
1	Lack of clarity and misalignment of goals	Technical (T)
2	Ambiguity in scope	T
3	Strict quality requirements	T
4	Ambiguity in technical methods	T
5	Conflicting norms and standards	T
6	Use of innovative technology	T
7	Lack of experience with technology	T
8	Lack of experience with parties involved	Organisational (O)
9	Multiple contracts	O
10	Number of stakeholders and variety of perspectives	Environmental (E)
11	Unstable political situation or political influence	E
12	High Level of competition	E
ID	**Project Risk**	
1	Poor labour productivity	O
2	Poor labour availability/shortage of skilled labour	O
3	Defective design/quality problems	T
4	Engineering changes/design variations	T
5	Unwillingness to share information/lack of visibility	E
6	Delays in design and regulatory approvals	T
7	Delays in obtaining required raw materials quantity	O
8	Escalation in raw material price	E
9	Misalignment of interests/conflicts with stakeholders	E
10	Increase in energy prices	E
11	Contract disputes	E
12	Increase in labour cost	E
13	Supplier/subcontractors' default	O
14	Occurrence of dispute	E
15	Equipment shortage	O
16	Non-availability of experienced design personnel	O
17	Unavailability of sufficient managers and professionals	O
18	Low management competency of subcontractors/suppliers	O
19	Changes in project specifications	T
20	Delays/interruptions	T/O/E

Table 4.1: Selected project complexity elements and risks.

Project Complexity Element ID	Project Risk ID 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1				■	■		■		■		■			■					■	■
2				■			■		■		■			■					■	■
3			■	■		■							■							■
4			■	■		■													■	■
5			■	■		■			■		■			■					■	■
6	■	■	■	■		■	■					■	■		■	■	■		■	■
7	■		■	■		■													■	■
8					■				■		■		■	■				■		
9									■		■			■						
10					■	■			■		■			■					■	■
11					■			■		■		■		■						■
12		■			■		■					■			■		■			

Table 4.2: Interdependency between project complexity elements and risks (shaded cells identify interdependency between the row and column).

project complexity and linked it to a single risk category and captured a single project objective (cost). The major concern associated with this model is its generalisation to different types of construction projects. Even if it is assumed that the model will be able to prioritise risks systematically, it is not foreseen to deal with the risk treatment and risk monitoring stages. The model used here (as shown in Figure 4.5) includes a limited number of project complexity attributes and risks identified by the empirical research conducted (see Table 4.1) to help readers focus on the mechanics of approach. The main purpose of presenting this simulation study is not to generalise a model representing a comprehensive list of variables and their interdependencies applicable to any construction project as, even within the same industry, each project and relevant circumstances would drive the structure of the network and the strength of interconnected variables in a different manner. Rather, the purpose is to demonstrate how practitioners can implement ProCRiM within the context of their projects and adopt the proposed modelling approach to prioritise risks and risk mitigation strategies.

For this application, we consider eight project complexity elements as shown

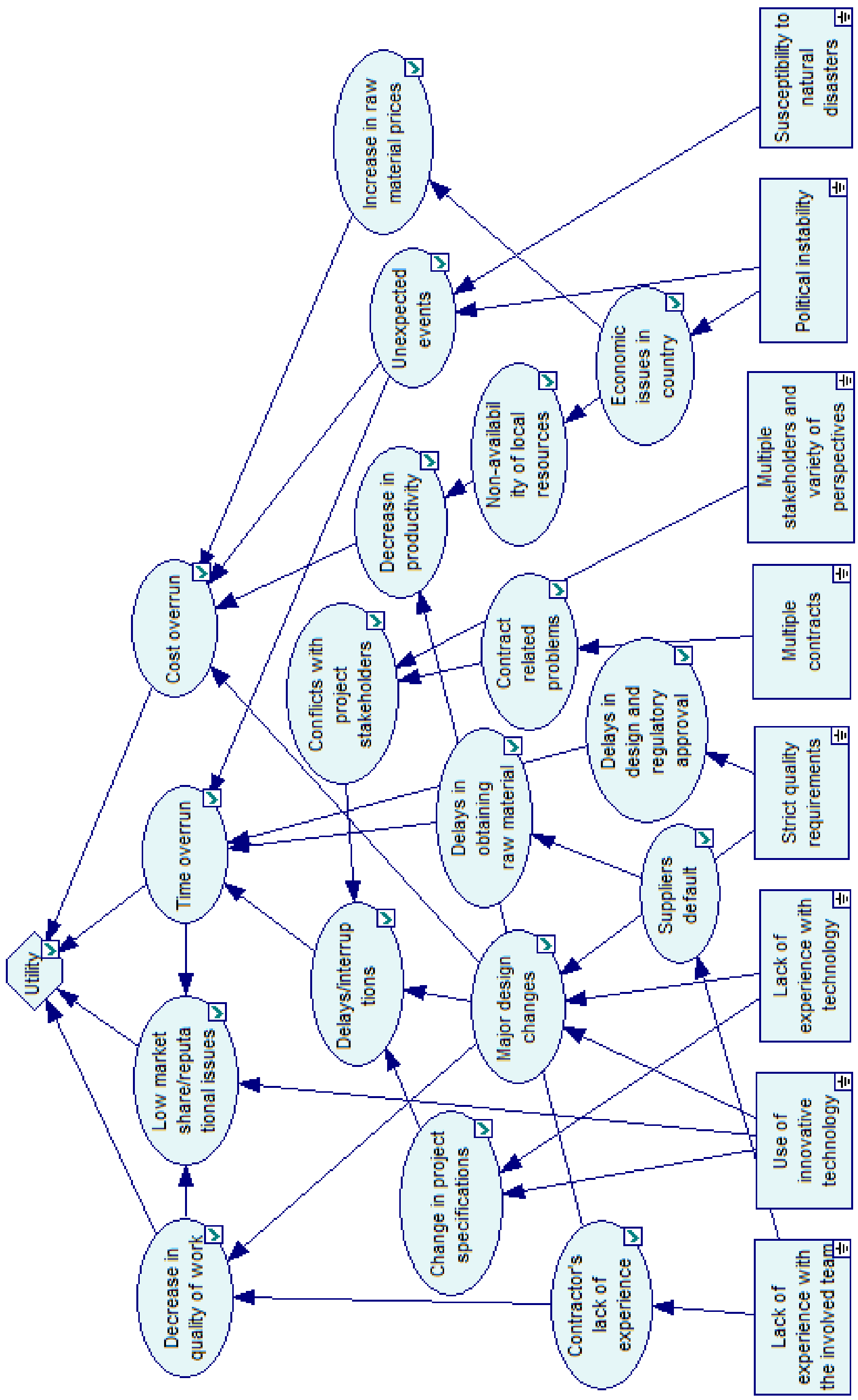

Figure 4.5: Simulation model developed in GeNIe.

Complexity Attribute	Complexity ID	State
Lack of experience with the involved team	C1	No
Use of innovative technology	C2	Yes
Lack of experience with technology	C3	Yes
Strict quality requirements	C4	Yes
Multiple contracts	C5	Yes
Multiple stakeholders and variety of perspectives	C6	Yes
Political instability	C7	No
Susceptibility to natural disasters	C8	No

Table 4.3: Project complexity attributes for the model (adapted from Bosch-Rekveldt et al. 2011).

in Table 4.3 and four project objectives, namely: timeliness; cost; quality; and market share. These objectives have been presented as negative counterparts in order to align these to the notion of risks. All risk factors and complexity elements have binary states of 'True (T)' or 'False (F)' and 'Yes (Y)' or 'No (N)', respectively. For illustrative purposes, it is assumed that all objectives are equally important in the decision-maker's utility function. Expected utility is a probability-weighted average of the utility in the different states the network may be in. By engaging in risk mitigation, the probability of these states occurring changes, as does the value of different outcome combinations of the objectives. More generally, a utility function could capture different weights being assigned to different objectives, objectives may be evaluated in a non-linear way, and complementarities between objectives could be captured. Assumed conditional probability values for the model are shown in Appendix A. These conditional probability values should represent the belief of experts and their past experience will help them to determine these values. The values reflect the efficacy of current risk mitigation strategies in dealing with the occurrence of different combinations of risks. If the already implemented strategies are very effective, the strength of interdependency between risks will be weak whereas ineffective strategies will yield higher values of these conditional probabilities.

ID	Risk	P(Ri=True)
R1	Contractor's lack of experience	0.05
R2	Suppliers' default	0.2
R3	Delays in design and regulatory approvals	0.9
R4	Contract related problems	0.8
R5	Economic issues in country	0.1
R6	Major design changes	0.99
R7	Delays in obtaining raw material	0.36
R8	Non-availability of local resources	0.25
R9	Unexpected events	0.02
R10	Increase in raw material price	0.27
R11	Changes in project specifications	0.95
R12	Conflicts with project stakeholders	0.85
R13	Decrease in productivity	0.17
R14	Delays/interruptions	0.98
O1	Decrease in quality of work	0.33
O2	Low market share/reputational issues	0.41
O3	Time overruns	0.91
O4	Cost overruns	0.69

Table 4.4: Marginal probability values of risks and objectives.

4.5.2 Application Results and Analysis

Once the model was updated, the marginal probability values were evaluated as shown in Table 4.4. R3, R4, R6, R11 and R12 appear to have high likelihood of occurrence; however, the probability values alone do not help in identifying the critical risks. It is also important to consider the strength of causal relationships between the risks and the relative influence of each risk factor on the objectives. Keeping the overall utility node as the target node, we instantiated each risk factor to the two extreme states and registered the corresponding utility values. In order to identify key risk factors for further improvement, we calculated the percentage improvement in utility given complete mitigation of each risk factor in turn. Furthermore, we also calculated the percentage variation in the utility across two extreme states of each risk factor that represents its relative significance for monitoring. These two risk measures considered together capture the relative probability of a risk which is important for selecting optimal risk mitigation strategies.

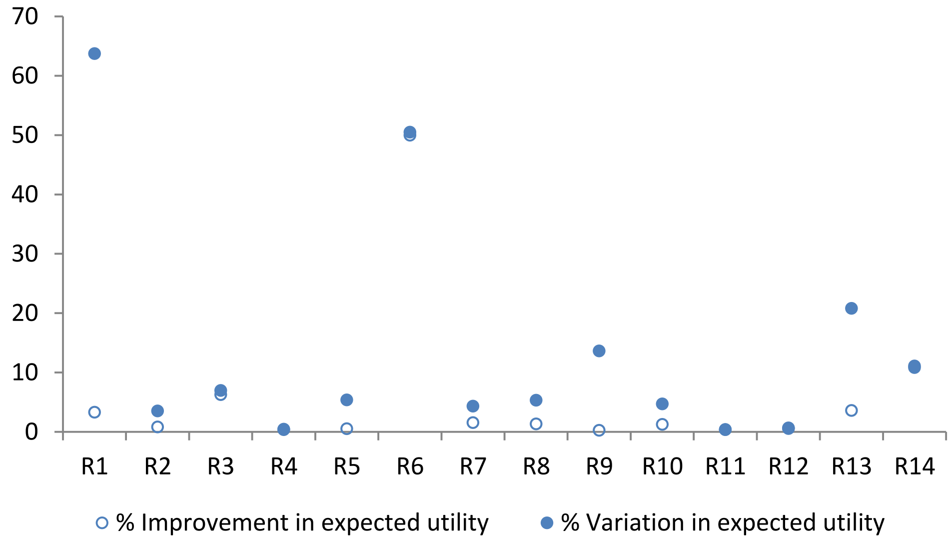

Figure 4.6: Risk measures representing the impact of an individual risk on the expected utility value.

The two risk measures for each risk are shown in Figure 4.6. R6 appears to be the most important risk having major influence on the utility function once it is mitigated. Though its probability is comparable to R3, R11 and R14, it is substantially important because of the strong dependency with the utility node. R1 is the most critical risk in terms of its major impact on the utility function if it is realised, however, its probability is quite low. The second risk measure helps in identifying critical risks for monitoring whereas the first risk measure prioritises risks for improving the overall expected utility value. The relative importance of project objectives will also influence the ranking of risks because of the change in relative importance of dependency relationships.

It is not only important to improve the state of critical risks but also to monitor their state. It is pertinent to consider the fact that some risks might not be detected easily and therefore, there is a need to investigate the root cause of such risks. If the risks appearing as significant factors are not observable or directly controllable then the underlying causes or risks must be dealt with. When the causality of key risks is mainly determined by their parent nodes and the key risks share common underlying causes, it will be beneficial to plan mitigation

Strategy	Connected Risk	Cost
S1	R1	200
S2	R2	50
S3	R3	150
S4	R4	100
S5	R7	150
S6	R8	100
S7	R10	50
S8	R11	300

Table 4.5: Cost of potential strategies and connected risks.

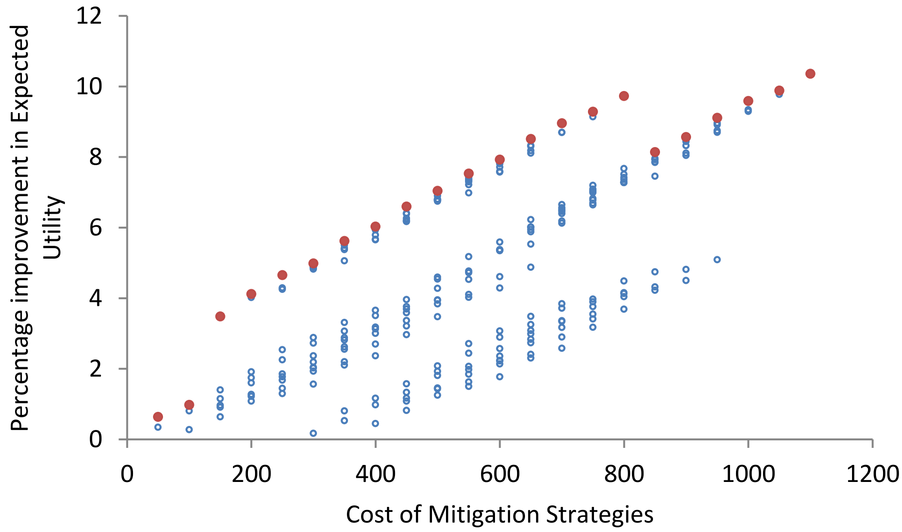

Figure 4.7: Impact of different combinations of risk mitigation strategies on the overall utility.

strategies in eliminating those common causes.

Although prioritisation of risks is an important step of the risk management process, appropriate risk mitigation strategies can only be selected after considering holistic interactions of risks and strategies (Qazi et al., 2015). We assume that the decision maker is considering implementation of cost-effective risk mitigation strategies out of the strategies identified in Table 4.5. Each strategy is represented by two states of 'Yes' or 'No' and the probabilistic impact of strategies on interconnected risks is shown in Appendix A. For the specific modelled project, we were able to evaluate the impact of different combinations of strategies on the overall utility as shown in Figure 4.7.

The model helped in identifying optimal combinations of strategies yielding the maximum percentage improvement in the overall utility for various overall mitigation costs represented by red coloured points. All blue coloured points represent combinations of strategies that are dominated or sub-optimal. It is interesting to observe that an increase in the cost of mitigation from 800 to 1000 actually gives rise to a reduction in expected utility. This approach helps in differentiating optimal strategies (red coloured points) from those that are sub-optimal (blue coloured points) for each given level of mitigation cost. It also helps the decision maker determine if investing in implementing strategies has a net benefit after considering the improvement in expected utility relative to the cost of mitigation.

The model can also be used for prioritising projects within a portfolio. Once the project characteristics of different projects are fed into the model, the relative state of risks associated with different projects can be calculated that helps in prioritising projects in terms of allocating resources. Marginal probability values of risks associated with two extreme levels of project complexity are shown in Figure 4.8. It can be observed that the risks and resulting consequences are highly sensitive to the project characteristics.

The proposed model can also be used to identify critical risks and the expected utility value corresponding to each project within a portfolio. As a total of 8 binary complexity elements were considered, there is a possibility of modelling 256 distinct projects characterised by different combinations of the complexity element states. The network wide impact of these complexity elements resulting in unique expected utility values corroborates our stance of managing project complexity and risk together. The variation of overall expected utility with the variation in project characteristics is shown in Figure 4.9. The expected utility value does not represent the significance of the relevant project within the portfolio, rather it represents the overall state of risks resulting from the complexity

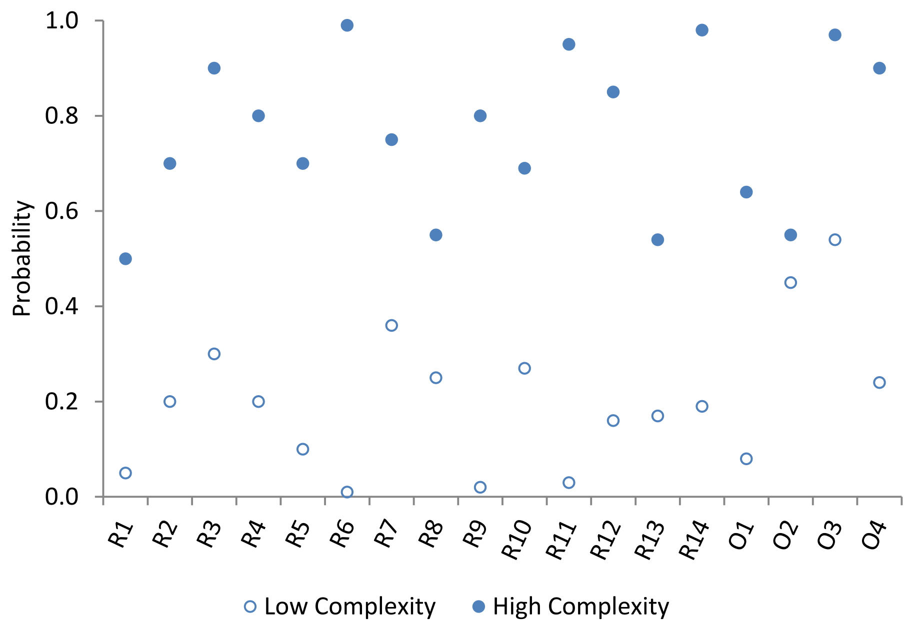

Figure 4.8: Sensitivity of risks and project objectives to project complexity attributes.

attributes of the project. The first point represents a highly complex project yielding a lower expected utility value, however, it is interesting to note that it is not the lowest value as the innovative aspect of technology is preferred although it amplifies the overall risk. Similarly, the last point indicates a project having the lowest possible complexity level yielding the maximum value of expected utility representing lower values of associated risks.

We also evaluated the impact of project characteristics on project objectives as shown in Figure 4.10. The projects having higher complexity level are more likely to result in cost overruns, however, the relationship is not linear as multiple project complexity elements and risks interact in a non-linear and systemic manner. The variation of low market share is also shown in Figure 4.10. Use of innovative technology was modelled as an enabler of increasing the market share but at the same time, market share would be affected by the attributes of time overrun and quality issues. Therefore, it can be observed that there is a marked variation in the probability of low market share with respect to the change in project characteristics.

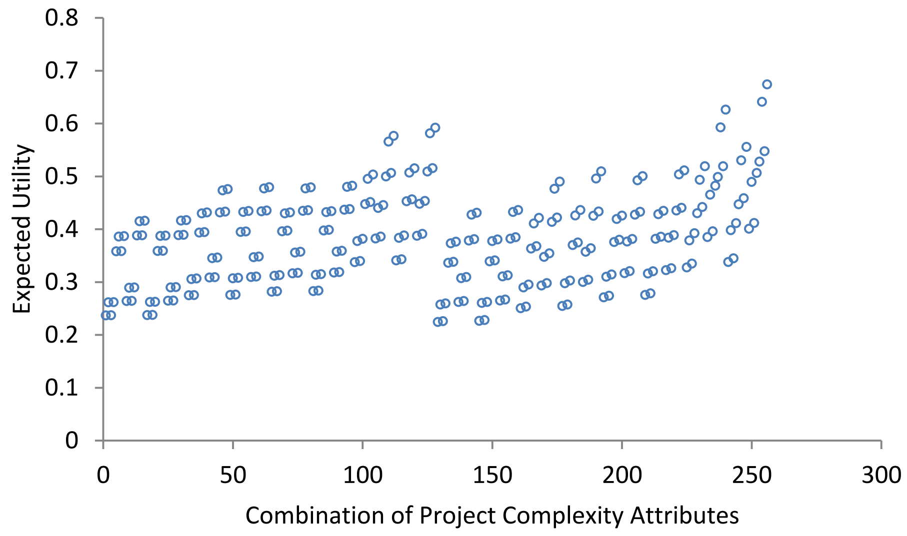

Figure 4.9: Impact of project complexity on the overall utility.

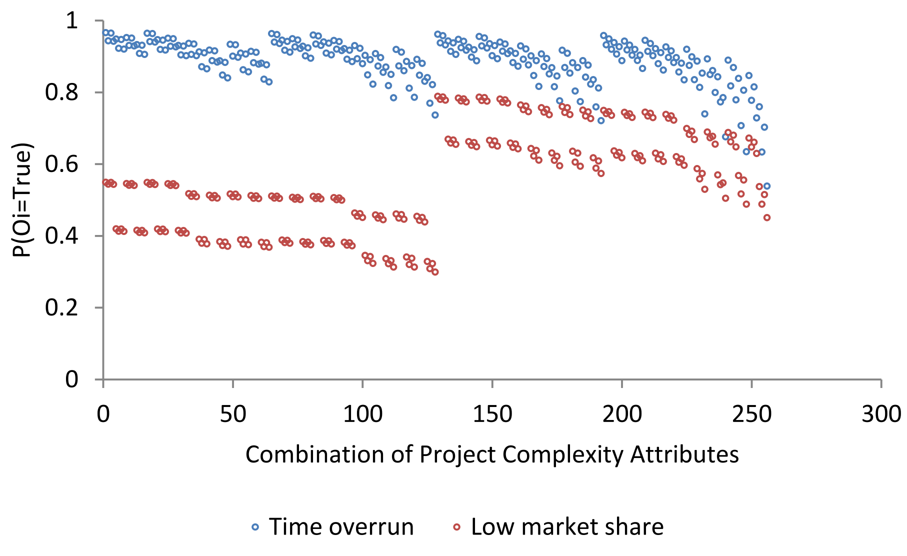

Figure 4.10: Impact of project complexity on the project objectives.

Higher complexity level is not necessarily associated with higher probability value of low market share and similarly, the probability value is mainly influenced by the use of innovative technology. Researchers have also introduced the notion of evaluating not only risks but also opportunities within the risk management process (Hillson, 2002; Ward & Chapman, 2003). In this context, the proposed process takes into consideration the positive impact of high complexity (like newness of technology) on the project objectives (like market share) but at the same time, these innovative ventures necessitate implementing appropriate strategies to mitigate the resulting chains of risks.

4.6 Discussion

4.6.1 Treatment of Interdependency between Project Complexity and Complexity Induced Risks in the Literature

The existing frameworks within the literature on project complexity have focused on representing different dimensions of project complexity (Bosch-Rekveldt et al., 2011; Geraldi et al., 2011; Thome et al., 2015). Although few studies focus on the nexus of project complexity, risk and performance (Thome et al., 2015; Carvalho et al., 2015; Floricel et al., 2016), no attempt has been made to integrate all stages of the risk management process. Generally, the scope of these studies is limited to the risk identification and/or risk analysis stage. Keeping in mind the comprehensive coverage of complexity attributes, the framework developed by Bosch-Rekveldt et al. (2011) is adaptable to any type of project and furthermore, their proposed complexity elements can be modelled as binary variables. However, instead of classifying the complexity elements and risks into technical, organisational and environmental categories and focusing on their independent evaluation, there is a need to capture systemic interaction across distinct categories.

It is important to measure project complexity (Lu et al., 2015) but this is not sufficient to understand the impact of complexity on different risks and project objectives. As the project characteristics may not be changed in most of the projects, it is vital to assess the impact of project complexity attributes on different risks in order to identify critical risks and plan mitigation strategies. There is not a general consensus on whether risk is an element of complexity (Bosch-Rekveldt et al., 2011; Geraldi et al., 2011) or the two concepts are distinct (Vidal & Marle, 2008; Saunders et al., 2016). It is argued that there is a problem with existing studies adopting any extreme stance. Project complexity evaluation models treat complexity and risk as distinct concepts (He et al., 2015; Qureshi & Kang, 2015) and although interdependency between complexity elements is captured in some studies like He et al. (2015), the influence of complexity on risk is not addressed. In other studies, researchers consider risk as an element of complexity and categorise complexity drivers and risks independently (Bosch-Rekveldt et al., 2011) whereas such an approach does not account for the 'interdependency' notion of the complexity-risk nexus. Even if robust risk management techniques are adopted (Boateng et al., 2015), evaluating complexity and risk in isolation is sub-optimal in relation to modelling interdependency between complexity and risk.

On the basis of the reviewed literature, it is deduced that the interdependency between complexity and risk has not been adequately captured in existing models. There is a need for bringing a paradigm shift towards appreciating the importance of exploring interdependency within the same categories of complexity elements and risks and across distinct categories as well. The philosophical debate on the concept of complexity and risk still goes on and the proposed approach brings a new paradigm that is to assess complexity and risk through the lens of interdependency modelling. ProCRiM attempts to contribute towards this new approach.

4.6.2 Efficacy of the Proposed Risk Management Process

As the standard risk management process (SA, 2009) is well-established in construction project management (Wang, 2015), the interdependency between complexity and risk –lacking in this approach–is not considered by practitioners. In order to address this issue ProCRiM is proposed. The main focus of the proposed process is on the management of complexity and risk network. The decision maker needs to identify a network of interacting project complexity drivers and risks. As an input, the importance of project objectives must also be elicited from the decision maker. The network presents a holistic picture of interacting project complexity attributes, risks and project objectives. Managers can visualise interaction between different risks, appreciate propagation patterns through risk paths and locate key risks endangering the success of a project. Furthermore, in case of high risks involved in a project because of project complexity, the project owner might either bring changes in project attributes at the commencement stage or plan effective control strategies taking into account the interdependency between various factors.

The process also captures the decision maker's personal preference of each project objective in the form of a utility function. EUT has been widely used in the literature on risk management (Aven, 2015), however, very few studies have used the technique in the literature on project risk management. Therefore, there is a need to develop robust tools and models grounded in the framework of EUT to help practitioners prioritise risks and mitigation strategies.

In contrast with the frequently used methods including AHP, ANP, FST and SEM to model project risks, the proposed technique of BBNs is efficient in integrating all stages of the risk management process and identifying not only critical risks but also optimal risk mitigation strategies. Modelling techniques other than BBNs are not robust enough to deal with the risk treatment and monitoring stages where optimal mitigation strategies are selected and new risks are identified, respectively.

The proposed process can bring a positive change in managing complex projects. Although the scope is limited to the commencement stage of a project, the process can be used throughout the project life-cycle. At the commencement stage, if the project manager is able to select adaptable strategies, these can be tailored in the subsequent stages of a project. Such a continuous implementation of ProCRiM will help monitoring the state of risks and efficacy of risk mitigation strategies over the project life-cycle. Other methods and techniques can be explored that fit well with the framework of ProCRiM.

4.6.3 Practice of Managing Interdependency between Complexity and Risk

Existing empirical studies have focused on understanding the practices of managing complexity in large projects (Koppenjan et al., 2011; Davies & Mackenzie, 2014; Saunders et al., 2015; Liu, 2015), however, the current practices with regard to understanding and managing systemic and complex interaction of risks within the context of project complexity have not been investigated. Moreover, it is also important to explore whether practitioners consider the notion of interdependency between complexity and complexity driven risks in complex projects.

The empirical finding of risks being treated as independent factors is in accordance with the main finding of Taroun (2014) who conducted an extensive review of the literature on Construction Risk Management. The ranking of risks on a probability-impact matrix is being commonly used within construction projects because of the ease in developing and analysing such models (Shi et al., 2015); the main problem associated with using sophisticated models is the limited awareness and experience in handling such models. However, we believe that even if a comprehensive quantitative modelling approach may not be exclusively adopted within the risk management process, use of causal mapping (the qualitative part of BBNs) can provide an insight into identifying key interdependencies between risks and such practice can help managers identify risk paths instead of focusing on independent categories of risks.

The empirical research presented here is original in terms of investigating risk management practices within the context of project complexity focusing on interdependency modelling. The adaptability of the framework proposed by Bosch-Rekveldt et al. (2011) to the construction industry was also validated. Based on the complexity-risk matrix filled in by the respondents, it was confirmed that practitioners consider such interdependency to be vital in complex projects. However, it was not intended to particularly focus on identifying critical complexity elements and risks as the aim of conducting empirical research was to explore the current practices in the industry with regard to management of project complexity and associated risks. Similarly, the activity of linking project complexity elements to risks was planned to establish the viability of the overall idea.

Although the respondents were located in South Australia, most of them were involved in different construction projects across the globe. It might not be possible to generalise the results to other industries that make use of sophisticated risk management techniques/tools that influence project performance (Carvalho et al., 2015). Therefore, the empirical research should be extended to other industries to gain better insight into the best practices.

4.7 Summary

Long-term projects involving NPD often result in major delays and cost overruns. The situation is further exacerbated by the complexity resulting from global outsourcing and risks associated with the supply chain. Through reviewing the literature on project complexity and interdependency modelling of risks in NPD in general and construction projects in particular, a major research gap is addressed with regards to establishing an integrated complexity and risk management process exploring interdependency modelling between project complexity attributes (known at the commencement stage), complexity driven risks and project objectives. It is important to consider chains of adverse events originating from the project complexity attributes and influencing the project objectives through active risk paths. A project complexity and risk management process and modelling approach are proposed for capturing the holistic interaction between the mentioned factors within the theoretically grounded framework of EUT and BBNs that present a very useful tool not only for capturing causal relationships between uncertain variables but also for establishing the strength of these interdependencies.

In order to investigate the current practices within the construction industry, a total of 13 semi-structured interviews were conducted with the experts in project risk management. The findings confirmed that the risk management process implemented in the industry does not consider complex interaction between project complexity and risks and furthermore, project managers generally rely on their intuition and past experience in dealing with risks. Although project complexity is considered an important factor at the commencement stage of a project, not all aspects of project complexity are included within the analysis. The experts interviewed considered the proposed process and modelling approach as an important contribution but they also identified challenges such as limited support from senior management and the requirement of populating such sophisticated models with data.

The proposed approach was demonstrated through an illustrative simulation study that gave an insight into understanding dynamics across risks and identifying key risks. The same key risks and complexity elements identified by our interviewees were used in the model. Two parameters were calculated for each risk signifying its relative importance for the utility node in terms of complete mitigation and the variation in the expected utility value corresponding to the two extreme states. The latter parameter helps in identifying risks for monitoring as the occurrence of low probability-high impact risks would have a significant impact on the entire network of interconnected risks. A project complexity measure can help practitioners understand the level of project complexity but it might not be of significant use in identifying and managing interdependent risks. It is important to investigate the interaction of project complexity and complexity induced risks. BBNs can capture these dynamics and help practitioners visualise propagation patterns of risk paths. The next chapter introduces dependency based probabilistic supply chain risk measures and utilises FMEA to model a supply chain risk network.

Chapter 5

Exploring Dependency based Probabilistic Supply Chain Risk Measures for Prioritising Interdependent Risks and Strategies

5.1 Introduction

This chapter introduces a method to manage supply chain risks within a network setting of interacting risks, risk sources and mitigation strategies that is grounded in the theoretical framework of BBNs. For risk identification, the key feature of FMEA is utilised in identifying supply chain risks, associated sources and potential mitigation strategies. For risk assessment, dependency based probabilistic risk measures are introduced for identifying the relative importance of each risk within the network of interacting risks. For risk treatment, two scenarios are considered: if the strategies and associated cost are not explicitly evaluated, Shapley value (Shapley, 1953) from the field of cooperative game theory is used in order to address the problem of allocating a fair amount of the budget to the critical risks identified through the measures; if the strategies with associated cost are already identified within the network, strategies are optimised in relation to resource and budget constraints. The proposed process is demonstrated through a simulation study that is based on the case study of Tuncel & Alpan (2010).

5.2 FMEA

FMEA or Failure Modes, Effects and Criticality Analysis (FMECA) is a systematic approach for identifying different modes of failure and evaluating associated risks during the development stage of a product or service. It is known to have been implemented in 1963 for projects at NASA and later, the Ford Motor Company utilised the technique in 1977 (Gilchrist, 1993). The typical process involves: identification of failure modes, associated causes and resulting consequences; assigning the values of occurrence (O), severity (S) and detection (D) to each failure mode on an ordinal scale of $1 - 10$ for each linguistic variable; calculating the Risk Priority Number (RPN) of each failure mode which is the product of three numbers identified previously; ranking the failure modes and planning actions on high ranking modes; and finally reviewing the effectiveness of implemented actions and revising the risk measures.

There are some major shortcomings of using RPN as a measure of prioritising risks (Gilchrist, 1993; Nepal & Yadav, 2015). The elicited value relative to each ordinal scale is quite subjective and furthermore, a risk having a high value of severity (O=6, S=10, D=6) might still score lower (RPN=360) in comparison with a risk (O=6, S=8, D=8) that might be less critical (RPN=384). Therefore, the calculation of RPN as a product of three numbers does not justify the rationale. In this chapter, we propose using the features of FMEA in identifying important risks and associated risk sources but instead of using the ordinal scales for occurrence and severity, we utilise the values of probability and losses resulting from realisation of risks. We also establish interdependency between identified risks and risk sources that helps in overcoming the notion of independent risks inherent in the conventional scheme of FMEA.

5.3 Literature Review: Models for Managing Interdependent Supply Chain Risks

As the research question investigates development of a SCRM process considering interdependency between supply chain risks and mitigation strategies, the focus will be limited to the literature dealing with interdependent risks. For a comprehensive overview of quantitative models in SCRM, interested readers may consult the literature review conducted by Fahimnia et al. (2015). A number of models have been proposed for identifying and assessing supply chain risks, however, limited studies have considered interdependency between risks. Cause-effect diagram (Lin & Zhou, 2011) and social network theory (Kim et al., 2011) have been used for mapping causal interaction between supply chain risks. ISM has been used for modelling interdependency between risks (Pfohl et al., 2011) and identifying the interdependent enablers of risk mitigation (Faisal et al., 2006b) which helps in not only mapping the relationship between variables but also in developing a hierarchy of the network. The main problem with these techniques is the inability of modelling the strength of relationship between interconnected risks.

FMEA has been used for identifying and assessing supply chain risks (Tuncel & Alpan, 2010; Nepal & Yadav, 2015). The major shortcoming of these studies is the use of RPN for ranking risks (Gilchrist, 1993) and failure to capture the network wide propagation of risks. Supplier selection/assessment has remained one of the active areas of research and a number of methods including AHP (Chen & Wu, 2013) and BBNs (Dogan & Aydin, 2011) have been developed to assess supplier related risks. The main limitation of these studies is their focus on addressing a specific problem without considering the holistic interaction of risks across the supply network (Garvey et al., 2015).

The likelihood of the occurrence of an (undesirable) event, and the negative implications of the event are two common measures of risk (Bogataj & Bogataj, 2007). Risk mitigation strategies are implemented in order to reduce the likelihood of occurrence and/or negative impact of risks (Tang & Tomlin, 2008). Robust strategies must be developed in order to help firms reduce cost and/or improve customer satisfaction under normal conditions and enable firms to sustain operations during and after the occurrence of a disruption. A number of studies have proposed selecting strategies specific to the supply chain configuration and risks (Zsidisin et al., 2004; Christopher & Peck, 2004; Christopher et al., 2011; Speier et al., 2011; Son & Orchard, 2013). Few studies (Micheli et al., 2014; Aqlan & Lam, 2015) have considered the optimisation problem of selecting cost-effective risk mitigation strategies, however, no study has ever considered the problem of evaluating optimal combinations of risk mitigation strategies within a probabilistic network setting of interacting risks and strategies.

BBNs have been extensively applied to the field of risk management (Norrington et al., 2008; Ashrafi et al., 2015; Wu et al., 2015) mainly because BBNs offer a unique feature of modelling risks combining both the statistical data and subjective judgement in the case of non-availability of data (Dogan & Aydin, 2011). However, their application to the field of SCRM in modelling holistic interaction between risks has recently gained the interest from researchers (Leerojanaprapa et al., 2013; Garvey et al., 2015). Badurdeen et al. (2014) introduced a supply chain risk taxonomy and a risk network map capturing interdependency between risks. Their model presents an effective tool to capture the interaction of risk factors and helps in identifying critical suppliers.

In a recent study conducted by Garvey et al. (2015), supply chain process and risks corresponding to various segments of the supply network are combined together and modelled as a BBN. They also introduce new risk measures for identification of important elements within the supply network. Their proposed modelling framework differs from the existing BBN based studies in SCRM (Dogan & Aydin, 2011; Badurdeen et al., 2014; Lockamy, 2014) in terms of exploring the propagation impact of risks across the network of interconnected risks and supply network elements, but their proposed risk measures only consider the impact of risks on the descendant nodes and ignore capturing the diagnostic effect. They also incorporate the loss values within their modelling framework thereby overcoming the major limitation of earlier studies in terms of focusing on only the probabilistic interdependency between risks. However, the proposed framework does not focus on modelling and evaluating risk mitigation strategies (risk treatment). Furthermore, it might not be feasible to adopt the method for mapping a substantial network as the method necessitates following the process flow of a supply chain.

Heckmann et al. (2015) conducted a critical review of quantitative approaches for managing supply chain risks focusing on the definitions, measures and modelling of risk. According to them: *"Standard deviation, mean-variance approaches, value-at-risk, conditional-value-at-risk or premiums are risk measures that aim at describing the interaction of uncertainty and the extent of its related harm or benefit. Owing to the lack of quantitative measures that capture the more complex realities of supply chains, these measures –developed in finance and insurance contexts –are applied for supply chain risk, too"* (Heckmann et al., 2015, p. 127). However, a closer look at the cited references in their study reveals that the measures are not developed for interdependent risks and that is why the risk measures introduced by Garvey et al. (2015) are deemed as state-of-the-art in terms of cap-

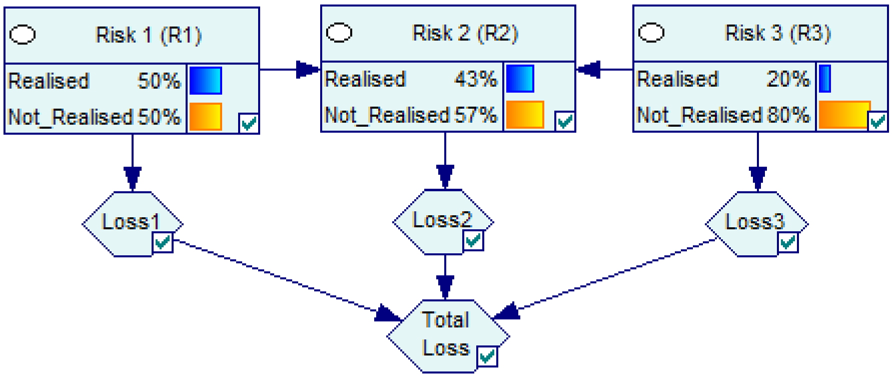

Figure 5.1: Bayesian Belief Network illustrating three risks each with an associated loss node and a total loss node (GeNIe).

turing the interdependency between risks and *"measuring monetary losses within supply chain management"* (Heckmann et al., 2015, p. 128). However, Garvey et al. (2015) rightly identify the limitation of their proposed measures as these only capture propagation of losses across the pure descendants of risks (causal effect) rather than evaluating the network wide propagation of losses (causal and diagnostic effects).

5.4 Metrics to Support Resource Allocation and Their Characteristics

5.4.1 Motivating Example

Consider a supply network with three identified risks and an associated Bayesian Network (BN) illustrated in Figure 5.1. Risk 1 (R1) and Risk 3 (R3) have no parent nodes with a probability of being realised of 0.5 and 0.2, respectively. Risk 2 (R2) is dependent on both R1 and R3 with Conditional Probability Table (CPT) provided in Table 5.1, and a marginal probability of being realised of 0.429. Associated with R1, R2 and R3 are a Loss 1, 2 and 3 of 100, 1000 and 500, respectively if the risk is realised. This produces a correlation between Loss 1 and Loss 2 of 0.34 and Loss 2 and Loss 3 of 0.53.

		State of Risk 1			
		Not Realised (0.5)		Realised (0.5)	
		State of Risk 3		State of Risk 3	
		Not Realised (0.8)	Realised (0.2)	Not Realised (0.8)	Realised (0.2)
State of Risk 2	Realised	0.1	0.9	0.5	0.99
	Not Realised	0.9	0.1	0.5	0.01

Table 5.1: Conditional probability table of Risk 2.

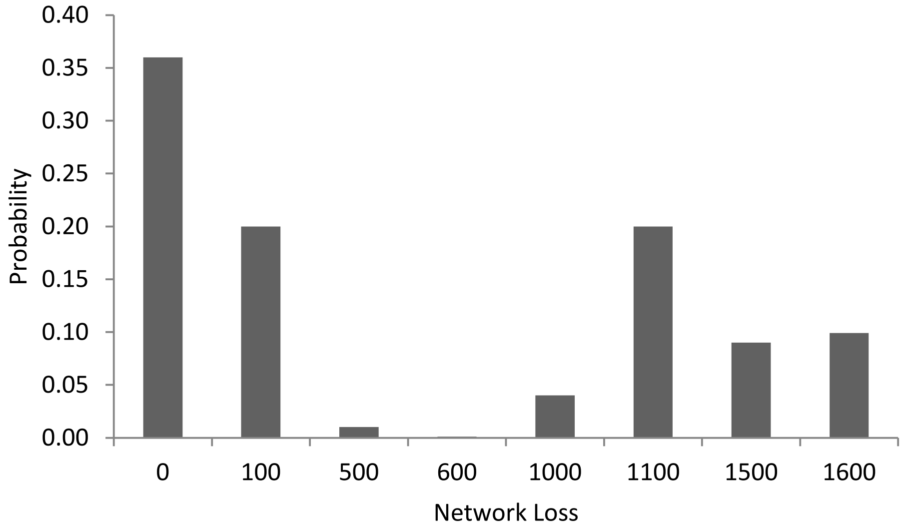

Figure 5.2: Probability distribution of Network Loss.

The expected direct loss from R1, R2 and R3 is 50, 429 and 100, respectively with an Expected Total Loss of 579 and a standard deviation of 638. We shall refer to the Expected Total Loss as the Risk Network Expected Loss ($RNEL$) to reflect that the loss represents a total loss across the network of risks after accounting for the propagation of risks through the network. Illustrated in Figure 5.2 is the probability distribution for the realised Total Loss, so while the mean of this distribution is 579, the probability of realising a total loss in excess of this is 0.43, of realising a loss of at least twice the mean is 0.389 and there is a probability of 0.099 that the total loss will be 1600, almost three times the mean.

Decision makers may have resources available to wholly or partially mitigate a risk, in which case assessing the impact a risk has on Network Loss becomes important. This is a challenging exercise in the presence of dependency or correlation between the direct losses, as once realised a risk can propagate consequences,

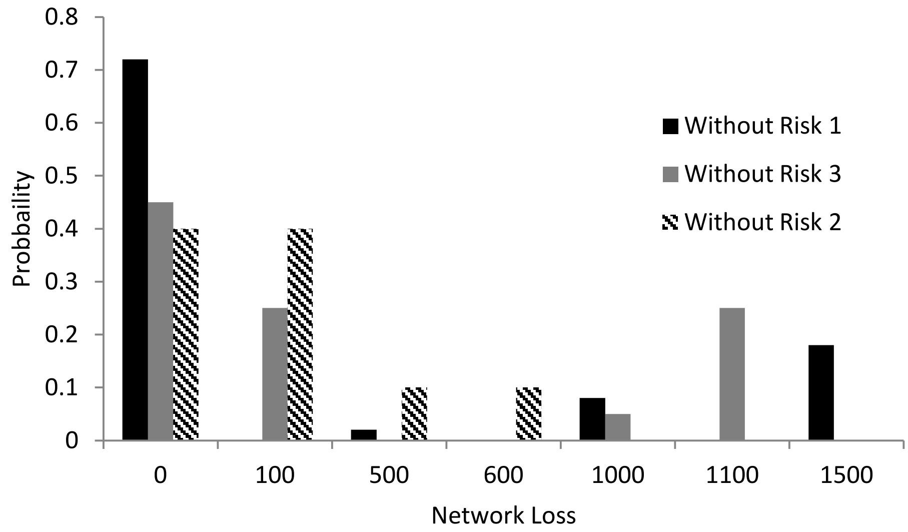

Figure 5.3: Probability distribution of Network Loss assuming Risk 1, Risk 2 or Risk 3 is removed showing a variety of shapes.

Risk Removed	RNEL	Standard Deviation	Best Case (probability)	Worst Case (probability)
None	579	638	0 (0.36)	1600 (0.099)
Risk 1	360	600	0 (0.72)	1500 (0.18)
Risk 2	150	206	0 (0.40)	600 (0.10)
Risk 3	350	482	0 (0.45)	1100 (0.25)

Table 5.2: Summary statistics from the distribution of Network Loss assuming Risk 1, Risk 2 or Risk 3 is removed.

increasing the likelihood of realising other risks. Figure 5.3 illustrates three probability functions representing the distribution with R1, R2 or R3 entirely mitigated (i.e. the probability of it being realised is set to zero). Key summary statistics of these distributions are provided in Table 5.2. The distributions are quite different which is not reflected in measures such as $RNEL$. No distribution stochastically dominates, so choosing the most important risk to manage will depend on the preferences of the decision maker: how mitigating each risk is valued by the decision maker depends on his assessment of the value of the change in the probability distribution that materialises.

Consider the conditional distributions of Network Loss given a risk has been realised (i.e. its probability is set to one). For the simple illustrative example in this section the three conditional distributions are provided in Figure 5.4. Note that, due to the direction of the causal relationship between R1 and R3, and

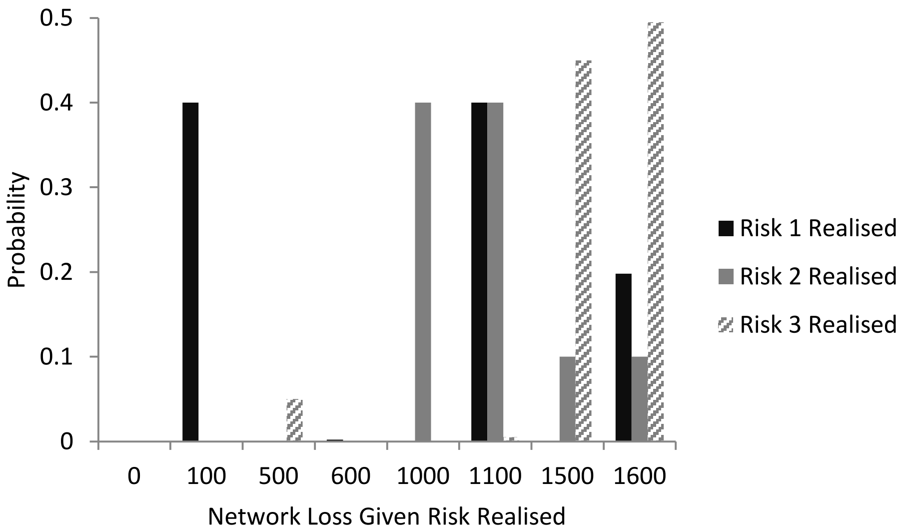

Figure 5.4: Probability distribution of Network Loss given Risk 1, Risk 2 or Risk 3 is realised.

Risk Realised	RNEL given risk realised	Probability of realising risk	RNELPM	Difference between RNEL given risk realised and RNEL	UTC
Risk 1	798	0.50	399	219	110
Risk 2	1150	0.43	495	571	246
Risk 3	1498	0.20	300	919	184

Table 5.3: Summary measures of Network Loss given risks realised.

R2, if R2 is realised the probability of R1 and R3 are not updated as there is no change in epistemic uncertainty. It is clear from this illustration that the influence of each risk on possible network losses is very different: for example, the expected loss if R3 is realised is much higher than if R2 is realised. Whilst $RNEL$ gives an *ex ante* measure of losses that are at stake on the network, it does not allow any inference about the importance of individual risks. In order to do this we propose the Risk Network Expected Loss Propagation Measure for Risk ($RNELPM_{\mathrm{i}}$), which measures the probability-weighted $RNEL$ if risk is realised. Table 5.3 provides a summary of the distributions illustrated in Figure 5.4 along with the $RNELPM$ for each risk.

The idea of proposing the $RNELPM$ is to allow decision makers to prioritise the reduction of risk on the network if resources are available to do so by identifying those risks that have the greatest effect on the network expected loss given the propagation of risks through the network, also accounting for the likelihood of them occurring. This takes the mean of the distribution for each risk in Figure 5.4 and weights it by the probability of the risk occurring. If decision makers are risk-neutral their assessment of the distribution is correctly summarised by the average. If a decision maker has non-neutral risk preferences, it would not be appropriate to use the expected loss to summarise the distribution, but to consider the expected utility of the loss: a probability-weighted average of the utility of the losses that might be realised if a risk is realised, which should then itself be weighted by the probability of the loss occurring. Eliciting a decision maker's utility function is known to be challenging (Ruan et al., 2015) leading to difficulties in operationalising such a measure and so, whilst it may be interesting to pursue this in future work, we turn our attention to a different line of inquiry.

There is lots of evidence to suggest that human decision makers evaluate the outcomes from the choices they make by comparing those outcomes relative to a reference outcome, and exhibiting 'loss aversion'. This is the characteristic that if an outcome is a certain amount worse than the reference outcome then this gives a greater reduction in the attractiveness of the outcome than the increase in attractiveness if an outcome is the same amount better than the reference outcome. The idea of loss aversion was made famous by Kahneman & Tversky (1979) in their 'Prospect theory', which has been developed in particular by Koszegi & Rabin (2006), who carefully consider the use of expectations as reference points, and applied extensively to many interesting scenarios.

In the context of a network of interdependent supply chain risks, it is far from inconceivable that a supply chain manager may have in mind an expected loss for the standard configuration of the network, and in evaluating the importance of particular risks may place more emphasis on those risks that increase the network expected loss above the expected loss for the standard configuration, which is taken as the 'reference loss'. While managers may have differing degrees of loss aversion, a straightforward way to capture this is to evaluate the impact of a risk being realised by focusing only on where realisation of that risk leads to losses that exceed the reference loss, and ignore instances where the loss falls below the reference loss. In the case of our simple example, we can easily evaluate the Expected Loss in Excess of the Mean ($ELEM$), i.e. $E[max(NetworkLoss - RNEL, 0)]$, using the distribution in Figure 5.2 to obtain 305. However, for more complex networks this measure becomes computationally burdensome, and as an approximation we consider that the decision maker is concerned with the maximum of the difference between the $RNEL$ if the risk is realised and the reference loss, and zero, which we define as the 'Upper Tail Contribution' (UTC) of a risk. By isolating expected losses in excess of the reference loss, this measure provides an alternative assessment of risk that captures the importance of reference dependence and loss aversion in the evaluation of risks. The calculations for these measures are given in Table 5.3.

While $RNELPM$ and UTC are similar in emphasis of purpose, upon comparing the summary measures in Table 5.3 we see that $RNELPM$ provides a different rank to the risks than UTC. Overall, R2 comes out as being high in importance, but using $RNEL$ R1 and R3 are marginally different, $RNELPM$ has R1 being more important than R3, and the opposite is true with UTC. In the following section we will formally define these measures and explore their characteristics.

5.4.2 The Risk Measures and Their Properties

The three measures introduced are the $RNEL$ (5.1), which is the expected total loss on the network, the UTC_{i} (5.2), which is the expected increase in $RNEL$ from realising risk i and $RNELPM_{\text{i}}$ (5.3), which is the expected network loss from realising risk i. The main intention is to investigate the applicability of these measures within an optimisation algorithm to determine the cost optimal level to target the probability of each risk.

$$RNEL = E[NL] \tag{5.1}$$

$$UTC_i = E_{R_i}[max(E[NL|R_i = 1] - E[NL], 0)] \tag{5.2}$$

$$RNELPM_i = E[NL|R_i = 1]P(R_i = 1) \tag{5.3}$$

With reference to Observation 1, where using $RNEL$ as a reference point, realising a risk will occur increases the updated $RNEL$ and realising a risk will not occur decreases the updated $RNEL$ for all risks.

Observation 1.

$$E[NL|R_i = 0] \leq RNEL \leq E[NL|R_i = 1]$$

Proof.

$$\begin{aligned} RNEL &= E[NL] \\ &= E[NL|R_i = 0](1 - P(R_i = 1)) + E[NL|R_i = 1]P(R_i = 1) \\ &= E[NL|R_i = 0] + P(R_i = 1)(E[NL|R_i = 1] - E[NL|R_i = 0]) \end{aligned}$$

As $E[NL|R_i = 1] > E[NL|R_i = 0]$ this is an increasing function in $P(R_i = 1)$ going from $E[NL|R_i = 0]$ to $E[NL|R_i = 1]$. □

Observation 2 establishes that UTC_{i} will never exceed the Expected Loss in Excess of the Mean ($ELEM$).

Observation 2.

$$ELEM \geq UTC_i$$

Proof.

$$\begin{aligned} E_{NL}[max(NL - E[NL], 0)] =& E_{NL}[max(NL - E[NL], 0)|R_i = 1]P(R_i = 1) \\ &+ E_{NL}[max(NL - E[NL], 0)|R_i = 0]P(R_i = 0) \end{aligned}$$

From Observation 1 we know when $R_i = 1$ then $E[NL|R_i = 1] > E[NL]$ as well $E[max(NL, E[NL))|R_i = 1] \geq E[NL|R_i = 1]$ and therefore

$$\begin{aligned} E_{NL}[max(NL - E[NL], 0)|R_i = 1] &\geq E[NL|R_i = 1] - E[NL] \\ &= max(E[NL|R_i = 1] - E[NL], 0) \end{aligned}$$

From Observation 1 we know when $R_i = 0$ then $E[NL|R_i = 0] < E[NL]$ and therefore

$$\begin{aligned} E_{NL}[max(NL - E[NL], 0)|R_i = 0] &\geq 0 \\ &= max(E[NL|R_i = 0] - E[NL], 0) \end{aligned}$$

□

Observation 3 establishes the relationship between the three measures for a specific risk on the network, and the expected loss on the network. As such a risk with a higher probability of being realised as a loss has a greater difference between $RNELPM_{\text{i}}$ and UTC_{i}.

Observation 3.

$$\frac{RNELPM_i - UTC_i}{P(R_i = 1)} = RNEL, \forall i$$

Proof.

$$\frac{RNELPM_i - UTC_i}{P(R_i = 1)}$$
$$= \frac{E[NL|R_i = 1]P(R_i = 1) - (E[NL|R_i = 1] - E[NL])P(R_i = 1)}{P(R_i = 1)}$$
$$= E[NL]$$
$$= RNEL$$

□

This leads to the first proposition concerning UTC_{i}, which shows the relationship between UTC_{i} and $ELEM$ with respect to the probability of experiencing a network loss below $RNEL$. The second proposition is motivated by focusing on the network losses that are in excess of a reference point, namely the $RNEL$. We can define the Lower Tail Gain for risk i, to be the expected gain from realising network losses below the reference point. The equivalence of these measures is expressed in Proposition 2.

Proposition 1. *As the conditional probability of realising an aggregate network loss below the* $RNEL$ *given risk* i *has been realised, i.e.* $P(NetworkLoss < RNEL|R_i = 1)$*, decreases* UTC_i *approaches* $ELEM$*, i.e.*

$$lim_{P(NetworkLoss<RNEL|R_i=1)\to 0} UTC_i = ELEM$$

Proof. From the proof of Observation 2 we have the inequality
$E[max(NL, E[NL])|R_i = 1] \geq E[NL|R_i = 1]$ which is an equality when
$P(NetworkLoss < RNEL|R_i = 1) = 0.$ □

Proposition 2. *The Upper Tail Contribution for risk i (UTC_i) equals the Lower Tail Gain for risk i (LTG_i), i.e.*

$$UTC_i = E_{R_i}[max(E[NL] - E[NL|R_i = 0], 0)]$$

Proof.

$UTC_i = E_{R_i}[max(E[NL|R_i = 1] - E[NL], 0)]$

$= (E[NL|R_i = 1] - E[NL|R_i = 1]P(R_i = 1) - E[NL|R_i = 0]P(R_i = 0))P(R_i = 1)$

$= (E[NL|R_i = 1] - E[NL|R_i = 0])P(R_i = 0)P(R_i = 1)$

$= (E[NL|R_i = 1]P(R_i = 1) - E[NL|R_i = 0]P(R_i = 1))P(R_i = 0)$

$= (E[NL|R_i = 1]P(R_i = 1) - E[NL|R_i = 0] + E[NL|R_i = 0]P(R_i = 0))P(R_i = 0)$

$= (E[NL] - E[NL|R_i = 0])P(R_i = 0)$

$= LTG_i$

□

The third proposition explicates the relationship between UTC_i and the variance of its associated risk denoted by σ_i^2.

Proposition 3. *UTC_i is proportional to the variance of the indicator variable for the risk, specifically*

$$UTC_i = \sigma_i^2[E[NL|R_i = 1] - E[NL|R_i = 0]]$$

Proof.

$$UTC_i = E_{R_i}[max(E[NL|R_i = 1] - E[NL], 0)]$$
$$= P(R_i = 1)(E[NL|R_i = 1] - E[NL|R_i = 1]P(R_i = 1) - E[NL|R_i = 0]P(R_i = 0))$$
$$= P(R_i = 0)P(R_i = 1)(E[NL|R_i = 1] - E[NL|R_i = 0])$$
$$= \sigma_i^2[E[NL|R_i = 1] - E[NL|R_i = 0]]$$

□

5.4.3 Optimal Control of Risk

Consider that a supply chain manager has been allocated a budget that can be used to reduce risk on the network, and consider the optimal way in which to reduce risk. It is supposed that risks are controllable, in the sense that the manager can undertake costly actions to reduce the probability that a risk is realised, or indeed perhaps release some cost by allowing the probability of a risk being realised to increase. For ease of notation, let $P_i = P(R_i = 1)$ and define $C_i(P_i)$ as the cost of achieving P_i. Since we are considering optimising from the standard configuration, we define the cost in the standard configuration as zero for each risk, and further suppose that for each i $C_i(.)$ is continuously differentiable as many times as required and strictly decreasing in its argument (i.e. $\dot{C}_i(.) < 0$), meaning it is costly to reduce the probability of a risk being realised. It is further supposed that the cost function is convex (i.e. $\ddot{C}_i(.) > 0$), implying that the incremental cost of further reductions in the probability of a risk being realised is higher the smaller the probability is. A risk mitigation problem will involve minimising a risk measure subject to the total cost of risk mitigation not exceeding the manager's budget constraint, that we denote c_0.

While UTC is a risk measure that captures reference dependence and loss aversion in decision making, an unfortunate consequence of Proposition 2 is that it does not make an effective decision making tool; as we show in the following corollary it can lead to very poor decisions being made.

Corollary 1. *If* $C_i(P_i)$ *is decreasing in* P_i*, optimising a portfolio of risks with the objective of min* $\sum_i UTC_i$ *with respect to* P_i *will lead to maximising* $E[NL]$*.*

Proof. As $UTC_i = \sigma_i^2[E[NL|R_i = 1] - E[NL|R_i = 0]] = P(R_i = 0)P(R_i = 1)(E[NL|R_i = 1] - E[NL|R_i = 0])$ this can be reduced to 0 either by setting $P(R_i = 0) = 0$ or $P(R_i = 1) = 0$. If we assume that costs increase with reducing $P(R_i = 1)$ then the optimal target for each risk would be $P(R_i = 1) = 0$. □

Instead, $RNELPM_i$ is considered as a risk measure to guide the management of risks on an interdependent supply network. In Proposition 4 the relationship between the optimal level to target probabilities of risks being realised in relation to $E[NL|R_i = 1]$ is characterised.

Proposition 4. *Optimising a portfolio of risks to minimise* $\sum_i RNELPM_i$ *with respect to* P_i *subject to a budget constraint results in an optimal* P_i *such that marginal cost at* P_i *is proportional to* $E[NL|R_i = 1]$ *for all* i*.*

Proof. The optimisation problem is

$$min \sum_i RNELPM_i s.t. \sum_i C_i(P_i) = c_0$$

The Lagrangian function for this constrained optimisation problem is

$$O = \sum_i P_i E[L|R_i = 1] + \lambda(\sum_i C_i(P_i)) - c_0)$$

And the first-order conditions (FOC) are

$$O_i = E[L|R_i = 1] + \lambda \dot{C}_i(P_i) = 0, \forall i$$

and

$$O_\lambda = \sum_i C_i(P_i) - c_0 = 0$$

This gives us

$$\frac{1}{\lambda}\begin{pmatrix} E[L|R_1 = 1] \\ . \\ . \\ E[L|R_n = 1] \end{pmatrix} = \begin{pmatrix} -\dot{C}_1(P_1) \\ . \\ . \\ -\dot{C}_n(P_n) \end{pmatrix} s.t. \sum_i C_i(P_i) = c_0$$

□

The optimal risk mitigation strategy calls for the marginal benefit of incrementally reducing a risk being realised to be weighed up against the marginal cost of further reductions in the probability, accounting for the fact that the budget is constrained. When optimising from a standard configuration with a fresh budget a manager may optimally reduce or increase certain risks. The solution to the optimisation problem allows one to consider optimal risk realisation probabilities as a function of the budget, and inspection of this relationship reveals that under our assumptions a relaxation of the budget constraint will result in the probability of all risks materialising being reduced. As such, while the further reduction of certain risks might be favoured over others, no risk will see an increase in the probability of it materialising. This is formalised in Proposition 5. Lemma 1, which is used in the proof of this proposition, characterises the relationship between the marginal benefit of increasing the budget, denoted by λ^*, and the budget, denoted by c_0, with the curvature of the cost function.

Lemma 1. *Assuming* $\dot{C}_i(P_i) < 0$ *and* $sign(\ddot{C}_i(P_i)) = sign(\ddot{C}_j(P_j)) \forall i, j$ *then*

$$sign(\frac{d\lambda^*}{dc_0}) = -sign(\ddot{C}_i(P_i))$$

Proof. From FOC we have

$$\frac{1}{\lambda^*}\begin{pmatrix} E[L|R_1 = 1] \\ . \\ . \\ E[L|R_n = 1] \end{pmatrix} = \begin{pmatrix} -\dot{C}_1(P_1) \\ . \\ . \\ -\dot{C}_n(P_n) \end{pmatrix} s.t. \sum_i C_i(P_i) = c_0$$

The unconstrained optimal solution has $\lambda^* = 1$. Assuming $sign(\ddot{C}_i(P_i)) = sign(\ddot{C}_j(P_j)), \forall i, j$ decreasing λ^* will result in higher costs (i.e. a lower P_i) only if $sign(\ddot{C}_i(P_i)) > 0$ and increasing λ^* will result in higher costs only if $sign(\ddot{C}_i(P_i)) < 0$. □

Proposition 5. *If the cost function of changing the probability of each risk being realised is convex, then increasing the budget, c_0, for risk mitigation will not result in increased optimal probability for any risk, $P_i^*(c_0)$. Specifically,*

$$\frac{dP_i^*(c_0)}{dc_0} = \frac{1}{\dot{C}_i + \frac{\ddot{C}_i}{\dot{C}_i}\sum_{j\neq i}\frac{\dot{C}_j^{\,2}}{\ddot{C}_j}} < 0, \forall i$$

Proof. We now seek to understand how the optimal risk mitigation strategy changes with a relaxation in the budget. Writing $P_i^*(c_0)$ for the optimal solution for each i, which is implicitly defined by the relationship $-\dot{C}_i(P_i^*(c_0)) = (\frac{1}{\lambda^*})E[L|R_i = 1]$, we differentiate each of the first-order conditions with respect to c_0 to deduce

$$\lambda\ddot{C}_i\frac{dP_i^*(c_0)}{dc_0} + \dot{C}_i\frac{d\lambda}{dc_0} = 0, \forall i$$

$$\dot{C}_i\frac{dP_i^*(c_0)}{dc_0} + \sum_{j\neq i}\dot{C}_j\frac{dP_j^*(c_0)}{dc_0} - 1 = 0$$

The ith equation in the first set gives

$$\frac{d\lambda}{dc_0} = -\lambda \frac{\ddot{C}_i}{\dot{C}_i} \frac{dP_i^*(c_0)}{dc_0}$$

Each of the other equations in the first set gives for each $j \neq i$

$$\begin{aligned} \frac{dP_j^*(c_0)}{dc_0} &= -\frac{d\lambda}{dc_0} \frac{1}{\lambda} \frac{\dot{C}_j}{\ddot{C}_j} \\ &= \frac{\ddot{C}_i}{\dot{C}_i} \frac{dP_i^*(c_0)}{dc_0} \frac{\dot{C}_j}{\ddot{C}_j} \end{aligned}$$

(using $\frac{d\lambda}{dc_0}$ just deduced). Inserting these objects into the final equation gives

$$\dot{C}_i \frac{dP_i^*(c_0)}{dc_0} + \frac{\ddot{C}_i}{\dot{C}_i} \frac{dP_i^*(c_0)}{dc_0} \sum_{j \neq i} \frac{\dot{C}_j^{\,2}}{\ddot{C}_j} = 1$$

$$\begin{aligned} \frac{dP_i^*(c_0)}{dc_0} &= \frac{1}{\dot{C}_i + \frac{\ddot{C}_i}{\dot{C}_i} \sum_{j \neq i} \frac{\dot{C}_j^{\,2}}{\ddot{C}_j}} \\ &= \frac{1}{\dot{C}_i + \sum j \neq i \dot{C}_j \frac{A_i}{A_j}} \\ &= \frac{1}{\dot{C}_i \frac{A_i}{A_i} + \sum j \neq i \dot{C}_j \frac{A_i}{A_j}} \\ &= \frac{1}{\sum_{k=1}^{n} \dot{C}_k \frac{A_i}{A_k}} \end{aligned}$$

Where $A_i = \frac{\ddot{C}_i}{\dot{C}_i}$ is the Arrow Pratt measure of risk aversion applied to the cost function that measures its curvature, and n is the total number of risks within the network. This allows us to understand how the probability of a particular risk would change through mitigation if extra budget became available. Note first that $\dot{C}_i < 0$. When seeking to allocate additional resource to mitigating risk a decision maker will be seeking to reduce probabilities in the most effective way, and this depends on the curvature of the cost function: a given additional resource to a risk will reduce the probability of it occurring more if the cost function is less convex. As such, when the ratio $\frac{\ddot{C}_i}{\dot{C}_i}$ is small in absolute terms for a risk, $\frac{dP_i^*(c_0)}{dc_0}$ will be larger in absolute terms (i.e. $P_i^*(c_0)$ is steeper) meaning the risk will be mitigated more when additional resource is available. □

5.4.4 Shapley Value

Shapley value is used to determine the relative contribution of controlling each risk to the overall reduction in the risk network expected loss. The Shapley value, having its roots in cooperative game theory, has been applied to various problems including environmental pollution cost allocation, production decisions, transportation, allocation of electricity transmission costs and insurance pricing (Quigley & Walls, 2007). It has also been applied for trading reliability targets between supply chain partners in an aerospace industry (Quigley & Walls, 2007). Shapley derived a formula for evaluating the contribution of a player to the value of a cartel in a cooperative game (Shapley, 1953).

The cooperative game theory setting is adapted to the problem of allocating resources to critical risks. Individual risks (and associated controls) are the players, cartel is represented by the coalition of risk controls applied to the specific risks and value corresponds to the relevant benefit in reducing the risk network expected loss. Any risk which is not the member of a network of controlled risks (coalition) is considered to be in its current (uncontrolled) state. As the formula for evaluating Shapley value is based on three axioms, these are adapted to the setting of SCRM as follows:

1. The benefit (reduction in risk network expected loss) attributed to the contribution of a risk control depends upon whether the risk control is implemented or not, and does not depend on the order in which the control was included in the set of risk controls.

2. The sum of the benefits attributed to the individual risk controls should equal the benefits made within the set of risk controls, with controls making no contribution to the set of controls being assigned a zero value.

3. There is no expected loss or gain in delaying the implementation of a risk control at any given decision point.

It is assumed that the number of risk controls to be considered is specified *a priori* and is denoted by $|N|$. Let Z represent the set of risk controls that have already been implemented prior to implementing the risk control i and $|Z|$ is the corresponding number of risk controls. The benefit arising from implementing the risk control i to a network of size $|N|$ is given by the Shapley value (Shapley, 1953):

$$\phi_i = \sum_{Z \in N-i} \frac{|Z|!(|N| - |Z| - 1)!}{|N|!}[v(Z \cup i) - v(Z)] \tag{5.4}$$

Where $v(Z \cup i)$ represents the benefit (reduction in risk network expected loss) of implementing risk controls Z and control i, $v(Z)$ is the benefit of implementing controls Z; $|Z|$ and $|N|$ indicate the number of elements in the sets Z and N, respectively. Shapley value is a weighted average of the marginal contribution risk control makes to a coalition, averaged over all possible permutations of entry to the coalition. The weights represent the probability of formation of a coalition of size $|Z|$ prior to the implementation of risk control i. The calculation of Shapley value for the risk network (Figure 5.1) is shown in Table 5.4.

It is clear from the calculations that controlling R2 will be most beneficial to the network whereas controlling R1 or R3 is relatively less important. These values help in evaluating a fair allocation of budget to the risks. The method captures all possible combinations of risk interactions. Shapley value provides a fair allocation of resources for risk mitigation as a starting point. Consider a situation where we have two risks (R1, R2) each with probability 1 of causing

Control Risks $Z \cup \{i\}$	Expected Loss	Benefit of Control	Marginal Contribution $[v(Z \cup \{i\}) - v(Z)]$			Weight $\frac{\lvert Z\rvert!(\lvert N\rvert - \lvert Z\rvert - 1)!}{\lvert N\rvert!}$
			$i = R1$	$i = R2$	$i = R3$	
None	579	0				
R1	360	219	219			1/3
R2	150	429		429		1/3
R3	350	229			229	1/3
R1, R2	100	479	50	260		1/6
R1, R3	100	479	250		260	1/6
R2, R3	50	529		300	100	1/6
R1, R2, R3	0	579	50	100	100	1/3
Shapley value Φ_i			139.7	269.7	169.7	
Relative importance (%)			24.1	46.6	29.3	

Table 5.4: Relative benefit of controlling each risk toward reduction in risk network expected loss.

loss and the total loss is 1 unit regardless of the cause, i.e. only one or both. The Shapley value would be 0.5 for each risk but the risk is not reduced by 50% through eliminating R1 or R2. Therefore, if we have a budget B, then Shapley value suggests an initial proposal would be to allocate $B/2$ to each risk. However, we might be able to mitigate R1 for $B/4$ and spend $3B/4$ on R2 and this could be an optimal allocation of the budget. So the optimisation aspect plays a different role and requires plans to be costed.

5.5 Proposed Risk Management Process

The proposed process comprises three main stages of problem structuring, instantiation and inference as shown in Figure 5.5. The model can be developed through conducting interviews and focus group sessions with the experts. Although we make use of FMEA, the criticism related to the subjective nature of RPN (Liu et al., 2013) is not relevant to our method because the FMEA is just utilised for identifying risks, sources and mitigation strategies. As the complete information or data concerning risks is generally not available, there is always a need to involve experts in modelling both the qualitative and quantitative parts of the model which makes the process quite subjective. However, any method will have to rely on expert judgement in the case of non-availability of data and as the proposed method is grounded within the framework of BBNs, well-established procedures and protocol can be adopted in order to develop and validate the model (Nadkarni & Shenoy, 2004; Pitchforth & Mengersen, 2013).

For better understanding, a block diagram is presented as Figure 5.6 which manifests the contribution of this study to the established risk management process (SA, 2009). Although we demonstrate the application of the model for a one-time decision problem of prioritising risks and mitigation strategies (at time: $T = t_0$), it can easily be extended to monitor and re-evaluate risks and strategies periodically. For a detailed discussion on each stage of the risk management process, interested readers may consult SA (2009).

The proposed process fits well with two distinct scenarios: in scenario 1, risk mitigation strategies and associated cost are not pre-defined; while in scenario 2, the strategies and associated cost are already established within the problem structuring stage. In both scenarios, the proposed risk measures help in prioritising critical risks for the risk monitoring stage. If the potential risk mitigation strategies are already identified within the network setting with associated cost and efficacy in mitigating risks, we do not need to assess risks before implementing strategies as each combination of strategies would have a unique impact on the risk network and therefore, it makes sense to re-evaluate risks after selecting optimal strategies. Once the strategies are not already defined, we need to identify critical risks using an appropriate risk measure and subsequently determine a fair allocation of resources to mitigate the critical risks using Shapley value. The detailed flow charts for the two scenarios are presented in Appendix B.

5.5.1 Stages of the Process

Problem Structuring

Firstly, supply chain risks (failure modes) and associated risk sources are identified using the FMEA. In the case of scenario 2, the objective function is also defined taking into account the budget and/or resource constraints. The second

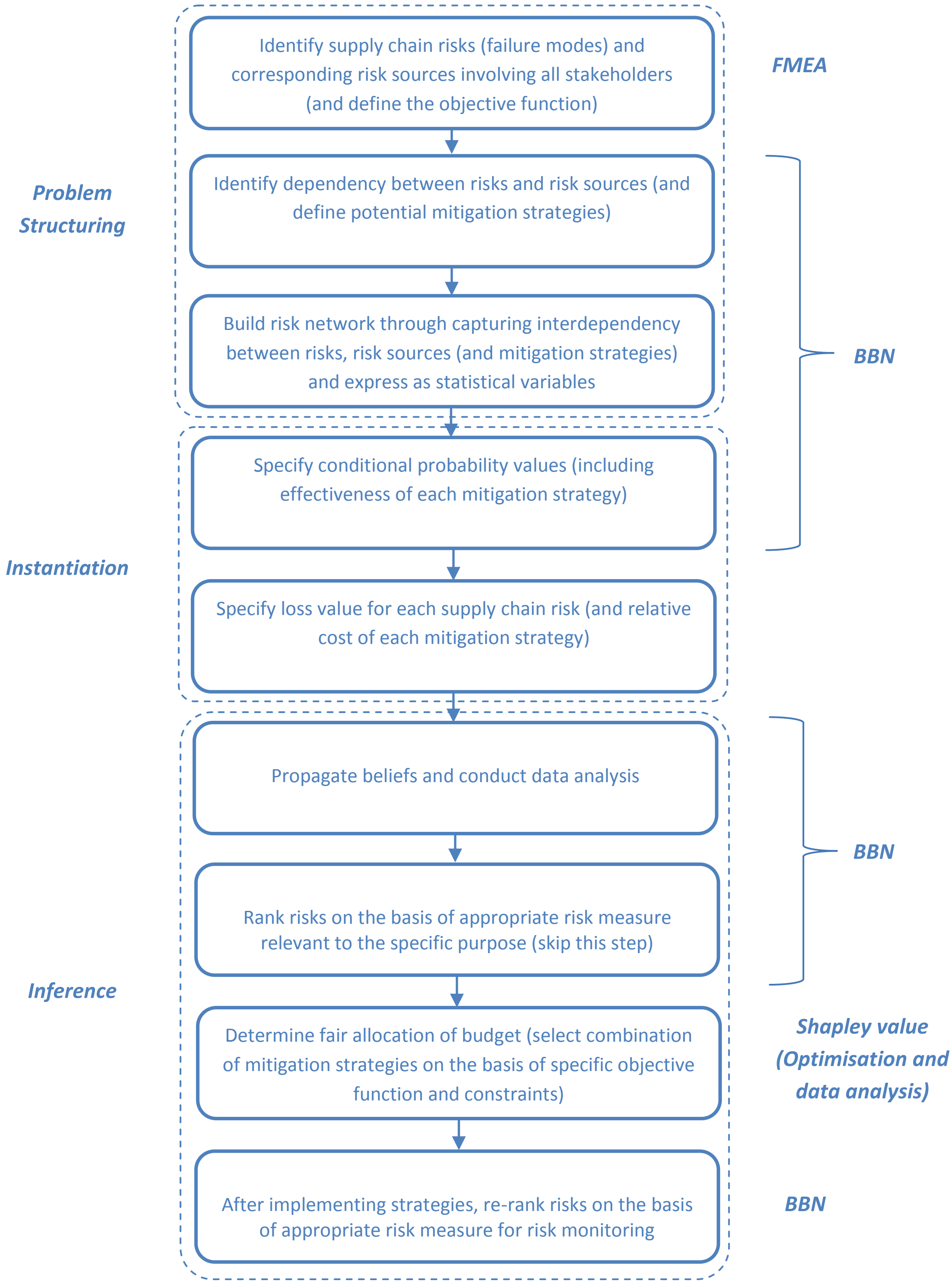

Figure 5.5: Modelling flowchart of the proposed process (steps in brackets are applicable to scenario 2 only where mitigation strategies and associated cost are already established in the problem structuring stage).

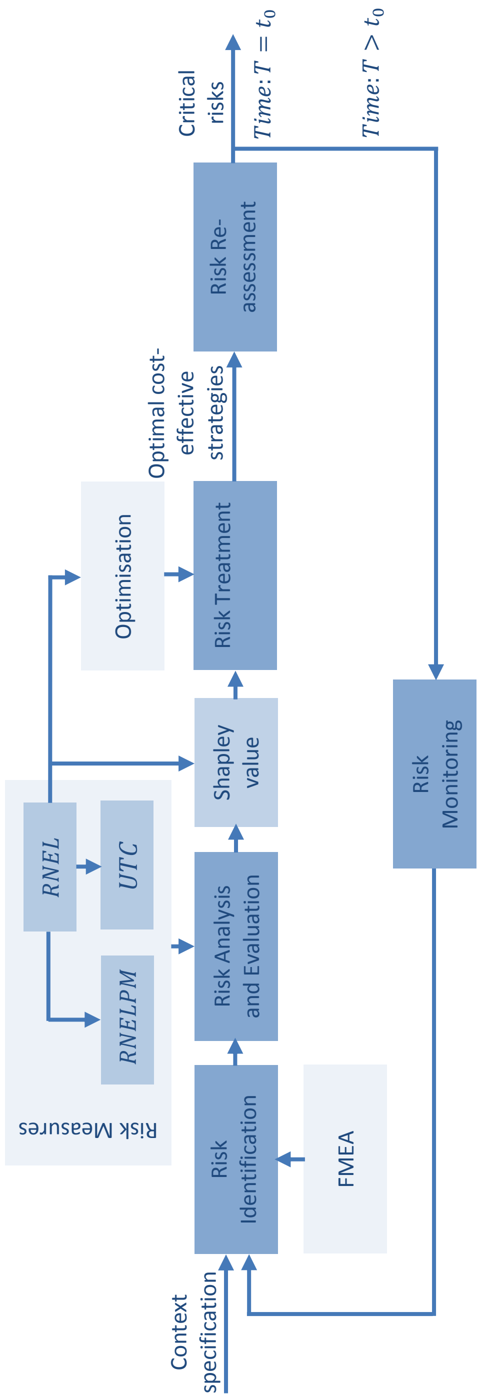

Figure 5.6: Block diagram representing the integration of proposed methodology in the risk management process (SA, 2009).

step involves identifying interdependency between common risk sources and risks using the technique of cognitive mapping (Nadkarni & Shenoy, 2004) besides selecting potential mitigation strategies in the case of scenario 2. Finally, the network structure is developed through connecting the arcs across related risk sources, risks and mitigation strategies (if applicable) and all nodes are expressed as statistical variables. The problem owner needs to ensure that the model is developed to represent the actual interdependency between risks. The model builder can assist in structuring the model keeping in view the mechanics of a BBN as the problem owner might not understand the importance of establishing correct relationships between causes and effects.

Instantiation

This stage involves evaluation of (conditional) probabilities (including effectiveness of mitigation strategies in the case of scenario 2) either through elicitation from the experts or extraction from available data. Probability elicitation is the most difficult task of the modelling process as experts find it challenging to describe conditional probabilities. Loss values are also elicited for all the risks and the cost of each mitigation strategy is ascertained through expert judgement in the case of scenario 2.

Inference

In the case of scenario 1, key risks are identified through evaluating specific risk measures suitable for the purpose: $RNELPM$ is suitable for capturing a risk-neutral appetite; whereas UTC is suitable for modelling risk-averse attitude where extreme losses are of greater concern. Once critical risks are identified, Shapley value is used for assigning resources to mitigate risks as well as comparing if the risk mitigation strategies are well priced. In the case of scenario 2, beliefs are updated and propagated across the interconnected risks, risk sources and mitigation strategies. For each possible combination of strategies, the network wide $RNEL$ is evaluated and cost and benefit analysis of various combinations of mitigation strategies is conducted. Depending on the objective function and constraints, appropriate strategies are selected. In both scenarios, once mitigation strategies have been evaluated (risk treatment), it becomes more important to re-assess the risks after implementation of strategies as the strength of interdependency between risks is reduced and the new network yields relatively independent risks. Therefore, an appropriate risk measure is used to prioritise critical risks for the monitoring stage and developing contingency plans.

5.5.2 Optimisation of a Portfolio of Risk Mitigation Strategies

We also investigate an important aspect of selecting optimal risk mitigation strategies within a network of interacting risk sources, risks and mitigation strategies subject to resource and budget constraints. Although we just make use of $RNEL$ within the objective function that reflects the risk attitude of a risk-neutral decision-maker, the function can be tailored for capturing other risk attitudes with the addition of constraints like mitigating critical risks identified through the proposed risk measures. The following two problems relate to different constraints: the first considers optimising a portfolio of strategies subject to a resource constraint; whereas the second relates to the optimisation problem subject to a budget constraint.

Problem No. 1

Given different options of implementing preventive and reactive strategies across a network of interconnected risk sources, risks and strategies, what is the optimal combination of these strategies yielding the maximum (minimum) value of an objective function subject to a resource constraint?

Objective function. In this study, we consider the following objective functions:

$$\begin{aligned} &min_{\gamma_{x_s} \in \gamma_{X_S}} RNEL_{\gamma_{x_s}} \\ &s.t. 0 < n \leq N \end{aligned} \tag{5.5}$$

$$\begin{aligned} &max_{\gamma_{x_s} \in \gamma_{X_S}} RNEL_{SC} - RNEL_{\gamma_{x_s}} - C_{\gamma_{x_s}} \\ &s.t. 0 < n \leq N \end{aligned} \tag{5.6}$$

where N is the total number of potential mitigation strategies,
$RNEL_{SC}$ is the risk network expected loss under the standard configuration of a risk network (with no potential strategy implemented),
γ_{X_S} is a set of all possible orderings of different states of N mitigation strategies,
$C_{\gamma_{x_s}}$ is the cost of implementing γ_{x_s} combination of mitigation strategies,
n is the number of strategies being considered for implementation.

Problem No. 2

Given different options of implementing preventive and reactive strategies across a network of interconnected risk sources, risks and mitigation strategies, what is the optimal combination of these strategies yielding the minimum value of an objective function subject to a budget constraint?

Objective function. In this problem setting, we consider the following objective functions:

$$\begin{aligned} &min_{\gamma_{x_s} \in \gamma_{X_S}} RNEL_{\gamma_{x_s}} \\ &s.t. 0 < C_{\gamma_{x_s}} \leq c_0 \end{aligned} \tag{5.7}$$

where c_0 is the budget constraint.

Few studies have considered addressing a similar problem. Micheli et al. (2014) used the stochastic integer linear programming approach to select optimal strategies considering fuzzy-extended pairwise comparisons for the categories of risk impact. Aqlan & Lam (2015) used the Bow-Tie technique to identify and evaluate critical risks, and solved the multi-objective mixed-integer linear optimisation problem (objectives: total risk reduction, mitigation cost) using goal programming. We consider a more complicated version of the problem where the value is calculated through running the BBN model for each combination of strategies. However, modelling the problem within the framework of BBNs makes it easier for the decision maker to only provide the effectiveness of each strategy in terms of reducing the probability and/or impact of related risk(s). Otherwise, it would be a daunting task to elicit these values from the decision maker in case of following the methods proposed by Micheli et al. (2014) and Aqlan & Lam (2015).

5.6 Demonstration of the Proposed Method

5.6.1 Description of the Case Study

We demonstrate the application of our proposed method through a simulation study. The study is based on the case study (Tuncel & Alpan, 2010) that was conducted in a medium-sized Turkish company involved in producing supplementary parts for electric, automotive and home appliance industries. Risk management is performed from the perspective of the manufacturer and only the immediate supply chain partners of the manufacturer are considered in the case study. Scope of the risk management is confined to the four sub-systems of the supply chain: the inbound/outbound logistics; the operations at the manufacturer; the operations at the suppliers; and the final customers (via the retailer).

We make use of the same risks, associated risk sources and mitigation strategies in our simulation study that were identified in the case study through the FMEA. Mainly the existing causal dependency between individual risks and corresponding risk sources and strategies as reflected in the case study is maintained in our simulation study. However, in order to demonstrate the interdependency between different risk sources, risks and mitigation strategies, we have established arbitrary connections across seemingly possible causal factors. We used GeNIe for modelling the network of risks and mitigation strategies. The qualitative structure of our model is shown in Figure 5.7 whereas all the parameters used in the model are given in Appendix B. The oval shaped nodes indicate the uncertain variables representing both the risks and risk sources. Rectangular nodes represent different potential mitigation strategies and diamond shaped nodes represent the losses corresponding to different risks. It is important to realise that some mitigation strategies are directly connected to the risk sources or risks representing preventive strategies that reduce the probability of associated events. Risk mitigation strategies directly connected to the diamond shaped nodes represent reactive strategies that mitigate the impact of loss once the risk is realised.

We have not used the ordinal data for the occurrence and severity for two reasons. Firstly, the occurrence data used in the FMEA does not consider the probabilistic interaction of risks and risk sources. Secondly, the use of ordinal data and subsequent multiplication of Occurrence, Severity and Detectability values for calculation of the RPN are mainly criticised in the literature for associated shortcomings (Gilchrist, 1993; Nepal & Yadav, 2015). Therefore, we have assigned assumed probability values to all the uncertain nodes using the framework of BBNs. Although we have used the same values of severity appearing in the case study, we assume that these are the perceived loss values in the event of occurrence of relevant risks. Assumed costs associated with different mitigation strategies are shown in Table 5.6.

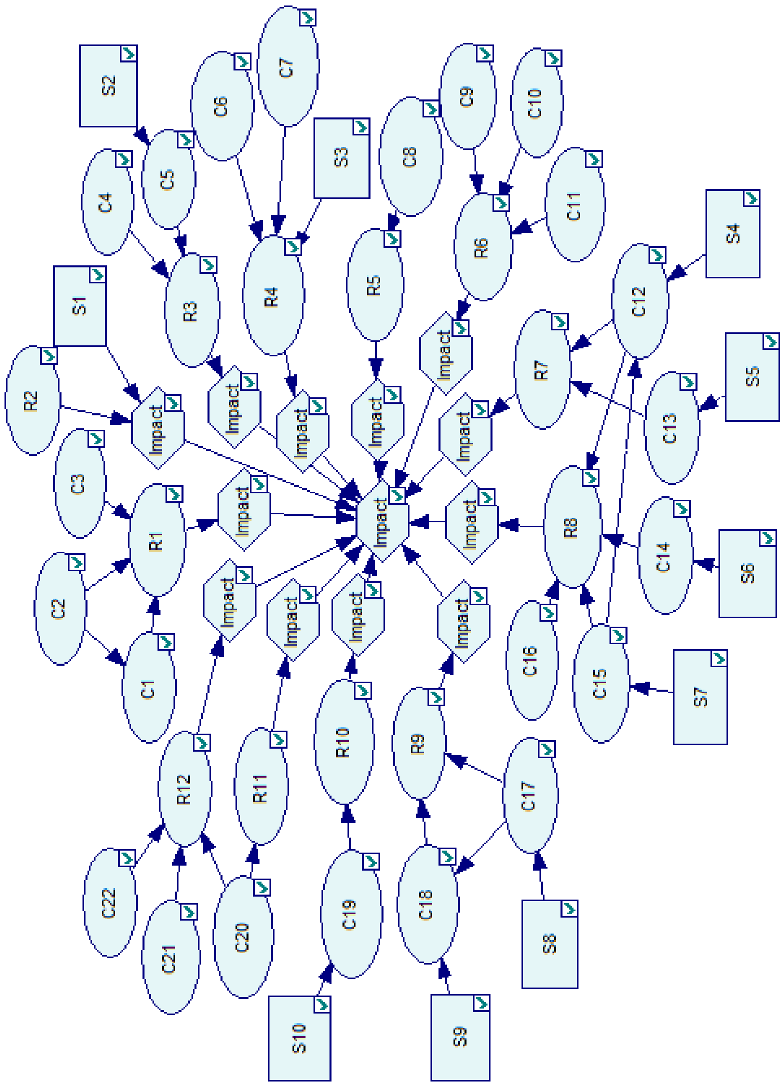

Figure 5.7: Supply chain risks, risk sources and mitigation strategies modelled as a BBN in GeNIe.

5.6.2 Results and Analysis

We focused on two different scenarios. In the first scenario, we assumed that the strategies shown in Figure 5.7 have not been already identified and the decision maker is interested in assessing risks first followed by the mitigation of critical risks. Therefore, considering the decision maker as risk-neutral, we used the $RNELPM$ to identify critical risks and subsequently used Shapley value to determine a fair allocation of budget to mitigate the critical risks identified. In the second scenario, we considered the decision problem of optimising the strategies shown in Figure 5.7 subject to different constraints. Here we assumed that the cost of strategies is already known and the strategies are fairly priced.

Scenario 1

We calculated the $RNELPM$ values corresponding to all risks through propagating the impact of each risk across the risk network. In contrast with the conventional norm of mapping (independent) risks on a two-dimensional plane of probability and impact, we propose assessing the network wide exposure of each risk over the risk spectrum as shown in Figure 5.8. The size of each bubble represents the product of probability and conditional expected loss related to each risk indicating its relative importance and rank. R7, R8 and R9 appear to be the most critical risks. Although R2 can pose a major threat to the network in case of its activation, its low probability does not necessitate mitigating the risk rather contingency plans may be tailored to deal with the risk.

Let us assume that the decision maker decides to mitigate the three critical risks identified. We determined the fair allocation of resources to deal with these risks using the Shapley value. The calculations are shown in Table 5.5. It can be seen that nearly equal budget should be allocated to the risks. However, it is important to realise that the allocation is a starting point as it might be possible to mitigate R7 at a relatively lower cost. If these three risks are related to different

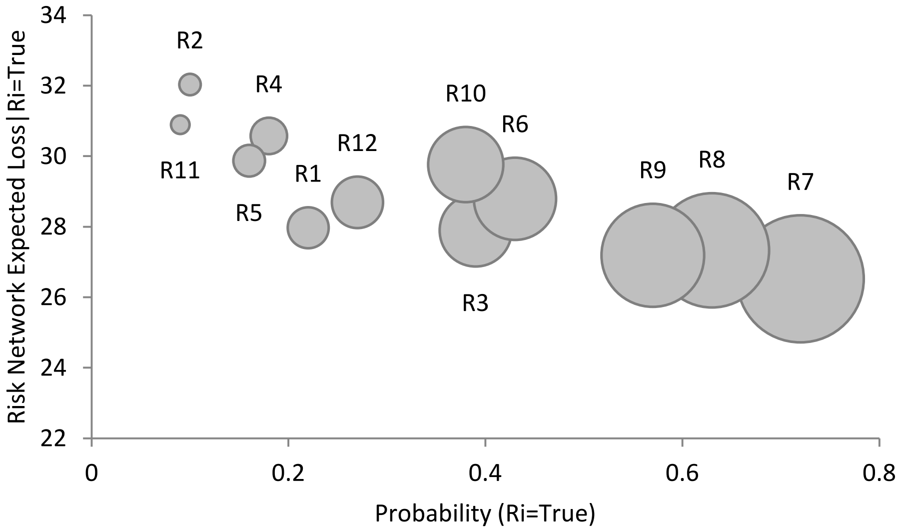

Figure 5.8: Risk spectrum representing ranking of interdependent risks for the risk analysis stage with size of each bubble reflecting the relative value of $RNELPM$.

Control Risks $Z \cup \{i\}$	Expected Loss	Benefit of Control	Marginal Contribution $[v(Z \cup \{i\}) - v(Z)]$			Weight $\frac{\lvert Z\rvert!\,(\lvert N\rvert - \lvert Z\rvert - 1)!}{\lvert N\rvert!}$
			$i = R7$	$i = R8$	$i = R9$	
None	24.59	0				
R7	20.22	4.37	4.37			1/3
R8	20.33	4.26		4.26		1/3
R9	21.19	3.4			3.40	1/3
R7, R8	17.21	7.38	3.12	3.01		1/6
R7, R9	16.82	7.77	4.37		3.40	1/6
R8, R9	16.92	7.67		4.27	3.41	1/6
R7, R8, R9	13.80	10.79	3.12	3.02	3.41	1/3
Shapley value Φ_i			3.75	3.64	3.40	
Relative importance (%)			34.76	33.73	31.51	

Table 5.5: Relative benefit of controlling each risk toward reduction in risk network expected loss.

suppliers, Shapley value helps in rewarding the suppliers fairly.

Once the critical risks are mitigated, there is a need for re-assessing the risks. Therefore, we re-calculated the $RNELPM$ values for prioritising risks and developing contingency plans. In order to compare the values corresponding to the risk assessment and risk monitoring stages, we used the normalised $RNELPM$ (with respect to $RNEL_{SC}$) as shown in Figure 5.9. As R7, R8 and R9 have been completely mitigated, the normalised $RNELPM$ value is shown as 0. R3, R6 and R10 need to be monitored owing to the higher measure values. The graph also helps in understanding the benefit of mitigating risks toward the risk network.

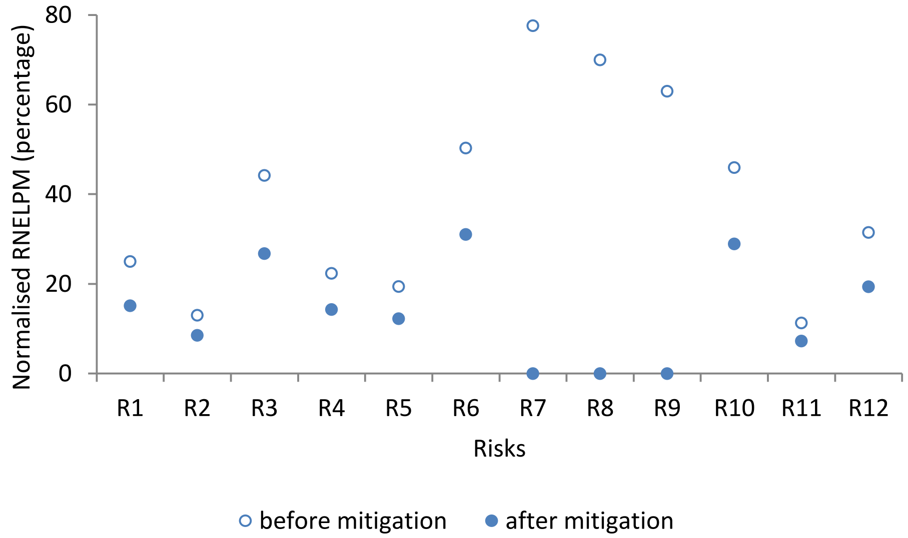

Figure 5.9: Comparison of normalised $RNELPM$ values corresponding to the risk analysis and risk monitoring stages.

Scenario 2

Once the model was populated with all the parameters, it was updated in order to obtain an array of ($RNEL$ and cost) values corresponding to different combinations of mitigation strategies. We considered addressing two different problems of selecting optimal mitigation strategies under resource (number of strategies) and budget constraints.

Prioritising Risk Mitigation Strategies under a Resource Constraint. It is extremely important for a decision maker to select optimal cost-effective mitigation strategies under a resource constraint as it might not be possible for the organisation to implement and manage all the strategies simultaneously. We consider the problem of selecting optimal strategies in relation to different objective functions (Equations 5.5 and 5.6) and resource constraint (i.e. limited number of strategies can be applied). We updated the model in GeNIe and exported the array of values to a Microsoft Excel worksheet in order to conduct the analysis. The results of optimal combinations of strategies corresponding to the two objective functions are shown in Table 5.6. A decision maker might be faced with

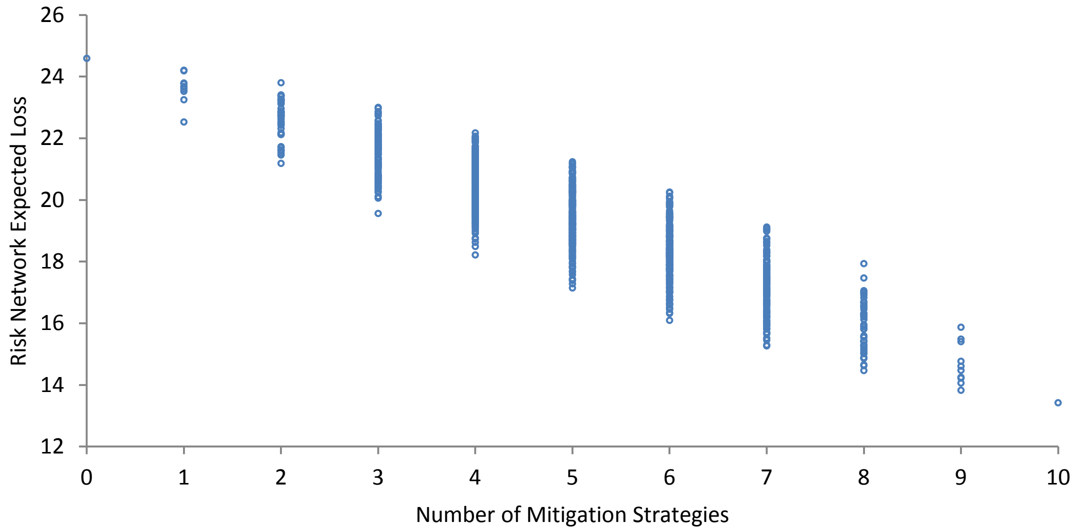

Figure 5.10: Variation of risk network expected loss with the number of strategies.

the problem of ranking mitigation strategies as in addition to the initial cost of implementing strategies, the effort involved in managing the smooth execution of these strategies might be an important factor. The first scheme considers only the risk network expected loss without incorporating the cost element whereas the second scheme includes both factors of improvement in risk network expected loss and associated cost of strategies. Different combinations of mitigation strategies corresponding to the two objective functions and number of strategies are shown in Figure 5.10 and Figure 5.11 which reveal that there are a number of possible solutions to implementing specific number of strategies except the two options of implementing 'no strategy' and 'all strategies'. All combinations of strategies except the optimal combinations as mentioned in Table 5.6 are not optimal for managing risks.

Prioritising Risk Mitigation Strategies under a Budget Constraint. In this problem setting, we consider the choice of selecting optimal strategies keeping in view the budget constraint. It can also be interpreted as a problem of selecting a cost-effective combination of mitigation strategies corresponding to a specific level of risk exposure (risk network expected loss). The results are shown in Table 5.7

No. of Strategies	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
No. of Combinations	1	10	45	120	210	252	210	120	45	10	1
Optimal Strategies based on Minimum Risk Network Expected Loss		S10	S7, S10	S4, S7, S10	S4, S5, S7, S10	S4, S5, S7, S9, S10	All except S1, S2, S3 and S6	All except S1, S2 and S6	All except S2 and S6	All except S2	All
Risk Network Expected Loss	24.6	22.5	21.2	19.6	18.2	17.1	16.1	15.3	14.5	13.8	13.4
Improvement in Risk Network Expected Loss less Cost		0.1	0.4	1.0	1.4	1.5	0.5	-0.7	-1.9	-3.2	-3.8
Mitigation Cost	0	2	3	4	5	6	8	10	12	14	15
Optimal Strategies based on Maximum Improvement in Risk Network Expected Loss less Cost		S7	S4, S7	S4, S5, S7	S4, S5, S7, S9	S4, S5, S7, S9, S10	All except S1, S3, S6 and S8	All except S1, S3 and S6	All except S1 and S6	All except S6	All
Risk Network Expected Loss	24.6	23.3	21.6	20.3	19.2	17.1	16.7	15.7	14.9	14.1	13.4
Improvement in Risk Network Expected Loss less Cost		0.3	1.0	1.3	1.4	1.5	0.9	-0.1	-1.3	-2.5	-3.8
Mitigation Cost	0	1	2	3	4	6	7	9	11	13	15

Table 5.6: Prioritisation of optimal risk mitigation strategies corresponding to different objective functions and resource constraint.

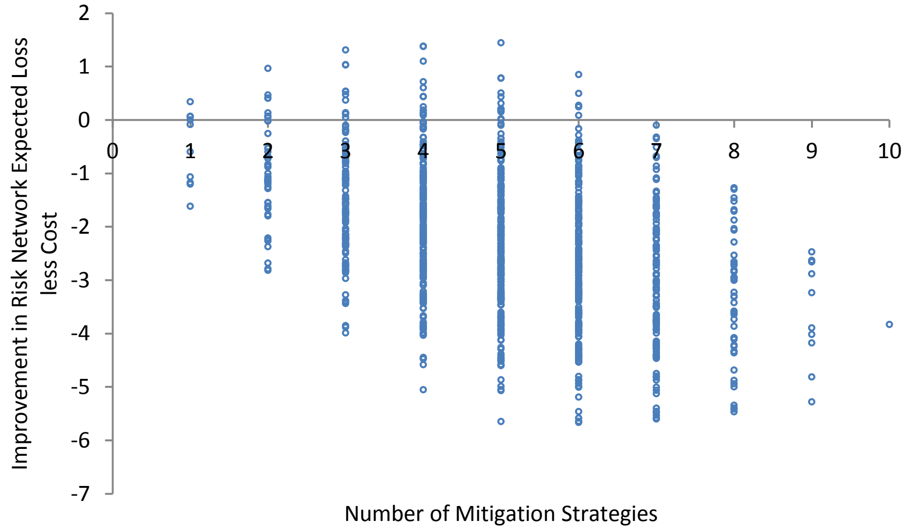

Figure 5.11: Variation of improvement in risk network expected loss less cost with the number of strategies.

which reveal the difference in selected combinations corresponding to the budget constraint. All combinations of strategies including the optimal solutions related to the objective function are shown in Figure 5.12. The optimal solutions for the objective function against specific budget constraints are represented by the corresponding lowest points. The graph indicates that the rate of improvement decreases with the increase in mitigation cost. Improvement in the risk network expected loss considering the cost of implementing strategies is shown in Figure 5.13. Maximum net benefit (improvement in risk network expected loss less cost) is achieved at a cost of 6 units.

Let us assume that the decision maker has implemented all potential strategies. In order to prioritise risks for the risk monitoring stage, we evaluated the values for the risks as shown in Figure 5.14. If we compare the results with the prioritisation results shown in Figure 5.8, the conditional expected loss and the marginal probability values for all the risks are reduced substantially. R6 is the most significant risk for developing a contingency plan. Evaluation of risk mitigation strategies through the proposed approach helps in identifying an optimal mix of preventive and reactive strategies. As the approach incorporates

Mitigation Cost	Minimum Risk Network Expected Loss	
	Strategies	Risk Network Expected Loss
0	-	24.6
1	S7	23.3
2	S4, S7	21.6
3	S4, S5, S7	20.3
4	S4, S5, S7, S9	19.2
5	S4, S5, S7, S10	18.2
6	S4, S5, S7, S9, S10	17.1
7	All except S1, S3, S6 and S8	16.7
8	All except S1, S2, S3 and S6	16.1
9	All except S1, S3 and S6	15.7
10	All except S1, S2 and S6	15.3
11	All except S1 and S6	14.9
12	All except S2 and S6	14.5
13	All except S6	14.1
14	All except S2	13.8
15	All	13.4

Table 5.7: Prioritisation of optimal risk mitigation strategies corresponding to the objective function with budget constraint.

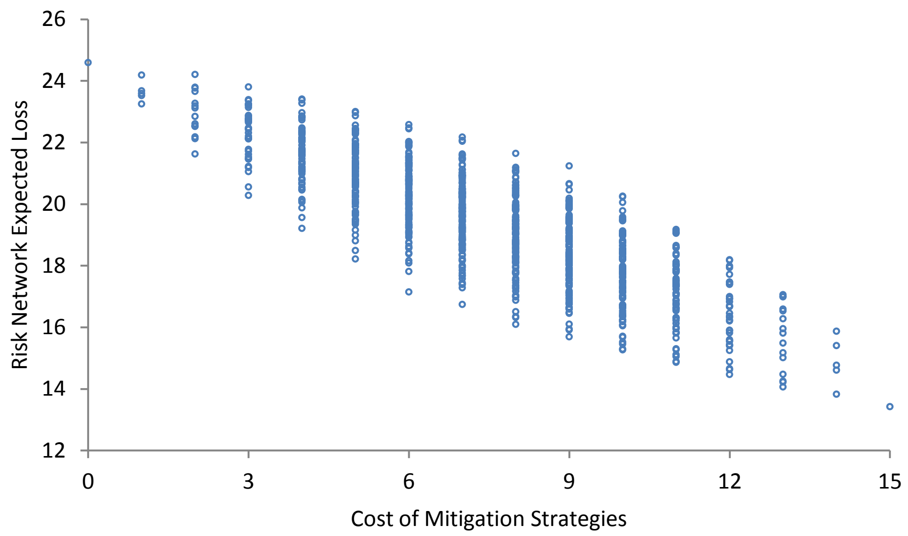

Figure 5.12: Variation of risk network expected loss with the cost of strategies.

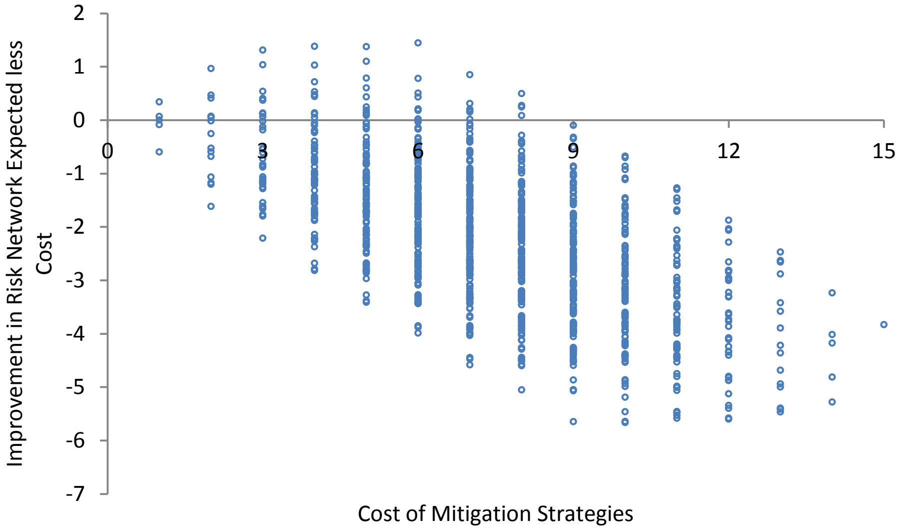

Figure 5.13: Variation of improvement in risk network expected loss less cost with the cost of strategies.

interdependencies between supply chain risks, risk sources and mitigation strategies and follows a rigorous approach grounded in the theoretical framework of BBNs, the resulting solution can be considered as viable. However, it is assumed that the network structure and elicited values would truly reflect the real-time risk scenario. Adopting standard procedures of expert judgement can reduce the associated problems.

5.7 Summary

This chapter proposes a SCRM process within the theoretically grounded framework of BBNs and FMEA in order to model risks ranging across a substantial network comprising many supply chain actors as opposed to the process mapping of a supply chain that involves brainstorming of risks following the supply network configuration. The proposed method can help in determining an optimal mix of strategies in relation to budget and resource constraints.

Dependency based risk measures were introduced for ranking risks and evaluating strategies that represent the relative contribution of each risk to the loss

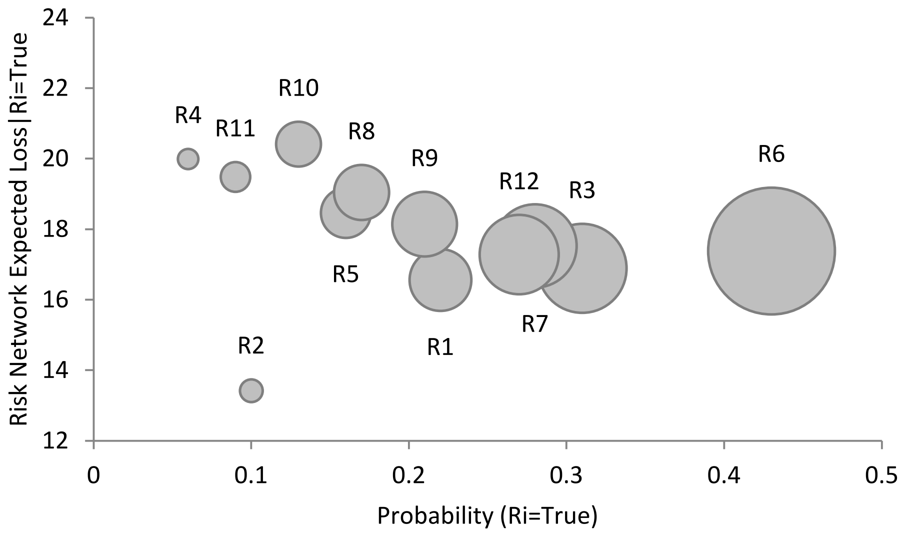

Figure 5.14: Risk spectrum representing ranking of interdependent risks for the risk monitoring stage with size of each bubble reflecting the relative value of $RNELPM$.

propagation across the network of interconnected risks in the scenario of its activation. The proposed risk measures will overcome the shortcomings related to the techniques adopting the notion of independent risks and solution concepts focusing on optimising a single variable or a set of variables. A simulation study was presented to demonstrate the application of the process. Measures based on techniques other than BBNs are not able to capture the probabilistic interactions between risks and they fail to account for causal and diagnostic inferencing. For a risk-neutral decision maker, $RNELPM$ is an appropriate risk measure whereas UTC is a suitable choice to capture the loss-averse attitude of a decision maker.

The concept of Shapley value was introduced in order to determine a fair allocation of resources to mitigate risks once the mitigation strategies with associated costs are not already established within a network setting. The key features of FMEA were utilised in identifying risk sources, risks and mitigation strategies and integrated within the framework of BBNs. The proposed modelling approach can help supply chain managers visualise interdependency between supply chain risks. Stakeholders can identify important risk sources, risks and mitigation strategies using the FMEA technique and evaluate the impact of different risk mitigation strategies on the entire web of interconnected risks. It is also important to realise that the crucial decision of selecting an optimal mix of preventive and reactive strategies can only be made after following the proposed rigorous approach of modelling interdependencies between risks and mitigation strategies. The next chapter develops upon the risk measures introduced to propose a process for capturing the risk appetite of a decision maker.

Chapter 6

Supply Chain Risk Network Management: A Paradigm Shift towards Modelling Systemic Risks and Risk Appetite

6.1 Introduction

This chapter introduces a major research gap that has gained limited attention in the literature on SCRM. Furthermore, a new supply chain risk management process namely SCRNM is proposed. Algorithms are introduced for assessing and mitigating interdependent risks with regard to the risk-neutral and risk-averse/seeking decision makers. The conventional risk matrix is transformed in order to make it compatible for assessing interdependent supply chain risks in relation to the utility indifference curves specific to a decision maker. A second approach is also introduced to help supply chain risk managers identify the Pareto optimal set of risk mitigation strategies and select an optimal solution subject to a budget constraint and specific risk appetite.

6.2 Literature Review

A number of articles focusing on the SCRM process/framework were reviewed as shown in Figure 6.1. Existing literature reviews were also reviewed in order to substantiate the findings. A number of journals were consulted for finding relevant studies. The main criterion was to select quality articles focusing on risk management process/framework through the lens of ABS that publishes quality ratings of academic journals. The list of journals and corresponding ABS rating are shown in Table 6.1. A total of 19 articles were found conforming to the criterion as shown in Table 6.2. We classified the articles with respect to four categories: interdependency modelling of risks; risk appetite of the decision maker; interdependency between risks and strategies; and research methodology (qualitative/quantitative).

S. No	Journal	ABS rating
1	Journal of Operations Management	4*
2	Management Science	4*
3	Omega	4*
4	European Journal of Operational Research	4
5	International Journal of Operations and Production Management	4
6	Production and Operations Management	4
7	Risk Analysis	4
8	Annals of Operations Research	3
9	Computers and Operations Research	3
10	Decision Sciences	3
11	Decision Support Systems	3
12	Expert Systems with Applications	3
13	IEEE Transactions on Engineering Management	3
14	International Journal of Management Reviews	3
15	International Journal of Production Economics	3
16	International Journal of Production Research	3
17	Journal of Risk and Uncertainty	3
18	Journal of Supply Chain Management	3
19	Journal of the Operational Research Society	3
20	Judgment and Decision Making	3
21	Naval Research Logistics	3

Continued on next page

Table 6.1 – continued from previous page

S. No	Journal	ABS rating
22	Operations Research	3
23	Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability	3
24	Production Planning and Control	3
25	Reliability Engineering and System Safety	3
26	Supply Chain Management: An international Journal	3
27	International Journal of Physical Distribution & Logistics Management	2
28	Journal of Business Logistics	2
29	Journal of Purchasing and Supply Management	2
30	Journal of Risk Research	2
31	Management Decision	2
32	Operations Research Letters	2
33	International Journal of Logistics Management	1
34	International Journal of Logistics: Research and Applications	1

Table 6.1: List of journals for selection of articles (Source: 2015 ABS Academic Journal Quality Guide).

Harland et al. (2003) developed a supply network risk management tool and applied it to the electronics sector through conducting four case studies. The main merit of the tool is its exclusive focus on collaborative risk management achieved through engaging the stakeholders across a supply network. Building on the same concept of network wide management of risks, Hallikas et al. (2004) introduced a risk management process integrating different perspectives of supply chain actors and emphasised the need for adopting Systems approach in order to understand the complex dynamics across a network. Systems-oriented SCRM process is also introduced by Oehmen et al. (2009) that captures the interdependency between risks. Advocating the need for adapting the degree of risk management with regard to the contextual factors, Giunipero & Eltantawy (2004) introduced a risk management framework contingent on four determinants: degree of product technology; need for security; importance of the supplier; and purchaser's prior

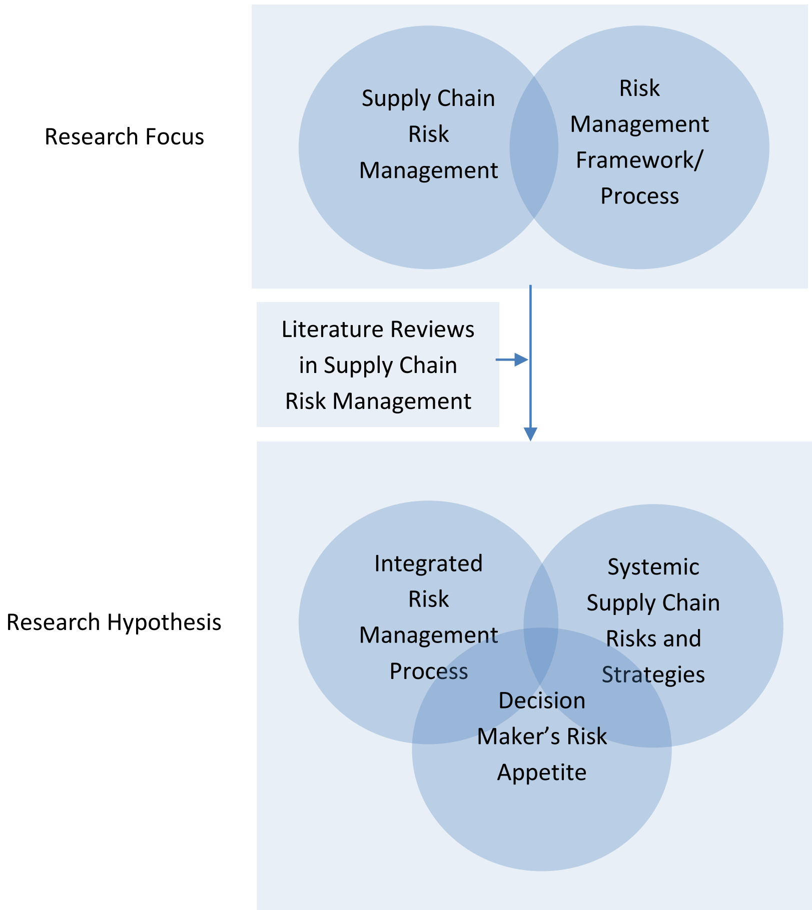

Figure 6.1: Research focus and the hypothesis.

Article	Interdependency modelling of risks	Risk appetite	Interdependency between risks and strategies	Qualitative (*)/ Quantitative (o)
Harland et al. (2003)				*
Hallikas, Karvonen, Pulkkinen, Virolainen, and Tuominen (2004)				*
Giunipero and Eltantawy (2004)				*
Norrman and Jansson (2004)				Semi-quantitative
Sinha et al. (2004)				*
Kleindorfer and Saad (2005)				Semi-quantitative
Khan et al. (2008)				*
Manuj and Mentzer (2008)			x	*
Knemeyer et al. (2009)		x	x	Semi-quantitative
Oehmen et al. (2009)	x		x	*
Tuncel and Alpan (2010)			x	o
Tummala and Schoenherr (2011)				*
Lavastre et al. (2012)		x		Semi-quantitative
Elleuch et al. (2014)			x	o
Rotaru, Wilkin, and Ceglowski (2014)				*
Micheli et al. (2014)			x	o
Aqlan and Lam (2015)			x	o
Giannakis and Papadopoulos (2016)	x			Semi-quantitative
Qazi et al. (2017)	x		x	o

Table 6.2: Selected articles with focus on different research themes.

experience with the situation. Supply chain operations reference model (SCOR) has also been modified and considered as an important framework for managing supply chain risks (Sinha et al., 2004; Rotaru et al., 2014). The main limitation of the aforementioned studies and other risk management frameworks proposed by Manuj & Mentzer (2008a), Khan et al. (2008) and Tummala & Schoenherr (2011) is their limited focus on capturing the interdependency between risks.

Only two of the selected studies (Knemeyer et al., 2009; Lavastre et al., 2012) considered the risk appetite of a decision maker as an important factor and included it in the SCRM framework. Although risk attitude has been considered in the modelling framework of a number of studies as mentioned in the literature review conducted by Heckmann et al. (2015), these articles fail to meet the selection criterion of this study because of their focus on a specific stage of the risk management process.

Among the quantitative studies, Tuncel & Alpan (2010) used a timed petri nets framework to model and analyse a supply chain which is subject to various risks. They used FMEA to identify important risks having higher values of RPN. Elleuch et al. (2014) proposed a comprehensive risk management process integrating the techniques of FMEA, design of experiments, AHP and desirability function approach. Micheli et al. (2014) and Aqlan & Lam (2015) introduced optimisation based techniques for selecting optimal risk mitigation strategies. Although all the mentioned quantitative studies consider interdependency between risks and strategies, critical aspect of modelling interdependency between risks and the risk appetite of a decision maker is ignored. Utilising BBNs, Qazi et al. (2017) introduced probabilistic supply chain risk measures to prioritise interdependent risks and strategies. Although one of the measures introduced captures risk-averse appetite, the entire risk management process does not explicitly model the risk attitude of a decision maker. Similarly, Garvey et al. (2015) introduced risk measures for prioritising interdependent risks assuming a risk-neutral decision maker.

A number of articles focusing on literature reviews were also reviewed (Juttner et al., 2003; Tang, 2006a; Khan & Burnes, 2007; Natarajarathinam et al., 2009; Rao & Goldsby, 2009; Ponomarov & Holcomb, 2009; Olson & Wu, 2010; Tang & Nurmaya Musa, 2011; Ghadge et al., 2012; Colicchia & Strozzi, 2012; Sodhi et al., 2012; Ho et al., 2015; Heckmann et al., 2015) and it was revealed that only two studies have emphasised the need for modelling interdependency between risks: *"... developing structured and systematic tools for risk identification and assessment that explicitly consider the dynamic interactions among supply chain partners and among risk sources"* (Colicchia & Strozzi, 2012, p. 412), and *"... While focusing on a particular risk type has its advantages, interdependencies and interrelationships among various risk types is certainly an issue that needs to be further explored. Investigating the joint impact of such risks can lead to better management of supply chains than treating each risk type in isolation"* (Ho et al., 2015, p. 5060).

Similarly, despite the fact that existing SCRM frameworks fail to integrate all stages of the risk management process within an interdependent setting of risks and strategies, only two articles have realised the importance of conducting research in this direction: *"The multidimensional perspective focusing on management processes, risk dimensions, impact flows and mitigation alternatives needs to be studied in whole"* (Ghadge et al., 2012, p. 329), and *"As there is a significant relationship between all SCRM processes, more attention should be given to legitimately integrated processes instead of individual or fragmented processes"* (Ho et al., 2015, p. 5053). Another major issue concerning these studies is their limited focus on the need for integrating risk appetite in the risk management process as only Heckmann et al. (2015) realise that *"More advanced (context-sensitive) approaches especially with respect to the risk attitude of the decision maker and with respect to the environment of the affected supply chain are needed"* (Heckmann et al., 2015, p. 130). Critical review of the selected articles focusing on the SCRM process/framework and literature reviews reveals an important finding that an integrated risk management framework considering the interdependency between risks and mitigation strategies and the risk appetite of a decision maker has neither been explored nor mentioned as a research gap for directing future research.

6.3 Expected Utility and Decision Making under Uncertainty

Within the context of decision making under uncertainty, risk can be related to a utility function that reflects the preference of a decision maker with regards to various possible losses or consequences of a decision. According to Aven (2012a), if X and $u(X)$ represent the possible outcomes associated with a decision and utility function respectively, then the expected utility '$E[u(X)]$' provides a decision criterion where probabilities and a utility function are assigned on the set of outcomes and a rational decision maker selects an action that maximises the expected utility value. The utility function represents the risk attitude of a decision maker where a risk-neutral decision maker would be indifferent between two outcomes having the same expected value and a risk-seeking (averse) individual would consider uncertainty to be an (un)favorable phenomenon. The following equations (inequalities) represent different risk attitudes:

$$\text{Risk-neutral} : E[u(X)] = u(E[X]) \tag{6.1}$$

$$\text{Risk-averse} : E[u(X)] < u(E[X]) \tag{6.2}$$

$$\text{Risk-seeking} : E[u(X)] > u(E[X]) \tag{6.3}$$

For gaining an insight into developing the utility function, interested readers

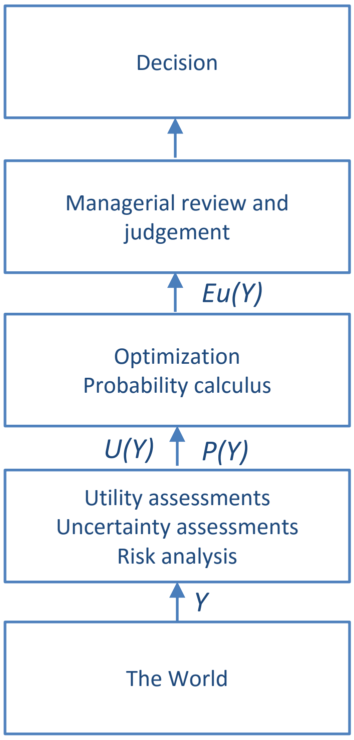

Figure 6.2: Basic structure of the decision-making process when utilities are used (Source: Aven 2012b).

may consult Kainuma & Tawara (2006). For the decision making under uncertainty (Aven, 2012b) (see Figure 6.2), the starting point is the world represented by Y that reflects the scope of the system for modelling. The uncertainty assessment of the real world results in the calculated values of probabilities $P(Y)$ and elicited values of utilities $u(Y)$. These values are combined together to evaluate the expected utility value, $Eu(Y)$ with the maximisation of this measure yielding the optimal decision alternative within the framework.

Although EUT provides a standardised normative framework to make decisions under uncertainty, it is not so much used in practice mainly because of the difficulty associated with assigning utility values to all possible outcomes (Aven & Kristensen, 2005). Secondly, a decision maker in many cases would not seek to maximise the expected utility rather solutions yielding satisfactory results might be preferred. Use of cost-benefit analysis (Spackova & Straub, 2015) and risk matrix based tools (Duijm, 2015) is widely reported in the literature where instead of utilising an array of utility values for all possible outcomes, the decision maker maps risks on a two-dimensional plane with associated probability and loss values and a simple approach is adopted to manage risks through the lens of cost-benefit analysis balancing costs with the benefits. The proposed method is aimed at enhancing the risk matrix and cost-benefit analysis based approach to account for interdependencies between supply chain risks and strategies and the risk appetite of a decision maker.

6.4 Existing SCRM Process and Concept of Utility Indifference Curves Based Risk Matrix

There is a consensus among researchers that the SCRM process comprises five sequential stages: risk identification; assessment; analysis; treatment; and monitoring (Giannakis & Papadopoulos, 2016) that are analogous to the stages of the standard risk management process (SA, 2009). We present a very simple example to illustrate these stages and identify the main issue with adopting this process in case of interdependent risks. In the risk identification stage, specific risks must be identified. Let us assume that there are five risks namely R1, R2, R3, R4 and R5 that have been identified for a hypothetical supply chain using standard tools of checklists, risk mapping and taxonomies. In the risk assessment stage, each risk is assigned the probability and impact values and in our example, we assign arbitrary values to the risks as shown in Table 6.3. These risks are subsequently mapped on a risk matrix for the sake of prioritisation (risk analysis) and selecting risk mitigation actions (risk treatment).

Risk matrix is a two-dimensional plot of risks characterised by the corresponding probability and impact values. For a detailed overview of the history of risk matrix based tools and associated shortcomings, interested readers may refer to the study conducted by Duijm (2015). One of the main limitations of these tools

Table 6.3: Risk parameters.

Risk	Probability	Impact
R1	0.7	1200
R2	0.4	600
R3	0.1	500
R4	0.5	800
R5	0.9	700

is their lack of capturing the risk attitude of a decision maker. Using utility theory, Ruan et al. (2015) introduced a three step process for integrating risk attitude in the risk matrix by: (a) describing risk attitudes of decision makers by utility functions; (b) introducing utility indifference curves and embedding these into the risk matrix; and (c) discretising utility indifference curves. Integration of indifference curves representing the decision maker's preferences within the risk matrix results in discretising the risk matrix into five risk zones: Negligible-no need for further concern; Acceptable-need for monitoring the risks with no investment; Controllable-need for adopting emergency plans; Critical-need for mitigating risks as long as the benefits exceed the costs; and Unacceptable-need for bringing the risks down to the critical level at any cost.

Firstly, the utility function of a decision maker must be established. As opposed to the concept of utility adopted in the standard expected utility approach where utility is mapped over the set of all possible outcomes, the utility function used here represents the utility of a decision maker with respect to the loss realising from an individual risk. In this example, we assume that the decision maker is risk-neutral (utility of loss $[u(l)] = loss$). The utility indifference curves segregate the entire risk matrix into five regions: unacceptable; critical; controllable; acceptable; and negligible risk zones (Ruan et al., 2015). Therefore, we need a total of four utility indifference curves in order to establish the boundaries of these five regions as shown in Figure 6.3. Each indifference curve represents a particular risk level comprising a number of points with different combinations of probability and utility of loss values. Equation 6.4 represents a utility indifference curve where p' and $u(l')$ are the probability and utility of loss values, respectively specific to a reference point on the curve (Ruan et al., 2015).

$$p * u(l) = p' * u(l') \tag{6.4}$$

Considering the reference point as having a probability of 1, Equation 6.4 is transformed as follows:

$$p * u(l) = u(l') \tag{6.5}$$

The value of $u(l')$ is unique for each curve and influenced by the risk appetite of a decision maker. For a detailed discussion on selecting the reference points and segregating the risk matrix into risk zones, interested readers may refer to Ruan et al. (2015). In the case of a risk-neutral decision maker, Equation 6.5 is reduced to:

$$p * l = u(l') \tag{6.6}$$

The five zones representing relative importance of risks are unacceptable (R-I), critical (R-II), controllable (R-III), acceptable (R-IV) and negligible (R-V) as shown in Figure 6.3. The unacceptable zone also includes the area of the risk matrix beyond the threshold impact (in this case, above the line: Impact=1500). We have assumed that 1500 is the maximum tolerance level of the decision maker beyond which a risk with any probability value must be mitigated. Each risk considered in our example occupies a specific zone. The values of $u(l')$ (corresponding to the reference points A, B, C and D) specific to the four indifference curves are assumed as -695, -521, -347 and -174, respectively.

As $R1$ is an unacceptable risk, it must be mitigated at any cost. $R5$ must be mitigated if the benefit exceeds the cost. We can identify a strategy or combinations of strategies that would either reduce the probability or impact of a risk or a

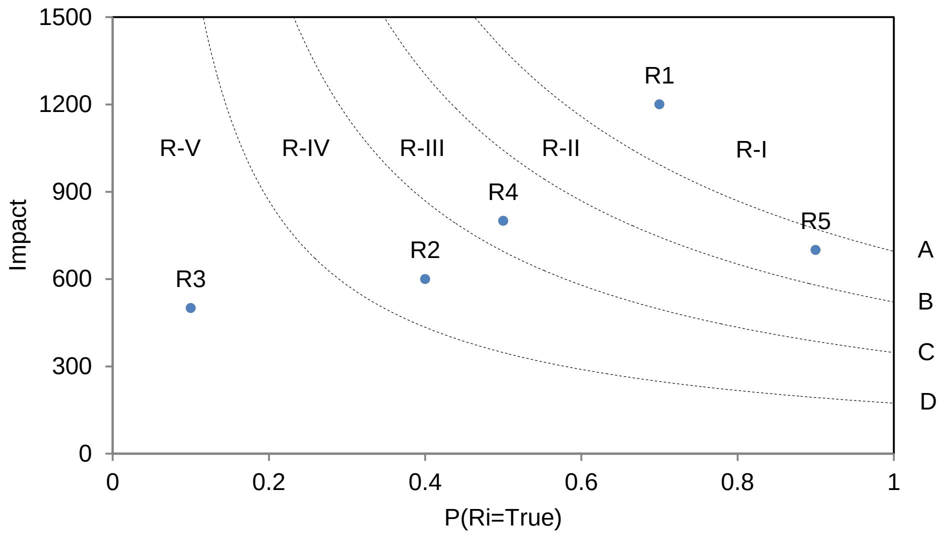

Figure 6.3: Utility indifference curves based risk matrix.

set of risks. It is very easy to conduct the risk treatment as we only need to evaluate the benefits through executing simple arithmetic operations and weigh these against the total cost of implementing strategies. Therefore, we can prioritise risks and select optimal strategies through following a sequential risk management process. During the risk monitoring stage, any new risk(s) and/or changes in the parameters of existing risks must be incorporated in the risk matrix.

6.5 Motivation for Developing a New Process

Now let us consider that instead of a set of independent risks, we are dealing with a network of risks where there are interdependencies between risks and a risk might have a (positive or negative) correlation with another risk or a set of risks. Similarly, a mitigation strategy can have an association with multiple risks or multiple strategies can influence a single risk. Existing frameworks fail to account for evaluation and treatment of such network of risks. In the case of interdependent risks, we need to marginalise the probability values through assigning conditional probability values to the risks. The existing risk matrix based tools are not capable of projecting the criticality of interdependent risks.

Furthermore, the criterion for conducting cost-benefit analysis for the network of risks and potential strategies taking into account the risk appetite of a decision maker and linking it back to the performance of individual risks on the risk matrix is not established. In the case of risk treatment, we can no longer rely on simple mathematical operations as each potential strategy or a combination of strategies must be linked to the risk network and the marginal probability values of risks must be re-evaluated and the resulting risks mapped again on the risk matrix. Therefore, it makes the process as iterative rather than sequential.

EUT being widely used in decision making under uncertainty provides a systematic approach of evaluating optimal strategies (Aven, 2015); however, even for a very simple network of 5 risks and 5 strategies, a total of 1024 values must be elicited from the decision maker with regard to the utility of different combinations of risks and strategies. Furthermore, as reported in the literature on risk management, practitioners rely on risk matrix based tools to prioritise risks (Ruan et al., 2015). Therefore, we aim to propose a method through modifying the utility indifference curves based risk matrix (Ruan et al., 2015) and utilising cost-benefit analysis to prioritise supply chain risk mitigation strategies taking into account the risk appetite of a decision maker.

6.6 Proposed Risk Matrix Based Process

We adapt the established risk management framework (SA, 2009) as it is used widely both by the researchers and practitioners (Ahmed et al., 2007). Although the description of terms and concepts used in the framework is controversial (Aven, 2011), our focus is limited to the stages involved in the process. The proposed process is shown as Figure 6.4. Instead of treating risks in silo, we introduce the concept of developing a risk network. The process starts with the specification of context in terms of defining the boundary of a supply chain/network and

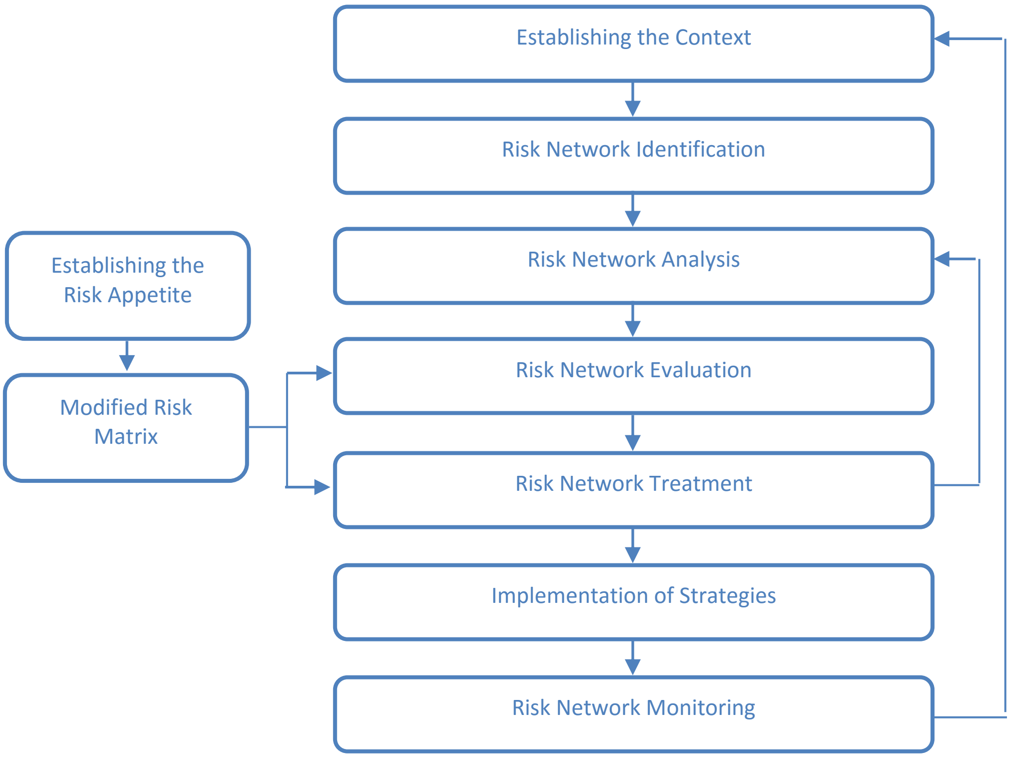

Figure 6.4: Supply chain risk network management (SCRNM).

identifying the stakeholders involved in the risk management process.

Risk network identification is a critical stage where there is a need for bringing a paradigm shift as the existing literature is rife with conventional tools and techniques of identifying risk categories and the concept of developing causal risk paths/risk network has gained limited attention (Badurdeen et al., 2014; Garvey et al., 2015). Besides identifying the risks and risk sources, potential risk mitigation strategies must also be included within the network. Risk network analysis involves determining the (conditional) probability values and loss values associated with risks subject to the implementation of specific risk mitigation strategies.

In the risk network evaluation stage, there is a need to explore new risk measures that can be computed easily and are capable of capturing the network wide impact of risks. The measures are also influenced by the risk appetite. In addition to registering the holistic impact of risks within the network setting,

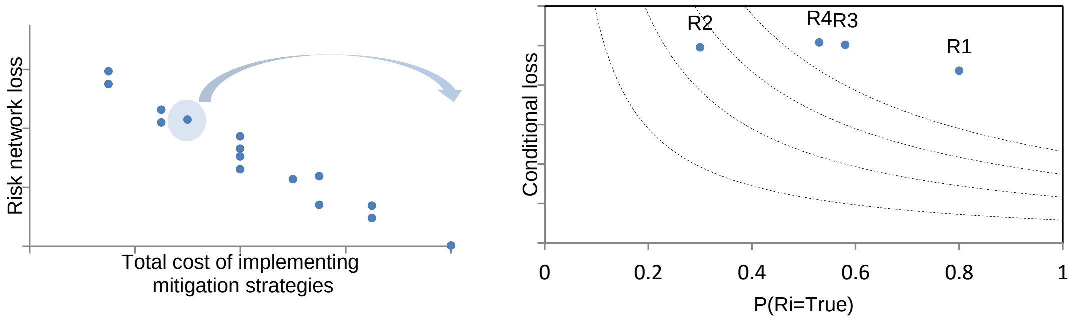

Figure 6.5: Mapping from risk network evaluation to modified risk matrix.

there is also a need for visualising the impact of each risk on the network of risks and ensuring that all risks are mitigated to the required level. Therefore, a modified risk matrix capable of evaluating interdependent risks coupled with the mapping of utility indifference curves (Ruan et al., 2015) must be developed and consulted for risk network evaluation as shown in Figure 6.5.

As the objective of our research is to introduce a risk management process for interdependent risks, we are not focusing on the techniques for establishing the risk appetite of a decision maker and mapping utility indifference curves on the modified risk matrix. The procedure proposed by Ruan et al. (2015) can be utilised for implementing the proposed process. However, we are not dealing with the discretisation of risk matrix because of the probability and loss values used in the proposed risk management process. Appropriate risk measures representing the network wide holistic impact of risks can be used for risk analysis/evaluation and corresponding to each combination of strategies, the configuration of individual risks ($R1$, $R2$, $R3$, $R4$) can be mapped on the modified risk matrix. The matrix is bounded by the upper limit of loss beyond which a risk irrespective of its probability value must be treated.

Risk network treatment deals with the evaluation of different combinations of risk mitigation strategies within the network setting. The modified risk matrix provides a lens to evaluate the efficacy of strategies and establish if additional strategies must be implemented. The proposed process flow is in contrast with the one established in extant literature as instead of following a unidirectional flow, it is an iterative process where evaluation of each combination of strategies necessitates re-assessing and re-evaluating the risk network. The iterative process results in the selection of an optimal combination of strategies that not only considers the network wide holistic effect of these strategies but also yields an acceptable configuration of risks mapped on the modified risk matrix. The matrix also helps in identifying critical risks that must be monitored periodically. After determining the optimal combination of strategies, these are implemented and as risk management is a continuous process, there is a need for continuously monitoring risks and updating the risk network on a regular basis.

6.6.1 Proposed Approach

Modelling Assumptions

The model is based on the following assumptions:

- Supply chain risks, corresponding sources and potential mitigation strategies are known and these can be modelled as an acyclic directed graph.
- All random variables and risk mitigation strategies are represented by binary states.
- Conditional probability values for the risks and associated losses can be elicited from the stakeholders and the resulting network represents close approximation to the actual perceived risks and interdependency between different risks.
- Cost associated with each potential risk mitigation strategy is known.

Supply Chain Risk Network

A discrete supply chain risk network $RN = (X, G, P, L, U, C)$ is a six-tuple consisting of:

- a directed acyclic graph (DAG), $G = (V, E)$, with nodes, V, representing discrete risks and risk sources, X_R, discrete risk mitigation strategies, X_S, and directed links, E, encoding dependence relations,
- a set of conditional probability distributions, P, containing a distribution, $P(X_{R_i}|X_{pa(R_i)})$, for each risk and risk source, X_{R_i},
- a set of loss functions, L, containing one loss function, $l(X_{pa(V)})$, for each node v in the subset $V_l \in V$ of loss nodes,
- a set of utility functions, U, containing one utility function, $u(X_{pa(V)})$, for each node v in the subset $V_u \in V$ of utility nodes,
- a set of cost functions, C, containing one cost function, $c(X_{pa(V)})$, for each node v in the subset $V_c \in V$ of cost nodes.

Risk network expected loss, $RNEL(X)$, is given by (Qazi et al., 2015):

$$RNEL(X) = \prod_{X_v \in X_R} P(X_v|X_{pa(v)}) \sum_{w \in V_L} l(X_{pa(w)}) \tag{6.7}$$

Expected utility for loss, $EU(X)$, is given by (Qazi et al., 2015):

$$EU(X) = \prod_{X_v \in X_R} P(X_v|X_{pa(v)}) \sum_{w \in V_L} u(X_{pa(w)}) \tag{6.8}$$

Risk network expected utility, $RNEU(X, C(X_{S_i}))$ or $RNEU$, is given by:

$$RNEU = f(EU(X), C(X_{S_i})) \tag{6.9}$$

where X_{S_i} is a combination of potential strategies.

Risk Measure. We make use of a risk measure namely Risk Network Expected Loss Propagation Measure ($RNELPM$) in order to evaluate the relative contribution of each supply chain risk towards the loss propagation across the entire network of risks. $RNELPM$ is the relative contribution of each risk factor to the propagation of loss across the entire network of supply chain risks given the scenario that the specific risk is realised (Qazi et al., 2017).

$$RNELPM_{X_{R_i}} = RNEL(X|X_{R_i} = true) * P(X_{R_i} = true) \tag{6.10}$$

Risk Configuration Metric. Risk configuration metric (RCM) represents the preference of a decision maker with regard to the configuration of risks on the modified risk matrix specific to a particular combination of available strategies represented by X_{S_i}. A pure qualitative metric focusing on the relative number of risks within each risk zone may be represented as follows:

$$RCM_{X_{S_i}} = \frac{n_1 * a_1 + n_2 * a_2 + n_3 * a_3 + n_4 * a_4 + n_5 * a_5}{N} \tag{6.11}$$

where n_i and a_i represent the number of risks in the risk zone i and the criticality significance of risk zone i on a normalised scale $(0 - 1)$, respectively, N is the total number of risks.

However, we consider following risk metric to be appropriate as defined over a range of continuous values and therefore, it will be used in the chapter:

$$RCM_{X_{S_i}} = \sum_{X_R} -u(RNEL_{X_{S_i}}(X|X_{R_i} = true)) * P(X_{R_i})_{X_{S_i}} \tag{6.12}$$

Equation 6.11 is the discretised form of Equation 6.12 where each risk zone is assigned a preference value and any pair of risks located in the same zone would have the same value. The main purpose of using Equation 6.12 is not to treat the individual utility functions of risks as mutually independent and add these together rather to evaluate the preference of the risk configuration specific to a combination of strategies with respect to the utility indifference curves mapped. Therefore, $RCM_{X_{S_i}}$ is a preference measure to help the decision maker prioritise between two different combinations of strategies with regards to the distribution of risks on the risk matrix. Unlike the expected utility approach where all possible combinations of outcomes are evaluated, we only consider the possibility that a particular risk materialises and register the impact of all risks in turn. A combination of strategies yielding an optimal aggregate value of these instantiations subject to the constraints of risk zones and cost-effectiveness is finally selected.

The normalised risk metric is defined as follows:

$$R\bar{C}M_{X_{S_i}} = 1 - \frac{RCM_{X_{S_i}}}{max(RCM_{X_S})} \tag{6.13}$$

where RCM_{X_S} is the entire set of RCM values for all possible combinations of strategies.

Problem Setting

Given five zones of risk prioritisation in the modified risk matrix segregated by the utility indifference curves ($p_i * u(l_i) = -A_j \forall X_{R_i}(p_i, l_i)$ on the curve j) and the threshold loss, l^* (defining the portion of unacceptable zone represented by the area of risk matrix above that threshold line) where the set (A_1, A_2, A_3, A_4) representing constant values arranged in descending order corresponds to the set of curves segregating the five risk zones: unacceptable; critical; controllable; acceptable; and negligible.

What is the optimal set of combinations of strategies, $\bar{S}_p = (\bar{S}_{p_1}, ..., \bar{S}_{p_r})$ with associated set of total cost of mitigation strategies $C(\bar{S}_p) = (C(\bar{S}_{p_1}), ..., C(\bar{S}_{p_r}))$ for the entire risk network such that each $\bar{S}_{p_i}$ (comprising a specific combination

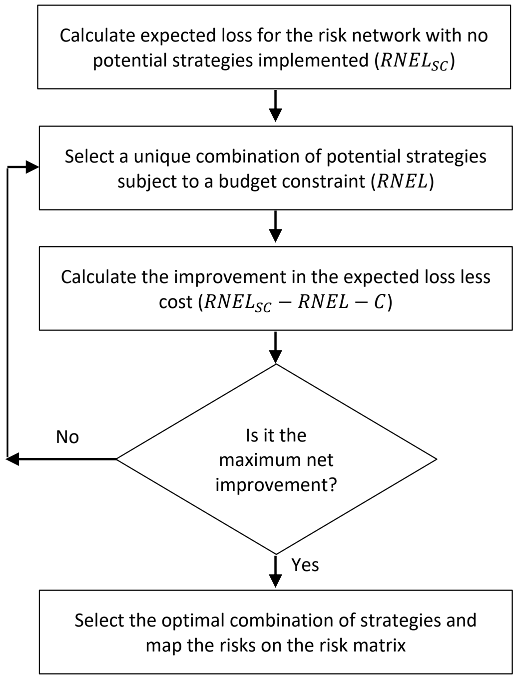

Figure 6.6: Flow chart for selecting optimal strategies specific to a risk-neutral decision maker.

of potential strategies) yields the (maximum) minimum value of the (normalised) risk configuration metric (RCM) subject to the risk mitigation requirements of each risk zone?

Proposed Algorithms

We propose two different algorithms for managing risks corresponding to the risk-neutral and risk-averse/risk-seeking decision makers as shown in Algorithm 1 and Algorithm 2, respectively (see Appendix C). Although the algorithms make use of our proposed risk measure, these are still adaptable for incorporating other risk measures. We have intentionally not included the stage of risk identification as a relevant algorithm already exists for developing the risk network (Garvey et al., 2015). The flow charts specific to Algorithm 1 and Algorithm 2 are shown in Fig 6.6 and Fig 6.7, respectively.

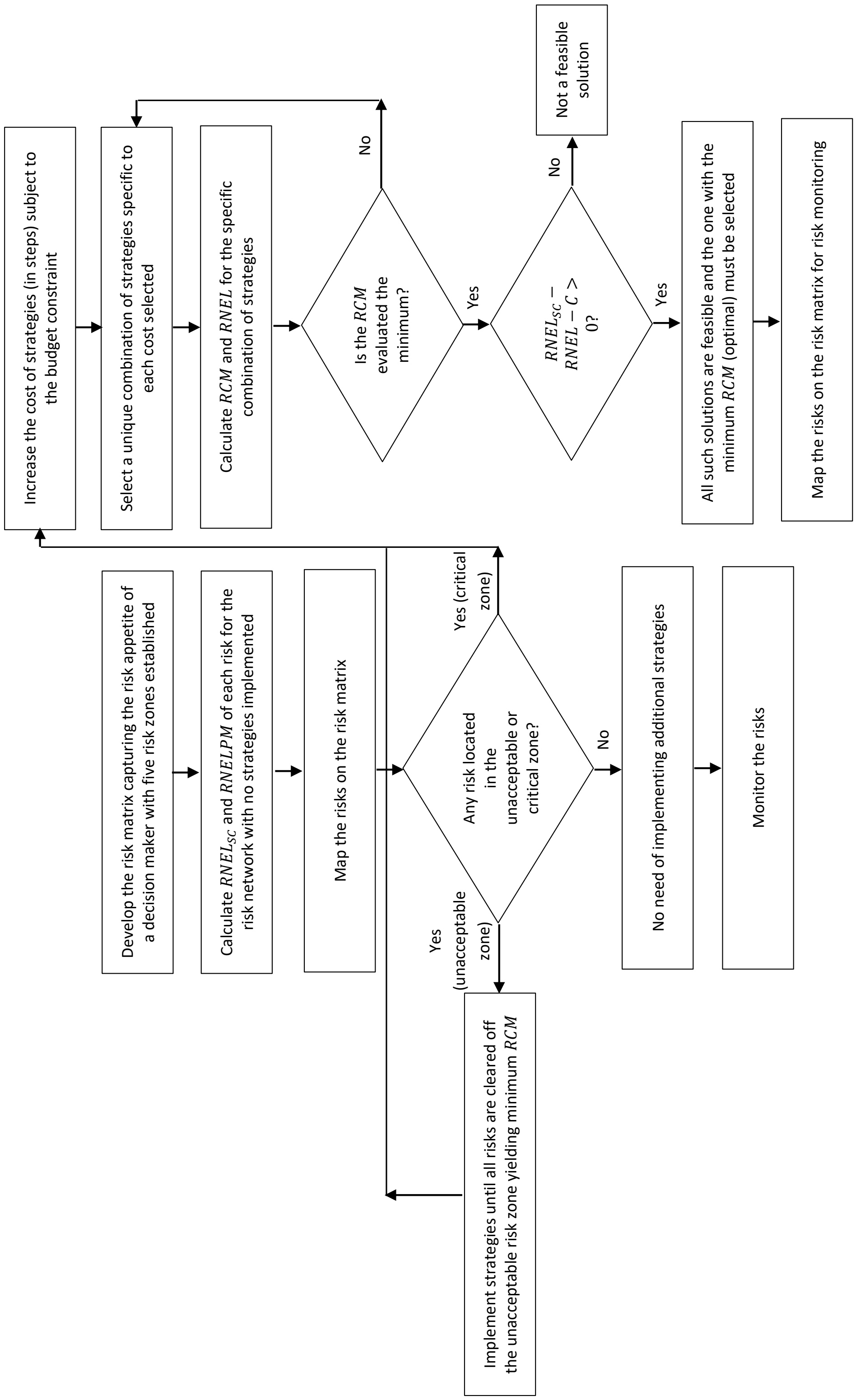

Figure 6.7: Flow chart for selecting optimal strategies specific to a risk-averse (seeking) decision maker.

Modelling Process

Following steps must be followed in developing a BBN based risk network of interacting supply chain risks and risk mitigation strategies:

- Define the boundaries of the supply network and identify stakeholders.
- Identify a network of key risks, corresponding risk sources and potential risk mitigation strategies on the basis of input received from each stakeholder through interviews and/or focus group sessions.
- Refine the qualitative structure of the resulting network involving all stakeholders.
- Elicit (conditional) probability values, loss (utility) values resulting from risks and cost associated with implementing each potential mitigation strategy and populate the BBN with all values.
- Run the model and follow Algorithms 1 and 2 specific to a risk-neutral and risk-averse/risk-seeking decision maker, respectively for assessing and treating risks.
- Validate the model output involving stakeholders.

6.6.2 Illustrative Example: Demonstration of Key Concepts

In order to demonstrate the key concepts introduced, we present a simple network comprising five risks (Ri) and four potential risk mitigation strategies (Si) as shown in Figure 6.8. It is assumed that each risk is associated with a loss value of 100 units and each strategy can be implemented at a cost of 30 units. Each risk is considered to have binary states: True (T) or False (F). Similarly, each mitigation strategy is assumed to be in one of the binary states: Yes (Y) or No

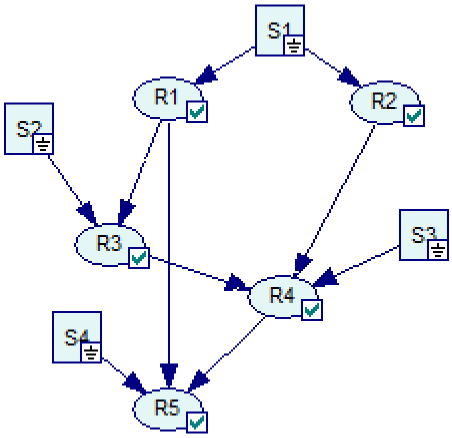

Figure 6.8: Risk network modelled in GeNIe.

(N). The (conditional) probability values are shown in Table 6.4. The shaded cells represent the (conditional) probability values once the corresponding mitigation strategy is selected. It is interesting to consider positive correlation of $S1$ with R2.

Risk-Neutral Decision Maker

A risk-neutral decision maker interested in maximising reduction in the risk network expected loss less cost does not account for the relative importance of each risk in terms of its relative position on the modified risk matrix. The decision maker would only select a combination of strategies and make an investment if there is an increase in the reduction of risk network expected loss less cost. Under the standard configuration, the risks are evaluated with respect to the existing strategies once none of the potential strategies is selected. All possible combinations of potential strategies ($S1$, $S2$, $S3$, $S4$) are shown in Table 6.5.

The relative performance of each combination of strategies is mapped in Figure 6.9. Each point represents a particular combination of strategies with corresponding cost and risk network expected loss. The solid line represents the threshold where the reduction in risk network expected loss is just equal to the cost of implementing strategies. The points (above) below this line represent all

Parents								P(risk = True|parents)				
$R1$	$R2$	$R3$	$R4$	$S1$	$S2$	$S3$	$S4$	$R1$	$R2$	$R3$	$R4$	$R5$
				N				0.8				
				Y				0.6				
				N					0.3			
				Y					0.6			
T					N					0.7		
					Y					0.2		
F					N					0.1		
					Y					0.02		
	T	T				N					0.9	
		F									0.5	
	F	T									0.7	
		F									0.1	
	T	T				Y					0.6	
		F									0.3	
	F	T									0.4	
		F									0.01	
T			T				N					0.7
			F									0.5
F			T									0.2
			F									0.1
T			T				Y					0.3
			F									0.1
F			T									0.1
			F									0.03

Table 6.4: Conditional probability values.

Combination of Risk Mitigation Strategies	Risk Mitigation Strategies	Total Cost
S	-	0
A	S2	30
B	S4	30
C	S3	30
D	S1	30
E	S2, S4	60
F	S2, S3	60
G	S3, S4	60
H	S1, S2	60
I	S1, S4	60
J	S1, S3	60
K	S2, S3, S4	90
L	S1, S2, S4	90
M	S1, S2, S3	90
N	S1, S3, S4	90
O	S1, S2, S3, S4	120

Table 6.5: Combinations of risk mitigation strategies.

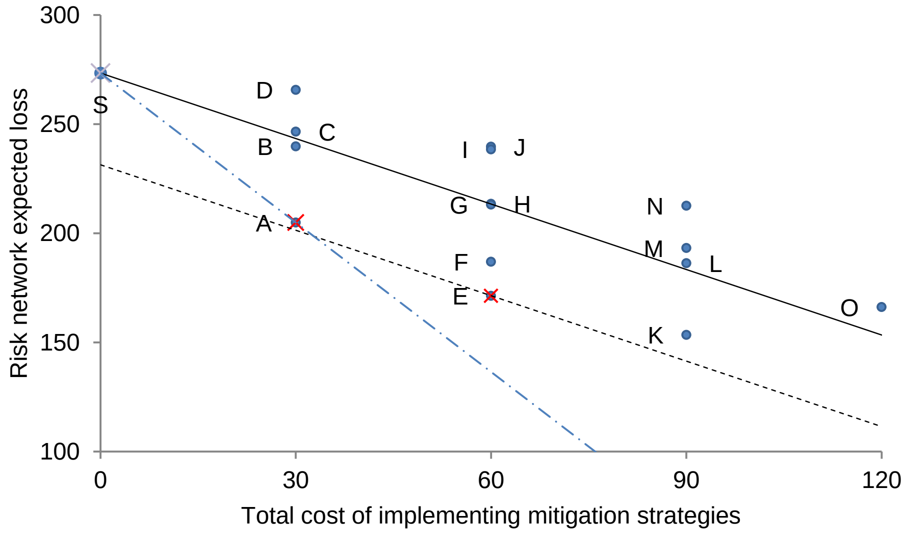

Figure 6.9: Identification of optimal combinations of strategies.

such combinations which are (in)feasible.

The dotted line in black contains the optimal solution (point E) yielding maximum reduction in the network expected loss less cost whereas the dashed line in blue contains the optimal solution (point A) following the criterion of maximising benefit to cost ratio. Although point K is a feasible solution, it is not optimal as it fails to yield a greater reduction in network expected loss less cost relative to that of point E. A red cross represents an optimal solution. The decision maker will select point A if the available budget is less than 60 units but at least 30 units whereas for a budget greater than and inclusive of 60 units, point E is the optimal solution.

Risk-Averse Decision Maker

In the case of a risk-averse decision maker, we assumed the utility function as represented by Equation 6.14. We also assumed that the upper threshold for the loss value is 500 units. Similarly, the selected $u(l')$ values corresponding to the four utility indifference curves are -200, -150, -100 and -50, respectively.

$$u(l) = -(l)^2 \tag{6.14}$$

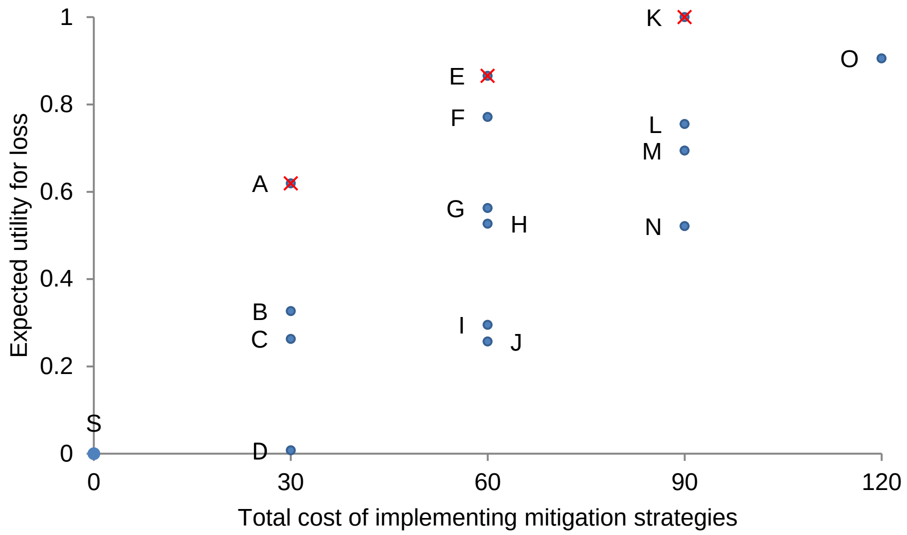

Figure 6.10: Expected utility for loss corresponding to various strategies.

Maximising Risk Network Expected Utility. There are two ways of evaluating the risk network expected utility. We can either combine the cost of strategies and loss associated with different combinations of risks and strategies, or evaluate utility of loss and utility of cost separately and combine these together using an appropriate function and a consistent scale. The first approach needs an input of 512 values as it is not possible to aggregate the individual utility values because of utility being a non-linear function in this example. Using the second approach, we can calculate the expected utility value for loss corresponding to different strategies needing only 32 values as shown in Figure 6.10. Points A, E and K are the optimal combinations of strategies considering expected utility for loss, however, selection of optimal strategies corresponding to risk network expected utility (function of loss and cost) depends on the relative importance of expected utility for loss (w) and utility for cost ($1-w$) as shown in Equation 6.15. Importantly, the scales used for the two functions must be consistent. Point O can never be an optimal solution under any preference setting.

$$RNEU = w * EU(X) + (1-w) * f(C(X_{S_i})) \tag{6.15}$$

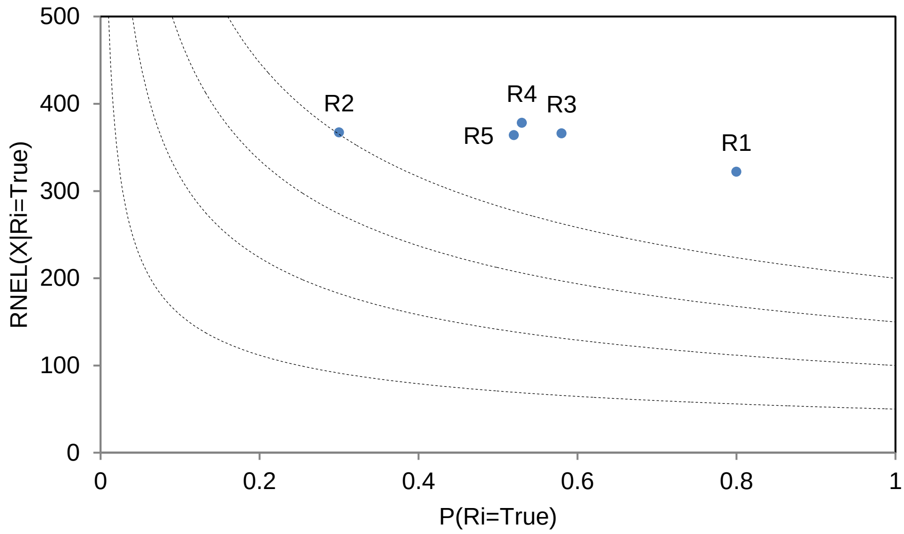

Figure 6.11: Risk network evaluation under standard configuration (Point S).

If we assume that the individual utility functions are independent, we can use Equation 6.16 (Keeney & Raiffa, 1993) to calculate the overall utility for the network.

$$U(A) = \sum_{i=1}^{n} c_i * U_i(A_i) \tag{6.16}$$

where A is the set of n attributes assumed as mutually utility independent, $U_i(A_i)$ is the conditional utility for attribute A_i,
c_i is the relative importance of attribute A_i.

Maximising Normalised Risk Configuration Metric subject to Constraints (related to the Risk Zones). We mapped the risks corresponding to the standard configuration of network as shown in Figure 6.11. It can be seen that all risks are located in the unacceptable zone. Next, we evaluated the normalised risk configuration metric for all combinations of strategies as shown in Figure 6.12. As there are risks located in the unacceptable zone, the constraint of benefit exceeding the cost can be ignored. Therefore, point A is the optimal solution corresponding to the cost of 30 units.

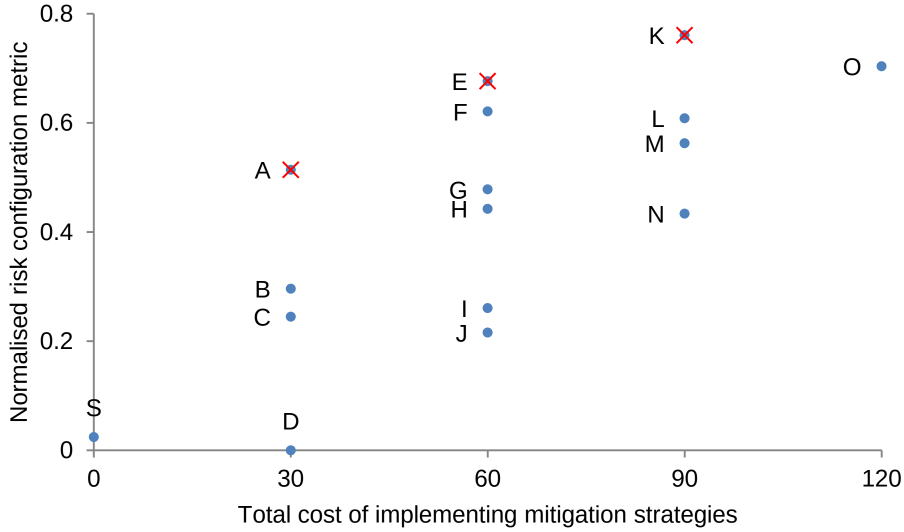

Figure 6.12: Identification of optimal solutions.

The risk configuration corresponding to point A is shown as Figure 6.13. As two risks are still in the unacceptable region, we can ignore the constraint of benefit exceeding cost, however, point E yields the best value corresponding to both criteria (maximising normalised RCM and minimising '$RNEL+cost$'). The risk configuration relative to point E is shown as Figure 6.14. There is no risk in the unacceptable region whereas two risks are located in the critical region. Therefore, point K is the only feasible solution as benefit must exceed cost for further investment as shown in Figure 6.9. As point K yields higher value for normalised RCM relative to that of point E, point K is the optimal solution for budget greater than or equal to 90 units with configuration of risks shown as Figure 6.15. Point O is not a feasible solution to be considered for optimality. A red coloured cross represents an optimal solution. Optimal solutions corresponding to different cost regimes are presented in Table 6.6.

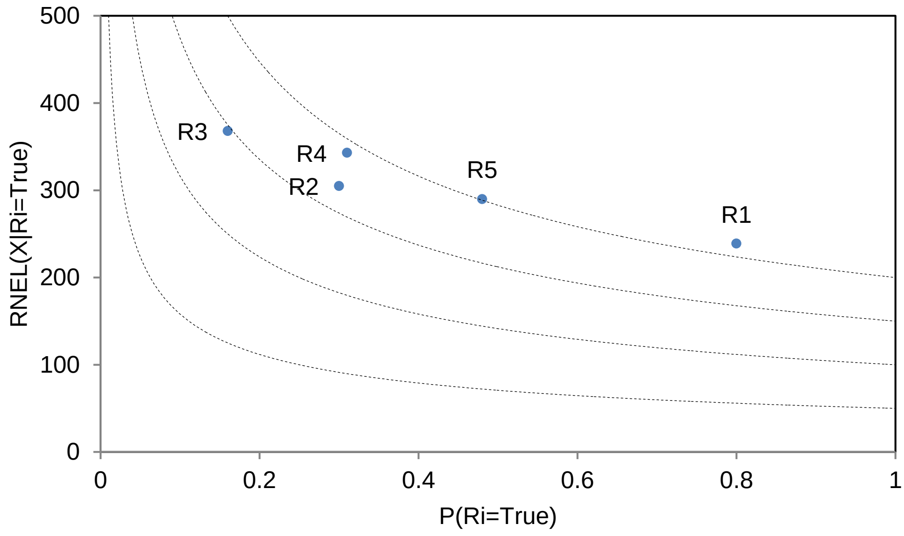

Figure 6.13: Risk network evaluation (point A).

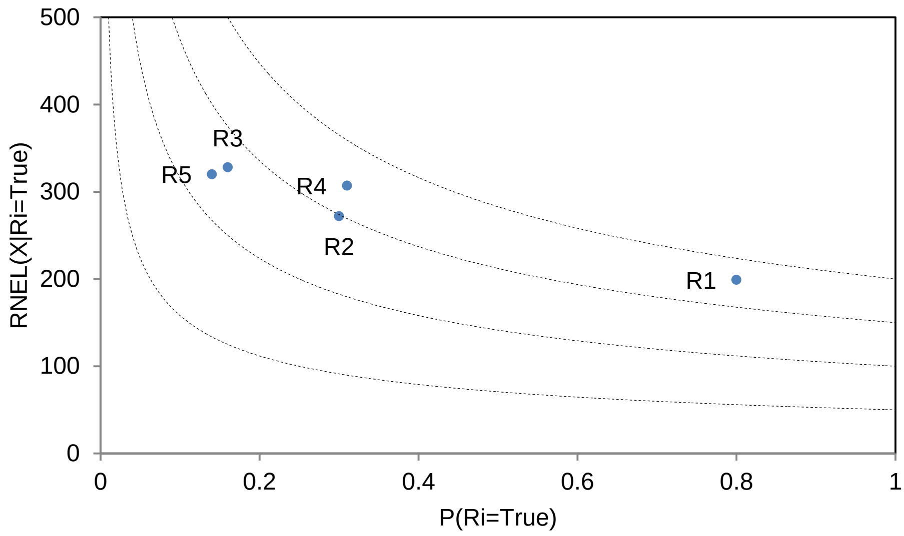

Figure 6.14: Risk network evaluation (point E).

Combination of Risk Mitigation Strategies	Cost of Strategies
A	$30 \leq Cost < 60$
E	$60 \leq Cost < 90$
K	$Cost \geq 90$

Table 6.6: Optimal solutions for the objective function of maximising normalised RCM.

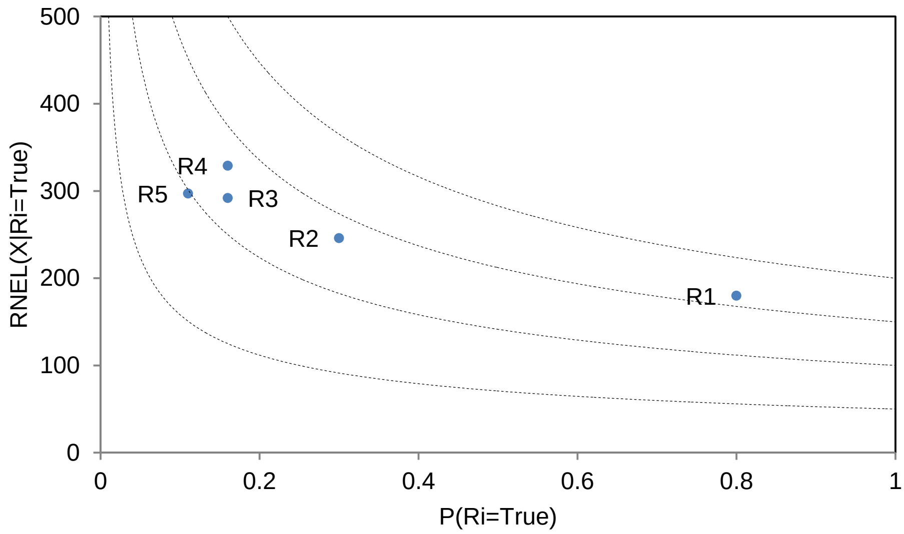

Figure 6.15: Risk network evaluation (point K).

6.7 Simulation Study

An application of the proposed method is demonstrated through a simple supply chain risk network (Garvey et al., 2015) as shown in Figure 6.16. The supply network comprises a raw material source, two manufacturers, a warehouse and a retailer. Supply chain elements, associated risks and loss values are shown in Table 6.7. Although each domain of the supply network may comprise a number of risks and corresponding sources, we consider limited risks for the sake of simplicity. Each risk and mitigation strategy is represented by binary states of 'True (T) or False (F)' and 'Yes (Y) or No (N)', respectively. Assumed (conditional) probability values are shown in Table 6.8 and the effectiveness of risk mitigation strategies is represented by values appearing in the shaded cells. Potential mitigation strategies, associated risks and costs are depicted in Table 6.9.

6.7.1 Results

It is assumed that the decision maker is risk-neutral. As six potential mitigation strategies were considered for implementation, a total of 64 different combinations of strategies were evaluated as shown in Figure 6.17. All the points below the

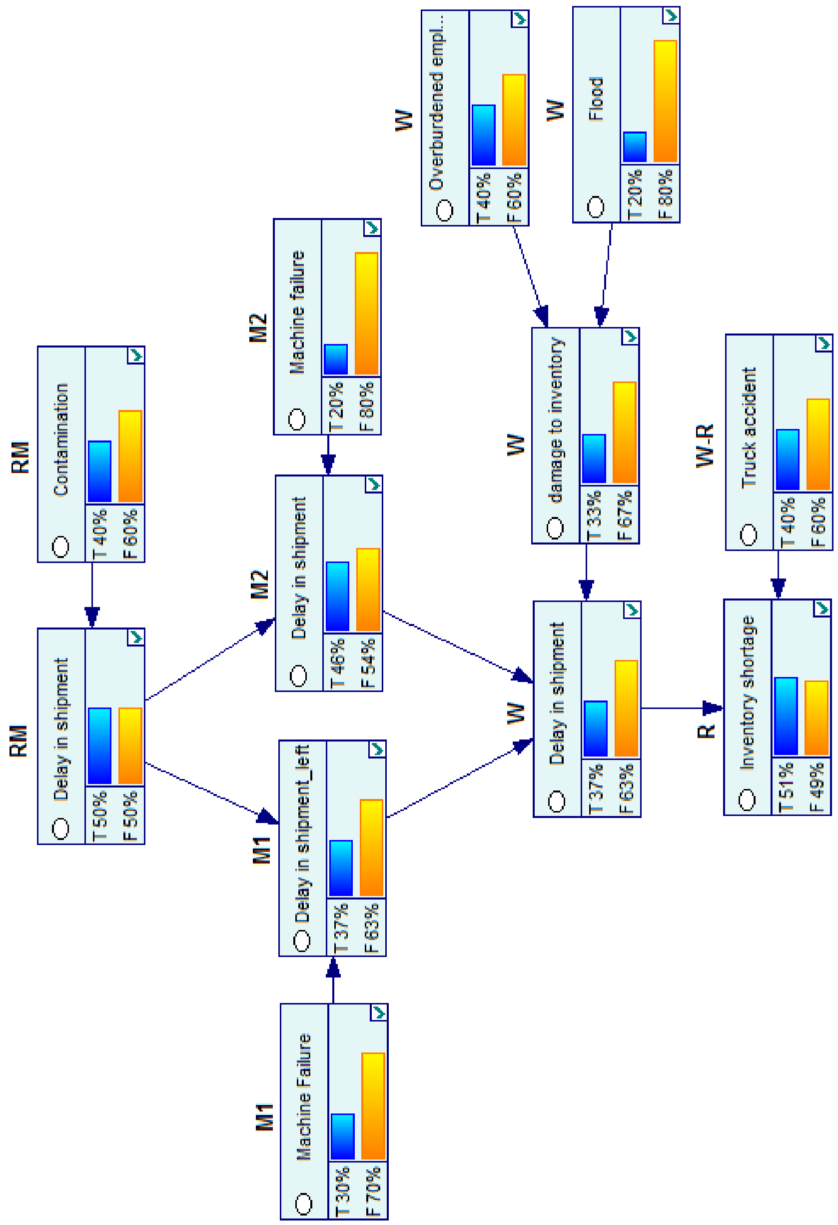

Figure 6.16: A supply chain risk network modelled in GeNIe (Source: Garvey et al. 2015).

Supply Chain Element	Risk	Loss
Raw Material Source (RM)	Contamination (R1) Delay in Shipment (R2)	200 400
Manufacturer-I (M1)	Machine Failure (R4) Delay in Shipment (R5)	200 400
Manufacturer-II (M2)	Machine Failure (R3) Delay in Shipment (R6)	200 400
Warehouse (W)	Overburdened Employee (R7) Damage to Inventory (R8) Delay in Shipment (R9) Flood (R12)	 500 600
Warehouse to Retailer (W-R)	Truck Accident (R10)	500
Retailer (R)	Inventory Shortage (R11)	800

Table 6.7: Supply chain elements, risks and loss values.

solid line represent solutions for which the improvement in risk network expected loss is more than the cost of implementing strategies. Only points A ($S6$) and B ($S1, S6$) are the optimal solutions as all other points in the feasible region (below the solid line) fail to meet the other constraint. Therefore, if the decision maker is only concerned about maximising the reduction in risk network expected loss less cost, an amount of 100 units must be invested for a budget range of $100 - 200$ (exclusive) units whereas only the strategies amounting to 200 units must be implemented for a budget regime of 200 units and more. The main problem with implementing these optimal solutions is their exclusive focus on the network wide expected loss without accounting for the configuration of risks corresponding to other feasible solutions.

6.8 Second Approach for Selecting Optimal Strategies (without using the Risk Matrix)

In this approach, a different line of inquiry is adopted where the decision maker utilises the information about cost of strategies and the impact of strategies on the risk exposure (risk network expected loss) to select a portfolio of optimal strategies. With reference to the risk network modelled in Figure 6.16, all pos-

Parents				***P*(*risk* = *True*|*parents*)**					
*R*1	*R*2	*R*3	*R*4	*R*1	*R*2	*R*3	*R*4	*R*5	*R*6
				0.4					
				0.1					
T					0.8				
F					0.3				
						0.2			
						0.1			
							0.3		
							0.2		
	T		T					0.7	
	T		F					0.4	
	F		T					0.6	
	F		F					0.1	
	T	T							0.9
	T	F							0.6
	F	T							0.5
	F	F							0.2

Parents							***P*(*risk* = *True*|*parents*)**					
*R*5	*R*6	*R*7	*R*8	*R*9	*R*10	*R*12	*R*7	*R*8	*R*9	*R*10	*R*11	*R*12
							0.4					
							0.3					
		T				T		0.8				
								0.5				
		T				F		0.3				
								0.15				
		F				T		0.6				
								0.4				
		F				F		0.2				
								0.15				
T	T		T						0.9			
T	T		F						0.5			
T	F		T						0.6			
T	F		F						0.3			
F	T		T						0.4			
F	T		F						0.3			
F	F		T						0.3			
F	F		F						0.2			
										0.4		
										0.15		
				T	T						0.9	
				T	F						0.7	
				F	T						0.6	
				F	F						0.2	
												0.2

Table 6.8: (Conditional) probability values.

Risk Mitigation Strategy	Description	Associated Risk	Cost
S1	Quality Assurance Program	R1	100
S2	Scheduled Maintenance Program	R3	50
S3	Scheduled Maintenance Program	R4	100
S4	Scheduling Software and Monitoring Program	R7	50
S5	Early Warning System	R8	200
S6	Training Simulator	R10	100

Table 6.9: Potential risk mitigation strategies, associated risks and cost.

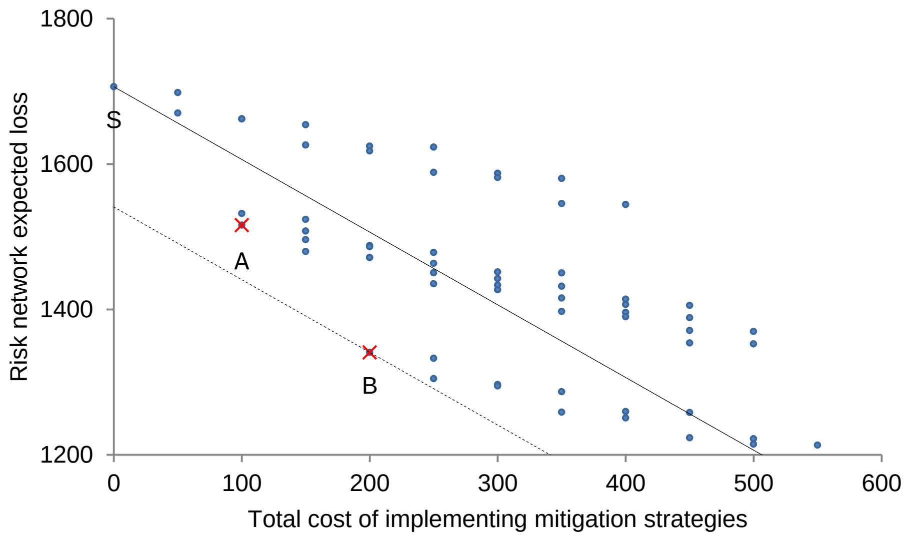

Figure 6.17: Identification of optimal combinations of strategies.

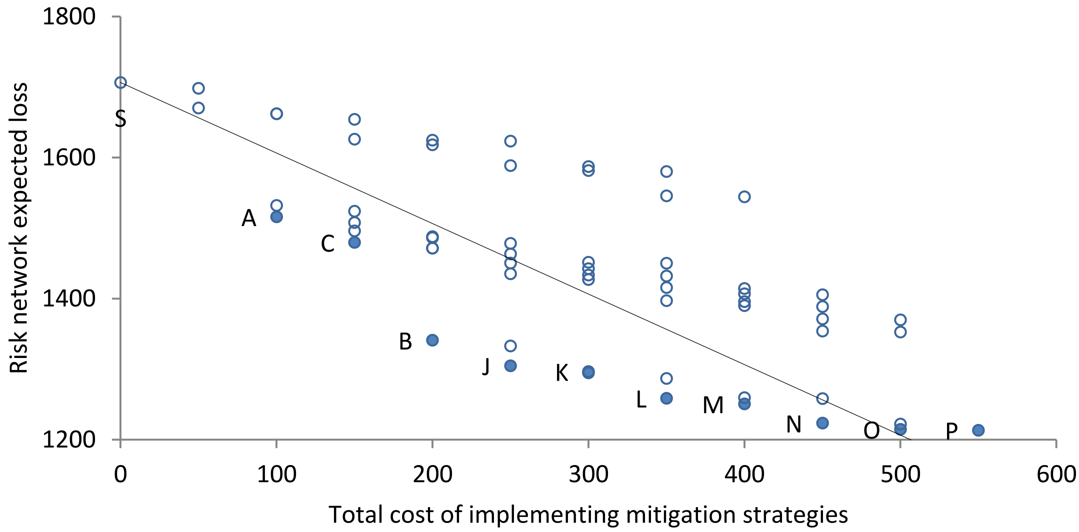

Figure 6.18: Pareto optimal solutions (filled circles) and dominated solutions (hollow circles).

sible combinations of strategies are mapped again in Figure 6.18; however, here we distinguish between the set of Pareto optimal solutions (non-dominated solutions) and the dominated solutions specific to different budget constraints that are represented by filled and blank circles, respectively. The definition of Pareto optimal set introduced by Spackova & Straub (2015) is adopted that contains all such combinations of strategies for which there are no other combinations that have simultaneously lower costs and lower risk exposure. Points O and P are included in the set of Pareto optimal solutions; however, for a risk-neutral decision maker, these points fall short of the threshold criterion demanding the equivalence of improvement in risk exposure and the additional investment. For each budget constraint, the point is selected which maximises the perpendicular distance between the solid line and the parallel family of lines. Therefore, for a budget lesser than 200 units, point A is the optimal mix of strategies whereas for all other budget constraints, point B is the optimal solution.

In contrast to a risk-neutral decision maker, a risk-averse individual would have greater concern with regards to the occurrence of risks and therefore, he will prefer to avoid such situations at the cost of enhanced investment. The

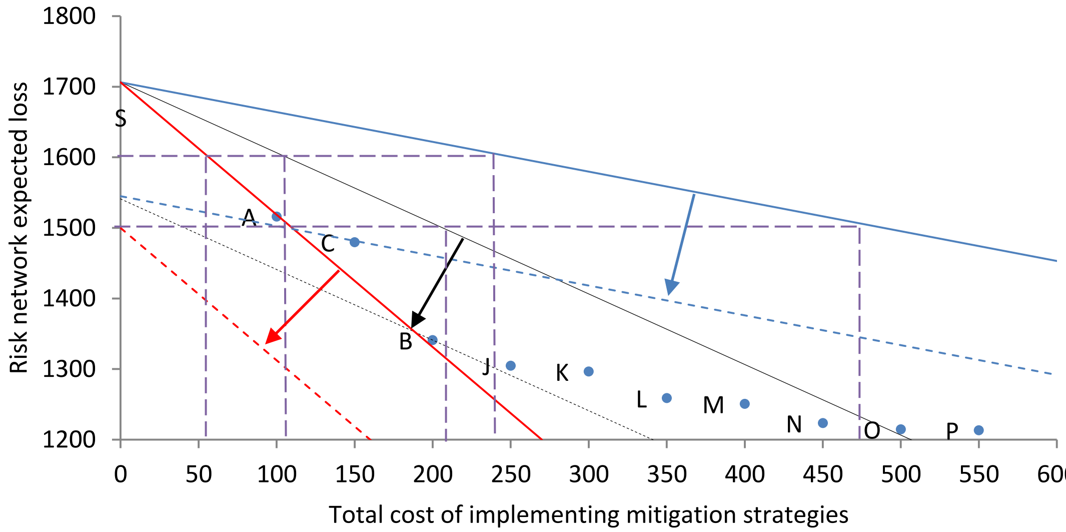

Figure 6.19: Family of lines representing risk appetite influencing the set of feasible solutions.

risk appetite of a risk-averse individual can be modelled through a line with lower gradient (like the solid blue line in Figure 6.19) which indicates that the individual is willing to invest relatively more than the risk-neutral individual to achieve same reduction in the risk exposure. Similarly, a risk-seeking individual represented by the red line as shown in Figure 6.19 (with a steeper gradient) would only be willing to invest if the improvement in risk exposure is more than the figure determined through the cost-benefit analysis.

For the blue line, all the solutions included in the Pareto optimal set are feasible solutions. Depending on the gradient of the line, different points will be optimal subject to the budget constraint. Once the line approaches a gradient of zero, all points will be optimal solutions subject to the respective budget constraint meaning that point P will be picked for a budget of at least 550 units and similarly, point O for a budget of at least 500 units but lesser than 550 units. For the red line mapped, it is evident that only point A is the optimal solution for a budget of at least 100 units.

Another approach to justifying the relevance of trade-off between the improvement in risk exposure and the additional investment specific to the risk appetite is illustrated through a simple example. With reference to Figure 6.18, a point represents a specific combination of strategies with associated cost and risk exposure across the risk network shown in Figure 6.16. Risk exposure across the 12 risk events can be represented as:

$$RNEL = P(\bar{R}_1 \cap \bar{R}_2 ... \bar{R}_{12}) * L(\bar{R}_1 \cap \bar{R}_2 ... \bar{R}_{12}) ... + P(R_1 \cap R_2 ... R_{12}) * L(R_1 \cap R_2 ... R_{12}) \tag{6.17}$$

Where $P(\bar{R}_i)$ and $L(R_i)$ represent probability of risk R_i not happening and the loss associated with the occurrence of risk R_i, respectively.

$$RNEL = P(\bar{R}) * 0 + P(\widetilde{R}) * L(\widetilde{R}) \tag{6.18}$$

Where $\bar{R}$ is a scenario of no risk realising and $\widetilde{R}$ represents a scenario of at least one risk realising.

$$RNEL = P(\widetilde{R}) * L(\widetilde{R}) \tag{6.19}$$

The improvement in $RNEL$ subject to an additional investment helps in reducing the value of $P(\widetilde{R})$ and/or $L(\widetilde{R})$. For a risk-neutral decision maker, the improvement in $RNEL$ must be equal to the additional investment at the minimum. However, the loss value ($L(\widetilde{R})$) might have reduced by a greater margin in comparison with the change in investment. For example, if a combination of strategies 'X' ['Y'] yields $P(\widetilde{R})$ and $L(\widetilde{R})$ values of 0.2[0.2] and 100[200], respectively at a cost of 70[50] units, the risk-neutral decision maker will be indifferent between X and Y. However, the risk-averse individual will consider the significance of X in reducing the loss value far greater than the increase in investment mainly because the loss values associated with different scenarios might be deleterious to his business. Similarly, a risk-seeking individual would want a greater margin of improvement in $RNEL$ with respect to the same investment made. For the same improvement in $RNEL$ from 1600 to 1500 units as shown in Figure 6.19, the risk-seeking individual is willing to invest 50 units whereas the risk-neutral (averse) individual would invest 100(240) units.

In order to combine the cost of strategies and associated risk exposure, there is a need to adopt a consistent method of mapping these together on a single scale. For each combination of strategies, we register the improvement in risk exposure and reduction in mitigation cost (negative of cost) with respect to the current configuration of strategies already implemented. It is proposed to use the method of 'swing weights' (Belton & Stewart, 2002) to determine the relative weight of the two criteria where the decision maker is asked to consider that both improvement in risk exposure and reduction in mitigation cost are at the least preferred states (all risks realised and maximum possible cost of strategies incurred each amounting to the value of 0). Subsequently, he is given a scenario that only one of these could be improved to the best possible state and the one picked by him should receive the maximum weight (100) reflecting the significance of that criterion. He is then required to assess the overall value (over a scale of $0 - 100$) arising from a swing from 0 (worst state) to 1 (best state) on the other criterion corresponding to the swing from 0 to 1 on the criterion already prioritised. The weights assigned can be normalised to add up to 1. We define β as the weighted sum of improvement in $RNEL$ and reduction in mitigation cost:

$$\beta = (1 - a) * \text{improvement in} RNEL + a * \text{reduction in mitigation cost} \quad (6.20)$$

Where a is a parameter that captures the importance of cost as to how a decision maker may place greater or lower weight on the cost of risk mitigation; when $a = 0$, the decision maker is not concerned about the cost of implementing strategies while in the case of $a = 1$, he will not consider implementing any additional strategy as the reduction in mitigation cost will be maximum at the current configuration of strategies.

For a risk-neutral decision maker, $a = 0.5$ because he wants to get the improvement in $RNEL$ to be equal to the additional mitigation cost at the minimum and therefore, $\beta = 0$ would represent the threshold where he is willing to invest additional amount in order to reduce risk exposure. Increasing values of β would yield a family of lines where the optimal solution subject to a budget constraint would be tangent to the line with the highest β. For a risk-averse (seeking) individual, a will be smaller (greater) than 0.5 and $\beta \geqslant 0$ would generate the corresponding family of lines.

Equations of three solid lines shown in Figure 6.19 can be deduced from Equation 6.20 as follows:

$$0 = (1 - a) * (RNEL_{SC} - RNEL) + a * (-\text{mitigation cost}) \tag{6.21}$$

$$RNEL = \frac{-a}{1 - a} * \text{mitigation cost} + RNEL_{SC} \tag{6.22}$$

Where 'mitigation cost' accounts for the additional cost with respect to the current cost of strategies implemented and $RNEL_{SC}$ is the risk exposure under the current configuration of strategies.

6.9 Discussion

The research reported in this chapter was based on the hypothesis that there is no such framework/process within the existing literature on SCRM that integrates all stages of the risk management process within a probabilistic setting of interacting risks and captures the risk appetite of a decision maker in evaluating interdependent risks and potential risk mitigation strategies. To the best of our knowledge, research has not been conducted to integrate all these themes within a single framework. However, one limitation of our study is its focus on limited number of high quality journal articles. Papers on literature reviews have focused on the need for exploring these themes in silo whereas an agenda on developing an integrated framework has never been presented.

There is a need to bring a paradigm shift towards modelling and managing network of risks (Badurdeen et al., 2014). Instead of defining categories of risks and classifying risks accordingly, we have proposed exploring chains of risks and adverse events. As opposed to the unidirectional flow of stages in the standard risk management process, the proposed framework follows an iterative process where the selection of potential strategies is contingent upon the configuration of risks corresponding to the current performance of implemented strategies. Furthermore, evaluating a particular combination of strategies necessitates re-assessing and re-evaluating the risk network.

BBNs have been proposed as a modelling tool for implementing the process. These are effective in capturing the probabilistic interdependency between risks and strategies and providing a visual aid to the decision maker to understand dynamics between interacting factors and visualise propagation patterns. A key merit of developing a BBN based model is its ability to include additional risks during the risk monitoring stage without needing major changes. The proposed algorithms provide a standard approach of implementing the process using any type of modelling technique. SCRNM and the proposed approach are meant to facilitate practitioners in implementing an effective risk management process.

As risk matrix based tools are widely used in practice (Duijm, 2015), practitioners will find this study useful in enhancing the capability of their existing tools to deal with the network of risks. The main benefit of adopting the risk matrix based approach is to be able to appreciate the configuration of risks on the risk matrix and ascertain if appropriate strategies are implemented to account for the possibility of any adverse event happening whereas the second approach proposed does not consider the implications of individual risk scenarios happening. However, the second approach might be viable in the case where a decision maker is not comfortable with the risk matrix based approach and it still helps in determining the set of Pareto optimal solutions and an optimal solution subject to a budget constraint and specific risk appetite.

6.9.1 Comparison of the Proposed Risk Matrix Based Method with the Standard Expected Utility based Method

In the case of a risk network where N risks and M strategies (each having binary states) are interdependent and the utilities associated with different consequences are not mutually independent, we need to elicit $2^{(N+M)}$ utility values; however, considering the cost of strategies being independent of the risk exposure, the elicitation burden is reduced to 2^N values assuming that the corresponding cost specific to each combination of strategies is evaluated as the summation of cost for each strategy and a weighted net utility function is defined to combine the utility and cost values. It is important to realise that the standard expected utility approach averages out the utility of all possible scenarios with respective probability values.

In the proposed risk matrix based approach, it is assumed that it is not possible to utilise the expected utility approach mainly because of the substantial number of nodes involved. The decision maker is able to partition the modified risk matrix into five zones. The risk matrix is modified in a way that instead of registering siloed consequence values specific to the realisation of individual risks, we make use of the impact of each risk on the risk network. In essence, different scenarios are modelled where each risk might realise in turn and all such scenarios are modelled for each possible combination of strategies with associated probability of occurrence and the resulting consequence on the network. In the case of a risk-neutral decision-maker, the use of $RNEL$ value alone is sufficient to decide if it is worth investing in implementing additional strategies where the cost is compared with the enhanced reduction in the risk exposure. However, in the case of a risk-averse (seeking) decision maker, the risk appetite can be modelled within the modified risk matrix in terms of establishing the boundaries of the five risk zones.

Appropriate partitioning of the boundaries (particularly for establishing unacceptable and critical risk zones) is significant because presence of any risk within these zones would necessitate investing in additional strategies (with condition of benefits exceeding costs for the critical zone). However, even if the boundaries are incorrectly mapped and a conservative stance is adopted, only cost-effective strategies would be selected yielding an improved configuration of risks on the modified risk matrix. It is because we make use of RCM in choosing the combination of strategies that helps in improving the configuration of risks and therefore, for each additional investment level, only cost-effective strategies would be selected whereas the '$RNEL$ vs. cost' map is utilised in the case of risks located in the critical risk zone to establish if the overall benefits exceed the cost of implementing additional strategies. Therefore, the company would still benefit from the implementation of additional cost-effective strategies resulting from the incorrect partitioning; however, these strategies would not conform to the actual risk appetite of the decision maker. Similarly, if the boundaries are incorrectly expanded beyond true limits, the company might be prone to vulnerable risks exceeding their true risk appetite.

6.10 Summary

A number of frameworks and modelling tools have been proposed in the literature on SCRM for identifying, assessing and mitigating risks. These studies have been periodically reviewed for directing future research. Focusing on the theme of risk management process/framework, this chapter presents a critical review of quality articles. It was established that there is no single study focusing on the SCRM process within an integrated framework of interacting risks and the risk appetite of a decision maker. The articles on literature reviews were also reviewed revealing that even these articles have not realised and emphasised the need for conducting research in this direction.

On the basis of the research gap identified, a new risk management process namely SCRNM was introduced. There is a need for bringing paradigm shift in terms of modelling chains/network of interacting risks and risk sources. Instead of modelling and managing supply chain risks in silo, researchers must embrace the notion of modelling and managing a network of risks and develop effective and efficient tools for practitioners to adopt in real scenarios. There is also a need for exploring tools that integrate all stages of the risk management process instead of focusing on separate stages (Ho et al., 2015).

There is a need for introducing risk measures that capture the network wide holistic impact of interacting risks. However, optimising the risk network against these measures alone might result in sub-optimal solutions as it is also important to consider the risk appetite of a decision maker. Although EUT provides a standard procedure for decision making under uncertainty, it is not viable to even assess a simple risk network comprising a limited number of risks and strategies. Therefore, we introduced the idea of adapting risk matrix for projecting the configuration of interdependent risks. Risk matrix has already been modified for mapping the risk appetite of a decision maker. However, the main limitation is its exclusive application to independent categories of risks. The chapter proposed its adaptation to the context of interdependent risk network.

The risk measure namely $RNELPM$ introduced in the previous chapter was utilised to develop two algorithms for managing a supply chain risk network with regard to risk-neutral and risk-seeking/averse decision makers. The algorithms can also be used in the context of other modelling techniques and/or risk measures. The proposed process was demonstrated through a simulation study in the context of SCRM. A second approach was also introduced to determine the set of Pareto optimal risk mitigation strategies where a decision maker needs to establish the trade-off between the improvement in risk exposure and the cost of strategies without utilising the risk matrix. The proposed risk matrix based process can help researchers focus on a new stream of research and develop it further. The next chapter presents the findings of two case studies conducted in global manufacturing supply chains that involved developing risk networks and establishing the merits and challenges associated with implementing interdependency based risk management frameworks.

Chapter 7

Empirical Investigation of Modelling Interdependent Supply Chain Risks

7.1 Introduction

Responding to the call for empirically evaluating a SCRM process that not only captures interdependency between risks but also integrates all stages of the process (Colicchia & Strozzi, 2012; Ho et al., 2015), this chapter proposes a comprehensive risk management process capturing interdependencies between supply chain risks, multiple (potentially conflicting) objectives (performance measures) and risk mitigation strategies, and reports on the merits and challenges associated with its implementation. An overview of the research focus and the methodology adopted is shown in Figure 7.1. The proposed process is adapted from the theoretically grounded frameworks within the literature on SCRM (Garvey et al., 2015; Sherwin et al., 2016) and project risk management (Qazi et al., 2016). It is demonstrated through conducting two case studies in reputed global supply chains resulting in the development of two different models of risk networks spe-

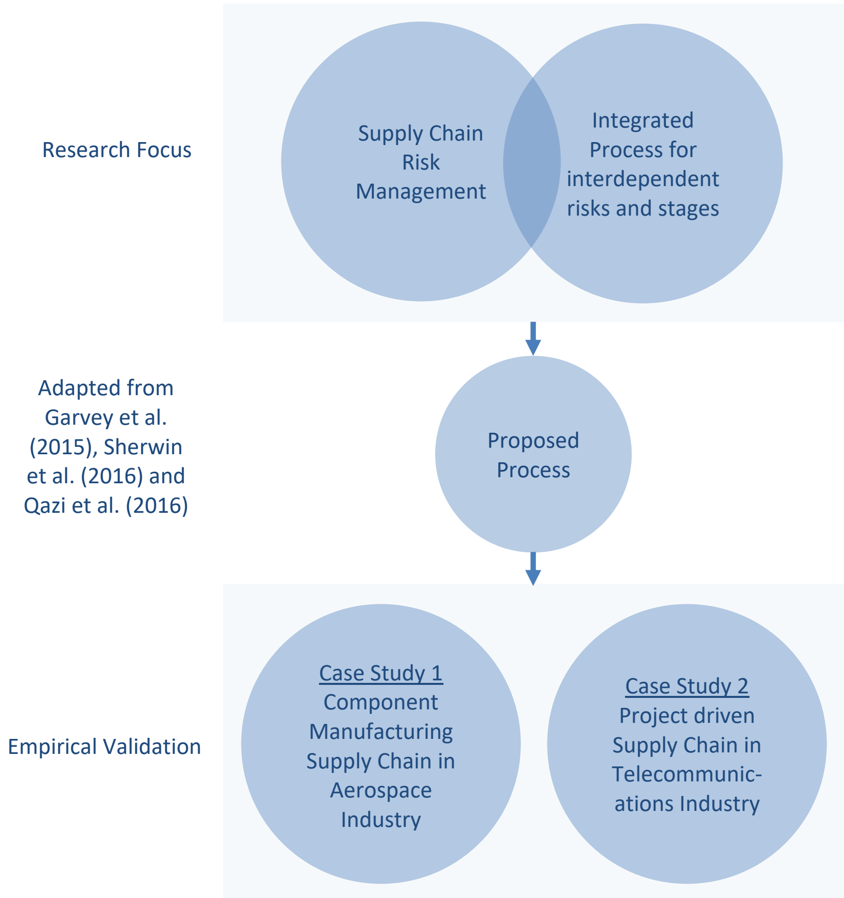

Figure 7.1: Research focus and methodology.

cific to a conventional and a project driven supply chain. Finally, propositions are presented to elucidate the importance of accounting for interdependence of risks by comparing the proposed process to a standard risk matrix-based approach.

7.2 Literature Review

In the following sections, we give an overview of the literature on SCRM process, interdependency modelling of supply chain risks and modelling of risks in project driven supply chains.

7.2.1 Supply Chain Risk Management Process/Framework

SCRM is *"the identification and management of risks for the supply chain, through a co-ordinated approach amongst supply chain members, to reduce supply chain vulnerability as a whole"* (Juttner et al., 2003, p. 201). Several risk management frameworks have been proposed using different terminology; however, there is a consensus that the SCRM process involves five sequential stages: risk identification; assessment; analysis; treatment; and monitoring (Giannakis & Papadopoulos, 2016). Ritchie & Brindley (2007) identified five components of a SCRM process: risk drivers (primary and secondary level); risk management influencers (rewards, supply chain risks, timescales, portfolio); decision maker characteristics (perceptions, risk profile, attitudes, experiences); risk management responses (risk taking, avoidance, mitigation, monitoring); and performance outcomes (profit related, strategic positioning, personal). We will briefly describe the merits of some of the frameworks proposed in the literature, and delineate the main limitation of these.

A number of qualitative frameworks have been proposed to identify risks and prescribe generalised strategies to deal with important risks. These frameworks generally utilise qualitative scales to discretise the conventional risk matrix across the probability and impact levels. Utilising FMEA based technique, Sinha et al. (2004) developed a process to manage risks in the aerospace industry whereas Giannakis & Papadopoulos (2016) proposed a risk management process to identify and manage sustainability related risks across the environmental, social and economic facets with its application demonstrated through empirical case studies and survey questionnaire. Khan et al. (2008) reported the conventional risk matrix based process used in a major UK retailer that helps the company deal with the design oriented supply chain risks. Bringing the perspective of a global supply chain and consolidating the concepts from logistics, supply chain management, operations management, strategy and international business management, Manuj

& Mentzer (2008a) proposed a procedure to help global supply chain managers identify risks and select appropriate strategies.

Quantitative frameworks have utilised hybrid methods to assess and manage risks. For example, Elleuch et al. (2014) combined FMEA, design of experiments, discrete event simulation, AHP and desirability function approach to develop a process and applied it to the pharmaceutical supply chain case study. Similarly, Aqlan & Lam (2015) proposed a hybrid approach of bow-tie analysis and stochastic integer programming to identify critical risks and assess suitable strategies taking into account their cost and effectiveness in reducing the risk exposure. Systems thinking has also been applied to develop a comprehensive process both in its qualitative (Oehmen et al., 2009) and quantitative forms (Ghadge et al., 2013).

There are mainly two limitations of the existing frameworks including the aforementioned studies. First, the frameworks have drawn limited focus on modelling the common cause failures and assessing their propagation impact. As such common cause failures can have a far reaching impact on the supply network, *"field and case studies are necessary to investigate and estimate such correlations and focus on developing methods to evaluate the probabilities of occurrence of particular risk types so that methods can be developed to appease such risks through mitigation strategies"* (Ho et al., 2015, p. 5060). Second, researchers generally focus on limited stages of the risk management process whereas *"there is a significant relationship between all SCRM processes, (therefore) more attention should be given to legitimately integrated processes instead of individual or fragmented processes. ... Similarly, the effectiveness of risk mitigation strategies requires explicit quantification of effectiveness and efficiency of such strategies"* (Ho et al., 2015, p. 5053). We endeavour to fill the mentioned gaps by developing and validating an integrated SCRM process to establish how practitioners perceive correlations between risks and whether they are able to evaluate the impact of risk mitigation strategies on the network of interrelated risks.

7.2.2 Interdependency Modelling of Supply Chain Risks

Various models have been proposed to capture interdependency between supply chain risks. ISM is a hierarchy based technique that establishes the order and direction of complex relationships among elements of a system. It has been used to determine causal relationships between risk mitigation strategies (Faisal et al., 2006b) and supply chain risks (Pfohl et al., 2011). Related to the same family of causal mapping techniques, fishbone diagram has been utilised to identify cause-effect relationships between supply chain risks (Lin & Zhou, 2011). Mapping a supply network as a web of interconnected nodes, measures from the Social Network Analysis have been adapted to identify critical supply nodes (Kim et al., 2011). Similarly, Cheng & Kam (2008) used the principal agent model to map an Original Equipment Manufacturer and its suppliers to assess critical nodes. The main limitation of aforementioned techniques is the inability to capture the strength of interdependency between risks.

AHP is a technique to conduct pair-wise comparisons between variables and identify their relative importance. Its application varies from the risk assessment of suppliers (Ganguly & Guin, 2013; Ganguly, 2014) to the prioritisation of supply chain performance measures (Gaudenzi & Borghesi, 2006). FMEA is a technique to prioritise risks depending on the relative product of probability, severity and detectability associated with each risk. It has been extensively used in SCRM to identify critical risks (Tuncel & Alpan, 2010; Chaudhuri et al., 2012; Lee et al., 2012; Nepal & Yadav, 2015). Similarly, utilising the established techniques from the field of reliability engineering, Aqlan & Lam (2015) proposed a bow-tie analysis based process to capture the interdependency of supply chain risks whereas Oehmen et al. (2009) and Sherwin et al. (2016) introduced a Fault Tree Analysis (FTA) based framework to assess risks. The main problem with these techniques is their limited focus on capturing common cause failures.

Mainly, supply chain risks are classified into distinct categories like process, control, demand, supply and environmental risks (Christopher & Peck, 2004). The first two risk categories relate to factors internal to an organisation, the third and fourth include factors internal to the supply chain, but external to the organisation and the fifth category relates to factors external to the supply chain. Similar to the concept of mapping causal chains in project risk management (Ackermann et al., 2014), Badurdeen et al. (2014) proposed a risk taxonomy capturing interdependency between supply chain risks that is in contrast with the established classification schemes. However, they do not validate the proposed risk taxonomy rather explore a supplier risk assessment model through a case study. In their effort to capture the probabilistic interdependency between supply chain risks, Garvey et al. (2015) introduced an algorithm to map the risks and proposed supply chain risk measures with the limitation of not validating their model and ignoring the risk treatment stage of the process. However, their work serves to illustrate the efficacy of BBNs in modelling and managing supply chain risks.

In response to the call for understanding the relationships between a set of strategies for managing risks and corresponding impact on performance (Colicchia & Strozzi, 2012), a few models have been developed (Micheli et al., 2014; Aqlan & Lam, 2015); however, these models do not explicitly capture interdependency between risks. The development of models for effectiveness and efficiency evaluation of risk reduction strategies would be beneficial for the supply chain managers in decision making. Another issue relates to the focus of these models on "minimising cost or maximising profit as a single objective" (Colicchia & Strozzi, 2012, p. 412) as *"purely cost-and waste-considering objectives, however, evaluate supply chain's performance in retrospect. They miss to assess both operational effectiveness and important strategic achievements like product quality* *and customer satisfaction"* (Heckmann et al., 2015, p. 130). In this study, we overcome the limitation of earlier studies by not only capturing the interdependency between risks but also across the entire risk management process. We also consider optimising a set of potentially conflicting performance measures within an interdependent setting of interacting risks and strategies.

7.2.3 Modelling of Risks in Project driven Supply Chains

Limited articles have explored supply chain risks associated with projects involving NPD. The literature on project risk management includes risk management frameworks to manage risks related to such mega projects (Kardes et al., 2013); however, to the best of our knowledge, supply chain risks have not been investigated in the literature and moreover, Aloini et al. (2012) also report in their review that none of the 140 research articles on supply chain management in construction projects deals with the risk management. Linking project characteristics to the risks, Qazi et al. (2016) introduced a process namely ProCRiM capturing interdependencies between project characteristics, risks and project objectives. Although the experts' opinion was elicited to validate the contribution of the process, its scope was limited to the construction industry and the application of the process was demonstrated through a simulation study rather than a real case study. Furthermore, supply chain risks have not been exclusively modelled in their simulation study.

There are few studies in the literature on SCRM that link supply chain risks to projects involving NPD. Tang et al. (2009) used secondary data to establish why the Boeing 787 project incurred a substantial financial loss despite Boeing having introduced a fair-sharing partnership with its Tier-1 suppliers. The undermining of the supply chain risks associated with the project was adjudged as the main underlying cause; however, the assessment of risks in isolation might not represent the systemic behaviour of risks (Ackermann et al., 2014). As opposed to utilising secondary data, efforts have been made to conduct case studies in the industry and establish the supply risk management process concerning such projects; however, such studies have either represented the conventional risk matrix based process thereby assuming independence of risks (Khan et al., 2008) or reported a stage of the process without integrating all the stages together (Lin & Zhou, 2011; Chaudhuri et al., 2012).

Badurdeen et al. (2014) conducted a case study in Boeing related to the development project of a missile guidance system. Their proposed model establishes the link between supply chain risks but instead of integrating the network wide risks, the model captures the risks specific to a Tier-1 supplier and aids in ranking the suppliers as does the model proposed by Lockamy (2014). There are two major limitations of the existing studies about the mentioned theme: first, these studies focus on few stages of the risk management process without establishing and validating a comprehensive risk management process in such projects; and second, interdependency modelling of risks is ignored in its entirety or few studies involving interdependency do not capture common cause failures and/or optimise a single objective or a set of objectives in isolation. To fill this gap, we adapt the process proposed by Qazi et al. (2016) to the context of SCRM and demonstrate it through a case study conducted in a project driven supply chain.

7.3 Proposed Process

As shown in Figure 7.1, the main purpose of this chapter is to develop and empirically evaluate an integrated SCRM process. In principle, we focus on two distinct application areas: the first being a conventional supply chain with exclusive focus on the interaction of supply chain risks and their influence on the supply chain performance measures (see Figure 7.2); the second relates to a project driven supply chain where ProCRiM is directly applicable though the risks considered

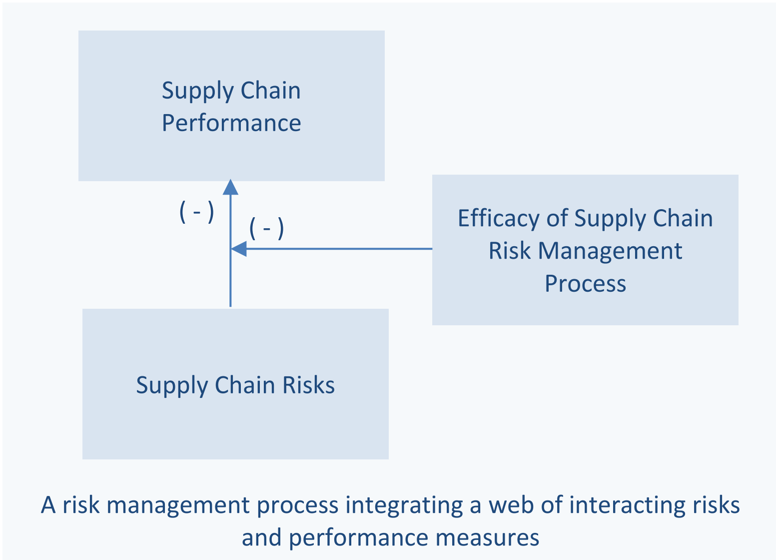

Figure 7.2: Supply chain risk management framework for conventional supply chains (adapted from Juttner et al. 2003).

are exclusively related to the supply chain (see Figure 7.3) whereas the focus of ProCRiM is on project related risks only. The rationale of selecting two different application areas is to ascertain whether there are any differences between developing a risk management process specific to a conventional and a project driven supply chain. We believe that the project characteristics of a specific project driven supply chain can have a significant impact on the results of risk assessment and the choice of risk mitigation strategies whereas in the case of conventional supply chains, there is not much uncertainty about the development of a risk network and the efficacy of risk mitigation strategies.

There are many studies in the literature with exclusive focus on the impact of supply chain risks on performance measures (Juttner et al., 2003; Zhao et al., 2013). However, we consider the impact of the risk network on performance measures whereas there is a moderating effect of the risk management process in terms of its efficacy in mitigating risks. The efficacy of the risk management process in turn needs to be evaluated within a network setting. The framework shown in Figure 7.2 is exclusively applicable to any type of supply chain that is not involved in NPD projects.

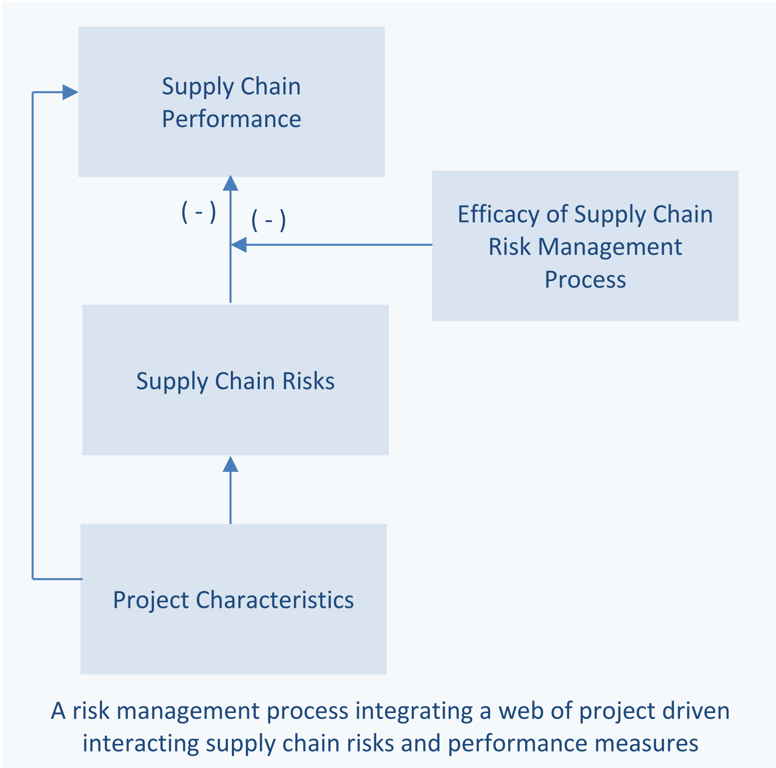

Figure 7.3: Supply chain risk management framework for project driven supply chains.

Considering the scarcity of studies on managing supply chain risks associated with NPD, Figure 7.3 reflects the impact of project characteristics on supply chain risks that influence performance measures. However, it is interesting to note that project characteristics can have a direct impact on performance as a project might entail high risks but it would be necessary to undertake the project because of its strategic importance and therefore, few project characteristics (like technological innovation) might directly increase the utility of the decision maker with respect to achieving competitive advantage.

The steps involved in the risk management process as shown in Figure 7.4 are adapted from the frameworks proposed by Garvey et al. (2015), Qazi et al. (2016) and Sherwin et al. (2016). However, as the aforementioned frameworks have not been empirically evaluated, the process had to be modified based on the results of the case studies and the feedback received. Like the standard risk management process (SA, 2009), the proposed process starts with establishing the context in terms of defining the scope of the supply chain and its boundaries. The main purpose of the modelling and analysis is ascertained through interviewing the decision maker or the main stakeholders. The decision maker also helps in identifying the key performance measures pertinent to the supply chain and in case of a project driven supply chain, project characteristics also need to be determined.

A focus group session must be conducted to identify risks and develop a causal network. We found it very useful to develop the causal network using the top-down approach where the informants were asked to link each performance measure with the corresponding risk(s) that were in turn linked back to causal factors. In a way, it mimics the technique adopted in conventional FTA (Sherwin et al., 2016); however, FTA does not capture the common-cause failures whereas we model such factors in our framework. Studies on developing the qualitative part of the BBNs and causal maps are useful in establishing the risk network (Nadkarni & Shenoy, 2004). Once the qualitative network is developed, there is a need to validate the structure and ensure whether all relevant risks have been considered. A focus group session involving all participants from the previous session and adding some new members is helpful in refining the structure and adding some missing risks. It is important to note that it is an iterative process until the final structure is validated and the participants are satisfied with the structure of the risk network.

The next stage relates to the quantitative modelling of the already validated qualitative risk network where the participants establish the strength of interdependency between the risks either through semi-structured interviews or a focus group session. Once all the conditional probability values have been elicited, a focus group session must be held to validate the model. Again studies specific to the quantitative modelling of BBNs are useful in developing and validating the

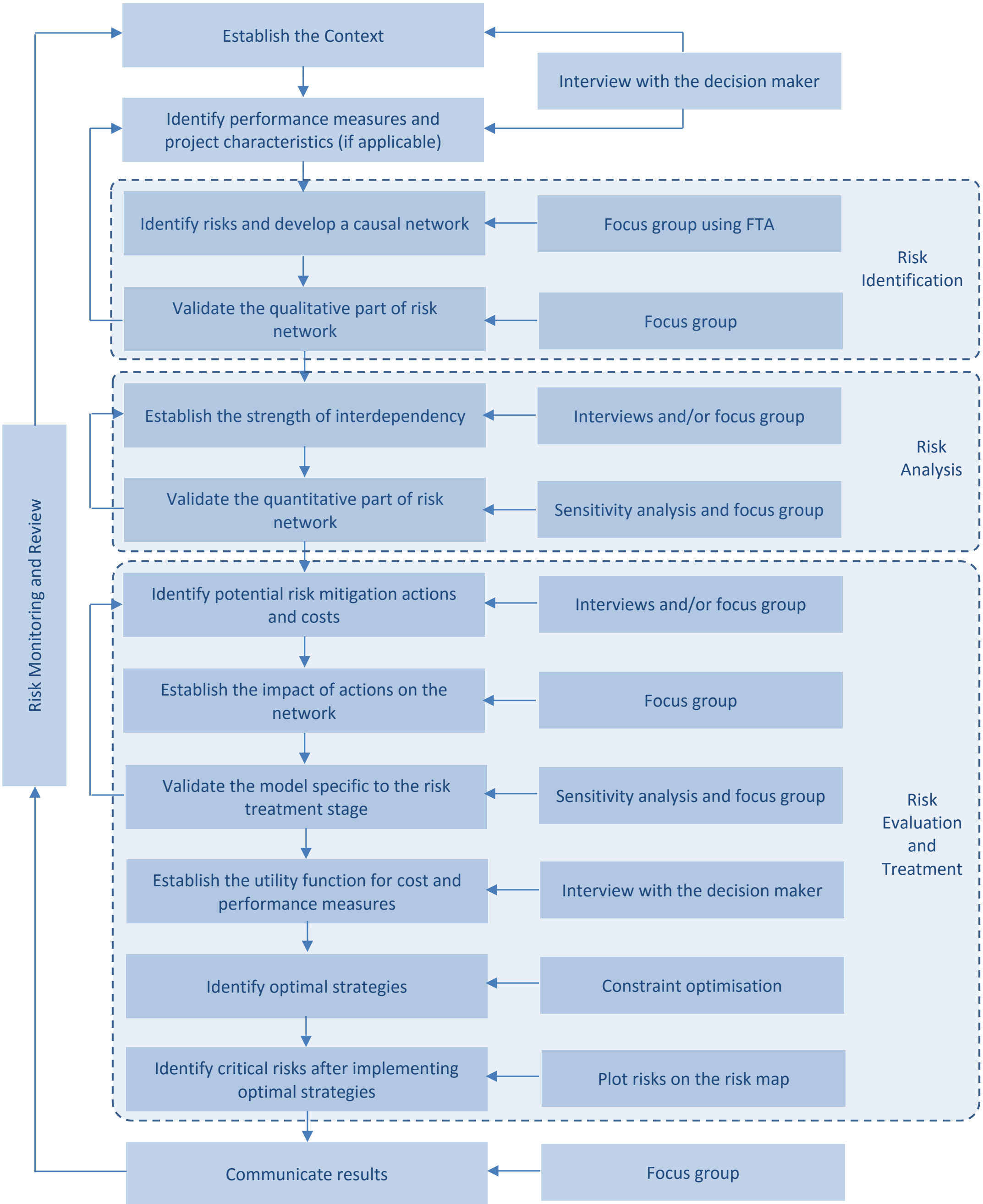

Figure 7.4: Supply chain risk management process adopted in the case studies.

model (Norrington et al., 2008). Sensitivity analysis is carried out to evaluate the impact of individual risks on each performance measure and ascertain whether the results make sense and conform to the perception of the participants. In the case of any discrepancy, the quantitative model is revisited and amendments incorporated until the sensitivity results are agreed upon.

Following the validation of a quantitative model, the decision maker is consulted with regards to the identification of potential risk mitigation strategies, associated cost and the budget constraint. A focus group session must be held to identify the connection of strategies with relevant risks and establish the efficacy of strategies in reducing the probability of risks. There is also a need for validating the efficacy of risk mitigation strategies. The decision maker is again consulted to determine the utility values corresponding to the performance measures and the cost of strategies. The model is subsequently run for all possible combinations of strategies subject to the budget constraint and the strategies are selected that maximise the overall expected utility of the decision maker. Finally, a focus group session is conducted to communicate the results to the participants and help the decision maker understand the impact of implementing different combinations of strategies. As risk management is a continuous process, the entire process is repeated requiring minimal changes in the model once new risks are discovered and updated.

7.4 Proposed Modelling Approach

Although EUT provides a standardised normative framework to make decisions under uncertainty, it is not so much used in practice mainly because of the difficulty associated with assigning utility values to all possible outcomes (Aven & Kristensen, 2005). Using the standard expected utility approach, in the case of a risk network with N interdependent risks and M strategies (each having binary states), we need to elicit 2^{N+M} utility values provided the utilities associated with different consequences are not mutually independent. As it is not viable to elicit these values even for a small network, we introduce a new approach to evaluate and manage risks specific to the risk appetite of a decision maker.

Let a risk network be composed of N risks, M mitigation strategies and O performance measures each having binary states. The utility of a decision maker is defined over different states of the performance measures as follows:

$$U(p_1^i, p_2^i, ..., p_O^i) \rightarrow (0,1) \forall i \tag{7.1}$$

where p_j^i represents the performance measure j realising in state i and the utility set comprises 2^O values specific to different combination states of the performance measures.

The expected utility of the decision maker is given as follows:

$$EU = \sum P(p_1^i, p_2^i, ..., p_O^i) * U(p_1^i, p_2^i, ..., p_O^i) \forall i \tag{7.2}$$

where $P(p_1^i, p_2^i, ..., p_O^i)$ represents the joint probability of performance measures realising in the specific combination of states.

In order to capture the impact of each risk on all performance measures, we define risk propagation measure (RPM) as the probability weighted conditional expected utility given a risk is realised.

$$RPM_{R_i} = P_{R_i} * EU | R_i = true \tag{7.3}$$

where P_{R_i} is the marginal probability of risk R_i.

In order to combine the cost of strategies and associated expected utility corresponding to all possible combinations of potential strategies M (2^M), we need to adopt a consistent method of mapping these together on a single scale. The utility is already defined over a scale of $0-1$, where a utility of $0(1)$ corresponds to the worst (best) case scenario of risks (not) happening. The cost of strategies has to be scaled in a similar fashion where spending no amount (maintaining the current status quo) would yield a utility of 1 and an amount not necessarily equal to the maximum cost of implementing all potential strategies would correspond to a utility of 0.

We propose using the method of 'swing weights' (Belton & Stewart, 2002) to determine the relative weight of the two criteria where the decision maker is asked to consider that both utility (relative to objectives) and cost are at the least preferred states (all risks realised and maximum possible cost of strategies incurred each amounting to the utility value of 0). Subsequently, he is given a scenario that only one of these could be improved to the best possible state and the one picked by him should receive the maximum weight (100) reflecting the significance of that criterion. He is then required to assess the overall value (over a scale of $0 - 100$) arising from a swing from 0 to 1 on the other criterion corresponding to the swing from 0 to 1 on the criterion already prioritised. The weights assigned can be normalised to add up to 1. Weighted Net Expected Utility ($WNEU$) is defined as the weighted sum of expected utility (EU) and the utility of mitigation cost [$U(C)$]:

$$WNEU = (1 - a)EU + aU(C) \tag{7.4}$$

Where a is a parameter that captures the importance of cost as to how a decision maker may place greater or lower weight on the cost of risk mitigation; when $a = 0$, the decision maker is not concerned about the cost of implementing strategies while in the case of $a = 1$, he will not consider implementing any additional strategy. For all other cases, different combinations of strategies will be prioritised.

7.4.1 Problem of Selecting Optimal Risk Mitigation Strategies

In this chapter, we also focus on solving the following problem:

Given different options of implementing M strategies across a network of interconnected risk sources, risks and strategies, what is the optimal combination of these strategies specific to the risk appetite of a decision maker and a budget constraint? The objective function is given as follows:

$$\begin{aligned} & max_{\gamma_{x_s} \in \gamma_{X_S}} WNEU_{\gamma_{x_s}} \\ & s.t. 0 < C_{\gamma_{x_s}} \leq c_0 \end{aligned} \tag{7.5}$$

where γ_{X_S} is a set of all possible orderings of different states of M mitigation strategies,
$C_{\gamma_{x_s}}$ is the cost of implementing γ_{x_s} combination of mitigation strategies,
c_0 is the budget constraint.

7.5 Results and Discussion

7.5.1 Results: Case Study I (Aero)

Founded in the early $20th$ Century, Aero is a leading global supplier of products, solutions and services within rolling bearings, seals, mechatronics, services and lubrication systems. Having 120 manufacturing units established in 29 countries and a distribution network across 130 countries, Aero serves a diversified mix of industries, including cars and light trucks, marine, aerospace, renewable energy, railway, metal, machine tool, medical and food and beverage.

Five performance objectives namely quality, timeliness, market share, profit and sustainability were identified during the interview. These objectives are interrelated as market share influences the profit margin and also, quality, timeliness and profit are potentially conflicting objectives. Instead of following a bottom-up approach as adopted in the Event Tree analysis, we developed the network using the FTA that utilises a top-down approach. The network was developed involving two members from the risk management group. They were asked to focus on a one-year time horizon and assess the probability of risks within that timeframe. Furthermore, the main focus was on identifying only main risks that would ultimately influence the performance objectives of the company. This exercise of brainstorming and linking risks to the performance measures identified (as used in the FTA) was guided by the principles of modelling a BBN (Nadkarni & Shenoy, 2004).

Once the qualitative structure of the network was developed, two other members of the group were involved in validating the structure. There were few changes suggested by the members in terms of adding new nodes to the network like financial issues and communication plan among others that were finally included after deliberation. The final qualitative part of the model is shown in Figure 7.5 with details of risks presented in Table 7.1. One main feature of the developed structure is capturing interdependency between risks ranging across different categories namely supply, demand, process and control risks (Christopher et al., 2011) and therefore, instead of conceptualising risks into distinct categories, we focus on intra- and inter- dependency across all such categories in the form of a risk network as shown in Figure 7.6. Control risks represent the problems associated with the management policies and these can be considered as the common causes affecting the entire web of risks as shown in Figure 7.5. For example, poor management policies might adversely affect the motivation of employees which in turn would influence the production rate and even the quality might be compromised triggering customer dissatisfaction.

Following the qualitative validation of the risk network, another focus group session was held to quantify the model. As the two participants were engineers

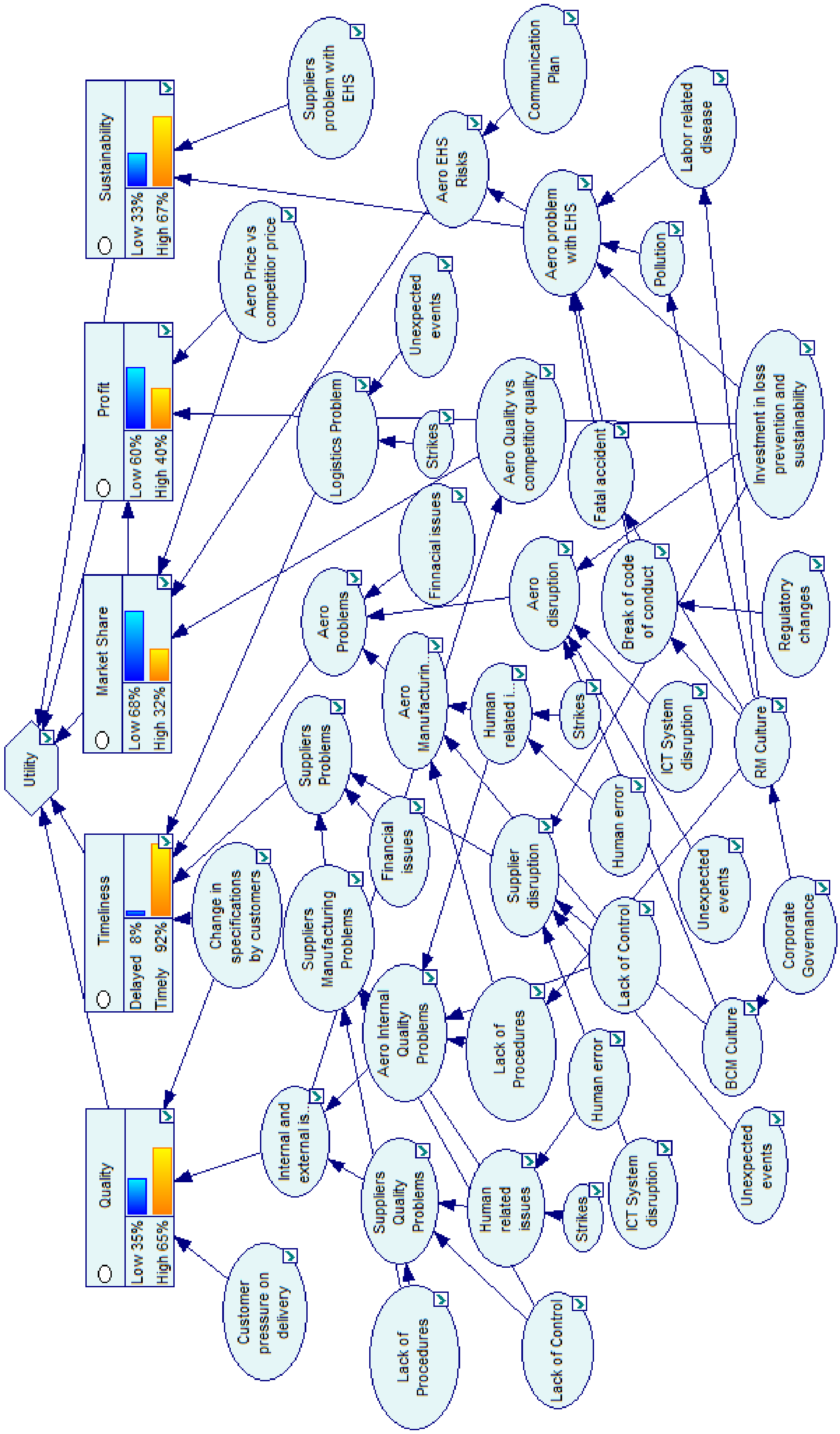

Figure 7.5: Network of interacting risks and risk sources with no potential strategies implemented (GeNIe).

Risk/Risk Source	States	ID
Unexpected event (Supplier)	Yes, No	R1
Unexpected event (Aero)	Yes, No	R2
Information and Communication Technology (ICT) System disruption (Supplier)	Yes, No	R3
ICT System disruption (Aero)	Yes, No	R4
Corporate governance	Bad, Good	R5
Regulatory changes	Yes, No	R6
Investment in loss prevention and sustainability	Low, High	R7
Labour related diseases	Yes, No	R8
Fatal accident	Yes, No	R9
Breaking code of conduct	Yes, No	R10
Business continuity management culture	Bad, Good	R11
Risk management culture	Bad, Good	R12
Strikes (Aero)	Yes, No	R13
Strikes (Supplier)	Yes, No	R14
Lack of control (Aero)	Yes, No	R15
Lack of control (Supplier)	Yes, No	R16
Lack of procedures (Aero)	Yes, No	R17
Lack of procedure (Supplier)	Yes, No	R18
Logistics problems	Yes, No	R19
Aero price vs. Competitor price	High, Low	R20
Supplier problems with environmental, health and safety (EHS)	Yes, No	R21
Communication plan	Ineffective, Effective	R22
Change in specification by customer	Yes, No	R23
Customer pressure on delivery	Yes, No	R24
Financial issues	Yes, No	R25
Aero quality vs. Competitor quality	Low, High	R26
Human error (Aero)	Yes, No	R27
Human error (Supplier)	Yes, No	R28

Table 7.1: Risks and risk sources considered in the modelling framework (Case Study I).

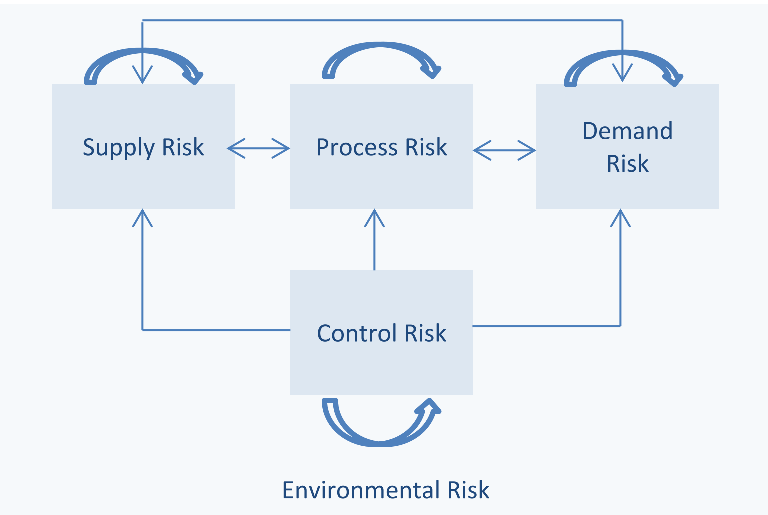

Figure 7.6: The relationship between supply chain risks (adapted from Christopher et al. 2011).

and well conversant with the fundamentals of probability theory, it was not difficult to elicit conditional probability values. The quantitative part was validated through conducting the sensitivity analysis and few conditional probability values had to be revised as the participants were not satisfied with few sensitivity results. The updated probabilities of the quality (low), timeliness (delayed), market share (low), profit (low) and sustainability (low) were calculated as 0.35, 0.08, 0.68, 0.60 and 0.33, respectively. The participants agreed with the optimistic results for quality, timeliness and sustainability and somehow justified their concern with regards to the higher probabilities associated with market share and profit. The results also conformed to their perception about the efficacy of already implemented strategies.

The decision maker was interviewed to determine the 'utility' associated with different values of the objectives as shown in Table 7.2 and potential mitigation strategies were identified during another focus group session with associated costs shown in Table 7.3. The strategies were finally mapped on the risk network as shown in Figure 7.7 and the impact of each strategy was established through eliciting the relevant conditional probability values. The rectangular shaped nodes (except the objectives appearing at the top) represent all possible strategies. Once all potential strategies were implemented, the updated probabilities of the quality (low), timeliness (delayed), market share (low), profit (low) and sustainability (low) were calculated as 0.23, 0.05, 0.37, 0.33 and 0.24, respectively. The efficacy of strategies elicited was validated through conducting sensitivity analysis.

The model was simulated for each possible combination of strategies (2^9 iterations) and the expected utility value evaluated for each instance. Subsequently, different strategies were grouped subject to a budget constraint and expected utility graph was plotted as shown in Figure 7.8. The variation in the expected utility value is non-linear and it is not always optimal to invest in implementing strategies ($195 - 235$ units of cost).

Quality	Low							
Timeliness	Delayed (Timely)							
Market Share	Low				High			
Profit	Low		High		Low		High	
Sustainability	Low	High	Low	High	Low	High	Low	High
Utility	0 (0.15)	0.1 (0.2)	0.3 (0.35)	0.4 (0.45)	0.2 (0.4)	0.3 (0.45)	0.45 (0.5)	0.6 (0.65)

Quality	High							
Timeliness	Delayed (Timely)							
Market Share	Low				High			
Profit	Low		High		Low		High	
Sustainability	Low	High	Low	High	Low	High	Low	High
Utility	0.4 (0.45)	0.45 (0.5)	0.5 (0.65)	0.6 (0.75)	0.5 (0.65)	0.55 (0.75)	0.7 (0.85)	0.8 (1)

Table 7.2: Utility values for the objectives (Case Study I).

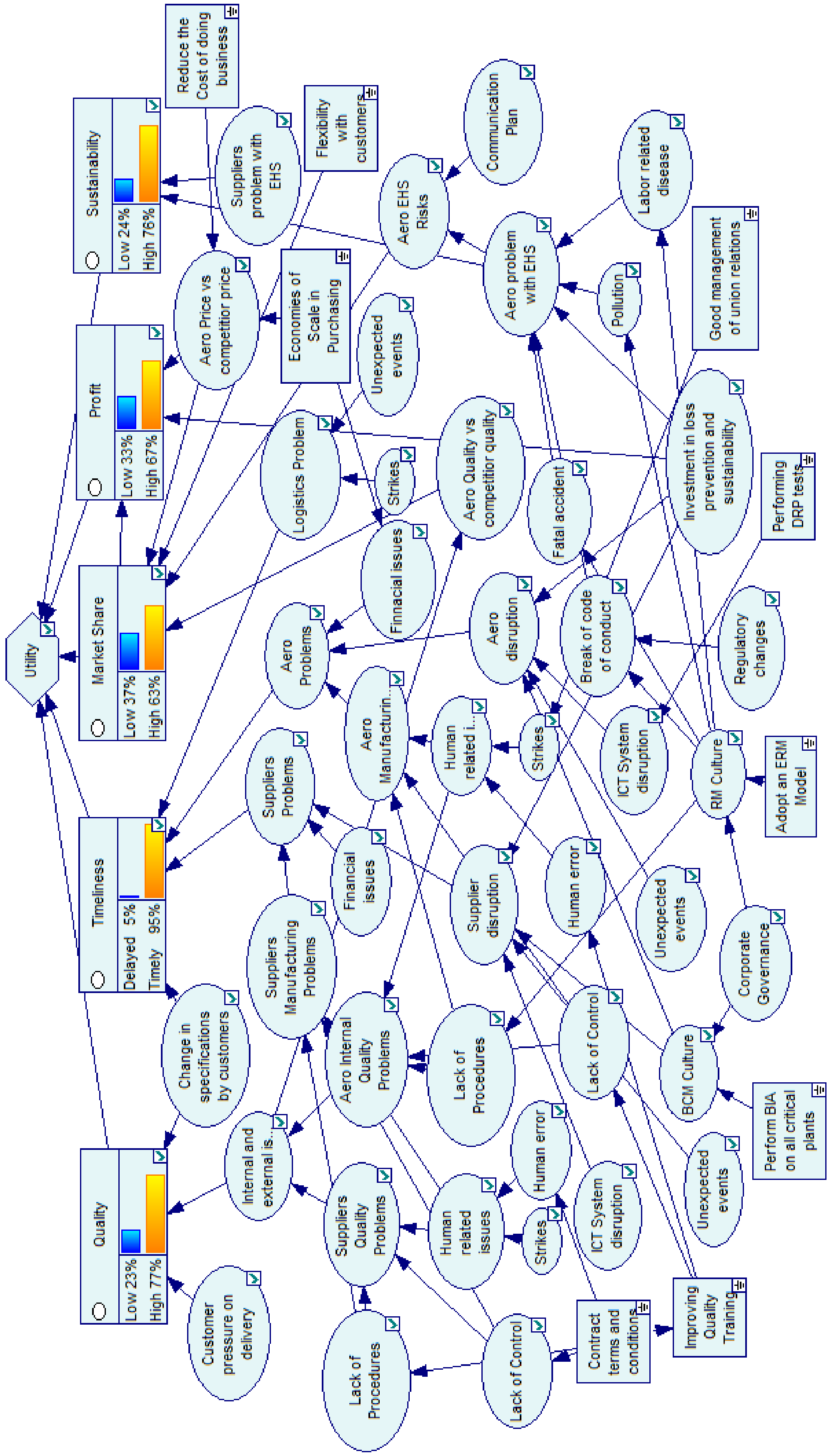

Figure 7.7: Network of interacting risks, risk sources and potential strategies (GeNIe).

Risk Mitigation Action	Cost (Monetary units)
Contract Terms	20
Quality Training	20
Perform Business Interruption Analysis	20
Adopt Enterprise Risk Management Model	30
Perform Disaster Recovery Plan (DRP) Testing	10
Union Relations	5
Economies of Scale	30
Flexibility	60
Reduce Cost	100

Table 7.3: Potential risk mitigation strategies and associated cost (Case Study I).

The weighted net expected utility was mapped subject to different weights assigned to the expected utility and cost as shown in Figure 7.9. This graph provides as a validity check as with the increase (decrease) in the preference for the expected utility (cost), the optimal solution moves away from the current investment level. Next, the optimal investment level (one maximising the $WNEU$) with respect to the budget constraint was determined as shown in Figure 7.10. A decision maker assigning equal importance to the improvement in expected utility value and the mitigation cost must never invest in strategies costing more than 30 units. Similarly if the decision maker attributes 90% of the importance to the improvement in expected utility, the investment level should be increased to 165 units.

For the sake of risk prioritisation, the updated probability of each risk was mapped with associated conditional impact (risk being realised) on the expected utility as shown in Figure 7.11. The two indifference utility curves plotted segregate the entire map into high, medium and low risk zones. These curves reflect the risk appetite of a decision maker where any risk within the high risk zone must be mitigated and risks within the medium risk zone reduced to the lower risk level provided the benefits exceed the cost. Here the purpose was not to specifically focus on the criteria to establish the boundaries of these curves that

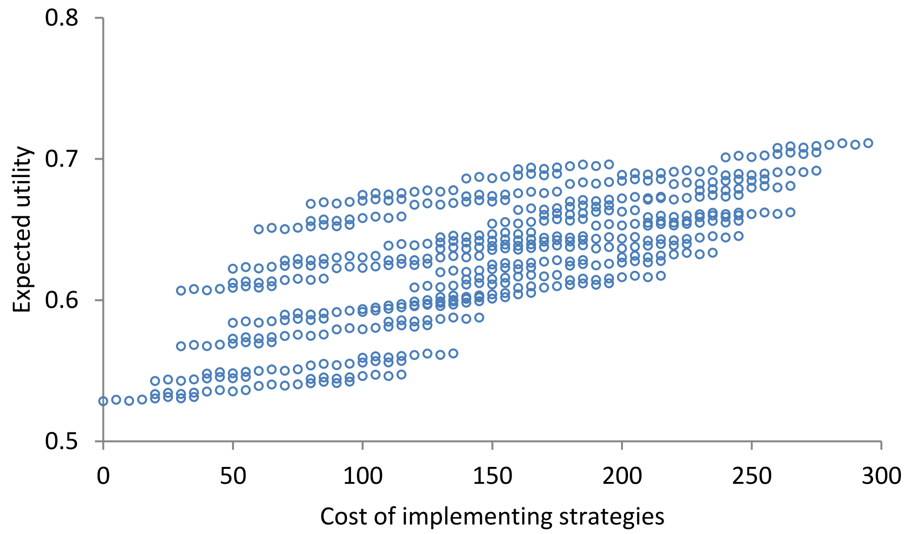

Figure 7.8: Variation of expected utility (across key performance measures) with mitigation cost.

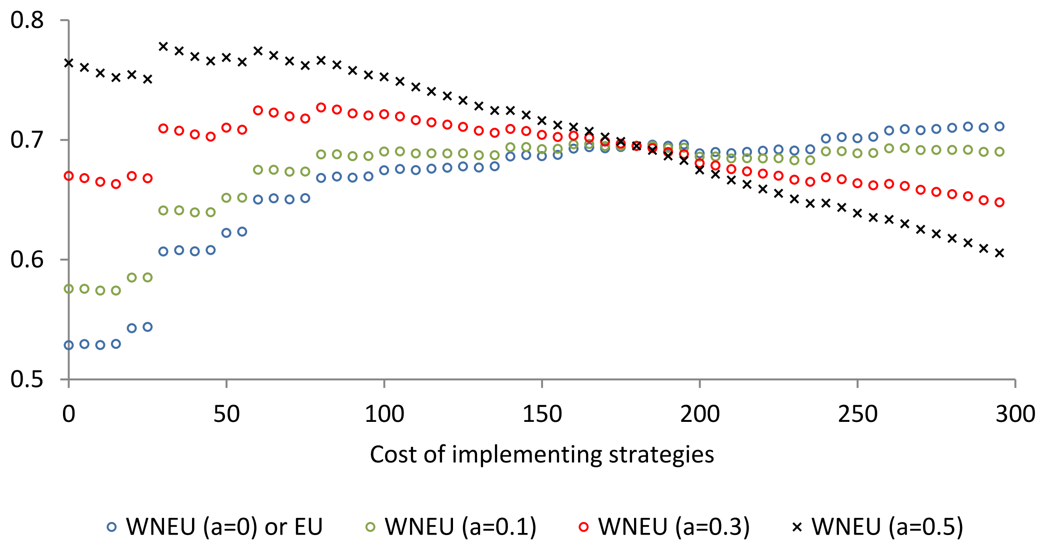

Figure 7.9: Variation of maximum weighted net expected utility ($WNEU$) with different importance weights for cost (a) and mitigation cost.

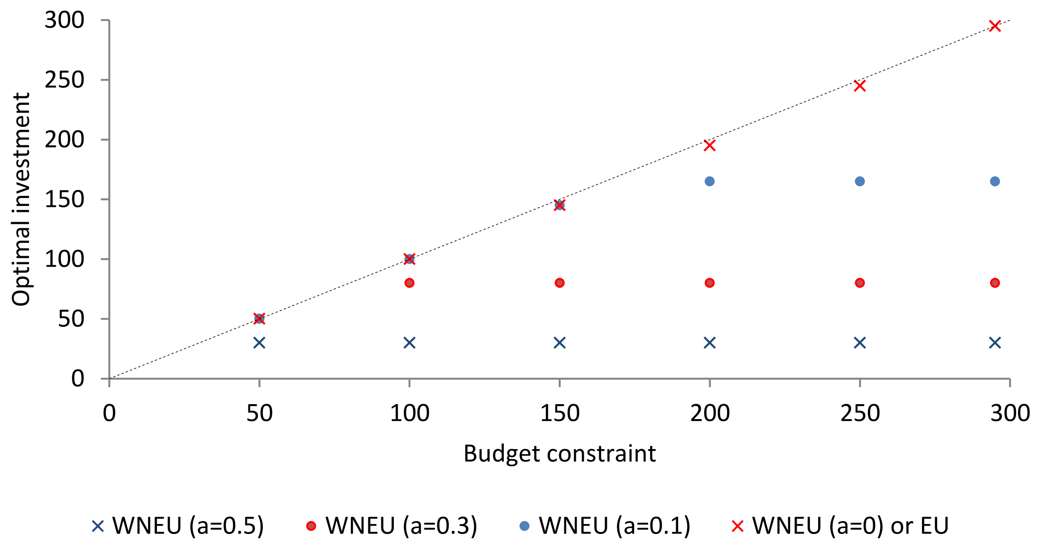

Figure 7.10: Optimal investment subject to different importance weights for cost (a) in the weighted net expected utility $(WNEU)$ and budget constraint.

are already explored by Ruan et al. (2015). R20, R26 and R11 appear to be the most critical risks. In order to gain an insight into the efficacy of implementing potential mitigation strategies, the configuration of risks is shown in Figure 7.12. With the same segregation of risk zones, there is no risk in the high risk zone whereas only R26 is located in the medium risk zone. Therefore, the implementation of all potential strategies helps in substantially improving the overall state of the risk network.

7.5.2 Results: Case Study II (Cell)

With its glorious history of over 150 years, Cell is one of the major companies in the telecommunications industry having its networks-oriented businesses organised into four business groups: Mobile Networks; Fixed Networks; Optical Networks; and Applications and Analytics. With manufacturing facilities in China, Japan, Finland and India, it needs to handle supply chain management of all its hardware, software, and original equipment manufacturer products.

For developing the model, we followed the similar approach adopted in the first case study. However, we could not focus on the risk treatment stage because

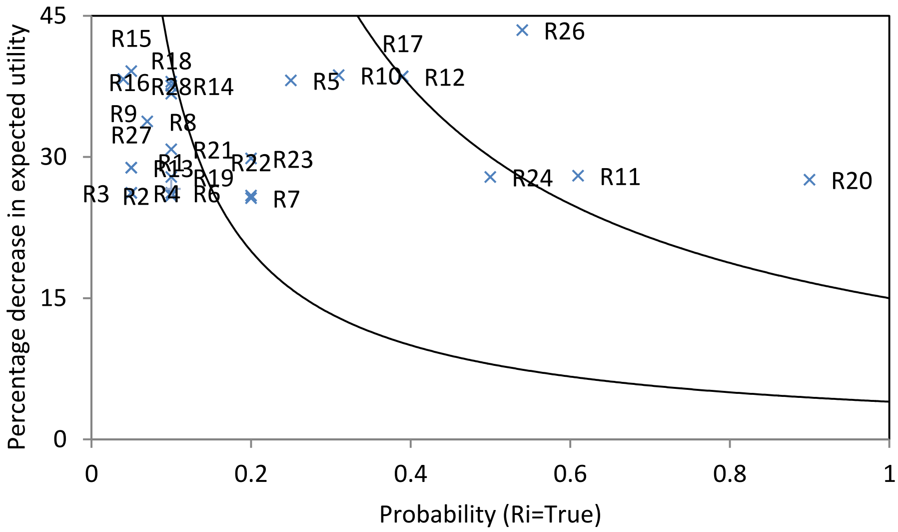

Figure 7.11: Risk matrix representing current state of risks (with no potential strategies implemented).

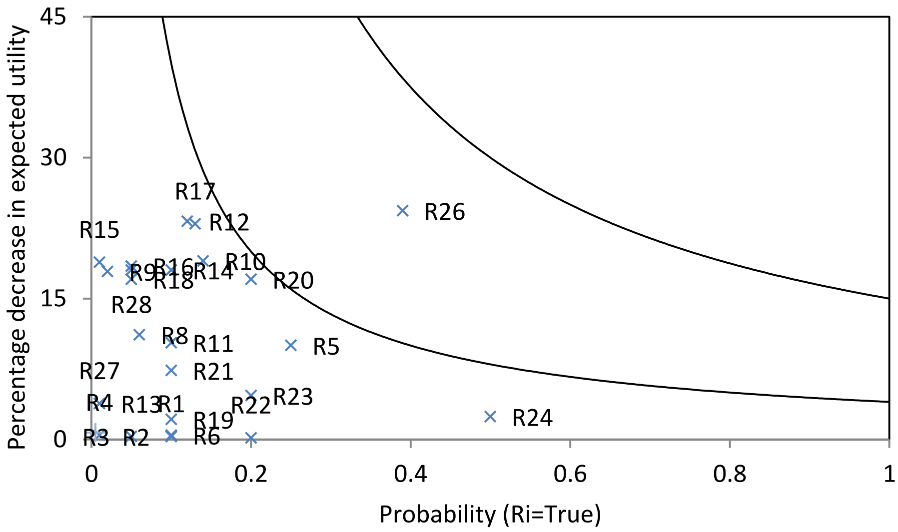

Figure 7.12: Risk matrix representing state of risks after implementation of all potential strategies.

Risk/Risk Source	States	ID
Feature deprioritisation	Yes, No	R1
Research and Development delays (Cell)	True, False	R2
Research and Development delays (3rd Party)	True, False	R3
Logistics issues	Yes, No	R4
Lack of experience	Yes, No	R5
Lack of training	Yes, No	R6
Admin issues	Yes, No	R7
Shortage of components	Yes, No	R8
Supply chain issues	Yes, No	R9
Shortage of experienced team (Cell)	Yes, No	R10
Shortage of experienced team (3rd Party)	Yes, No	R11
Defects	High, Low	R12
Change in specifications	Yes, No	R13
Access to site	Yes, No	R14
Availability of site	Yes, No	R15
Availability of connectivity at site	Yes, No	R16
Availability of equipment (Cell)	Yes, No	R17
Availability of equipment (3rd Party)	Yes, No	R18
Human error	True, False	R19

Table 7.4: Risks and risk sources considered in the modelling framework (Case Study II).

of the time constraint. Nonetheless, we were able to evaluate the adapted version of ProCRiM and discuss the merits and challenges associated with implementing the proposed process. The main informant was asked to choose a particular project and identify the key performance objectives associated with the project. Cost, time, volume of activities and fitness for purpose were the main objectives identified. Following the similar approach of FTA and involving two other participants, supply chain risks were connected across the objectives and the risk network was developed as shown in Figure 7.13 with details of risks presented in Table 7.4. A list of selected project complexity attributes (Qazi et al., 2016) was shared with the informant and five attributes (shown as rectangular nodes at the bottom of Figure 7.13) were finally selected to have significant impact on the risk network modelled.

A focus group session was held to validate the qualitative part of the network. The presented network reflects the final version of the network that was ultimately accepted following a discussion with the participants. The quantitative part of the model was developed with the help of key informant. Unlike the participants

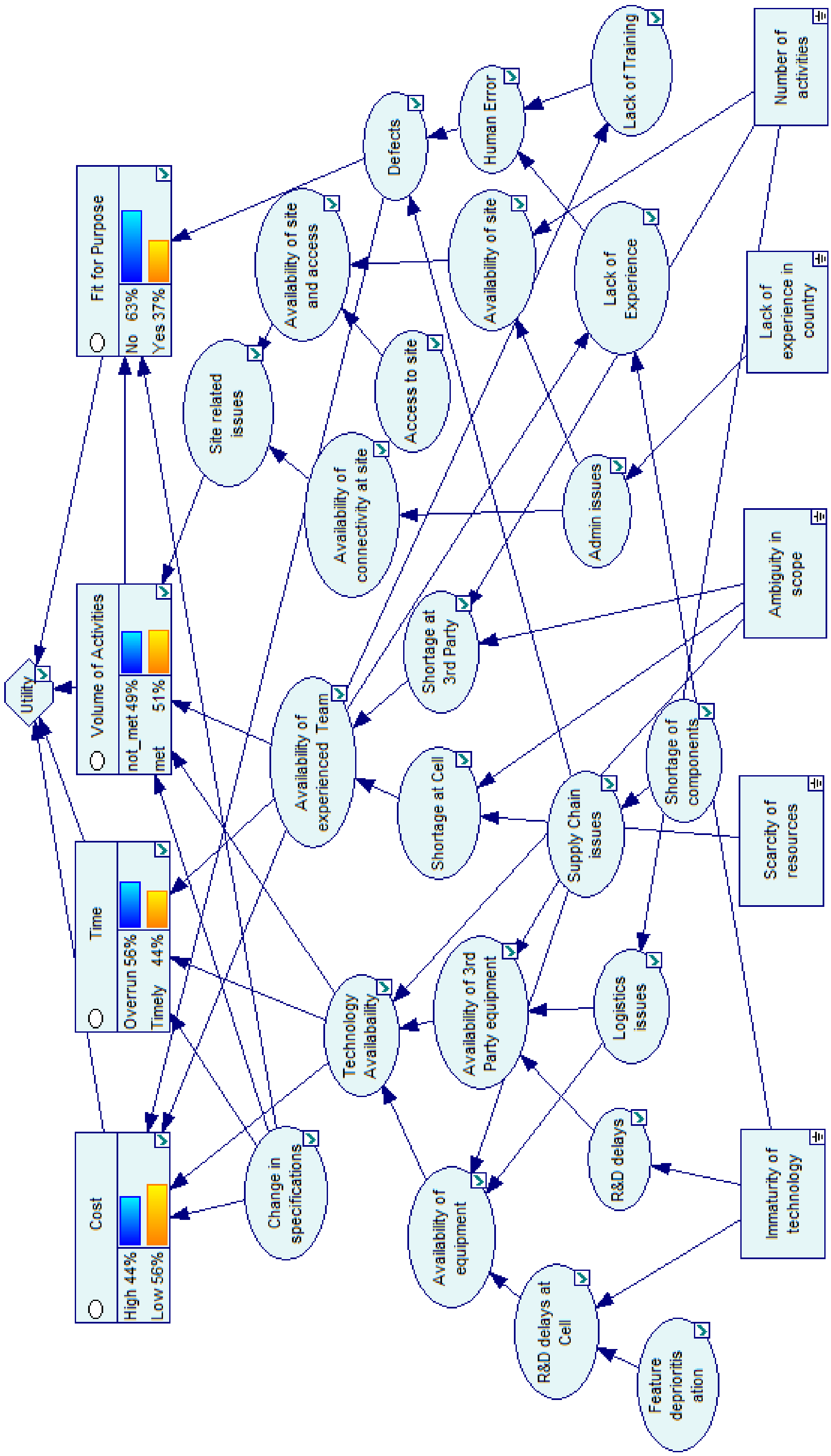

Figure 7.13: Network of interacting risks and risk sources (GeNIe).

Classification	Range (Point estimate)
Almost certain	(0.99)
Highly likely	0.8-1 (0.9)
Likely	0.6-0.8 (0.7)
Fifty-fifty	0.4-0.6 (0.5)
Unlikely	0.2-0.4 (0.3)
Highly unlikely	0-0.2 (0.1)
Almost uncertain	(0.01)

Figure 7.14: Scale used for eliciting probability values.

Classification	Range (Point estimate)
Maximum	(1)
Very high	0.8-1 (0.9)
High	0.6-0.8 (0.7)
Medium	0.4-0.6 (0.5)
Low	0.2-0.4 (0.3)
Very low	0-0.2 (0.1)
Minimum	(0)

Figure 7.15: Scale used for eliciting utility values.

involved in the first case study, the key informant was not comfortable with providing the probability values. Therefore, a qualitative scale was introduced to elicit the probability values and utility values as shown in Figure 7.14 and Figure 7.15, respectively. The utility values elicited are presented in Table 7.5. As there were five project attributes considered in the model, a total of 32 different projects could be analysed. The variation of the expected utility with the project attributes is shown in Figure 7.16. The $1st$ point represents the most complex project whereas the $32nd$ point reflects the least complex project in terms of the complexity attributes selected.

We mapped all the risks on the risk matrix with associated probability value

Fit for Purpose	No (Yes)							
Volume of Activities	Not Met				Met			
Time	Overrun		Timely		Overrun		Timely	
Cost	High	Low	High	Low	High	Low	High	Low
Utility	0 (0.3)	0.1 (0.5)	0.1 (0.3)	0.3 (0.7)	0.1 (0.3)	0.3 (0.5)	0.3 (0.7)	0.5 (1)

Table 7.5: Utility values for the objectives (Case Study II).

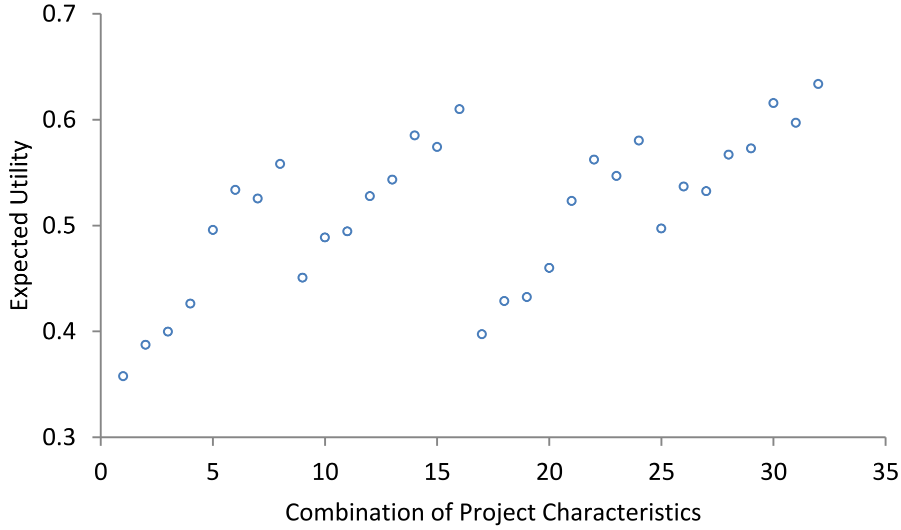

Figure 7.16: Variation of expected utility with project characteristics.

and the impact on expected utility in case of their realisation as shown in Figure 7.17. The graph reflects the risk configuration corresponding to the most complex project. R13, R1, R10, R5 and R3 are the most critical risks to be mitigated. If the least complex project is modelled, all the risks move to the low risk zone as shown in Figure 7.18.

7.5.3 Description of Currently Used Risk Matrix Based Tools

The respondents confirmed that they utilise a risk matrix based approach similar to the one shown in Figure 7.19 where each risk is mapped with corresponding probability and impact (in monetary units) values. The matrix is segregated into three risk zones: high; medium; and low with partitions selected on the basis of the company's risk appetite. Let us consider that there are three risks mapped onto the matrix with $R1$ located in the high risk zone, $R2$ in the medium zone and $R3$ in the low risk zone. Following are the major concerns about the risk matrix based approach used:

- All the risks are assessed only in terms of their impact on a single objective

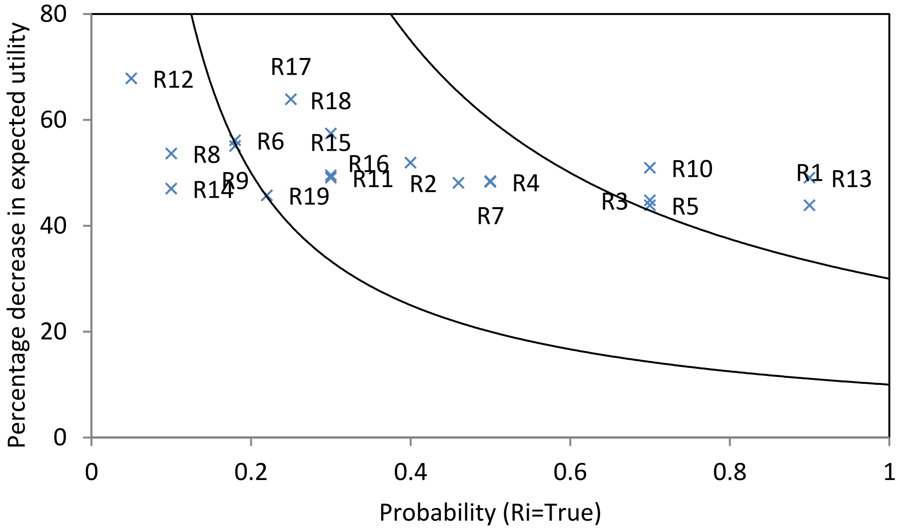

Figure 7.17: Risk matrix representing state of risks for the most complex project.

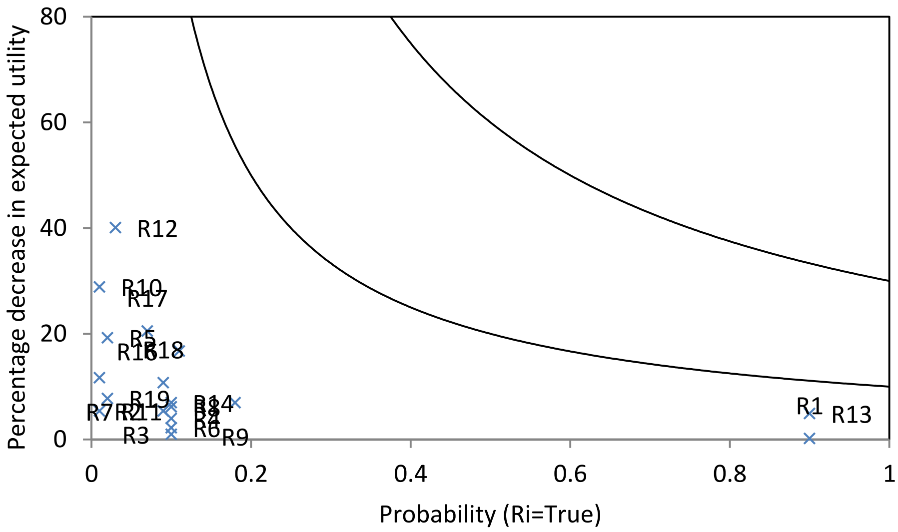

Figure 7.18: Risk matrix representing state of risks for the least complex project.

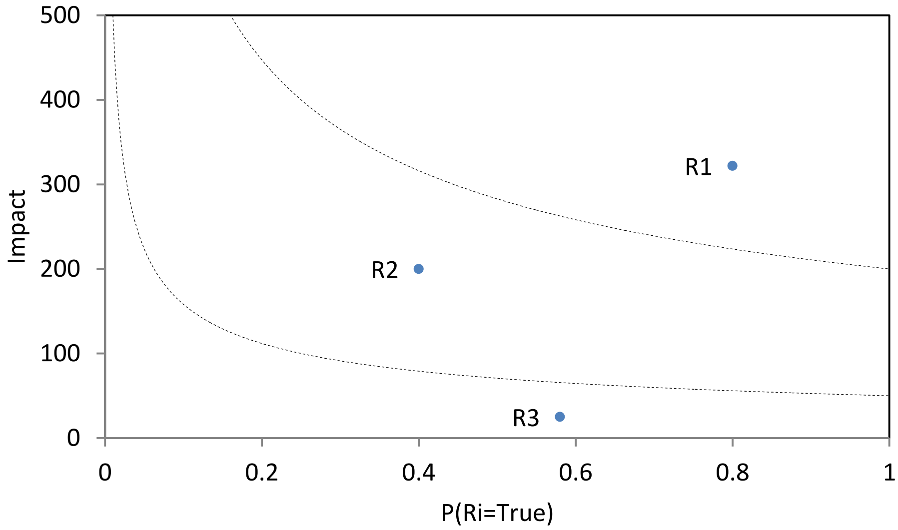

Figure 7.19: Risk matrix based approach currently used in the two companies.

i.e. project cost (or project delay with impact on the cost) and therefore, optimising a portfolio of strategies considering a single objective and ignoring other important (potentially conflicting) objectives (quality, competitive advantage, sustainability etc.) would yield a sub-optimal solution.

- Assuming the single objective considered as the only objective important to the decision maker, let us consider $S1$, $S2$ and $S3$ as relevant strategies to mitigate $R1$, $R2$ and $R3$, respectively. If there is no interdependency between risks, the decision maker would be better off mitigating $R1$ first provided $S1$ effectively reduces the probability and/or impact of $R1$. However, if it is established that $R3$ is the common trigger for both $R1$ and $R2$ and the only causal factor of $R1$, it will be optimal to invest in $S3$ provided it is cost-effective. The analysis gets complicated once the strategies have contrasting correlations with one another. Therefore, in the case of any interdependency between risks and/or strategies, utilising a risk matrix based approach might yield a sub-optimal solution.

7.5.4 Findings: Semi-Structured Interviews

This section is a collection of sample quotations from the interview narratives transcribed. The findings are organised into three categories: current practices of managing supply chain risks; benefits of implementing the proposed process; and the challenges involved in implementing the process.

Current Practices of Managing Supply Chain Risks

Most participants believed that there are established guidelines to conduct the risk management and generally the endeavor is to adopt the risk management standards within the enterprise. As reported in the literature, risks are classified into separate categories and assessed accordingly.

"We have standard templates which guide us what kind of topics and risks to consider during the risk management process. ... We have a tool where we nail down all kinds of risks. Cost estimation and probability are documented and signed by all stakeholders". (Resp#6)

"We are still in a position that we don't adopt ISO 31000 *standard yet. So, actually we adopt COSO (Committee of Sponsoring Organisations of the Treadway Commission) model and classify risks into two categories: financial risks and pure risks. Pure risks are subject to losses that are to some extent insurable whereas financial risks are associated with opportunities as well as downside risks".* (Resp#1)

"During risk analysis, a team composed of different team members with different roles assesses risks. The risks are considered without any correlation. Usually, given the probability and impact of risks, we try to implement mitigation plan on high risks in the risk review meeting. The risks are categorised according to the business area and categories like commercial, operational, logistics etc. are used". (Resp#7)

A few participants acknowledged the limitation of their current practices;

however, others were optimistic about the efficacy of ISO 31000 (SA, 2009) based frameworks.

"I think that the risk management process is quite mature and it serves our purpose. We started from much shallow position few years back. Project and risk management offices were introduced across the organisation to cope with the requirement of systematically managing risks". (Resp#5)

"Since the beginning of this year, we are trying to broaden the scope of risk analysis because in silo view, we miss important things. Still we are not working on the ERM (Enterprise Risk Management) perspective. Different pieces are put together by different groups and the current risk management process does not capture the systemic interactions". (Resp#1)

With regards to the risk treatment, it was revealed that there is no such procedure to model the trade-off between performance measures. Similarly, it is assumed that a strategy only affects a single risk and therefore, not much effort is made to assess the correlations between strategies and risks.

"During the risk review meeting, the team agrees on the selection of strategies to address the risks. Commercial issues like customer satisfaction are the main risks. The experience and knowledge of the team members help in selecting the best strategy to apply. For each risk, you could apply different strategies and therefore, we assess different plans". (Resp#6)

"There is no tool available to model the trade-off involved in the objectives. For well-known risks, we take proactive approach. If we already know from our experience about the potential risks, we rely on proactive approach. However, the risk management process is more reactive. To be honest, today it is more reactive where the risks are not predictable". (Resp#2)

"The only thing I can think of is historical trend relevant to the project. It is not really a methodology rather it is based on historical data and best practices. There is a strong element of the experience of people. In very sizable cases, we

will appoint people who have done the same thing. ... No, we do not have any such causal technique to assess strategies within the network of interacting risks". (Resp#7)

"In terms of risk treatment, we are rude in the sense that it is the experience of your supply chain risk manager and accounts manager because in many cases, the supply chain risk manager is interested in improving the quality and the accounts manager just wants to reduce the budget. It is a negotiation between the two parties to reach an agreement. ... Rude in the sense that there is no such complex process involved in understanding the complex situation". (Resp#6)

"We have different tools for managing risks but there is no link between the two. Like there is one tool for tracking the deviation of a project. The other is for tracking the cost but there is no connection between the two. There is no evaluation of cost and effort involved in implementing a mitigation strategy". (Resp#7)

Benefits of Implementing the Proposed Process

The participants involved in developing the model appreciated the significance of capturing interdependencies between risks and mitigation strategies.

"To start more people around the table will actually help capture holistic risks across different disciplines. If you build it for a certain project and supply chain characteristics putting much more expert knowledge, the graph would be relevant and even if new risks are introduced, the same graph can be used without starting from the scratch". (Resp#3)

"It boils down to what happens in reality. It is all about risk management. You can only evaluate after you have gone through the project rather several of those. Once a project is finished, it is more important to learn from the project and this model can be helpful in maintaining the progress of risks over time and learning from the past experiences". (Resp#5)

"I think that the process helped us develop a risk network in a very short time and it was quite helpful to think through developing the network from the performance measures. We could identify some interesting patterns and specifically the identification of sub-optimal strategies through the process is fascinating and worth investing time and effort. I am sure that such decision tools will add real value to any enterprise and help them make efficient investment decisions". (Resp#1)

"It is a very interesting model where you get to know about the correlations between risks. Having something in place to provide a guideline to initial risk analysis would be a great opportunity as it can incorporate key lessons from the past in terms of the strength of dependency between risks. The most powerful thing is to take decisions. Managerial decision making is not always correct as it involves a number of biases and such tools can help the decision maker look at different facets of the problem". (Resp#2)

"We do not have tools to model the trade-off across the objectives within an interdependent setting of interacting risks. If you do not map the main sources of risks to your performance and if you do not map the correlations then you can have a serious problem and now we are able to identify the main limitation of our current process". (Resp#4)

"The process will really benefit from the brainstorming session involving top managers where they will be able to identify interesting patterns of risks and evaluate different strategies". (Resp#1)

Challenges involved in implementing the Process

The main challenges were identified as the commitment to developing and updating the model, training required to enhancing the skill and knowledge of the team, the focus of established risk management standards on identifying and assessing independent categories of risks and the resistance of the organisation to bringing the paradigm shift.

"Such type of process aimed at modelling interdependency between risks is quite expensive in terms of involving a lot of people and needing a lot of discipline. There is a cost that the company has to incur. The first challenge is to evaluate the cost and benefit analysis. The second challenge is about knowledge and how exactly you develop the competence of people involved in implementing the process. In case of a very distributed organisation like ours, it is not easy to train all the people across the organisation. The third challenge is how we capture knowledge in such project driven supply chains including risk management. It is not a simple thing". (Resp#5)

"If we look at the ISO guide and all the standards, these describe a lot of tools for assessing risks and return on investment. Companies do not care about these correlation analyses because there is no such requirement and also, there is no literature about it from the application perspective". (Resp#1)

"The challenge is to establish a standard tool. Checking and updating every single risk is really challenging. Secondly, usability of the tool is very important. The challenge is to get the people work and use the tool on regular basis. We have plenty of tools. We must be sure that people should be able to realise the benefit of using a new tool. It is important to demonstrate the merit of the tool so that its continuous use must be justified and guaranteed". (Resp#7)

"Even if the process or tool is a simple one, there is always a resistance. Organisation is what it is so you have to play with the cards you have in your hand. The biggest obstacle is the organisation as you cannot change it. The main challenge is to convince the top management and internalise the process. We need to create a steering committee or appoint a CRO (Chief Risk Officer) who is in charge of the risk management process". (Resp#6)

"It is costly in terms of time but the results are great. The challenge is in terms of eliciting values from the experts. There will be biases involved in the

group decision making". (Resp#2)

7.5.5 Reflections and Discussion

The main aim of the study was to develop and empirically evaluate an integrated SCRM process and to investigate the merits and challenges associated with implementing the process. The case studies helped us gain an insight into the real practices of managing supply chain risks. Our findings conform to the widely reported literature on supply chain risk classification where risks are classified into independent categories and on risk management frameworks where the notion of assessing these risks in silo is embraced (Rangel et al., 2015). Limited tools or techniques focusing on the interdependency modelling are confined to optimising a single performance measure and therefore, the optimisation of these measures in isolation does not necessarily yield a global optimal solution (Colicchia & Strozzi, 2012; Garvey et al., 2015). This finding corroborates the study conducted by Ho et al. (2015) who have emphasised the need for integrating all stages of the risk management process and linking systemic risks to (potentially) conflicting objectives. The participants also echoed the same concern and acknowledged the limitation of existing practices.

Interdependency modelling is not something new to the literature on SCRM. There have been attempts in the past to propose tools that are capable of capturing interdependency between risks (Badurdeen et al., 2014; Garvey et al., 2015). However, the main problem with these tools is their focus on limited stages of the process. Similarly, the merits and challenges involved in implementing the techniques were not investigated in detail. The participants involved in both case studies found it a very interesting exercise to develop a risk network and link risks to multiple performance measures. Related to this, the use of an approach similar to the FTA was highly appreciated as it would ensure focusing on important risks only and not considering risks having insignificant impact on a performance measure. To the best of our knowledge, there are limited studies having explored the use of FTA in modelling supply chain risks (Sherwin et al., 2016). However, merging the two techniques of FTA and BBNs helps in modelling common cause failures that cannot be achieved through the use of FTA alone.

The elicitation of conditional probability values was easier in the case of experts having the background knowledge in engineering or mathematical science whereas it was a challenging task otherwise. The use of qualitative scale helped the experts provide their judgement and with the passage of time, they were able to indicate numeric values. The participants could appreciate the significance of optimising conflicting objectives within the same model. The main merit of the proposed process was acknowledged as the ability to visualise the interconnectedness between the risks and how exactly a risk or a set of risks influences multiple objectives. Techniques other than BBNs are not able to depict the similar kind of transparency and visual patterns of risk propagation (Garvey et al., 2015). The graphs representing the efficacy of potential risk mitigation strategies were highly appreciated as these helped the decision makers realise the significance of adopting the proposed process without which it would not be possible to segregate optimal strategies from the dominated ones.

Despite acknowledging the merits of the proposed process, the participants were apprehensive of the challenges involved. As the risk management process is often governed by regulations, the established frameworks (SA, 2009) with their exclusive focus on evaluating and managing individual risks would need to be challenged and replaced by interdependency based frameworks. The second major problem relates to the organisational culture and the resistance to change. The development of SCRM in theory dates back to the start of $21st$ century (Manuj & Mentzer, 2008a) and therefore, it is too early for practitioners to realise and implement the risk management process in its true essence. It needs a lot of commitment from the top management to indoctrinate the culture of risk management as practitioners mostly rely on their intuition and past experiences and they tend to be reluctant to change their practices. The cost and benefit analysis of implementing such robust frameworks would also help the decision makers undertake such a paradigm shift. Also, it needs a lot of effort in terms of educating the people involved and maintaining such models over a period of time.

We are not aware of any study in the literature on SCRM where the merits and challenges associated with implementing an interdependency based process are explored. However, it is worth looking in the literature on project risk management where in contrast, the concept of risk management is well established. Exclusively focusing on systems perspective within the realm of project risk management, Ackermann & Alexander (2016) and Loosemore & Cheung (2015) deliberated on the merits and challenges associated with implementing causal mapping and systems thinking based tools, respectively. Our study provides a similar kind of insight into SCRM but involves a different modelling technique i.e. BBNs. Unlike the work of Loosemore & Cheung (2015) where the participants did not necessarily have the knowledge of System Dynamics (SD), the participants in our study were themselves involved in developing the model and therefore, they could assimilate and appreciate the underlying mechanism. Similar to the causal mapping and systems thinking, our proposed process builds on a technique capturing interdependency between risks. However, unlike causal mapping the proposed process models the strength of interdependency between the interconnected factors and also integrates all the stages of the risk management process within a probabilistic network setting that is not possible in case of deploying an SD approach.

Our study corroborates a number of findings reported in the aforementioned papers. As reported in the work of Loosemore & Cheung (2015), resistance to change, lack of time and resources, and external validation of existing risk management practices are the main barriers of implementing interdependency modelling (in SCRM). However, we think that the issues reported involving sharing of risks among the stakeholders and contractual confrontations would be relevant at a very later stage once the risk management process is mature enough to involve all external stakeholders. We believe that the very first step is to gradually implement the proposed process within the organisation itself as it would still necessitate a lot of effort in bringing the change and imparting necessary training even at the organisation level (Ackermann & Alexander, 2016). Moreover, our findings contradict the finding of Loosemore & Cheung (2015) that people find it difficult to think systematically as the participants found it very easy to develop a risk network within a limited timeframe. Rather we believe that there is no incentive or obligation to think systematically while managing risks.

Studies focusing on the cost and benefit analysis of implementing these sophisticated frameworks would incentivise practitioners towards adopting interdependency modelling in managing risks. Like advocated by Ackermann & Alexander (2016), we think that there is a need for *"finding mechanism to encourage the application of the (interdependency based) approach"* (Ackermann & Alexander, 2016, p. 899) by the SCRM professionals. Similarly, the dynamic nature of risk could be captured as the risk networks *"created at a particular point in time could be compared with those of a later time period thus enabling longitudinal analysis of projects, allowing for shifting patterns of behaviour to be explored"* (Ackermann & Alexander, 2016, p. 899).

7.5.6 Key Merits of the Proposed Process

Risk Identification

Instead of following the conventional risk classification schemes, the proposed process introduces development of a risk network where performance measures (objectives) are identified first followed by linking risks to these measures. Adopting such a technique (similar to the FTA) helps in not only modelling material risks but also common cause failures. The participants involved in developing the risk network (Case Study I) were able to identify around 65 connections within the network (see Figure 7.5). Furthermore, few risks located at the bottom of the network (business continuity management culture, risk management culture) were evaluated as critical risks having major influence on a number of risks.

Risk Analysis

Risk matrix based tools and interdependency based models proposed in the literature generally focus on a single performance measure (monetary loss resulting from a risk realised) whereas it is important to consider all material performance measures including but not limited to quality, time, profit, competitive advantage, sustainability, cost and reputation. Instead of focusing on the monetary value of a loss resulting from a risk, the proposed process utilises the concept of expected utility and each risk is evaluated with respect to its influence on the overall expected utility across the risk network. Instead of mapping each risk onto a 'probability-impact' matrix, the process introduces the 'probability-conditional expected utility' matrix thereby capturing the impact of each risk on all performance measures considered.

Risk Treatment and Risk Monitoring

In contrast with the treatment of individual risks and selection of individual risk specific strategies as followed in the risk matrix based tools, the proposed process helps in mapping risk mitigation strategies onto the risk network modelled. 'Weighted net expected utility' makes it possible to establish the trade-off between the efficacy of potential risk mitigation strategies and the associated cost keeping in view the risk appetite of a decision maker. Ignoring the proposed process would increase the risk of selecting sub-optimal strategies.

As the proposed process is grounded in the framework of BBNs, it is very easy to update the model once new risks are identified without the need for developing a new model from scratch. Similarly, a BBN based model can be easily maintained and monitored over a longer period to conduct a longitudinal study and systematically analyse important lessons learnt.

7.5.7 Propositions

Based on the critical comparative analysis of the proposed risk management process with the established frameworks, following propositions are introduced that will help supply chain managers appreciate the significance of implementing a comprehensive interdependency based SCRM process. The propositions are specifically developed to reveal the risk inherent in following the proposed risk mapping tools (Oke & Gopalakrishnan, 2009; Thun & Hoenig, 2011) and adopting generalised risk mitigation strategies.

Proposition 1

Neglecting interdependency between risks and strategies would result in over-investment if all the risks are positively correlated and the strategies are negatively correlated with the risks.

In case of an exclusively independent supply risk network with no correlations between the risks, risk exposure is the summation of risk values corresponding to individual risks. Treating such independent risks with strategies influencing individual risks would yield a marginal benefit in terms of reducing (increasing) the overall risk exposure (expected utility) (see Figure 7.19). However, when there is a positive correlation between any single pair of risks and even though each potential strategy does influence a single risk, the net reduction in the overall risk exposure will be greater than the case with no correlation between the risks and the same intended level of risk exposure could be achieved through investing lower amount of mitigation cost. Therefore, a firm interested in achieving a specific risk exposure needs to invest less if realisation of any risk triggers other risks and the strategies implemented have positive impact on the risk network.

As discussed in Section 7.5.3, the risk matrix based approach currently used in the two companies studied helps in treating each risk in silo without motivating the stakeholders to plan strategies that are cost-effective for the risk network. This approach results in implementing optimal strategies for individual risks that would only be optimal for the risk network with no interdependency between risks and strategies. With reference to the evaluation of risk mitigation strategies specific to the risk network shown in Figure 7.7 (see Figure 7.8), ignoring interdependencies between risks would expose the decision maker to selecting sub-optimal strategies at random.

Proposition 2

Neglecting interdependency between risks and strategies might increase the risk exposure of the network in case of implementing strategies where some risks are negatively correlated and/or some strategies are positively correlated with some risks.

In the worst case scenario of interdependency between risks and negative correlation of strategies and risks, it would be optimal not to implement any strategy rather to maintain the already implemented strategies as implementing new strategies might improve the state of certain risks but overall, the risk exposure might enhance because of the adverse correlations. Therefore, a commonly held belief about the positive moderation impact of risk mitigation strategies on the causal effect of supply chain risks and consequences (Juttner et al., 2003; Tummala & Schoenherr, 2011) is challenged in case of interdependent risks and strategies.

In case of exclusively independent risks, a risk manager just needs to select optimal strategies specific to individual risks (as discussed in Section 7.5.3) whereas in case of negatively correlated risks, an optimal strategy suitable for the independent risk might actually yield the worst solution for the risk network. Similarly, selecting a portfolio of risk mitigation strategies suitable for individual risks might result in increasing the overall risk exposure with value proportional to the strength of adverse correlations.

Proposition 3

The upper (lower) bound of the expected utility value corresponding to the set of objectives modelled within a risk network is determined by the efficacy of potential (already implemented) risk mitigation strategies in reducing the risk level of related risks.

All the performance measures are not necessarily equally important to the decision maker (Juttner et al., 2003). When these performance measures are treated in isolation and independently optimised, the resulting strategies might not yield a global optimal solution corresponding to the holistic interaction of these measures within the network setting (Qazi et al., 2016). Expected utility is a probability-weighted average of the utility in the different states the network may be in. By engaging in risk mitigation, the probability of these states occurring changes, as does the value of different outcome combinations of the objectives. More generally, a utility function could capture different weights being assigned to different objectives, objectives may be evaluated in a non-linear way, and complementarities between objectives could be captured.

The lower bound of the expected utility reflects the efficacy of already implemented strategies as to how much comfortable the decision maker is with regard to the current state of risk management process. With reference to the model developed in Case Study I, the point corresponding to the mitigation cost of 0 represents the efficacy of already implemented strategies with the global minimum expected utility value of 0.528 (see Figure 7.8). As discussed earlier, this lower bound can further drop in the event of unfavorable correlations within the network. The upper bound of the expected utility is determined by the efficacy of potential strategies; however, there is another constraint of the budget and the need for an important consideration as to how significant is the relative improvement in the expected utility with respect to the marginal cost of implementing these strategies. Although an investment of 295 units yields the highest expected utility to the decision maker (see Figure 7.8), the same is not viable considering the cost-effectiveness of strategies (see Figure 7.10).

Proposition 4

Even in the case of all risks being positively correlated with each other and strategies negatively correlated with risks, increased investment in strategies might not necessarily increase the expected utility of the decision maker.

Keeping in view a given set of potential risk mitigation strategies with associated cost, there are different possible combinations of strategies subject to a budget constraint with only one optimal combination (see Figure 7.8). However, with the increase in the budget constraint, it is not always the case that the new optimal combination contains all strategies included in the optimal set previously determined subject to a lower constraint that could lead to a reduction in the expected utility (see the budget range of $195 - 235$ in Figure 7.8). Therefore, there is always a need for analysing a complete portfolio of all such combinations of strategies rather than evaluating the strategies at the given constraint only. The optimistic viewpoint with regards to the favorable correlations between risks and strategies might be misleading as the supply chain manager would incorrectly assume that investing in more strategies and choosing the optimal combination right at the constraint level is viable.

Proposition 5

Project driven supply chains necessitate experimenting untested (unique) mitigation strategies depending on the level of project complexity and also there might be contrasting views with regards to the development of the risk network whereas in case of conventional supply chains, the process of risk management can benefit from the use of tested strategies and moreover, there is generally a consensus in establishing interdependencies within the risk network and evaluating the efficacy of strategies.

Project driven supply chains are unique in a way that some new challenging features of the project (product) might be developed like in case of the development of Boeing 787 aircraft, an untested technology with regards to the structural and aerodynamic facets was developed and introduced (Tang et al., 2009). These novel characteristics of the project engender unknown risks and there is a need to consult experts across all disciplines and specialisms to reach a consensus with regards to modelling the risk network (Ackermann et al., 2014). Similarly, the risk and reward involved in implementing innovative strategies need to be balanced within the network setting.

In dealing with managing other supply chains where there are no such unconventional undertakings involved, the experts generally have a clear understanding of the cause-effect relationships and the efficacy of strategies is well established. Nonetheless, without evaluating potential strategies within a network setting, it is not possible to visualise and differentiate between optimal strategies and dominated strategies (see Figure 7.8) leading to the likely selection of sub-optimal strategies. The risk management of conventional supply chains can be better categorised as 'simple' and/or 'complexity-induced' risk problems whereas that of project driven supply chains as 'uncertainty-induced' and/or 'ambiguity-induced' risk problems (Renn, 2008). There is a limited uncertainty involved in assessing and managing risks of conventional supply chains whereas the risk management of project driven supply chains necessitates an extensive reliance on expert judgement.

Proposition 6

Within a network setting and in the case of partially effective risk mitigation strategies, it is not always optimal to mitigate the most critical risk(s) identified; instead strategies implemented for relatively non-critical risk(s) might be cost-effective.

It is very important to realise that within an interdependent setting of risk management framework (see Figure 7.4), risk prioritisation follows the risk treatment stage in contrast to the sequence proposed in the standard risk management framework (SA, 2009) and established SCRM frameworks (Manuj & Mentzer, 2008a; Tummala & Schoenherr, 2011; Giannakis & Papadopoulos, 2016). It is mainly because of the complexity involved in evaluating the efficacy of strategies that is a function of strength of interdependency between risks, relative impact of strategies, cost of these strategies and the relative importance of performance measures influenced by the risks. Therefore, implementing cost-effective strategies might not necessarily reduce the most critical risks substantially and that is why the risk assessment must follow the risk treatment stage to prioritise risks for risk monitoring stage and developing contingency plans.

With reference to the model developed in Case Study I, although $R20$ is evaluated as a critical risk during the risk assessment stage (see Figure 7.11), it is not optimal to adopt the relevant strategy subject to a budget constraint of 30 units (see Figure 7.8 and Table 7.3). It is mainly because the optimal set comprises two cost-effective mitigation strategies applied to relatively less critical risks ($R4$ and $R12$) yielding maximum expected utility to the decision maker. Therefore, it is not always optimal to mitigate the most critical risk(s) identified and also, adopting a risk matrix approach would fail to capture the complex dynamics between risks and strategies considering the cost of strategies and relative importance of each performance measure.

7.6 Summary

Although a number of quantitative tools and techniques have already been developed for managing supply chain risks, there is a limited focus on introducing holistic frameworks that not only integrate all stages of the risk management process but also capture the cascading effects of common risk triggers. Also, the existing frameworks generally focus on optimising a single objective (performance measure) without exclusively modelling the trade-off between conflicting objectives. Another important requirement is to empirically evaluate these frameworks and establish the merits and challenges involved in implementing such interdependency based tools. In order to bridge the mentioned gaps, this chapter introduces an integrated SCRM process and reports on the findings of two case studies conducted to demonstrate the process.

The two organisations studied exclusively utilise risk matrix based tools to assess risks. As conceptualised in the literature, risks are classified into independent categories and correlations are neglected in all stages of the risk management process. Such assumptions are deleterious to the main objective of implementing an effective process as the risk health of a supply chain might worsen if strategies are adopted that are in fact positively correlated with few risks within the risk network. Developing a risk network originating from the performance measures helps in confining the scope to significant risks only and therefore, risks having insignificant impact on the measures are not considered. The risk network also helps in identifying potential mitigation strategies and establishing their correlations with relevant risks.

The practitioners adhere to using conventional tools treating risks as independent factors because of various reasons: sophisticated interdependency based tools introduced in theory are rarely applied in the industry; practitioners are unable to appreciate the significance of capturing correlations until they acknowledge the extent of damage relevant to adopting risk matrix based tools; use of risk matrix is governed by established risk management standards; there is not always a commitment from the top management as the implementation of a robust process necessitates time and investment in terms of training the staff and enhancing their knowledge to assimilate the underlying mechanism of the process. The next chapter concludes the thesis and delineates future research directions.

Chapter 8

Conclusions

8.1 Introduction

This concluding chapter presents a brief overview of the research and introduces future directions for developing the work. Initially the chapter provides a summary of the research and delineates important findings. This is followed by description of the contribution to the established knowledge and its practical implications. The chapter then introduces limitations of the research and finally concludes the thesis with formulation of future research directions.

8.2 Summary of Research

The overarching aim of the research was to design a SCRM process capturing systemic interactions between risks and mitigation strategies across all stages of the risk management process. Both conventional and project driven supply chains were considered for developing the process. A multi-methodology approach involving two case studies, focus group sessions and semi-structured interviews was adopted to address the research questions. Following is a brief summary of the research output specific to each question.

RQ1: What are the limitations of existing studies in the literature on SCRM?

SLR of the articles selected helped in identifying important research directions: there is a need to explore holistic methods for capturing interdependency between risks mainly because most of the studies reviewed have assumed risks as independent and/or focused on modelling a specific domain in a supply chain and addressing a particular problem; developing a risk taxonomy based on causal chains is paramount as existing risk classification schemes assign risks to independent categories and fail to capture the interdependency between causal chains of vulnerabilities, risk sources, risk events and resulting losses; based on the categorisation of articles with respect to risk classification, the results necessitate conducting an extensive research in exploring organisational risks in order to ascertain the factors that differentiate firms with regard to their ability or maturity in recovering from major disruptions (Hittle & Leonard, 2011); disruptions are unpredictable and in order to safeguard a supply chain from the adverse effects of these disruptions, managers need to have complete visibility across the entire network (Colicchia & Strozzi, 2012; Ghadge et al., 2012) and therefore, it is proposed to treat a supply network as an engineering system network and apply the techniques of system reliability in modelling complexity and assessing reliability of the supply network; there is a need to explore the synergy of SCRM and project risk management as long-term projects involving NPD often result in major delays and cost overruns and the development of a new product demands integration of capabilities in managing supply chain risks and project risks.

RQ2: How can we design a SCRM process capturing systemic interactions between risks and mitigation strategies across the integrated stages of the risk management process; and subsequently, how can the potential mitigation strategies be evaluated within the network of interdependent risks and strategies in relation to different resource and budget constraints?

In order to address the research question, a SCRM process is proposed that is theoretically grounded within the framework of BBNs and FMEA to model risks ranging across a huge network comprising many supply chain actors as opposed to the process mapping of a supply chain that involves brainstorming of risks following the supply network configuration. The proposed method can help in determining an optimal mix of strategies in relation to budget and resource constraints.

Dependency based probabilistic supply chain risk measures are introduced for ranking risks and evaluating strategies that represent the relative contribution of each risk to the loss propagation across the network of interconnected risks in the scenario of its activation. The proposed risk measures are able to overcome the shortcomings related to the techniques adopting the notion of independent risks and solution concepts focusing on optimising a single variable or a set of variables. A simulation study is presented to demonstrate the application of the process. Measures based on techniques other than BBNs are not able to capture the probabilistic interactions between risks and they fail to account for causal and diagnostic inferencing. For a risk-neutral decision maker, $RNELPM$ is an appropriate risk measure whereas UTC is a suitable choice to capture the loss-averse attitude of a decision maker. The concept of Shapley value is introduced in order to determine a fair allocation of resources to mitigate risks once the mitigation strategies with associated cost are not already established within a network setting. The key features of FMEA are utilised in identifying supply chain risk sources, risks and mitigation strategies and integrated within the framework of BBNs.

The proposed modelling approach can help supply chain managers visualise interdependency between supply chain risks. Stakeholders can identify important risk sources, risks and mitigation strategies using the FMEA technique and evaluate the impact of different risk mitigation strategies on the entire web of interconnected risks. It is important to realise that the crucial decision of selecting an optimal mix of preventive and reactive strategies can only be made after following the proposed rigorous approach of modelling interdependencies between risks and mitigation strategies.

RQ3: How can we develop a risk management process and an effective modelling approach for capturing interdependency between complexity and risk in order to facilitate the decision making process of prioritising risks and risk mitigation strategies at the commencement stage of a project?

On the basis of the literature reviewed, it is deduced that the interdependency between complexity and risk has not been adequately captured in existing models. There is a need for bringing a paradigm shift towards appreciating the importance of exploring interdependency within the same categories of complexity elements and risks and across distinct categories as well. The philosophical debate on the concept of complexity and risk still goes on and the proposed approach brings a new paradigm that is to assess complexity and risk through the lens of interdependency modelling. ProCRiM attempts to contribute towards this new approach.

As the standard risk management process (SA, 2009) is well-established in project risk management (Wang, 2015), the interdependency between complexity and risk –lacking in this approach –is not considered by practitioners. In order to address this issue ProCRiM is proposed. The main focus of the proposed process is on the management of complexity and risk network. The decision maker needs to identify a network of interacting project complexity drivers and risks. As an input, the importance of project objectives must also be elicited from the decision maker. The network presents a holistic picture of interacting project complexity attributes, risks and project objectives. Managers can visualise interaction between different risks, appreciate propagation patterns through risk paths and locate key risks endangering the success of a project. Furthermore, in case of high risks involved in a project because of project complexity, the project owner might either bring changes in project attributes at the commencement stage or plan effective control strategies taking into account the interdependency between various factors.

The process captures a decision maker's personal preference of each project objective in the form of a utility function. EUT has been widely used in the literature on risk management (Aven, 2015), however, very few studies have used the technique in the literature on project risk management. Therefore, there is a need to develop robust tools and models grounded in the framework of EUT to help practitioners prioritise risks and mitigation strategies. In contrast with the frequently used methods of AHP, ANP, FST and SEM to model project and supply chain risks, the proposed technique of BBNs is efficient in integrating all stages of the risk management process and identifying not only critical risks but also optimal risk mitigation strategies. Modelling techniques other than BBNs are not robust enough to deal with the risk treatment and monitoring stages where optimal mitigation strategies are selected and new risks are identified, respectively.

RQ4: How is the interdependency between risks managed in industry?

In order to investigate the current practices within the industry, a total of 13 semi-structured interviews were conducted with the experts in project risk management. The findings confirmed that the risk management process implemented in the industry does not consider complex interactions between project complexity and risks and furthermore, project managers generally rely on their intuition and past experience in dealing with risks. Although project complexity is considered an important factor at the commencement stage of a project, not all aspects of project complexity are included within the analysis. The experts interviewed considered the proposed process and modelling approach as an important contribution but they also identified challenges such as limited support from senior management and the requirement of populating such sophisticated models with data.

The empirical finding of risks being treated as independent factors is in accordance with the main finding of Taroun (2014) who conducted an extensive review of the literature on Construction Risk Management. The ranking of risks on a probability-impact matrix is being commonly used within construction projects because of the ease in developing and analysing such models (Shi et al., 2015). The main problem associated with using sophisticated models is the limited awareness and experience in handling such models, however, we believe that even if the comprehensive quantitative modelling approach may not be exclusively adopted within the risk management process, use of causal mapping (the qualitative part of BBNs) can provide an insight into identifying key interdependencies between risks and help managers identify risk paths instead of focusing on independent categories of risks. The same findings were observed in the case of case studies conducted in global manufacturing supply chains where risks were assessed and treated in silo.

RQ5: How can we design a SCRM process integrating the systemic interaction between risks and the risk appetite of a decision maker?

There is a need for introducing risk measures that capture the network wide holistic impact of interacting supply chain risks. However, optimising a risk network against these measures alone might result in sub-optimal solutions as it is also important to consider the risk appetite of a decision maker. Although EUT provides a standard procedure for decision making under uncertainty, it is not viable to even assess a simple risk network comprising limited number of supply chain risks and strategies. Therefore, we introduced the SCRNM process through adapting the conventional risk matrix for projecting the configuration of interdependent supply chain risks. Risk matrix has already been modified for mapping the risk appetite of a decision maker. However, the main limitation is its exclusive application to independent categories of risks. We proposed its adaptation to the context of interdependent supply chain risk network.

The risk measure namely $RNELPM$ introduced previously is utilised to develop two algorithms for managing a supply chain risk network with regard to risk-neutral and risk-seeking/averse decision makers. The algorithms can also be used in the context of other modelling technique and/or risk measures. The proposed process is demonstrated through a simulation study in the context of SCRM. A second approach is also introduced to determine the set of Pareto optimal risk mitigation strategies where a decision maker needs to establish the trade-off between the improvement in risk exposure and the cost of strategies without utilising the risk matrix. The proposed risk matrix based process can help researchers focus on a new stream of research and develop it further.

RQ6: What are the merits and challenges of implementing the proposed SCRM process that captures interdependency between risks, multiple (potentially conflicting) objectives and risk mitigation strategies?

Case studies were conducted in two leading global manufacturing supply chains involving focus group sessions and semi-structured interviews with the experts in risk management. The two organisations studied exclusively utilise risk matrix based tools to assess risks. As conceptualised in the literature, risks are classified into independent categories and correlations are neglected in all stages of the risk management process. Such assumptions are deleterious to the main objective of implementing an effective process as the risk health of a supply chain might worsen if strategies are adopted that are in fact positively correlated with few risks within the risk network. Developing a risk network originating from the performance measures helps in confining the scope to significant risks only and therefore, risks having insignificant impact on the performance measures are not considered. The risk network also helps in identifying potential mitigation strategies and establishing their correlations with relevant risks.

The elicitation of conditional probability values was easier in the case of experts having the background knowledge in engineering or mathematical science whereas it was a challenging task otherwise. The use of qualitative scale helped the experts provide their judgement about the strength of interdependency between risks. The participants could appreciate the significance of optimising conflicting objectives within the same model. The main merit of the proposed process was acknowledged as the ability to visualise the interconnectedness between risks and how exactly a risk or a set of risks influences multiple objectives. Techniques other than BBNs are not able to depict the similar kind of transparency and visual patterns of risk propagation (Garvey et al., 2015). The graphs representing the efficacy of potential risk mitigation strategies were highly appreciated as these helped the decision makers realise the significance of adopting the proposed process without which it would not be possible to segregate optimal strategies from the dominated ones.

Practitioners adhere to using conventional tools treating supply chain risks as independent factors because of various reasons: sophisticated interdependency based tools introduced in theory are rarely applied in the industry; practitioners are unable to appreciate the significance of capturing correlations until they acknowledge the extent of damage relevant to adopting risk matrix based tools; use of risk matrix is governed by established risk management standards; there is not always a commitment from the top management as the implementation of a robust process necessitates time and investment in terms of training the staff and enhancing their knowledge to assimilate the underlying mechanism of the process.

8.3 Contribution to Knowledge

There are several contributions of the thesis to the theoretical and practical stream of knowledge. First, the research contributes to the literature on SCRM through conducting a comprehensive SLR of selected articles published over a period of last 15 years. Although existing reviews have also helped in identifying potential research avenues, the thesis presents some new insights that have not been mentioned in existing studies. These findings will help align the direction of future research with the changing requirements of managing complex supply chains.

Through reviewing the literature on project complexity and interdependency modelling of risks in NPD in general and construction projects in particular, a major research gap has been established related to developing an integrated complexity and risk management process exploring interdependency modelling between project complexity attributes (known at the commencement stage), complexity driven risks and project objectives. It is important to consider chains of adverse events originating from project complexity attributes and influencing project objectives through active risk paths. A project complexity and risk management process and modelling approach have been proposed that help in capturing the holistic interaction between the mentioned factors within the theoretically grounded framework of EUT and BBNs. It is a very useful tool not only for capturing causal relationships between uncertain variables but also for establishing the strength of these interdependencies.

The methodological contribution to the literature on SCRM with exclusive focus on modelling process is multi-faceted: a comprehensive and integrated SCRM process is introduced that is grounded in the theoretical framework of BBNs and to the best of our knowledge, a probabilistic graph integrating all stages of the risk management process and capturing interdependencies between supply chain risks and strategies has never been explored; dependency based probabilistic supply chain risk measures are proposed capturing network wide impact of risks that help in prioritising risks both in the risk assessment and risk treatment stages; the concept of Shapley value is utilised to determine a fair allocation of resources to the critical risks identified; and a method of prioritising risk mitigation strategies specific to a probabilistic network setting is established.

With focus on integrating the risk appetite of a decision maker within a probabilistic network of interacting supply chain risks, the main contribution is to introduce a new risk management process namely SCRNM. Algorithms are developed for assessing and mitigating interdependent supply chain risks with regard to the risk-neutral and risk-averse/seeking decision makers. The conventional risk matrix is transformed in order to make it compatible for assessing interdependent risks in relation to the utility indifference curves specific to a decision maker. A second approach is also introduced to help a supply chain risk manager identify the Pareto optimal set of risk mitigation strategies and select optimal solution subject to a budget constraint and the risk appetite.

Finally, a SCRM process integrating interdependent supply chain risks, risk mitigation strategies and multiple (potentially conflicting) objectives is proposed with contributions across multiple facets. First, the process is adapted from the theoretically grounded frameworks within the literature on SCRM (Garvey et al., 2015; Sherwin et al., 2016) and project risk management (Qazi et al., 2016). Second, the process is demonstrated and empirically evaluated through conducting two case studies in reputed global supply chains resulting in two different models of risk networks specific to a conventional and a project driven supply chain. Third, merits and challenges associated with the implementation of such interdependency based frameworks are explored. Fourth, propositions are developed to elucidate the importance of accounting for interdependence of risks by comparing the proposed process to a standard risk matrix-based approach.

8.4 Limitations

Like any research there are limitations of the research conducted. With regard to the SLR, only peer-reviewed articles were reviewed to establish research gaps. Furthermore, the scope of the SLR was confined to articles published over a period of last 15 years. However, while developing the themes identified, different sources (including recent publications) were consulted to ascertain the novelty of work.

ProCRiM was only tested in the construction industry and therefore, the findings might not be generalisable to other industries. Also, the project complexity characteristics of other industries might not correspond to the elements selected. Optimisation of the risk network specific to a stakeholder might not yield a global optimal solution for the entire supply network where different stakeholders could have conflicting incentives. Therefore, the concept must be integrated with assessing strategic risks.

The FMEA based risk management process has few limitations: only binary states are considered for the risks and mitigation strategies; the detectability of risks is not modelled as to how early a risk could be detected before its activation; and finally, the risk network captures a particular moment in time whereas the dynamic nature of a risk is not exclusively modelled.

The SCRNM process has not been validated. However, as risk matrix based tools are widely used, the proposed process can easily be adopted in practice as it does not involve elicitation of utility values specific to all possible scenarios. Secondly, instead of calculating the expected value of utility across all possible instantiations of risks, the utility of expected loss contribution of each risk is used.

In the case of ProCRiM based SCRM frameworks, only two case studies were conducted without involving other stakeholders of the supply chain. Also, one-time risk state of the risk network was captured rather than monitoring the dynamic nature of the risk and again, risks and mitigation strategies were modelled as binary variables.

8.5 Future Research Considerations

As supply chains are becoming complex, existing conventional classification of risks and methods relying on unrealistic assumption of independent risks are not appropriate for coping with the increasing supply chain complexity. There is a need for shifting the focus from such simplified tools and classification schemes to more realistic and effective methods that can capture the holistic account of complex interactions. A new supply chain risk taxonomy representing causal chains of interacting vulnerabilities, risk sources, risk events and consequences can serve as a major contribution to the existing literature.

In future, ProCRiM must be validated in the context of different industries through case studies. Furthermore, empirical research needs to be conducted to investigate the best practices in managing complex interdependencies between project complexity and resulting risks. It will also be important to devise methods for reducing the effort involved in populating such models as when there is limited available data, experts will have to be consulted and elicitation of the set of conditional probability values will be a real challenge. Methods other than BBNs can be explored to implement ProCRiM and investigate the trade-off between effort involved in developing the model and the precision of results.

In the case of FMEA based process, we have assumed binary states for all the risk factors and mitigation strategies. Future research may focus on representing risks by continuous variables. Furthermore, a control strategy may also be represented by a continuum of control levels, associated effectiveness and cost. In future, the proposed method may be applied in real case studies in order to evaluate its efficacy. The proposed process may be extended to account for strategic risks where the state of a risk is not driven by chance rather players within the supply network behave opportunistically and therefore, the actors make a choice based on maximising their expected utility value. Another important aspect is to model the detectability of risks as the response time before complete activation of a risk is a critical factor. Furthermore, the model can be extended to establish the source of defects within a supply chain especially in the case of food sector where it is hard to ascertain the main source of contamination.

With regard to the risk matrix based process, a tool integrating a number of techniques feasible for each stage of the process can be developed and validated through case studies. The proposed algorithms can also be used to develop robust risk management tools. Risks and mitigation strategies modelled as binary variables can be represented by continuous variables. It will also be interesting to find out the optimal combination of continuum of strategies for mitigating risks. In future, empirical studies may be conducted to gauge the feasibility of the proposed modelling framework and determine the associated challenges.

The research work related to the integration of project risk management and SCRM can be developed further along different lines of inquiry. The efficacy of the proposed framework may be monitored over a long period of time through a longitudinal study and the merits and challenges analysed. The framework may be extended to involve different stakeholders across a supply chain and contracts be designed to encourage active participation of stakeholders within the risk management process. Risk networks may be developed across different industries and compared to establish common patterns in order to develop a generalised risk taxonomy. The cost and benefit analysis may be conducted to help practitioners understand the utility of interdependency based frameworks. Once the framework gets established in its simplified form of risks and strategies with binary states, these can be modified as continuous variables. The framework may also be extended to capture the dynamic behaviour of risk over time.

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Appendices

Appendix A

Parents													$P(Ri = True \mid Parents)$												
C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**R1**	**R2**	**R4**	**R5**	**R8**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**	**R11**	**R12**	**R13**
Y													0.5	0.7											
													0.3	0.5											
N													0.05	0.2											
													0.02	0.1											
			Y												0.9										
															0.4										
			N												0.3										
															0.1										
				Y												0.8									
																0.2									
				N												0.2									
																0.05									
						Y											0.7								
						N											0.1								
						Y	Y														0.8				
						Y	N														0.3				
						N	Y														0.5				
						N	N														0.02				
											T									0.7		0.9			
																				0.4		0.4			
											F									0.2		0.2			
																				0.04		0.08			
								T				T													0.95
								T				F													0.6

Table A.1: Conditional probability values (shaded cells represent conditional probabilities given implementation of respective strategies).

Parents													*P(Ri = True|Parents)*												
C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**R1**	**R2**	**R4**	**R5**	**R8**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**	**R11**	**R12**	**R13**
								F				T													0.5
								F				F													0.03
					Y					T														0.99	
					Y					F														0.3	
					N					T														0.7	
					N					F														0.02	
									T										0.99						
																			0.6						
									F										0.2						
																			0.02						
	Y	Y																					0.95		
																							0.5		
	Y	N																					0.5		
																							0.2		
	N	Y																					0.3		
																							0.15		
	N	N																					0.03		
																							0.01		
	Y	Y	Y															0.99							
	Y	Y	N															0.8							
	Y	N	Y															0.7							
	Y	N	N															0.4							
	N	Y	Y															0.6							
	N	Y	N															0.5							
	N	N	Y															0.3							
	N	N	N															0.01							

Table A.2: Conditional probability values (shaded cells represent conditional probabilities given implementation of respective strategies).

Parents													$P(Ri[Oi] = True \mid Parents)$				
C2	R1	R3	R6	R7	R9	R10	R11	R12	R13	R14	O1	O3	R14	O1	O2	O3	O4
			T				T	T					0.99				
			T				F	T					0.95				
			T				T	F					0.92				
			T				F	F					0.89				
			F				T	T					0.92				
			F				T	F					0.9				
			F				F	T					0.9				
			F				F	F					0.02				
	T		T											0.99			
	T		F											0.6			
	F		T											0.3			
	F		F											0.05			
Y											T	T			0.7		
Y											T	F			0.5		
Y											F	T			0.3		
Y											F	F			0.01		
N											T	T			0.99		
N											T	F			0.7		
N											F	T			0.6		
N											F	F			0.2		
		T		T	T					T						0.99	
		T		T	F					T						0.95	
		F		T	T					T						0.95	
		F		T	F					T						0.9	
		T		F	T					T						0.95	
		T		F	F					T						0.9	
		F		F	T					T						0.9	
		F		F	F					T						0.8	
		T		T	T					F						0.95	
		T		T	F					F						0.9	

Table A.3: Conditional probability values.

Parents													$P(Ri[Oi] = True\|Parents)$				
C2	R1	R3	R6	R7	R9	R10	R11	R12	R13	R14	O1	O3	R14	O1	O2	O3	O4
		F		T	T					F						0.9	
		F		T	F					F						0.8	
		T		F	T					F						0.9	
		T		F	F					F						0.8	
		F		F	T					F						0.8	
		F		F	F					F						0.01	
			T		T	T			T								0.99
			T		F	T			T								0.9
			T		T	F			T								0.95
			T		F	F			T								0.8
			F		T	T			T								0.8
			F		F	T			T								0.7
			F		T	F			T								0.9
			F		F	F			T								0.3
			T		T	T			F								0.9
			T		F	T			F								0.7
			T		T	F			F								0.8
			T		F	F			F								0.65
			F		T	T			F								0.75
			F		F	T			F								0.65
			F		T	F			F								0.8
			F		F	F			F								0.01

Table A.4: Conditional probability values.

Appendix B

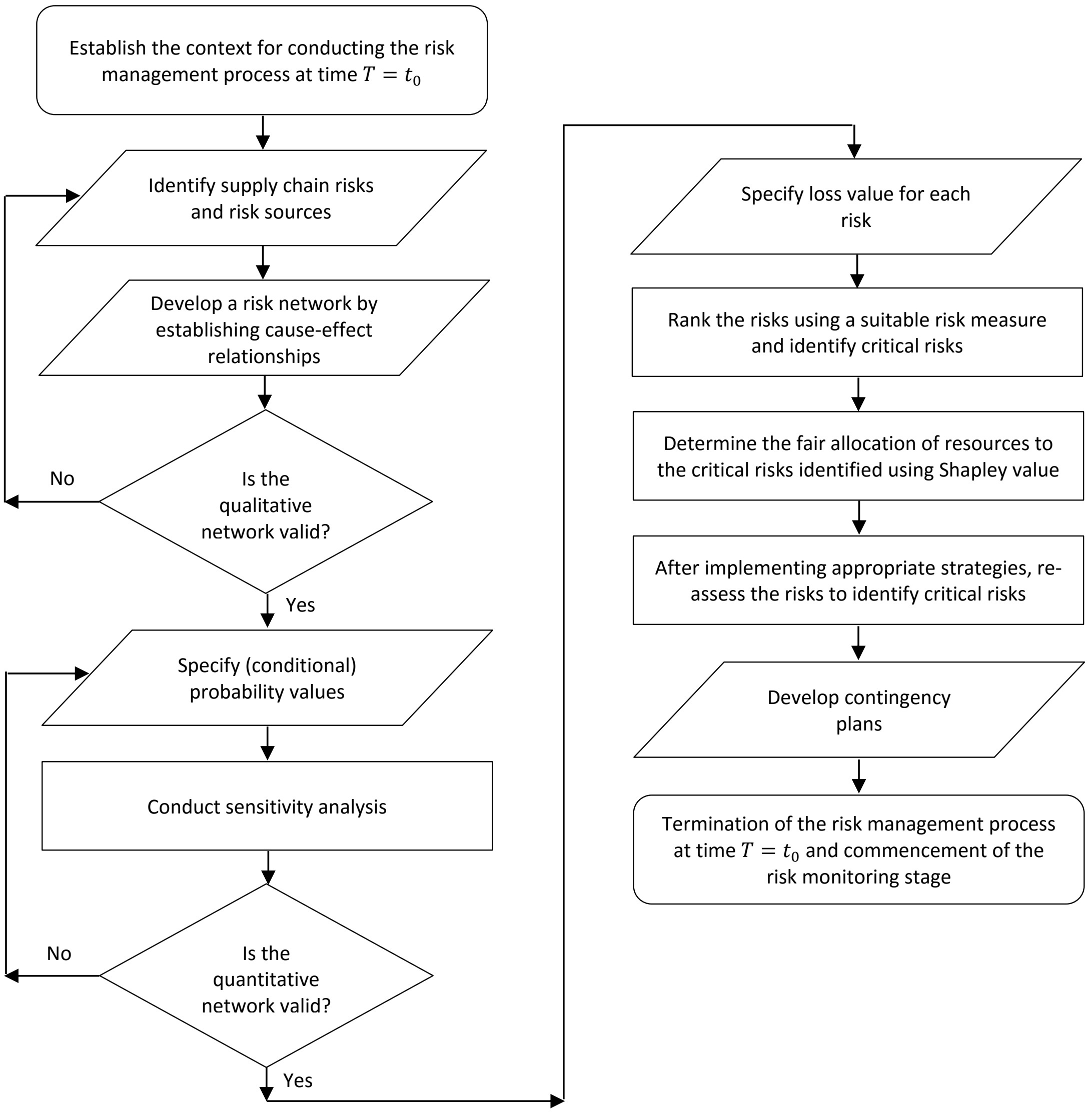

Figure B.1: Flow chart for implementing the process where the strategies and associated cost are not already established.

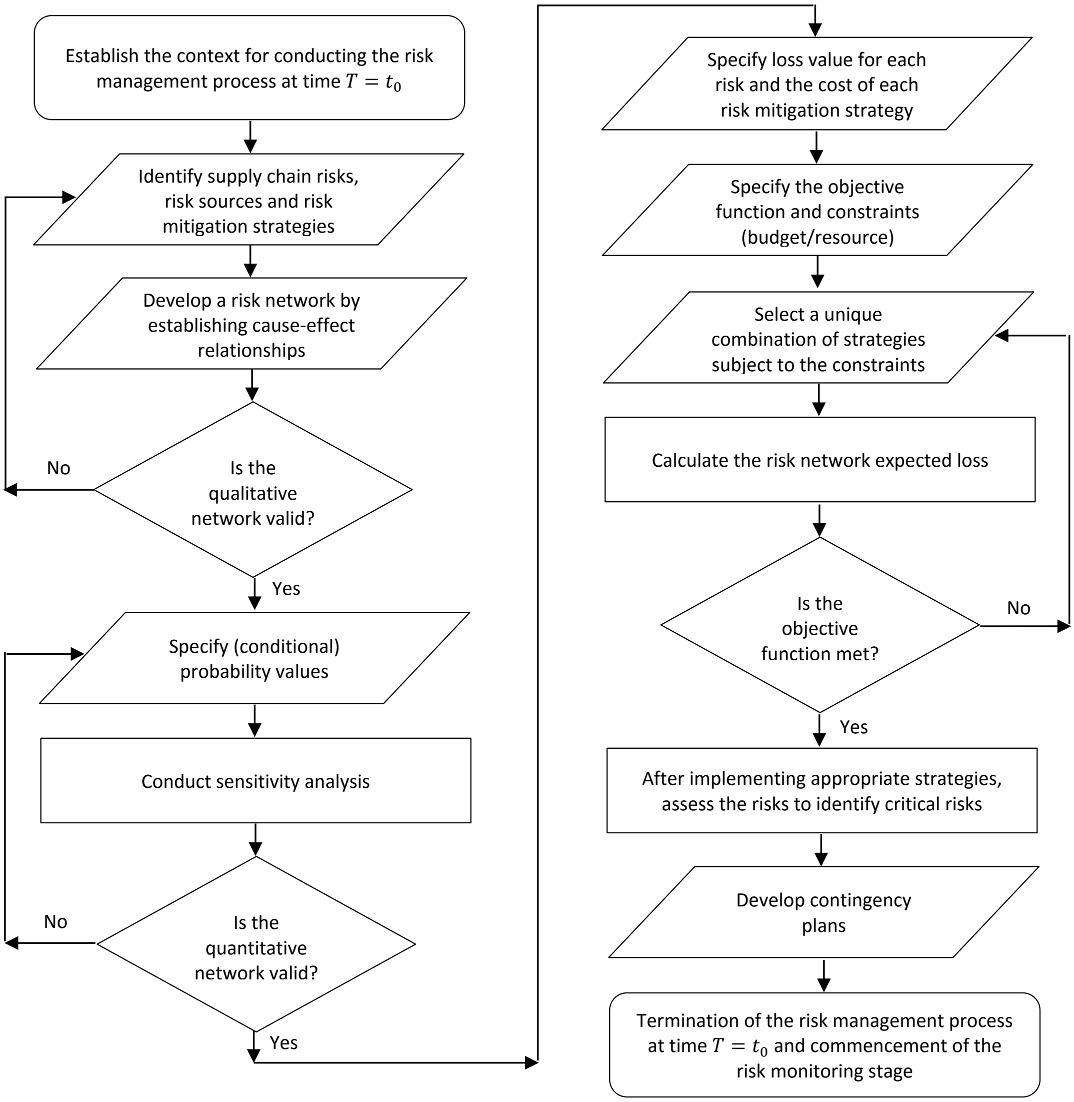

Figure B.2: Flow chart for implementing the process where the strategies and associated cost are already established.

Symbol	Risk Source (C)/Risk (R) [associated supply chain domain]/Strategy (S)
C1	Stress on crew
C2	Long working times
C3	Lack of training
C4	Negligence in maintenance
C5	Old technology
C6	High competition
C7	Opportunistic behaviour
C8	Decline in Customer Resource Management function
C9	Instable manufacturing process
C10	Low technical reliability
C11	Insufficient maintenance
C12	Dissatisfaction with work
C13	Strikes
C14	Lack of training
C15	Poor working conditions
C16	Insufficient breaks
C17	Planning and scheduling errors
C18	Bullwhip effect
C19	Low technical reliability
C20	Technological changes
C21	Contractual problems
C22	Monopoly
R1	Human error [Inbound/Outbound Logistics]
R2	Natural hazards [Inbound/Outbound Logistics]
R3	Technical problems with transportation vehicles [Inbound/Outbound Logistics]
R4	Loss of market share [Customers]
R5	Fluctuations in customer demands [Customers]
R6	Technical problems [Manufacturer]
R7	Absence of operator [Manufacturer]
R8	Human error [Manufacturer]
R9	Scarcity of raw parts [Suppliers]
R10	Poor quality in purchased products from supplier [Suppliers]
R11	Loosing competitive advantage of supplier [Suppliers]
R12	Decline in business relations with supplier [Suppliers]
S1	Insurance
S2	Capital investment
S3	R&D and marketing strategies
S4	Reward system
S5	Good relations with labour union
S6	Training
S7	Ergonomic Awareness program
S8	Investment in Enterprise Resource Planning
S9	Information sharing with supplier
S10	Rigorous process of Supplier selection

Table B.1: Description of risk sources, risks and mitigation strategies.

Causes or Risks (X_i)	$P(X_i = True)$
C2	0.2
C3	0.1
R2	0.1
C4	0.3
C6	0.05
C7	0.1
C8	0.2
C9	0.3
C10	0.4
C11	0.2
C16	0.1
C20	0.1
C21	0.3
C22	0.1

Table B.2: Probability values of root nodes.

Parents										$P(X_i = True \mid Parents)$					
C1	C2	C3	C4	C5	C6	C7	C8	S2	S3	C1	C5	R1	R3	R4	R5
	T									0.7					
	F									0.3					
T	T	T										0.9			
T	T	F										0.5			
T	F	T										0.7			
T	F	F										0.3			
F	F	T										0.6			
F	T	F										0.3			
F	T	T										0.7			
F	F	F										0.01			
								Y			0.1				
								N			0.4				
			T	T									0.9		
			T	F									0.7		
			F	T									0.4		
			F	F									0.1		
					T	T			Y					0.4	
					T	F			Y					0.3	
					F	T			Y					0.3	
					F	F			Y					0.02	
					T	T			N					0.98	
					T	F			N					0.5	
					F	T			N					0.7	
					F	F			N					0.1	
							T								0.4
							F								0.1

Table B.3: Conditional probability values of child nodes.

Parents												$P(X_i = True \mid Parents)$						
C9	C10	C11	C12	C13	C14	C15	C16	S4	S5	S6	S7	R6	C12	C13	C14	C15	R7	R8
T	T	T										0.99						
T	F	T										0.8						
T	T	F										0.8						
T	F	F										0.6						
F	T	F										0.6						
F	F	T										0.5						
F	T	T										0.8						
F	F	F										0.01						
						T		Y					0.7					
						F		Y					0.02					
						T		N					0.8					
						F		N					0.4					
									Y					0.2				
									N					0.6				
										Y					0.2			
										N					0.5			
											Y					0.1		
											N					0.6		
			T	T													0.99	
			T	F													0.6	
			F	T													0.8	
			F	F													0.1	
			T		T	T	T											0.99
			T		T	T	F											0.9
			T		T	F	T											0.9
			T		T	F	F											0.8
			T		F	T	T											0.8
			T		F	T	F											0.75
			T		F	F	T											0.7
			T		F	F	F											0.65
			F		T	T	T											0.7
			F		T	T	F											0.6
			F		T	F	T											0.5
			F		T	F	F											0.4
			F		F	T	T											0.5
			F		F	T	F											0.4
			F		F	F	T											0.2
			F		F	F	F											0.01

Table B.4: Conditional probability values of child nodes.

Parents									$P(X_i = True \mid Parents)$						
C17	C18	C19	C20	C21	C22	S8	S9	S10	C17	C18	C19	R9	R10	R11	R12
						Y			0.1						
						N			0.4						
T							Y			0.4					
F							Y			0.2					
T							N			0.8					
F							N			0.5					
								Y			0.1				
								N			0.4				
T	T											0.95			
T	F											0.6			
F	T											0.7			
F	F											0.02			
		T											0.9		
		F											0.04		
			T											0.4	
			F											0.05	
			T	T	T										0.99
			T	T	F										0.8
			T	F	T										0.7
			T	F	F										0.4
			F	T	T										0.8
			F	T	F										0.7
			F	F	T										0.3
			F	F	F										0.01

Table B.5: Conditional probability values of child nodes.

Symbol	Risk	Loss
R1	Human error	4
R2	Natural hazards	8
R3	Technical problems with transportation vehicles	5
R4	Loss of market share	7
R5	Fluctuations in customer demands	6
R6	Technical problems	7
R7	Absence of operator	5
R8	Human error	6
R9	Scarcity of raw parts	6
R10	Poor quality in purchased products from supplier	8
R11	Loosing competitive advantage of supplier	6
R12	Decline in business relations with supplier	5

Table B.6: Loss values of risks.

Symbol	Mitigation Strategy	Cost
S1	Insurance	2
S2	Capital investment	1
S3	R&D and marketing strategies	2
S4	Reward system	1
S5	Good relations with labour union	1
S6	Training	2
S7	Ergonomic Awareness program	1
S8	Investment in Enterprise Resource Planning	2
S9	Information sharing with supplier	1
S10	Rigorous process of Supplier selection	2

Table B.7: Costs associated with mitigation strategies.

Appendix C

procedure RISKMANAGEMENT
procedure OPTIMALSTRATEGIES (STANDARDAPPROACH)
for $X_{s_i} = \emptyset$ **do**
for $X_{R_i} \in X_R$ **do**
$P\left(X_{R_i}\right)_{SC} = \sum_{Y \in X_R \setminus \{X_{R_i}\}} \prod_{X_{R_i} \in X_R} P(X_{R_i} | X_{pa(R_i)})$
$RNEL_{SC}(X)$
$RNEL_{SC}\left(X | X_{R_i} = True\right) * P\left(X_{R_i}\right)_{SC}$
for $X_{s_i \setminus \emptyset} \in X_s$ **do**
for $X_{R_i} \in X_R$ **do**
$P\left(X_{R_i}\right)_{X_{s_i}} = \sum_{Y \in X_R \setminus \{X_{R_i}\}} \prod_{X_{R_i} \in X_R} P(X_{R_i} | X_{pa(R_i)})$
$RNEL_{X_{s_i}}(X) - C(X_{s_i})$
$RNEL_{X_{s_i}}\left(X | X_{R_i} = True\right) * P\left(X_{R_i}\right)_{X_{s_i}}$
if $RNEL_{SC}(X) - RNEL_{X_{s_i}}(X) - C\left(X_{s_i}\right) > 0$ **then**
$X_{s_i \setminus \emptyset} = \hat{S}_{p_i}$
for $\hat{S}_{p_i} \in X_s$ **do**
if $RNEL_{\hat{S}_{p_i}}(X) + C\left(\hat{S}_{p_i}\right) < RNEL_{\hat{S}_{p_j}}(X) + C\left(\hat{S}_{p_j}\right) \;\; \forall\, C\left(\hat{S}_{p_i}\right) > C\left(\hat{S}_{p_j}\right)$ **then**
select $\hat{S}_{p_i} \rightarrow \min\left(RNEL_{\hat{S}_{p_i}}(X) + C\left(\hat{S}_{p_i}\right)\right) \forall C\left(\hat{S}_{p_i}\right)$

Algorithm 1: Risk network management for risk-neutral decision maker.

procedure RISKMANAGEMENT
procedure OPTIMALSTRATEGIES (STANDARDAPPROACH)
for $X_{s_i} = \emptyset$ **do**
for $X_{R_i} \in X_R$ **do**
$P(X_{R_i})_{SC} = \sum_{Y \in X_R \setminus \{X_{R_i}\}} \prod_{X_{R_i} \in X_R} P(X_{R_i} | X_{pa(R_i)})$
$RNEU_{SC}$
for $X_{s_i \setminus \emptyset} \in X_s$ **do**
for $X_{R_i} \in X_R$ **do**
$P(X_{R_i})_{X_{s_i}} = \sum_{Y \in X_R \setminus \{X_{R_i}\}} \prod_{X_{R_i} \in X_R} P(X_{R_i} | X_{pa(R_i)})$
$RNEU_{X_{s_i}}(X)$
$RNEU_{X_{s_i}} = f(RNEU_{X_{s_i}}(X), C(X_{s_i}))$
if $RNEU_{X_{s_i}} - RNEU_{SC} > 0$ **then**
$X_{s_i \setminus \emptyset} = \hat{S}_{p_i}$
for $\hat{S}_{p_i} \in X_s$ **do**
if $RNEU_{\hat{S}_{p_i}} > RNEU_{\hat{S}_{p_j}} \forall C(\hat{S}_{p_i}) > C(\hat{S}_{p_j})$ **then**
select $\hat{S}_{p_i} \rightarrow \max(RNEU_{\hat{S}_{p_i}}) \forall C(\hat{S}_{p_i})$
procedure OPTIMALSTRATEGIES (PROPOSEDAPPROACH)
for $X_{R_i} \in X_R$ **do**
$RNEL_{SC}(X)$
if $abs(u(RNEL_{SC}(X | X_{R_i} = True))) * P(X_{R_i})_{SC} < A_2$&&
$RNEL_{SC}(X | X_{R_i} = True) < l^* \forall X_{R_i}$ **then**
$\bar{S}_p = \emptyset$
else
for $C_j(X_{s_i \setminus \emptyset}) > 0$ **do**
$RNEL_{X_{s_i}}(X)$
$RCM_{X_{s_i}} = \sum_{X_R} abs(u(RNEL_{X_{s_i}}(X | X_{R_i} = True))) * P(X_{R_i})_{X_{s_i}}$
If $RCM_{X_{s_i}} < RCM_{X_{s_{-i}}}$ **then**
$X_{s_i \setminus \emptyset} = \tilde{S}_{p_i}$
if $RCM_{\tilde{S}_{p_i}} < RCM_{\tilde{S}_{p_j}} \forall C(\tilde{S}_{p_i}) > C(\tilde{S}_{p_j})$&&
$abs(u(RNEL_{\tilde{S}_{p_j}}(X | X_{R_i} = True))) * P(X_{R_i})_{\tilde{S}_{p_j}} > A_1 || RNEL_{\tilde{S}_{p_j}}(X | X_{R_i} = True) > l^*$ **then**
$\tilde{S}_{p_i} = \bar{S}_{p_i}$
else if $RCM_{\tilde{S}_{p_i}} < RCM_{\tilde{S}_{p_j}} \forall C(\tilde{S}_{p_i}) > C(\tilde{S}_{p_j})$&&
$A_1 > abs(u(RNEL_{\tilde{S}_{p_j}}(X | X_{R_i} = True))) * P(X_{R_i})_{\tilde{S}_{p_j}}) > A_2$ &&
$RNEL_{\tilde{S}_{p_i}}(X) + C(\tilde{S}_{p_i}) < RNEL_{SC}(X)$ **then**
$\tilde{S}_{p_i} = \bar{S}_{p_i}$
else $\tilde{S}_{p_i} \neq \bar{S}_{p_i}$

Algorithm 2: Risk network management for risk-averse or risk-seeking decision maker.