This item was submitted to Loughborough University as a PhD thesis by the author and is made available in the Institutional Repository (https://dspace.lboro.ac.uk/) under the following Creative Commons Licence conditions.

creative commons

COMMONS DEED

Attribution-NonCommercial-NoDerivs 2.5

You are free:

- to copy, distribute, display, and perform the work

Under the following conditions:

Attribution. You must attribute the work in the manner specified by the author or licensor.

Noncommercial. You may not use this work for commercial purposes.

No Derivative Works. You may not alter, transform, or build upon this work.

- For any reuse or distribution, you must make clear to others the license terms of this work.
- Any of these conditions can be waived if you get permission from the copyright holder.

Your fair use and other rights are in no way affected by the above.

This is a human-readable summary of the Legal Code (the full license).

Disclaimer

For the full text of this licence, please go to:
http://creativecommons.org/licenses/by-nc-nd/2.5/

A Systems Thinking Approach for Modelling Supply Chain Risk Propagation

by

Abhijeet Ghadge

Submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy

School of Business and Economics,

Loughborough University, UK

© Abhijeet Ghadge, 2013

Abstract

A SYSTEMS THINKING APPROACH FOR MODELLING SUPPLY CHAIN RISK PROPAGATION

Summary

Supply Chain Risk Management (SCRM) is rapidly becoming a most sought after research area due to the influence of recent supply chain disruptions on global economy. The thesis begins with a systematic literature review of the developments within the broad domain of SCRM over the past decade. Thematic and descriptive analysis supported with modern knowledge management techniques brings forward seven distinctive research gaps for future research in SCRM. Overlapping research findings from an industry perspective, coupled with SCRM research gaps from the systematic literature review has helped to define the research problem for this study.

The thesis focuses on a holistic and systematic approach to modelling risks within supply chain and logistics networks. The systems thinking approach followed conceptualises the phenomenon of risk propagation utilising several recent case studies, workshop findings and focus studies. Risk propagation is multidimensional and propagates beyond goods, finance and information resource. It cascades into technology, human resource and socio-ecological dimensions. Three risk propagation zones are identified that build the fundamentals for modelling risk behaviour in terms of cost and delay. The development of a structured framework for SCRM, a holistic supply chain risk model and a quantitative research design for risk assessment are the major contributions of this research. The developed risk assessment platform has the ability to capture the fracture points and cascading impact within a supply chain and logistics network. A reputed aerospace and defence organisation in UK was used to test the experimental modelling set up for its viability and for bridging the gap between theory and practice. The combined statistical and simulation modelling approach provides a new perspective to assessing the complex behavioural performance of risks during multiple interactions within network.

Keywords

Supply Chain Risk Management, Systems Thinking, Risk Modelling, Systematic Literature Review

Acknowledgements

I would like to take this opportunity to thank everyone for being with me during my challenging PhD journey. My deepest gratitude goes to my first supervisor Dr Samir Dani for consistent moral and intellectual support. Without his illuminating ideas and constructive comments, the doctoral thesis would not have been possible. I owe him a biggest share of my success during PhD for his honest guidance. I would also like to thank my second supervisor Prof Roy Kalawsky for being very helpful and supportive during my PhD studies.

My sincere thanks go to Michael Chester from BAE Systems, UK for providing the platform and guidance for the experimental research. To place on record, my wholehearted appreciation also goes to my previous supervisor Prof M. K. Tiwari for generating research interest within me during my master studies at IIT, India. I acknowledge the generous financial support provided by Loughborough University and other funding bodies for research dissemination and professional development opportunities.

I would like to acknowledge my family and friends for their continued support, encouragement and understanding throughout my doctoral studies. Patience, sacrifice and love, intangible and invaluable assets provided by my parents, brother Sujeet and wife Shruti kept me going during challenging time of my life. I shall never forget the support of my friends Aravindan, Krishna, Anurag, Umesh, Kedar, Dipak, Vipul, Amit, Nilesh and others for being there to encourage me throughout the doctoral studies.

Special thanks to my PhD colleagues from School of Business department for their warmth and comfort during my pleasant stay at Loughborough University, UK.

Dedicated to my loving parents

Publications

Research discussed in the thesis contributed to following academic publications:

Journal publications:

1. A. Ghadge, S. Dani and R. Kalawsky. (2012), *Supply Chain Risk Management: Present and Future Scope*, ***The International Journal of Logistics Management***, Vol. 23 No. 3, pp. 313-339.

2. A. Ghadge, S. Dani, M. Chester and R. Kalawsky. (2013), *A Systems Approach for Modelling Supply Chain Risks*, ***Supply Chain Management: An International Journal,*** Vol. 18 No. 5, 523-538.

Conference Publications:

3. A. Ghadge, S. Dani and R. Kalawsky. (2010), *A Framework for Managing Risks in the Aerospace Supply Chain Using Systems Thinking*, **5th International Conference on System of Systems Engineering, IEEE**, 22-24 June, 2010, Loughborough University, UK. pp. 1-6.

4. A. Ghadge, S. Dani and R. Kalawsky. (2010), *Managing Risks in Next Generation Supply Chains: A Systems Approach*, **15th International Symposium on Logistics**, 4-7 July 2010, Kuala Lumpur, Malaysia. pp. 488-495.

5. A. Ghadge and S. Dani. (2010), *Supply Chains Risks: A Systems Thinking Perspective*, **10th International Research Seminar on Supply Chain Risk Management, ISCRiM**, 6-7 September, Loughborough University, UK. pp. 51-55.

6. A. Ghadge, S. Dani and R. Kalawsky. (2010), *Systems Thinking for Sustainability and Supply Chain Risks*, **15th Logistics Research Network Annual Conference**, 8- 10 September 2010, Harrogate, UK. pp. 230-237.

7. A. Ghadge, S. Dani and R. Kalawsky. (2011), *Supply Chain Risk Management: An Analysis of Present and Future Scope*, **16th International Symposium on Logistics**, 10-12 July 2011, Berlin, Germany. pp. 245-254. ***(Best doctoral paper award)***

8. A. Ghadge, S. Dani and R. Kalawsky. (2011), *Systems Thinking for Modelling Risk Propagation in Supply Networks*, **5th International Conference on Industrial Engineering and Engineering Management, IEEE**, 6-9 December, 2011, Singapore. pp. 1685-1689.

9. A. Ghadge, S. Dani and R. Kalawsky. (2012), *Risk Modelling for Creating Economically Sustainable Supply Chains*, **17th Logistics Research Network Annual Conference**, 5-7 September 2012, Canfield University, UK, pp. 1-6.

Working paper:

10. A. Ghadge, S. Dani, R. Kalawsky, C. Lalwani and K. Pawar, *Configuring Future Supply Chains using a Systems Approach*.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

DM: Data Mining

ICT: Information and Communication technology

RSSE: Research School of Systems Engineering

SBE: School of Business and Economics

SCRM: Supply Chain Risk Management

SCM: Supply Chain Management

SC: Supply Chain(s)

SCR: Supply Chain Risk

SE: Systems Engineering

ST: Systems Thinking

SLR: Systematic Literature Review

TM: Text Mining

Chapter 1 Introduction

This chapter introduces the research background and the scope of the research. The thesis outline is provided to present the different stages in research development. Every chapter begins with a similar short abstract providing a quick overview of the research discussed within the associated section.

1.1 Background of the research

The School of Business and Economics (SBE) and Research School of Systems Engineering (RSSE) at Loughborough University proposed a joint research project. The research project aimed at developing a dynamic capability for managing supply chain risks utilising System Engineering (SE) principles. The primary objective of the research was to investigate the suitability of the SE approach for understanding supply chain risks in the manufacturing environment.

Supply Chain Risk Management (SCRM) is gaining importance with supply chain researchers as well as practitioners due to the impact of risks on organisation's financial position and brand reputation in the global market. SCRM has been receiving a considerable and increasing attention in the industry in the recent decade (Kouvelis *et al.*, 2006; Oehmen *et al*., 2009; Manuj and Mentzer, 2008; Norrman and

Lindroth, 2004). A supply chain network consists of numerous links/stakeholders interconnecting into a complex network. Various predictable and unpredictable risks expose such links within the supply chain network. As the research focuses on managing risks in the supply chain using SE principles, the fundamental knowledge of three broad areas is necessary. These three areas are namely, Supply Chain Management (SCM), Risk Management and Systems Engineering as depicted in Figure 1. SCM is the platform or environment for the problem; Risk Management is a process to solve the problem and use of SE tools and techniques as an approach to the problem.

Figure 1: Integration of three research areas

The thesis will discuss all three areas extensively to build the fundamentals for the research study. These areas form a structure of meshing gears driving the defined research aim of developing a dynamic capability for managing supply chain risks following System Engineering (SE) principles.

1.2 Objectives of the research

The background knowledge of three research areas supported with an extensive literature survey defines the objectives of the research. The broad objectives of the research focus on capturing the dynamic behaviour of risks in a complex network of entities within the supply chain.

SBE and RSSE set the following research objectives for the joint research project:

1. **To establish the current research links between the SE approach and supply chain modelling.**
2. **To understand the impact of supply chain risks due to disruptions.**
3. **To design a methodology for measuring the dynamic behaviour of supply chain risks.**
4. **To test the developed research with industry collaborators and disseminate the research outcome widely.**

1.3 Scope of the research

The research attempts to provide a working system for predicting risk behaviour in the dynamic supply chain environment. Manufacturing industries and logistics providers expect to benefit from the research by managing their risks proactively. After the initial conceptual development and modelling of supply chain risks, the research further develops to test and validate the proposed theory and system. The research aimed at supporting the industry collaborators by providing a methodology to understand the complex behaviour of risks. The research offers a perspective to supply chain managers and risk managers for taking proactive measures for mitigating supply chain risks based on their behavioural understanding. Risk modelling based on System Engineering principles expects to capture the intricate behaviour of risks and measure its deviations for effective mitigation strategies. This will help in capturing the behaviour and deviations of the overall impact from fracture nodes within the supply chain network.

The research findings and information have been disseminated through several academic publications in reputed journals and at international conferences. This research expects to provide ideas to researchers and practitioners for further research on SCRM. It is hoped that the research will also lead to more collaborative projects with academic and industrial partners in the future.

1.4 Outline of the thesis

This section discusses the research process as presented in the thesis. Figure 2 shows the followed structured approach for conducting and presenting the research. The outline classifies the stages as identification of research gap, development of research, validation and conclusion. The rest of this thesis is organised as given below:

Chapter 2 discusses the state-of-the-art of SCRM following a rigorous systematic literature review process. To cross validate the manual research findings, modern knowledge management applications are used. Thematic and descriptive analysis predicts seven distinctive research areas/gaps within the SCRM domain.

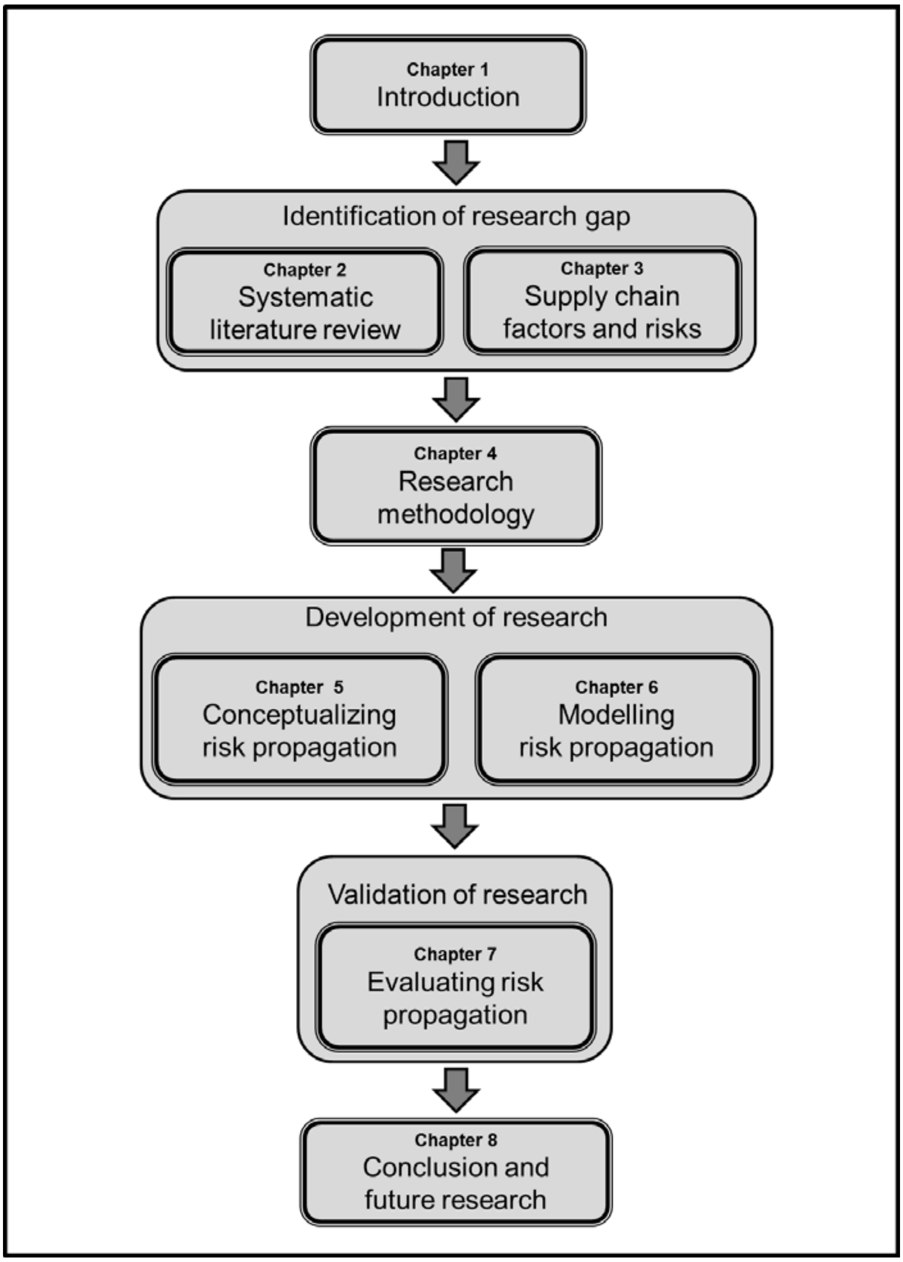


Figure 2: Outline of the thesis

Chapter 3 discusses the case study undertaken to probe the link between various supply chain factors and risks. The exploratory study attempts to find the link between several supply chain factors and their influence on risks during disruption. To predict research gaps from an industry perspective the research utilizes secondary data findings from several workshops and manufacturing sector cases. The intersection of SCRM research gaps and gaps from an industry perspective guide in defining the research problem for the study.

Chapter 4 discusses different methodological approaches suitable to achieve the defined research objectives. The investigation of different research paradigms and methods supported in developing the research design for the study. The research process has identified that the systems thinking approach is capable of capturing the holistic picture of supply chain risks. Mixed methods used within systems thinking approach are broadly discussed to represent its suitability for the defined research problem.

Chapter 5 discusses the conceptual development of the risk propagation phenomenon utilising a systems thinking approach. The conceptualization phase for risk propagation utilizes two different case studies to build the fundamentals for the modelling stage. The operational risk based case study looks at secondary data related to recalls in the automotive and food industry. Whereas, the external risk based case study captures the Japan tsunami disaster. Both case studies combine together to apprehend the fundamental behaviour of risks and their propagation phenomenon within supply chain networks.

Chapter 6 builds the risk propagation modelling approach from conceptual thoughts generated in the previous chapter. Following a systems thinking approach framework for SCRM, supply chain risk model and research design for risk assessment are proposed for modelling the holistic behaviour of risks. A collaborative case study tested the dynamic behaviour of risks using the proposed modelling framework and methodology. The research discussed in this chapter was an experimental study conducted at a collaborating organisation for six-month duration. The developed models capture the failure point(s) and the cascading impact of the risk propagation within the network.

Chapter 7 validates the risk modelling theory developed in the previous chapter. The statistical and simulation model systematically follows the proposed SCRM framework, the supply chain risk model and the research design for assessing the holistic behaviour of risks. The sensitivity analysis compliments and supersedes the risk modelling activity for drawing comprehensive results. Attribute based and parameter based sensitivity analysis provides a dynamic analysis of the behaviour of risks within the SC network. The combined results demonstrate the validity of the developed theory for modelling the risk propagation.

Chapter 8 presents a discussion and a summary of the research outcomes when compared with the research objectives and the aims as set at the start of the study. Different scenarios captured from the multi-interactive nature of risks are analysed in detail in this chapter and interpreted to develop further understanding of the intricate behaviour of risk propagation. The chapter also focuses on limitations and future opportunities arising from the research work.

The appendix section presents information related to the research output that was presented in form of research posters, workshop and conference presentations. Short abstracts of all journal and conference publications derived out of this research are provided to support the research dissemination activity.

Chapter 2 Systematic Literature Review (SLR)

This chapter discusses the process of conducting a rigorous systematic literature review. To cross validate the manual research findings in terms of research gaps and predicted future directions, modern knowledge management applications are used. Thematic and descriptive analysis predicts seven distinctive research areas within SCRM. Later, these research gaps are utilised to define the research problem for the study.

2.1 SLR methodology

Literature reviews build a foundation for the research and help in identifying the gaps in current research. It also supports in determining the future research agenda by providing brief summary and synthesis of the subject area. It is essential to have an unbiased understanding of '*what is already known*' before undertaking any research (Ananiadou *et al.,* 2009). Today's information explosion from multiple data sources (in form of e-sources) demands more explicit and justifiable knowledge about the research area. Such wealth of information needs careful selection, analysis and collection through structured literature review process to develop new research.

Phase of review	Key activities
Identification of review research question	Consultation with Review Group members to develop and refine the review research question.
Developing inclusion/exclusion criteria	Developing inclusion and exclusion criteria to enable decisions to be made about which studies are to be included in the review.
Producing the protocol for the review	Producing an overall plan for the review, describing what will happen in each of the phases.
Searching	Search of literature for potentially relevant reports of research studies to include electronic searching, hand searching and personal contacts.
Screening	Applying inclusion and exclusion criteria to potentially relevant studies.
Key-wording	Applying core keywords and review specific keywords to included studies to characterize their main contents.
Producing the systematic map	Using keywords to generate a systematic map of the area that summarizes the work that has been undertaken.
Identifying the in-depth review question	Consultation with Review Group members to identify area(s) of the map to explore in detail, and develop the in-depth research review question.
Data extraction	Extracting the key data from studies included in the in-depth review, including reaching judgements about quality.
Producing the report	Writing up the research review to a specified format.
Dissemination	Publicizing the findings of the review, including the production of summaries by users.

Table 1: Different phases of systematic review

(Source: Bennett *et al.*, 2005)

The initiative to conduct a Systematic Literature Review (SLR) in field of education started in USA and later was undertaken in UK by establishing the ‘Evidence for Policy and Practice Initiative’ (EPPI) centre in early 2000 (Bennett *et al.,* 2005). Different organisations within the UK utilised the funding available at the centre to develop a systematic methodology. Table 1 shows different phases identified by EPPI for SLR. Various organisations used these systematically identified phases to propose their own stages for the SLR process.

- SLR proposed by Higher Education Career Service Unit, UK identified four phases as (Bimrose *et al.*, 2005): Searching and screening, Data extraction, Synthesis and data analysis and Reporting.
- Centre for reviews and dissemination (2009) proposed the stages as: Planning the review, Conducting the review, Conducting the analysis and Reporting with dissemination.

Several other organisations came up with their own stages or phases for SLR in the last decade. Although different organisations proposed their own SLR methodology, the main phases involved during a SLR process remained very standard. The first phase commonly looked at searching and screening with different protocols predefined for inclusion and exclusion. The second phase looked at actual data extraction followed by third stage looking at conducting the synthesis of the data. The last phase looked at reporting the findings and disseminating to the wider audience. All the above-defined phases were found to be consistent with the EPPI systematic review as presented in Table 1 (Refer to Bennett *et al.*, 2005 for more information).

2.1.1 Conventional versus systematic reviews

This section presents the differences between conventional reviews and systematic reviews as researched when conducting the literature survey for this project. The SLR process differs from traditional narrative reviews by adopting a *replicable, scientific and transparent process* with aims to minimize bias through exhaustive literature searches (Tranfield *et al.,* 2003). Predefined stages during the SLR process remove any possibility of influence of reviewers on the findings, making it unbiased. Exploratory research focused on literature survey helps to draw insights into gaps, scope and future directions of the research. A comprehensive and unbiased search is one of the fundamental requirements of any good literature review. Reproducible and comprehensive survey is the major difference between a traditional narrative review and a systematic review (Lemmer *et al.,* 1999). Thoroughness and rigour are lacking in narrative literature reviews (Tranfield *et al.,* 2003). Evidence based reviews are considered to be thorough and transparent as they provide insights into the field by literature being analysed through a number of perspectives. The Systematic review approach provides an evidence base for literature survey (Tranfield *et al.,* 2003; Rousseau *et al.,* 2008; Denyer and Tranfield, 2009). Several other differences related to conventional and systematic review are presented in Table 2. Numerous academic sources were used to collate the differences (e.g. Torgerson, 2003; Bennett *et al*., 2005; Petticrew and Roberts, 2006; etc.).

Conventional Literature Review	Systematic Literature Review
• Addresses multiple questions	• Addresses specific research questions
• Purpose is to identify and discuss the area	• Purpose is to provide systematic map and research judgements
• Search criteria's likely to be undefined and flexible	• Search criteria's well defined and documented
• Reliability dependent on extent of search strategy and parameters articulated	• High reliability due to clear search strategy and quality assurance checks
• The process can't be replicated as it is in future	• The process can be replicated due to step-by-step procedure.
• In the interest of wider researchers due to broader focus	• In the interest of limited researchers due to limited review questions/areas

Table 2: Comparison between literature reviews

Although the SLR methodology is not widely used within the management field, it has found to have a reasonable acceptance as a desired methodology for literature review (Badger *et al.*, 2000). Systematic review is mostly carried out manually and is found to be time consuming and laborious. However, new knowledge management technique help to build evidences and makes the process quicker. Few researchers in the past have carried out literature surveys in SCRM based on academic peer-reviewed journals. Table 3 shows the list of all contributing authors providing literature review on SCRM. These literature reviews provide a good platform for SCRM beginners as well as for practitioners in making sense of the on-going research and identifying the state-of-art within the field. However, all the SCRM reviews are focussed around certain journals or focus on identifying risks and risk management practices. It is thus important to consider conducting a SLR of SCRM to identify research gaps on a broader perspective. The objective of SLR on SCRM is to see the current advances in the field and to filter the unexplored or less explored areas for this study. The broader picture of SCRM is captured by studying the development of the SCRM research domain over the last one decade. The SLR study initially started by considering the journal papers published over a period of ten years (2000-2010) to capture prominent strategic changes in SCRM research.

Tranfield *et al.* (2003) proposed the methodology that is widely used for conducting literature reviews in the management field. Several academic papers on the literature review process and techniques have identified its fit for research in management field. It was also identified that the SLR methodology was found to have a wide acceptance in some of the universities in the UK as a standard process for the literature review. The SLR process followed in the next section is adapted from the work done by Tranfield *et al.* (2003) for developing evidence informed knowledge management.

Author(s)	Data and Research Methodology	Key Findings/Contributions
Juttner *et al.* (2003)	Literature survey findings are compared with results from exploratory semi-structured interviews and focus groups to discover practitioners' perceptions.	Used four basic constructs to develop the concept: Sources of risk, Adverse consequences of risk, Drivers of risk and Mitigation strategies. Identified normative issues for future research in SCRM focusing need of empirically grounded research.
Khan and Burnes (2007)	Literature review of broad literature on risk and precise literature on supply chain risk.	Emphasize on the need to devise a robust and well-grounded models. In-depth empirical research by incorporating risk management tools from other disciplines of research is needed.
Williams *et al.* (2008)	Through review of the literature on supply chain security (SCS) from academic publications, white papers, and practitioner periodicals.	Provides good empirical findings and theory building through categorization of literature on SCS. Quantitative assessments are needed to better understand SCRM. SCS can lead to improved organisational performance.
Vanany *et al.* (2009)	Thorough review of journal publications from 2000-2007 with help of classifications into several typologies.	RFID and ERP will become important part of SCRM. Use of IT for visibility, collaborative risk management strategies for making supply chains robust is lacking.
Natarajarathinam *et al.* (2009)	Review of academic peer-reviewed journals and case publications in supply chain management literature.	Much of the research is focused on external sources and proactive approaches to crisis in supply chains. Recovery planning and scales for crisis management needs attention.
Rao and Goldsby (2009)	Review of the literature on supply chain risk and synthesis of the broader domain of risk management.	Provides a typology of risks classified broadly as Environmental, Industry and Organisational risks. SCRM needs further investigation.
Tang and Nurmaya Musa (2010)	Literature survey and citation/co citation analysis using academic database to disclose SCRM development.	Desire of an integrated view of SCRM is growing significantly. Quantitative modelling in risk management is lacking and has a huge potential in developing quantitative models to make tough decisions in SCRM.
Colicchia and Strozzi (2012)	SCRM Systematic literature review combined with citation network analysis.	Identified four main themes for future research directions namely; Complexity and uncertainty, Practices and tools for SCRM, Organisation of SCRM and Increased SC resilience.

Table 3: Past literature reviews in SCRM

Knowledge management is defined as "*the systemic and managerial approach to gathering, management, analysis, discovery and sharing of knowledge in order to maximize performance*" (Chen *et al.,* 2010). Researchers have used different knowledge management tools and techniques in the past for knowledge discovery both in the research and in the business world. Data mining and Text mining are commonly used techniques utilizing an artificial intelligence methodology to analyse the set of textual and numerical information data to discover unknown patterns or knowledge.

Text Mining (TM) is an important technique for realizing intelligent and automated data analysis. Data mining is also found to be useful for supporting systematic reviews for quick and evidence proof data discovery (Ananiadou *et al.*, 2009). Models or patterns can be successfully extracted from the data using both techniques. Text mining tools like content analysis and statistical analysis can be used to develop different frequency charts and plots to bring forth new research findings. Cluster chart, proximity plot, Dendrogram are some of the tools used during TM to generate critical knowledge insights. The research insights and gaps identified following the SLR methodology combined with the use of knowledge management tools is believed to build confidence in achieving the right directions for modelling risks in the dynamic supply chain environment.

2.1.2 SLR research process

The SLR methodology is designed to reduce any unintended bias, which may occur with other review methodologies (Bimrose *et al.,* 2005). The SLR process followed in this section is adapted from Tranfield *et.al* (2003) and follows four stages as shown in Figure 3. This adapted design is utilised to analyse the SCRM literature holistically and to identify clear research gaps. Data mining tools are used for knowledge exploration and discovery within the literature. The different activities involved in each stage of the SLR process are discussed in the following sections to provide a generic overview of the review process.

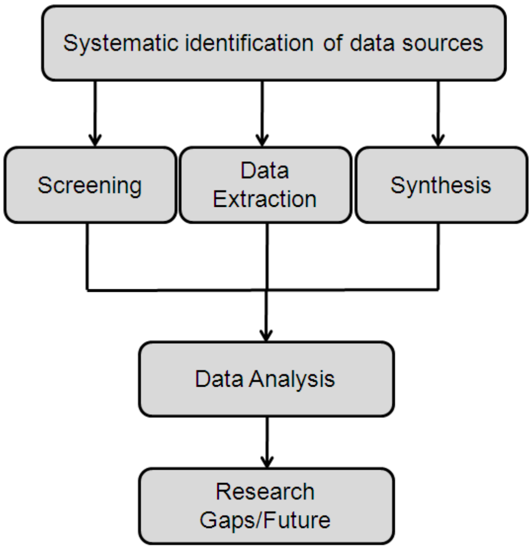


Figure 3: SLR process design

(Adapted from Tranfield *et al.*, 2003)

- **Systematic identification of data sources**

In the first stage, a review panel of experts share their valuable opinions in areas of research methodology and research theory. This preliminary stage of the SLR process is mainly an iterative process of definition, clarification and refinement of concepts (Clarke and Oxman, 2001). In this stage, bibliographic databases are searched with manually constructed keywords commonly called as '*search strings*'. While managing SLR, it is necessary to assess the relevance of the literature and to delimit it by considering cross-disciplinary perspectives (Tranfield *et al.*, 2003). Hence, the inclusion and exclusion criterion should be predefined for identification of data sources. The SLR review plan usually contains a conceptual discussion on the research problem rather than a defined research question. By the end of this stage, data sources and keywords are identified and documented. In certain cases, a clear research problem is defined.

- **Screening, Data extraction and Synthesis**

The SLR screening is conducted based on keywords or search strings that are considered most appropriate after a discussion with the experts. The output of this stage is expected to be a full listing of core contributing articles on which the data analysis will be carried out in a structured, objective and unbiased manner. This listing should meet all inclusion and exclusion criteria as decided in the initial review plan. The number of sources included and/or excluded needs good documentation with appropriate reasons for further knowledge management. The TM technique is used at this stage to extract the important words and phrases automatically within a set of documents. This technique may need further screening to exclude the terms not useful for SLR. Research synthesis is a term referred for ‘family of methods’ used in the review for analysing and summarising the findings (Davies, 2000). This could be done manually, statistically or by using TM tools. TM facilitates in carrying multiple iterations of screening and data extraction enabling continuous improvement for accurate and balanced results.

- **Data analysis**

Systematic reviews use both qualitative as well as quantitative methods. Data analysis is considered the most rigorous process of all other stages in SLR. In order to develop confidence in the data analysis stage, it is necessary to see that the quality of dataset is good. Identification of the quality rating of academic journals is trivial at first instance. Data analysis is conducted by using qualitative and quantitative tools like statistical analysis and citation/co-citation analysis. TM can support data analysis stage by calculating the word and phrase frequency. The systematic approach for screening, data extraction and synthesis processes can facilitate the development of numerous classifications for a holistic data analysis.

- **Dissemination and reporting**

Management research output is presented in two stages as defined by Tranfield *et al.* (2003). Initially this is done through a descriptive analysis, providing a set of classification based on various attributes used in data analysis. The thematic analysis is then reported through an aggregative and interpretative approach. The results are represented in the form of research findings, gaps and future scope. Results from the 'descriptive analysis' are expected to provide a brief management summary report, whereas the results from the 'thematic analysis' will provide more in-depth reporting of the research field studied.

2.1.3 Strengths and weaknesses of SLR

SLR is a well-defined process for conducting the literature survey as observed from its systematic stages and activities. The process clearly defines the search strategy in terms of keywords or search strings. This ensures consistency in the search process. The development and application of predefined inclusion and exclusion criteria ensures the results are objective and unbiased (Birmose *et al.*, 2005). The possibility of adding knowledge management tools during data analysis is unique and is found to be lacking in the conventional literature review as well as SLR. The activities conducted during the SLR process are documented for quick retrieval of important information related to the respective process. The SLR brings reliability, validity, coherence and completeness to the literature survey, yielding important information for evidence-enriched practices and policy decision-making (Bennett *et al.,* 2005).

Similar to any other method for literature review, the SLR also has its own limitations. The process is time consuming and labour intensive compared to a conventional literature review. Although a methodical process drives and provides a strong evidence base for research, the process is criticised to be '*mechanical*' in its operation. An evident weakness of the methodology is that it sacrifices too much of the efforts and efficiency. Although the SLR reviews attempts to capture an overall picture of the past literature, many restrictions had to be imposed due to time constraints, budget, etc. during the review. In spite of all above-mentioned drawbacks, Bennett *et al.* (2005) argues the systematic reviews of research conducted are rigorous as well as rigid in their approach. The next section discusses the SLR on SCRM, which utilises the process design to explore past research findings and propose new research gaps.

2.2 Supply chain risk management (SCRM)

SCRM has progressively attracted researchers as well as practitioners for the last several years. Managing risks in the modern environment is becoming increasingly challenging (Christopher and Lee, 2004). This is because of several reasons like uncertainty in demand and supply, globalization of markets, unprecedented events, volatile market and short product life cycles. Risk is defined as a "*potential for unwanted negative consequences to arise from an event or* *activity*" (Rowe, 1980). Supply chains are growing more global and complex. These are driven by market volatility for reduced costs and increased flexibility. Today's Leagile, Just-In-Time (JIT) supply chains are overly vulnerable to disruptions due to globalized supply chain network of operations. "*Vulnerability is defined as an exposure to serious disturbance arising from risks within the supply chain as well as risks external to the network*" (Peck and Christopher, 2004).

The fundamental challenge of SCM is to plan and control the demand and supply gap to achieve better profits. Traditional supply chain problems studied in the literature are related to location decisions, demand planning, forecasting, contract negotiations, dynamic pricing, supplier selection, strategic outsourcing, inventory forecasting, shop-floor layout designs, network optimization, etc. A supply chain consists of numerous links interconnecting vast networks and these links are exposed to various operational risks as well as disruption risks (Craighead *et al.*, 2007). Operational risks are termed as inherent uncertainties such as uncertain customer demand, uncertain supply and uncertain cost whereas disruption risks are referred to major disruptions caused by natural and man-made disasters (Tang, 2006). Global competition expects that the products and services must be improved not only based on quality, lead time and cost, but also on the basis of environmental sustainability, ethical norms and others to stay profitable and competitive in the global market.

There are diverse classifications of supply chain risks found in the literature. Risk as a topic has many synonyms such as disruption, vulnerability, uncertainty and disaster in field of SCRM. During the preliminary study, it was found that many researchers as well as practitioners described risk as disruption. Although it may seem that there is no significant difference between the terms; the following section discusses the fundamental concepts associated with supply chain risks and/or disruptions. Commonly referred risk management theories are discussed in the subsequent section.

2.2.1 Supply chain risks

Tang (2006a) argues that with so many (e.g. terrorist attacks, hurricanes, earthquakes, floods) disruptions that have happened in recent times, supply chain risk will become an important criterion for cost reduction in SCM. Chopra and Sodhi (2004) classify supply chain risks in the form of delays of materials from suppliers, large forecast errors, system breakdowns, capacity issues, inventory problems and

Author(s)	**Classification of supply chain risks**
Chopra and Sodhi (2004)	Classified supply chain risks as disruptions, delays, systems, forecast, intellectual property, procurement, receivables, inventory, and capacity.
Sinha *et al.* (2004)	Classified four areas of risks which include standards, supplier, technology, and practices.
Finch (2004)	Classified risks into three broad categories which include the three levels of coverage: application level, organisational level, and inter-organisational level.
Norrman and Lindroth (2004)	Categorize the type of risks into operational accidents, operational catastrophes, and strategic uncertainty.
Kleindorfer and Saad (2005)	Divided risks in two broad risk categories as (1) risks arising from the problems of coordinating supply and demand, (2) risks arising from disruptions to natural activities.
Tang (2006a)	Concluded there exist two kinds of risks in supply chain as operational risk and disruption risk.
Tang and Tomlin (2008).	Companies usually manage supply chain risks either at the strategic (long term) or at the tactical (medium term) level.

Table 4: Some examples of risk classification

disruptions. Whereas, Tang (2006a) classifies risks as supply chain risks into operations and disruptions risks. According to Ritchie and Marshall (1993) risks emerge from one of the following sources: (1) Environmental factors (2) Industry factors (3) Organisational factors and (4) Problem-specific factors. Tang and Tomlin (2008) classified supply chain risks as strategic (long term) or tactical (medium term). Similarly, there are several other classifications of supply chain risks (e.g. Sinha *et al.*, 2004; Finch, 2004; Norrman and Lindroth, 2004; Kleindorfer and Saad, 2005) available within the literature. The classification of these risks is diverse in its nature as evidenced from Table 4.

Supply chain disruptions are generally unplanned and unanticipated events that disrupt the normal flow of goods and materials within a supply chain network (Svensson, 2000; Kleindorfer and Saad, 2005). However, sometimes supply chain disruptions may occur when supply chain professionals have knowingly not responded proactively to the risk. Supply chain disruptions provide relevant insights into issues such as supply chain risks, vulnerability, resilience and continuity (Craighead *et al.*, 2007). Supply chain disruptions can result in significant delays triggering problems such as stock-outs, inability to meet customer demand and increases in logistics costs. Blackhurst *et al.* (2005) provides various examples of supply chain disruptions. Disruption may occur due to various types of unpredictable causes such as terrorist attacks, wars, earthquakes, volcanoes, economic crisis, machine breakdown, labor strikes etc. Tang (2006b) suggests a few robust strategies for mitigating supply chain disruptions such as postponement strategy, strategic stock, use of make-and-buy strategy, strategy to provide economic supply incentives, etc. One such strategy for protecting against disruptions is to hold additional inventory (Ross *et al.,* 2008); but it may not be the best solution always as additional inventory tends to increase the holding cost and obsolescence cost. As supply risks increase, it is crucial for organisations to learn how to anticipate, prepare and manage potential supply disruptions (Yang *et al.*, 2008). Supply disruptions affect not only the organisations overall cost but also affect in terms of their reputation profile. The SCRM approach generates benefit to industry by providing better understanding of supply chain risks and ways to mitigate them.

2.2.2 Risk management

Risk management is becoming an integral part of a holistic SCM design (Christopher and Lee, 2004). Risk management in SCM follows a traditional risk

Figure 4: Risk management process

management process as shown in Figure 4. During risk identification, the risks are identified from its sources and later classified based on the predefined categories. Evaluating and assessing the risks is the next stage in the risk management process.

After the assessment, the findings are utilized for mitigating risks within the supply chain network (proactive/reactive). The lessons learned during the mitigation stage are further utilized to build risk control approaches for future risks during the risk management process. Risk mitigation and risk control processes are sometimes combined together to form the risk mitigation and control process. In such a case, the risk mitigation is considered to be reactive approach and risk control as proactive method. Risk mitigation and control process forms a closed loop for a continuous improvement process. SCRM is a systemic approach of identification, assessment and mitigation of risks not only at the operation's level but also at focusing on the entire supply chain network. In general, SCRM consists of a three-stage risk management approach in a supply chain and compliments with any standard risk management process followed in other interdisciplinary areas such as Finance, Information technology, etc.

- **Risk theories in supply chain**

The academic literature discusses several risk theories and this section attempts to provide a brief background of some of the prominent risk theories utilized within the SCM context. Risk is a function of uncertainty and impact. The simple tool for risk assessment is a 'probability-impact matrix' following probabilistic theory. However, a decision theory may combine two or more theories together to draw insights.

Probabilistic theory

This is the most preferred risk management theory. In probabilistic theory, the risk is considered a function of uncertainty and the impact factor. In probabilistic risk assessment, risks are evaluated based on the likelihood of an event with severity of occurrence that follows a linear curve. Figure 5 shows the probability versus impact factor matrix. Low-level risks are associated with low probability and has low impact factor in probabilistic theory. Similarly, high probabilities with high impact factor associated risks are classified as critical whereas the rest are classified as medium level risks.

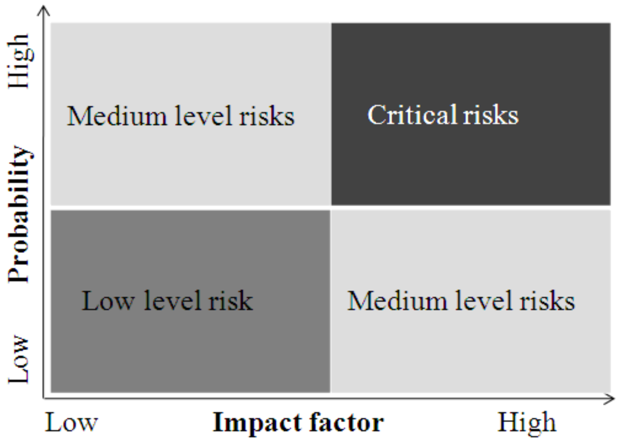


Figure 5: Probability-impact matrix

Utility theory

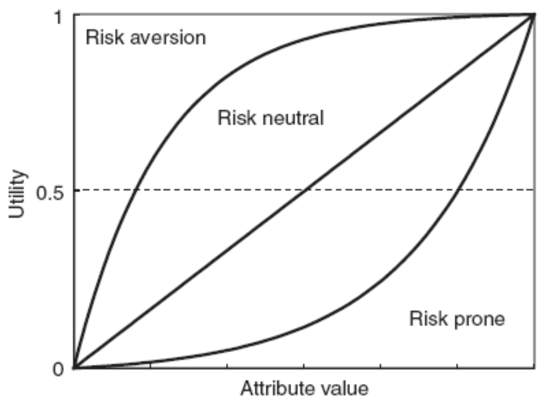


Figure 6: Utility theory curve

(Source: Kainuma and Tawara, 2006)

Kainumaa and Tawara (2006) use multiple attribute utility theory for assessing a supply chain. The expected utility based model was first proposed by Nicholas

Bernoulli in 1713. Utility theory is derived from financial management principles and more recently within the SCM field. In this theory, a utility function measures an investor's relative preference for different levels of total capital. In SCRM, utility function can be used to measure loss due to disruptions. Utility theory slightly contradicts the probabilistic theory in terms of the level of severity. Ben-Asher (2008) has proved that, utility-based loss function follows a non-linear curve where less probabilistic event(s) can have high severity. Figure 6 illustrates three types of single-attribute utility functions as risk averse, risk neutral and risk prone.

Graph theory

Graph theory is used to assess the vulnerability by developing and calculating a supply chain vulnerability index (Wagner and Neshat, 2010). Faisal *et al. (*2007) used graph theory and matrix methods for supply chain risk mitigation. The graph theory associates the dynamics of the relationship among the drivers and interdependencies.

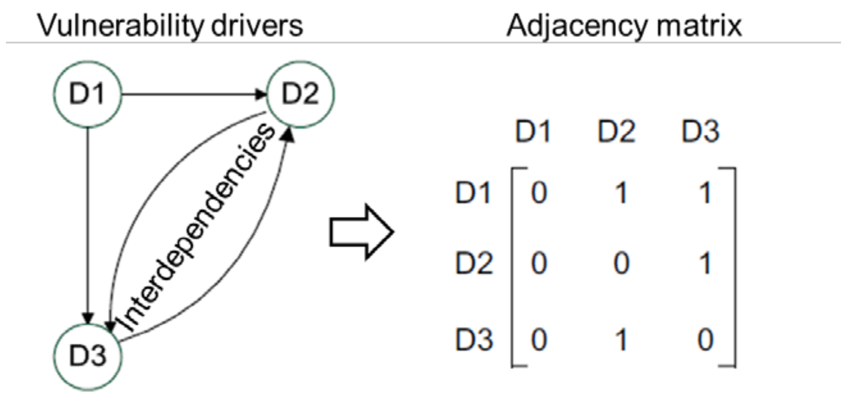


Figure 7: Graph theory example

(Source: Wagner and Neshat, 2010)

It is often found in supply chains that, vulnerability in one entity of the supply chain network influences the vulnerability of another network entity. Hence, the graph theory seems an appropriate method to quantify vulnerability and tap the interdependencies within supply chains. Wagner and Neshat (2010) attempts to develop an approach based on graph theory to quantify and mitigate supply chain vulnerability as seen in Figure 7. More recently, Shin *et al.* (2012) combined the elements of graph theory and probability theory to develop a Bayesian belief network model for solving transportation problem.

Based on the literature on risk management theories within the SCM context, the three risk theories discussed above are found to be useful for SCRM. Several other risk management theories found in the financial, enterprise and project management literature are beyond the scope of the research and hence not discussed in this section.

2.3 SCRM analysis and findings

Following the proposed SLR process design, the systematic approach for data collection and analysis was followed. The keywords and search strings used for filtering the raw data from data sources were identified based on the understanding of commonly used terms by the academic researchers in SCRM field. Keywords such as “risk”, “disruption”, “vulnerability” and “uncertainty” are commonly referred words within the SCRM literature. These data strings were selected based on the author's earlier understanding of the SCRM field supported by discussions held with SC experts. These discussions consisting of academicians and practitioners were conducted during the 10th International Research Seminar on Supply Chain Risk

Management (2010) organised by the International Supply Chain Risk Management Network (ISCRiM) in Loughborough, UK. ISCRiM is a network of SCRM researchers founded in 2001 initially by a small group of active researchers from the UK, US and Europe.

Subject field/area	List of journals	ABS Ranking*
Operations Management (OM)	• Journal of Operations Management (JOM)	4
	• Production and Operations Management (POM)	3
	• International Journal of Production Economics (IJPE)	3
	• International Journal of Operations and Production Management (IJOPM)	3
	• Supply Chain Management: An International Journal (SCMIJ)	3
	• International Journal of Production Research (IJPR)	3
	• Production Planning and Control (PPC)	3
	• International Journal of Logistics: Research and Applications (IJLRA)	2
	• The International Journal of Logistics Management (IJLM)	2
	• International Journal of Physical Distribution and Logistics Management (IJPDLM)	2
Operations Research and Management Science (OR/MS)	• Management Science (MS)	4
	• European Journal of Operational Research (EJOR)	3
	• Naval Research Logistics (NRL)	3
	• Omega: The International Journal of Management Science (OMEGA)	3
	• Decision Sciences (DS)	3

Table 5: Identified data sources

(Source: ABS Ranking as on 17 November 2010)

To identify research articles for conducting a quality analysis we used the quality rating of journals in Operations Management (OM), Operations Research (OR) and Management Science (MS) area. We strictly followed the journal quality rating provided in 'Journal Quality Guide' published by ABS (Association of Business Schools, UK) and referred to only journals in above mentioned areas with an average of 3 star quality rating from two years (2009, 2010). There were a few exceptions as the journal guide has some of the high quality supply chain and logistics journals rated as only 2 star. These journals were also included in the final list. These papers were heavily refereed and the research is highly regarded in academic world (ABS Journal Guide, 2010). Table 5 shows 15 such identified data sources with their ABS ranking in OM and OR/MS area.

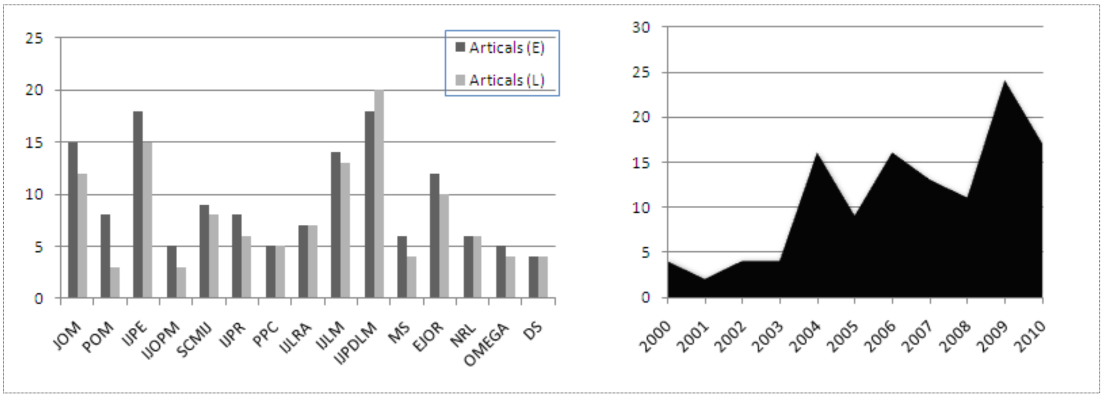


Figure 8: Journal-wise and year-wise distribution of articles

In order to restrict the scope of literature survey, we decided to analyse articles published only in last one decade (from 2000 to 2010). We believed the year 2000 as an appropriate starting point even though an American industry consultant first coined the term ‘Supply Chain Management’ in the early 1980s. After year 2000, greater numbers of quantitative orientated articles were published (Tang and Nurmaya Musa, 2010). The preliminary search also pointed out that a significant number of researchers started researching on SCRM in the early 2000. Global recession affecting supply chain in 2001-02 (Hilmola *et al.*, 2005) and challenges in outsourcing seem to have given a sound platform for research on supply chain risks in the early part of the decade. The preliminary search using data strings within the 15 identified international journals found a significant number of articles. Filtering this data further and considering only publication between 2000 to 2010 yielded 140 articles.

The search was further refined by setting exclusion criteria for articles discussing risk management in other interdisciplinary fields like Finance, Enterprise, Information Technology, etc. In order to improve the quality of research, 120 quality articles were selected manually after a careful consideration of inclusion and exclusion criteria. Data extraction and analysis from these individually and independently selected articles was conducted using TM techniques. Initially the analysis was done using manual and statistical techniques. TM tools were further used to validate the manual and statistical findings.

It was evident in the first stage of screening that, there was a significant increase in number of articles published from year 2004 in field of SCRM (Figure 8). Preliminary studies showed that, the traditional focus of supply chains looking at operational risks shifted towards more tactical and strategic risks due to an increase in global outsourcing activities. The 9/11 terrorist attack (2001) disrupting major supply chain in the early decade also triggered an interest in the SCRM field (Chopra and Sodhi, 2004; Sheffi, 2001). The year 2009 represented the most promising year in SCRM research contributing most in volume. The global financial meltdown by the middle of 2008 can be attributed as one of the reasons for the surge in research in the subsequent year. Descriptive analysis of keywords and countries contributing to SCRM showed countries like USA and UK contributing most to SCRM research. Countries like USA, UK along with other European countries outsourcing the most and are thus vulnerable to disruptions. This could be a possible driving factor for researchers from these countries. Risk and disruption are commonly used terms to represent exposure to serious disturbance in the supply chain. Some other prominently used terms found in the literature were vulnerability, uncertainty, disaster and crisis as seen in Figure 9. *QDA Miner*©, a qualitative data analysis software developed by Provalis Research facilitated the SLR process.

	FREQUENCY	% SHOWN	% PROCESSED	% TOTAL	NO. CASES	% CASES	TF • IDF
SUPPLY	8428	16.8%	2.2%	0.9%	101	84.2%	630.9
CHAIN	4688	9.3%	1.2%	0.5%	101	84.2%	350.9
RISK	5625	11.2%	1.5%	0.6%	105	87.5%	326.2
RETAILER	524	1.0%	0.1%	0.1%	33	27.5%	293.8
SUPPLIER	1931	3.8%	0.5%	0.2%	88	73.3%	260.1
SECURITY	501	1.0%	0.1%	0.1%	39	32.5%	244.5
SUPPLIERS	1513	3.0%	0.4%	0.2%	83	69.2%	242.2
RISKS	1536	3.1%	0.4%	0.2%	85	70.8%	230.0
SCRM	229	0.5%	0.1%	0.0%	13	10.8%	221.0
DISRUPTION	784	1.6%	0.2%	0.1%	64	53.3%	214.0
DISASTER	413	0.8%	0.1%	0.0%	37	30.8%	211.0
LOGISTICS	1250	2.5%	0.3%	0.1%	83	69.2%	200.1
RESILIENCE	270	0.5%	0.1%	0.0%	22	18.3%	198.9
OUTSOURCING	479	1.0%	0.1%	0.1%	50	41.7%	182.1
CONTRACT	417	0.8%	0.1%	0.0%	45	37.5%	177.6
SIMULATION	268	0.5%	0.1%	0.0%	27	22.5%	173.6
MANAGEMENT	3787	7.5%	1.0%	0.4%	108	90.0%	173.3
SHARING	487	1.0%	0.1%	0.1%	53	44.2%	172.8
POSTPONEMENT	203	0.4%	0.1%	0.0%	17	14.2%	172.3
TRUST	306	0.6%	0.1%	0.0%	33	27.5%	171.6
VULNERABILITY	470	0.9%	0.1%	0.0%	52	43.3%	170.7
DEFAULT	181	0.4%	0.0%	0.0%	15	12.5%	163.5
GLITCHES	145	0.3%	0.0%	0.0%	9	7.5%	163.1
MODEL	1338	2.7%	0.4%	0.1%	91	75.8%	160.7
DISRUPTIONS	555	1.1%	0.1%	0.1%	62	51.7%	159.2
MANUFACTURER	365	0.7%	0.1%	0.0%	47	39.2%	148.6

Figure 9: Keywords identified in TM tool

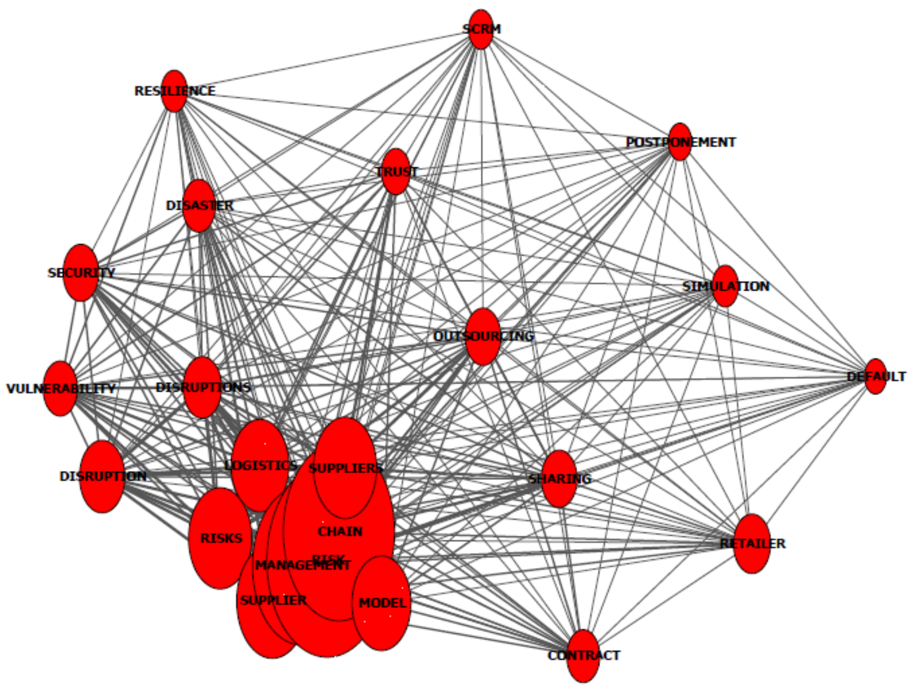


Figure 10: Clusters identified in TM tool

The term ‘risk’ is found to be referred to organisational and network related disturbance; whereas, ‘disruption’ is commonly referred to exposure to environmental (man-made and natural) disturbances. The frequency of keywords signifies the importance of word/phrase in the research area. Identifying these keywords and phrases through a TM tool provided confidence in using manually identified search strings. Using TF-IDF (Term Frequency-Inverse Document Frequency) weight search criteria in the TM tool, frequently used keywords and phrases were identified along with a cluster diagram of key words as shown in Figure 10. TF-IDF weight measures the relevance of a specific word as a statistical measure. This is the commonly used weight for information retrieval in data mining techniques. The similarity in manual search strings and keywords identified by the TM tool provided an assurance for keywords used during the data screening process. Risk, disruption, uncertainty, vulnerability and Security were found to be most commonly used keywords in most number of cases or articles as seen in Figure 11.

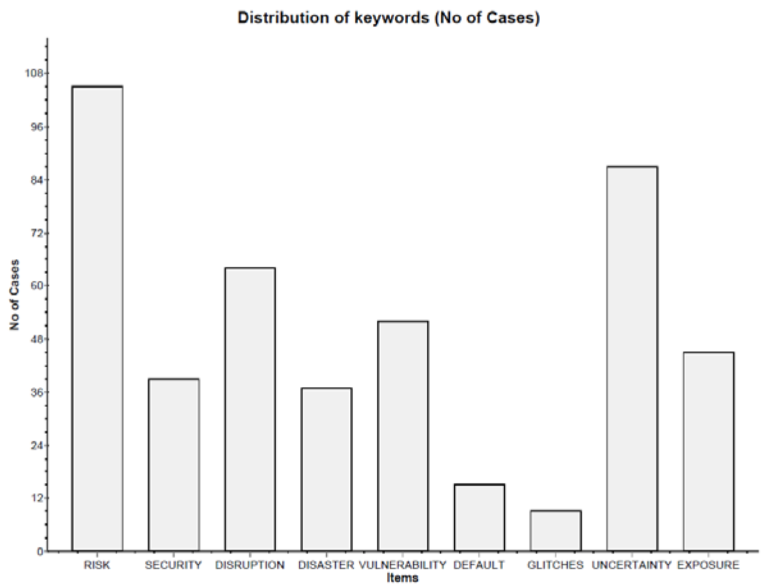


Figure 11: Distribution of keywords

Data synthesis was achieved using various predetermined criteria for developing family of classifications based on risk classification, management level, research methods, etc. These predetermined criteria's were identified from various SCRM aspects as well as by using concept mapping as seen in Figure 12. Concept mapping

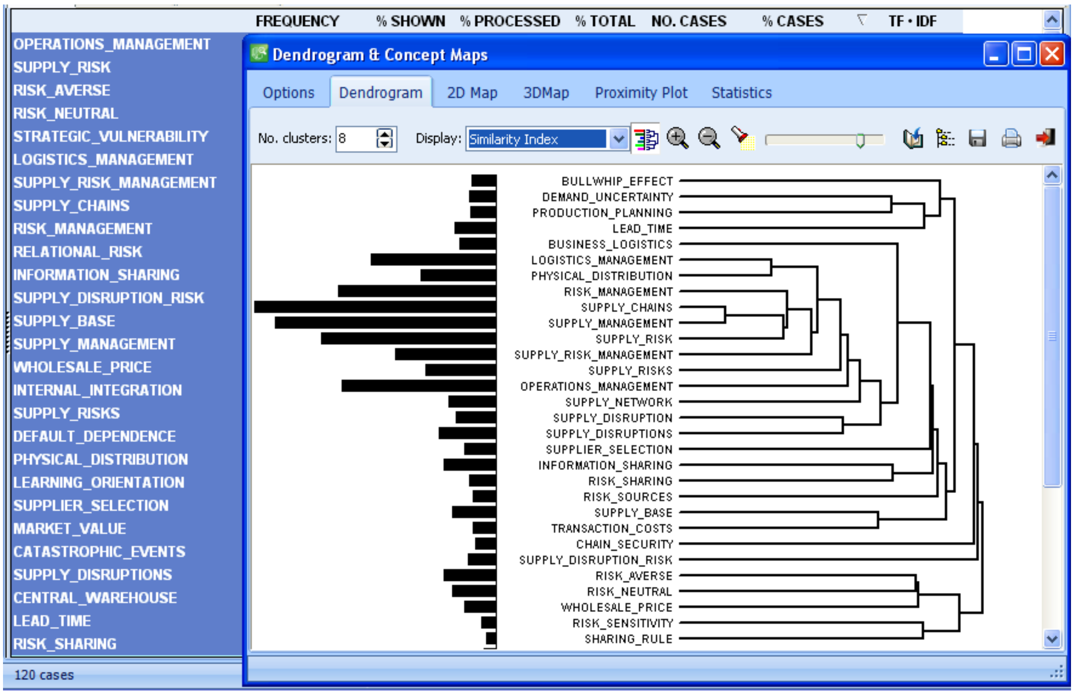


Figure 12: Concept mapping using dendrogram for classification

shows the association of different areas within a broad area. These identified classifications (typologies) form the backbone of data analysis. Developed typologies were as given below,

Based on type of risk: Diversity in classifying risks within the SCRM literature is discussed in the previous section but the review demanded clear and distinct classification for the data analysis capturing all possible risks within the SC. The classification provided by Juttner *et al.* (2003) based on sources of risk as organisational risk, network risk and other risks comprising of environmental (man-made and natural disasters), political/social and exchange rate risks is followed for clear distinction of risks during the analysis.

***Based on Management level*:** Applied risk mitigation strategy may differ depending on the level of management. The management level could be operational, tactical or strategic depending on the nature of problem and management requirement.

Based on research methodology: A classification of qualitative and quantitative research methodologies helps to understand tools and techniques used in SCRM.

***Based on risk management process**:* Based on the perception of researchers in SCRM, the risk management process is classified as risk identification, assessment and mitigation and/or control.

Based on approach to SCRM: The risk mitigation approach could be either proactive or reactive. This further helps to identify mitigation strategies commonly used in the field of SCRM.

Preliminary analysis based on various typologies showed the length and breadth of the SCRM field as seen in Table 6. It is surprising to see that, almost all SCRM research contribution from UK academics is published only in OM journals. The journals from OM domains are more influential then OR/MS (Petersen *et al.*, 2011). Most of UK research work is found to be qualitative in nature and this could be a possible reason for not being published in OR/MS journals focusing largely on application of quantitative methods for decision-making (Chase *et al.,* 2006).

Typology type	All Journals	OM Journals	OR/MS Journals
Contributing country	%	%	%
USA	46.66	43.47	57.14
UK	15.83	20.65	0.00
International	16.66	11.95	32.14
Other countries	21.66	25.00	10.71
Publication period			
2000-2005	32.50	35.86	78.57
2006-2010	67.50	64.13	21.42
Type of Risk			
Organizational	4.85	5.87	0.00
Network	48.78	52.69	11.65
Other	14.63	12.38	50.61
Holistic	31.66	28.58	38.42

Typology type	All Journals	OM Journals	OR/MS Journals
Research approach	%	%	%
Qualitative	54.16	67.39	10.71
Quantitative	36.66	23.91	78.57
Mixed	9.16	8.69	10.71
Risk management process			
Identification	35.00	32.39	5.89
Assessment	14.33	16.64	78.14
Mitigation/Control	5.83	4.72	13.84
Holistic	44.16	46.47	2.85
Risk mitigation approach			
Proactive	56.33	41.60	60.71
Reactive	23.33	13.91	18.42
Holistic	20.83	44.92	21.07

Table 6: Descriptive analysis of SCRM

By dividing the decade into two halves for analysis, it showed a distinctive progress of SCRM research. The significant shift from an undefined area to an emerging area for practitioners and researchers in supply chain management is evident from this classification. Publications on SCRM in the later part of the decade have almost doubled as seen in Figure 8. This clearly shows the potential of SCRM research in current business environment. The detailed analysis of other important developed typologies provided interpretative results underlining the scope of the SCRM field for the future. This detailed analysis is discussed in the next section.

The classification tree for systematic analysis of the SCRM literature was developed. Risk classification, research methodology and risk management process typologies were subdivided in the classification tree as shown in Figure 13 and further studied using a thematic analysis approach. Rao and Goldsby (2009) developed a similar supply chain risk typology by conducting a SCRM literature review. Supply chain risks were broadly identified as organisational, network and other risks comprising of natural and man-made disasters.

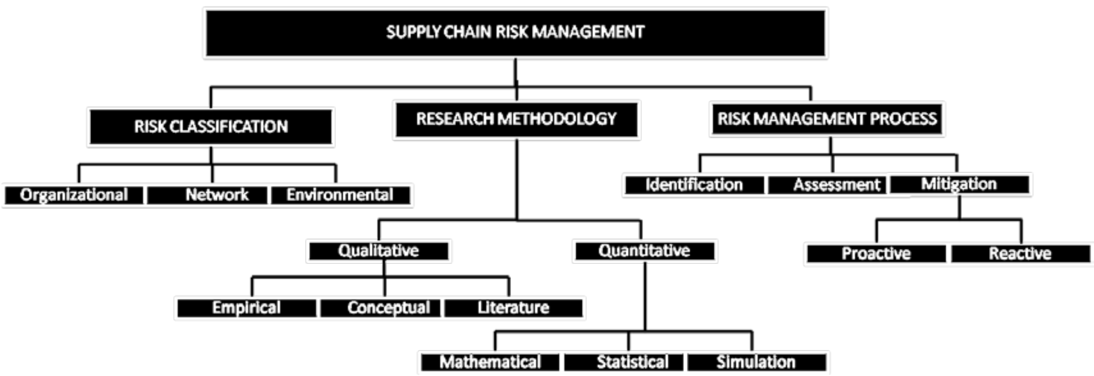


Figure 13: Classification tree for literature review in SCRM

- **Organisational risks**

Organisational risks are associated with the organisation and are independent in its nature. Organisational risks are grouped as inventory risk, process/operational risk, quality risk and management risk. Inventory risk is the risk arising from buffer or stock out inventories leading to unnecessary handling or lost opportunity cost. (Cachon, 2004; Juttner *et al.*, 2003; Childerhouse *et al.*, 2003; Zsidisin, 2003a; Chopra and Sodhi, 2004). Inventory risk could be reduced by reducing the cash-to-cash cycle and utilising improved forecasting techniques (Papadakis, 2006). Process or operational risk can be defined as risks initiated with operational events disrupting material or information flows within the supply chain. (Christopher and peck, 2004; Jiang *et al.*, 2007; Lewis, 2003; Cavinato, 2004; Colicchia *et al.*, 2010; Cigolini and Rossi, 2010). Quality risk may result from problems at plant or due to supplier failure. As such, this is considered as organisational risk as this is mainly due to issues in the operational aspects of the organisation and is contrary to past SCRM literature. Researchers identify outsourcing activity being responsible for the product quality risk (e.g. Zsidisin *et al.*, 2000; Zsidisin *et al.*, 2004; Chopra and Sodhi, 2004; Kaya and Ozer, 2009) and this is considered more of a network risk than organisational risk. Management risk is a risk that arises from poor management ability to anticipate and react to market demands. The literature lacks in identifying management risk as a critical risk for any business success.

- **Network risks**

Network related risk sources arise from interactions between organisations within the supply chain network (Juttner *et al.*, 2003). Supply risk, supplier default and demand risk (network related risks) are found to be most researched (48.78%) for its obvious reasons of being "extrinsic" in nature of risk. Supply risk according to Zsidisin (2003a) is the potential occurrence of an incident associated with the inbound supply leading to the inability of the purchasing organisation to meet customer demand. Supply risk is one risk found most discussed and researched in the literature. Wu *et al.* (2006) provides an integrated approach to classify, manage and assess supply risks. Supplier default or failure risk mainly emanates from the inability of the supplier to meet the orders. This may further lead to supplier bankruptcy and could become a very critical risk in the case of a strategic supplier. Proactive strategies like long term contracts, dual and/or multi-sourcing are being effectively used in supply chain environments; but supply chain disruption due to supplier default risk has been widely neglected (Wagner *et al.,* 2009). Demand risks are the risks associated with demand uncertainty (Tang and Tomlin, 2008) or risk associated with the outbound logistics flows (Svensson, 2000). Supply and demand risks are unified in its nature and are influenced by external disturbances or risks.

- **External risks**

External or other types of risks are events driven by external forces such as weather, earthquakes, political, regulatory and market forces (Wagner and Bode 2006). Recent research has shown increased attention towards environmental (man-made and natural) disruptions due to several global events in the recent past disrupting supply chains such as: 9/11 terrorist attack (2001), SARS (2003), Indian Ocean Tsunami (2004), Hurricanes (2005), geopolitical instability (2010) and Japan Tsunami (2011). Environmental risk sources comprise of any uncertainties arising from the interactions in the supply chain environment (Juttner *et al.,* 2003). Environmental risk can arise due to physical, social, political, legal or economic environment (Bogataj and Bogataj, 2007). Due to current environmental disruptions globally, the research on these types of risks is expected to grow further with a focus on holistic risk management.

It is found during the analysis of the risk management process that most of the articles are focused on the risk identification activity (35%). This clearly shows the embryonic stage of research in SCRM. Very less attention is given to a holistic risk management process and this is evident from the analysis. Only half of the articles analysed in the SLR actually discussed about either implementing proactive or reactive risk mitigation strategies (61 out of 120). The general approach of researchers to risk mitigation is preferred to be proactive (58.33%) as compared to being reactive (23.33%). However from a practitioner's perspective, it is difficult to justify the investment in proactive risk mitigating strategies (Dani, 2008) and hence is not preferred by SC practitioners. There is sufficient scope for research in identifying and implementing robust proactive as well as reactive risk mitigation strategies as found in the review.

Agility, flexibility and preparedness are the preferred generic strategies for the holistic risk mitigation (Ponomarov and Holcomb, 2009). At a strategic level; contingency planning and risk sharing outsourcing contracts are prominently used as risk mitigation strategies. Use of multi-strategy approach like combining supplier alliance network with lead-time reduction and/or recovery planning system (Tang, 2006) can be effective for mitigating situational disruptions/risks.

Data synthesis of research methodologies used for decision making in the SCRM field was broadly classified as qualitative and quantitative. It was evident in the descriptive analysis that, researchers in SCRM commonly prefer qualitative methods. Following the classification tree represented in Figure 13, SLR on qualitative and quantitative research methods used in SCRM are discussed below.

Qualitative research methods were divided into several research approaches by broadly classifying them as empirical study, conceptual theory and literature survey for a detailed thematic analysis.

- **Empirical study**

Empirical research employs case study, industrial survey, structured/informal interview and focus group methodologies for analysing information gained by means of observation or secondary data study. Case study is found to be a preferred approach in exploratory research and is commonly used to generalize the theoretical proposition (Yin, 1984). A detailed analysis of data classified as qualitative, quantitative and mixed methods showed that researchers dealing with problems mainly at the strategic management level adopted the case study approach. Applying a qualitative research approach to supply chain redesign, Vorst and Beulens (2002) identified sources of uncertainty based on case studies in three food industries. Similarly, Finch (2004) has used the case study approach to examine various risk and best practices to mitigate for different levels of company environments. The development of information and knowledge systems is a potential means to manage risks as identified by Hallikas *et al.* (2004) following case studies in supply network. Mauricio *et al.* (2009) has classified supply chain vulnerability as financial, strategic, hazard and operations; providing a holistic picture of supply chain risks based on a study of 46 cases from the automotive and electronic industries in Brazil. Strategies for global supply chain environments are identified based on case studies in clothing and fashion industries (e.g. Christopher *et al.*, 2006; Khan *et al.* 2008). These examples depict that the case study method is found to be very useful for a holistic view of the supply chains risks. In the literature, about 80% of the case studies were found to be focussed on network related risks.

In qualitative research methods, other prominently used tools are exploratory analysis of secondary data using industrial surveys (11.67%), Conceptual theory building for developing frameworks (10.83%) and the use of Interviews/Questionnaires/Focus group study (10.00%). Case study approach is commonly combined with other qualitative methods like questionnaires, focus groups and interviews. Industrial survey is another way for empirical data analysis and is found to be preferred in SCRM research. Jonsson (2000) with the help of an industrial survey of maintenance and manufacturing managers in several industries revealed that, preventive and integrated maintenance is important for companies having high breakdown and stop costs. Blackhurst *et al.* (2005) using multi-methodology empirical study identified a critical need for quantitative assessment tools that could identify high probability nodes for disruptions within supply chains. Similarly, Craighead *et al.* (2007) based on a three-phase empirical study of a case study, interviews and focus groups derived propositions relating to severity of supply chain disruptions with design characteristics and mitigation capabilities. Questionnaires and interviews are usually combined in qualitative research. This combined approach is found to be effectively used for SCRM research in past (e.g. Lewis, 2003; Jiang *et al.*, 2009; Mantel *et al.*, 2006; Blos, 2009; Brun *et al.*, 2006; Autry and Bobbitt, 2008; Perry, 2007).

- **Conceptual model/theory**

'Conceptual' is meant to represent a research methodology describing fundamental concepts on SCRM (Vanany *et al.*, 2009). Due to the nascent stage of the SCRM field, Conceptual theory or framework development is found to be frequently adopted by many SCRM researchers. Svensson (2000) has conceptualized the inbound and outbound vulnerability in a supply chain based on sources and categories of disturbances. Similarly, other conceptual frameworks like supply chain security orientation framework (Autry and Bobbitt, 2008), supplier risk management framework (Matook *et al.*, 2009), model for SC network risk (Trkman and McCormack, 2009), risk and performance framework (Ritchie and Brindley, 2007), disaster recovery pyramid (Richey. Jr. 2009), interactive adaptive system (Peck, 2005; Peck, 2006), SC disruption risk management (Kleindorfer and Saad, 2005), reactionary risk mitigation model (Dani and Deep, 2010) are found to be used for future research developments in SCRM. Conceptual frameworks mainly focused on risk identification activity whereas outcomes of case studies were developed as risk mitigation strategies for implementation in similar case environments. Interviews, Questionnaires and Focus group study are found to be commonly used for risk identification and risk assessment activities primarily at a strategic level of management. Since a literature review provides a stage for conceptual theory building, it is found to be often used in most of the SCRM research.

Quantitative research methods are broadly classified into mathematical modelling, simulation and statistical testing for detailed thematic analysis as seen in Figure 14.

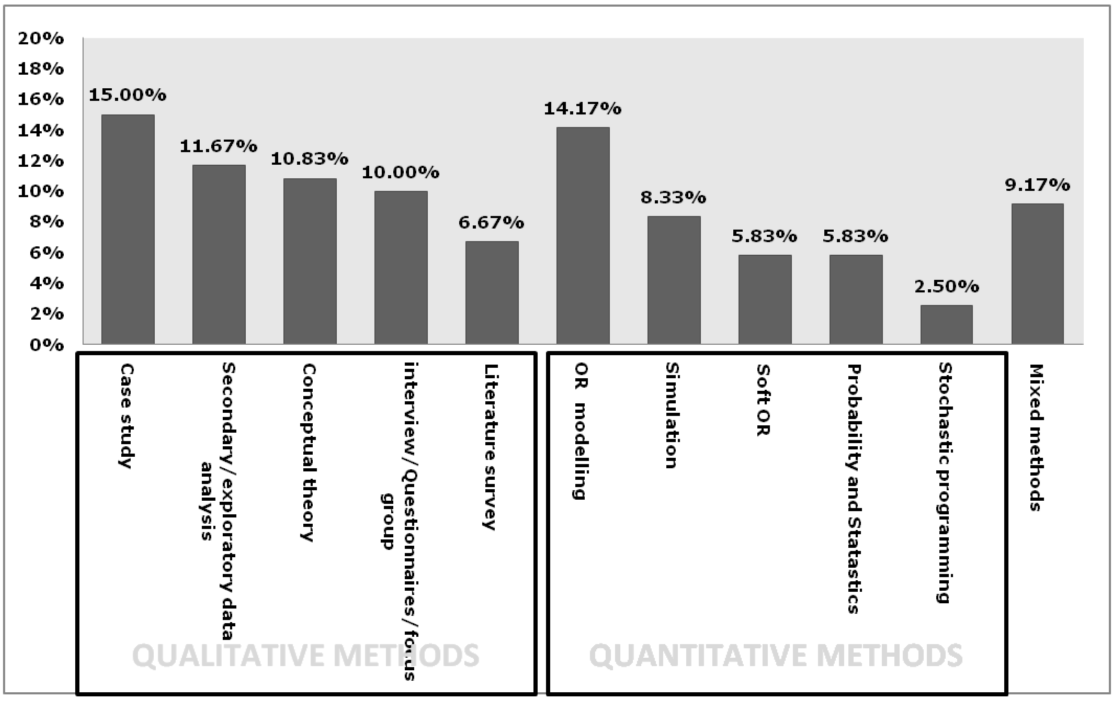


Figure 14: Preferred research methodologies in SCRM

- **Mathematical modelling**

Mathematical modelling is used in all kinds of research. Operations Research (OR) modelling, a part of it is interconnected to OR/MS field. OR modelling can be broadly classified into hard OR and soft OR techniques. Hard OR techniques broadly consists of linear programming, game theory, queuing theory, Markov process (Carter and Price, 2001) and soft OR comprises of SWOT/PEST analysis, viable systems model, Scenario planning and systems thinking.

In quantitative research methods, OR modelling comprises of multi-objective programming, linear/non-linear optimization modelling and other mathematical algorithms are preferred by researchers in SCRM research (14.17%). The Linear programming method is used to manage demand/supply uncertainty related problems (e.g. Sodhi, 2005; Lai *et al.*, 2009). Parametric linear programming (Bogataj and Bogataj, 2007), Stochastic modelling (Goh *et al.*, 2007), mixed-integer modelling (Bryson *et al.*, 2002; Barbarosoglu *et al.*, 2002) and dynamic programming (Yang *et al.*, 2005) are few noticeable OR modelling related approaches used for risk modelling and analysis. Few researchers have combined different modelling tools like algorithms and simulation for disruption management related problems. It is interesting to observe a marked increase in adopting quantitative approach to SCRM in later half of decade primarily focusing on operational level problems.

Soft OR decision support tool AHP is capable of selecting the most appropriate solution from a set of solutions (Satty, 1990) and is found to be a preferred tool by researchers in SCRM (e.g. Leopoulos and Kirytopoulos, 2004; Gaudenzi and Borghesi, 2006). Scenario planning (Dani and Deep, 2010) has found potential for strategic decision making in SCRM. Other soft OR approaches like viable systems model and systems thinking are finding its application in SCRM research.

- **Statistics and probability theory**

Statistics and Probability theory is another commonly used quantitative research tool efficiently used mainly for the hypothesis testing. With help of a linear regression model, Hung and Ryu (2008) have tested the hypothesis for changing risk preferences in supply chain inventory decisions. It can be ascertained from the SLR that most of the researchers use statistics and probability theory mainly to validate the results of empirical or descriptive research. Multivariate analysis and options theory is also found in SCRM research. Probability and Statistics is used to analyse the data mainly at operational and tactical level of problems like production and inventory management, demand uncertainty, etc.

- **Simulation**

Simulation modelling provides a systematic approach to understanding the relative and interactive impact of factors/parameters for different scenario settings. Simulation methods are common for assessing and modelling supply chain risks (Zsidisin *et al.,* 2004). Agent based simulation (e.g. Datta *et al.,* 2007), Monte Carlo simulation (Ermoliev *et al.,* 2000; Wagner *et al.,* 2009) and Discrete-event simulation (Manuj *et al.,* 2009) are few of the noticeable simulation related articles identified in the SLR. Most of the simulation platforms are used for solving operational management level problems. Manuj *et al.* (2009) provide an exceptional eight-step development process for the design, evaluation and implementation of logistics and supply chain simulation models. The supply chain literature lacks analytical research using simulation to investigate supply chain risks (Kull and Closs, 2008). Commercial simulation software like Arena® and Stella® are used for simulation modelling. Problems related to supplier uncertainty, production planning and bullwhip effect are analysed with help of simulation modelling; As they tend to simulate a real time environment scenario represented in a mental model. System dynamics simulation capturing risk propagations within supply chain networks is found to be lacking in the existing SCRM research.

Mixed methods combining two research methodologies have been located in the review (9.17%). Undoubtedly, there is huge potential in developing quantitative models to make hard decisions in SCRM (Tang and Nurmaya Musa, 2010). The SLR points out the lack of research methods suitable for capturing the holistic, dynamic behaviour of risks within supply chain networks.

2.3.1 SCRM research gaps

The SLR of 120 quality articles discussed in the previous section followed the research design adapted from Tranfield *et al.* (2003) and found some interesting results. The TM technique facilitated the data screening, extraction and synthesis process. SLR has provided few critical insights into SCRM research. The data analysis of the quality data sources provides confidence on the expected quality of results. SLR is important to propose a future research agenda (Torgerson, 2003). The extensive analysis has identified seven distinctive SCRM research gaps and new directions in the field. The identified research gaps will support in narrowing the research problem domain. Some of the identified research gaps identified through the SLR are presented below:

1. ***Holistic approach to risk management***

There exists a lot of classification of risks looking at nature and sources of risks (Rao and Goldsby, 2010), which was evident from the fact that risk itself has so many synonymous terms used in the SCRM field. Individual or group of risks based on its nature are considered and attempts have been made by past researchers to find local solutions to specific risks. This process was not based on considering all kinds of risks acting concurrently. Modelling the critical point of failure within a supply chain network is un-attempted and demands further research. The holistic SCRM approach is clearly lacking in the current literature and systems approach has the potential to guide in that direction. Studying dyadic relationships (Williams *et al.,* 2008) are important for the holistic understanding of SCRM. Holistic or ‘system of systems’ approach is expected to bring fresh thinking for existing problems and to a further uncertain world (Mingers and White, 2010).

An integrated approach to SCRM needs to incorporate the risk issues from industry practice (Tang and Nurmaya Musa, 2010). Research on redesigning SC strategies is a fertile area in the current global, uncertain and dynamic environment. To the best of the author's knowledge, no paper relates product life cycle to SCRM. Quality risks like vehicle recalls, poor customer service are regular and primarily associated with the design and development aspects in the product life-cycle management. The multidimensional perspective focussing on management processes, risk dimensions, impact flows and mitigation alternatives needs to be studied in whole. The possibility of connecting all above aspects together can provide robustness and resilience for future supply chains. Perceiving the supply chain as a system with multiple stakeholders and multiple interactions and then using systems thinking to understand the risk challenges is a largely unexplored area.

2. Application of quantitative models

Although, this study is related to academic work on SCRM, it is vital to put it in the context of the impact that the work creates within industry. Although there may be a debate on which methodology is the most appropriate and whether quantitative models provide a better understanding and theory than qualitative work, it is important that the research should have a direct influence on the industry practices.

Novel qualitative as well as quantitative methods are needed for developing SCRM theory as well as practice. Empirically grounded research is needed for SCRM (Juttner *et al.*, 2003), which from the literature survey looks well developed in terms of qualitative modelling with many empirical studies and conceptual models. This is evident from descriptive as well as thematic analysis of SCRM literature that, quantitative modelling approach to SCRM problems is in demand in recent years. Quantitative tools like mathematical programming models, simulation models (Rao and Goldsby, 2009), Analytical/Network Hierarchy Process (Vanany *et al.*, 2009), complexity and graph theory (Colicchia and Strozzi, 2012) are unexplored for SCRM problems. There is need to develop well-grounded models by considering other interdisciplinary research approaches (Khan and Burnes, 2007). Quantitative tools like system dynamics have the potential to capture dynamic behaviour of a holistic supply chain for making hard decisions in SCRM. Financial theories like real options, agency theory and utility theory are finding potential for managing supply chain disruptions. Simulation modelling captures the dynamic behaviour of the complex system and can be effectively utilized for modelling and holistic study of SCRM.

3. Risk propagation and recovery planning

Identifying the risk drivers and their risk impact in supply chain is becoming increasingly important for risk management (Juttner *et al.*, 2003). There is a critical need for recovery planning to mitigate against the effect of disasters (Bryson *et al.*, 2002). Research on disruption propagation examining effects and recovery of the supply chain risks is lacking in the literature (Wu *et al.*, 2007; Khan and Burnes, 2007; Natarajarathinam *et al.*, 2009). There are no robust contingency/recovery planning strategies for unpredictable future disruptions like volcanic ash disruption, nuclear radiation, Epidemic disease, political turmoil, etc. and hence provides a challenging dimension to SCRM research.

Risk profile modelling and disruption impact evaluation in terms of cost, duration and service will provide greater visibility for effective risk management. Development of global risk assessment index/standards for practical application in supply chain and logistics industry is challenging and can help in revolutionising the field of SCRM.

Understanding the risk potential beyond the entity through the chain will provide an insight into how risk can propagate. Uncertainties in the supply chain environment and some instances of known risks provide instances when the only strategy available is to recover quickly after the risk has occurred. Creating the appropriate risk recovery models needs proactive planning and a combination of the appropriate information and human intervention.

4. Sustainable supply chain risk management

Green/Sustainable supply chain practices need more focussed research to meet global compliance standards and regulatory demand. This will support in more reverse logistics activities for remanufacturing and recycling of materials. The implication of stricter government legislations on supply chains will be an important area for future research. In the modern marketplace, companies need to be increasingly focused on remaining profitable while mitigating risks and implementing sustainability practices. The interrelationship between risks (and their impact) and sustainability is evident with increasing pressure on using natural resources and greater level of scrutiny concerning ethical sourcing. Development of new risk assessment methodologies taking into consideration the interrelationship between risks and sustainability perspective is essential for companies in the current competitive global market.

5. ***Use of next generation technology for SCRM***

Information and Communications Technology (ICT) is expected to make a big impact in terms of the visibility of supply chain performance. Current technologies such as RFID, ERP and GPRS will become important information tools for management of supply chain risks (Tang, 2006; Wilson, 2007; Rao and Goldsby, 2009; Vanany *et al.*, 2009). As the technology matures and becomes more affordable it is clear that companies will be able to achieve real-time monitoring of the products through the supply chain and logistics networks. Use of technology in risk management demands extensive investigation in two directions, one as a potential source of risk and another as a mitigation strategy.

6. SC Network development through risk contracts

It was evident during the analysis that, supplier default risk, quality risk and management risk within SC network are underexplored. Collaboration and outsourcing by introducing risk sharing and/or contracts amongst supply chain partners can help to improve the network efficiency (Urciuoli, 2010). Development of supplier partnerships and strategic alliances is becoming a key element for long-term profitability as well as robust risk mitigation strategy. Contingency/recovery planning strategies needs to be industry or supply chain specific (Juttner *et al.*, 2003). Network information communication and sharing avoids defaults and generates trust in the volatile global market. Most of the previous research has focussed on different SC contracts in the context of price and demand fluctuations (Wakolbinger and Cruz, 2011) but long-term contracts for disruption management are still lacking in the literature. Risk sharing contracts have potential for handling risks in supply chains for network coordination in the future.

7. Behavioural aspect on management of risk

Researchers in the past have studied the managerial perception of risks within SCRM (Zsidisin, 2003b; Sodhi *et al.*, 2012), but the behavioural dimension associated with decision making in context of SCRM is still lacking. Abundant scope in identifying and implementing robust mitigation strategies was observed in the study. The behavioural aspect on choosing the appropriate risk management strategy in terms of risk averse, risk neutral, risk sharing or risk taking (Vanany *et al.*, 2009) can provide transparency in the risk mitigation process. Bounded rationality due to asymmetrical and incomplete information of the disruption (Tang and Nurmaya Musa, 2010) influences the decision-making. The decision to choose the right risk strategy is crucial and is found to be often dominated by the behavioural aspect of managers. Research on developing practices for unbiased or rational decision making is another unexplored area in SCRM.

Figure 15 shows the seven distinctive research gaps identified through SLR on SCRM. Each gap in this Figure presents future areas for study. Although it is difficult to address all the research gaps together, the fitting gaps associated with SCRM and SE are selected for developing further research. It is evident that studying the SC as a system with multiple stakeholders and multiple interactions is vital for holistic understanding of the risk behaviour. Some of the remaining research gaps are addressed in the future research directions section.

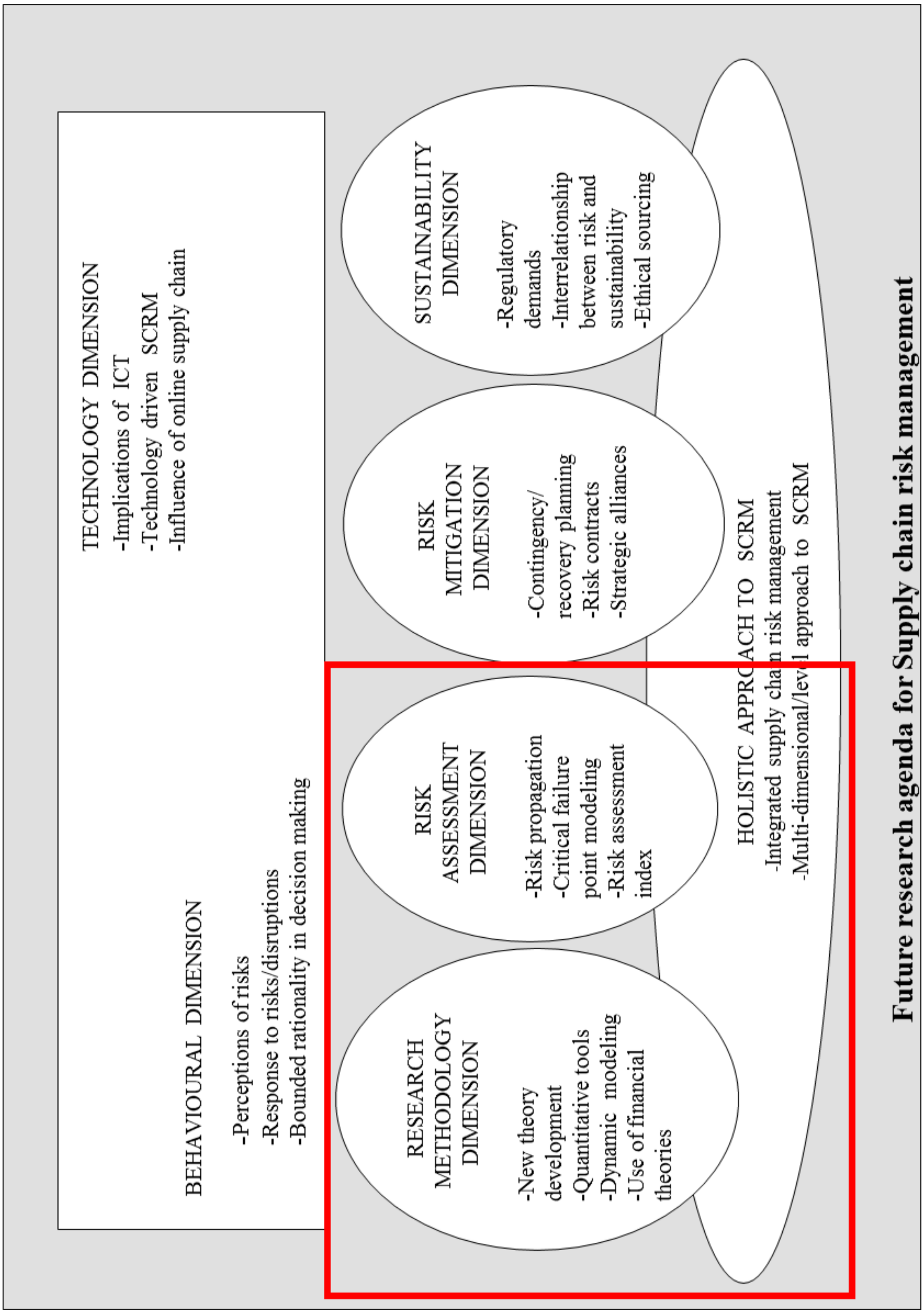


Figure 15: Research agenda for SCRM

Chapter 3 Supply Chain Factors and Risks

The chapter discusses the case study undertaken to see the link between various supply chain factors and risks. The exploratory study attempts to find the interaction between several supply chain factors and risks to understand the dynamics of risks during disruption. The secondary data findings from workshops and the manufacturing sectors are utilized for predicting research gaps from the industry perspective. The intersection of SCRM research gaps and gaps from industry perspective guide in defining the research problem and questions for this study.

Fast changing global business requirements are forcing companies to reconfigure their supply chains around new processes and strategies to meet multidimensional challenges. As the supply chain reconfigures them to meet new demands, it further generates new challenges. Financial instability, outsourcing, shorter time-to-market, reduced product lifecycle and uncertainty have influenced today's international business environment (Stefanovic *et al.,* 2009). In order to stay competitive and resilient in the market, supply chain demands improvement in the product and service delivered to the customer. Future SCM is not just about managing the forward supply chain, but equally managing the reverse supply chain by efficiently utilizing Information and Communication Technologies (ICT). Configuring such modern future of supply chains requires attention into multi-dimensional aspects such as designing the right network, engaging in the right alliances and partnerships, developing contingency plans against uncertainties and selecting the right supply chain processes (Pawar and Lalwani, 2010). Several researchers and practitioners have developed new approaches for managing supply chains in order to meet ever-changing global supply chain requirements and standards.

3.1 Configuring the supply chains

The SLR on SCRM depicted that the papers discussing future issues/challenges in supply chain were very limited. A comprehensive analysis of SLR in SCRM has been already discussed in the previous chapter. Key words such as ‘sustainable supply chains’, ‘future supply chains’, ‘supply chain design and configuration’ were used during preliminary screening to identify new approaches followed for configuring future supply chains. It was noticed that the academic publications contributing towards ‘configuring supply chains’ were very less and the ones available did not pertain towards identifying challenges faced by the existing or future SCM.

Configuring the supply chains has become essential for meeting growth and changing demands of market. SC configuration enables organisations to maximize its long-term economic performance (Chaabane *et al.*, 2012). Chandra and Grabis (2007) describe the problem of supply chain configuration as one that relates to determining units, size and location in the supply chain network. It also looks at establishing and maintaining the linkages between the networks. Srai and Gregory (2008) lists the key elements of supply network configuration as the supply structure, the flow of material and information between the networks. Nevertheless, SC configuration is not just associated to operational design aspects but also looks at strategic design aspects like long-term sustainability and resilience. Designing of supply chain configuration is the most critical problem in SCM (Garavelli, 2003). Beamon (1998) reviews the available literature pertaining to the design and optimization of supply chains and identifies several performance measures for supply chain modelling. These can be classified based on cost reduction (cost vs. quality), inventory reduction (lean vs. agile) or customer satisfaction (good vs. poor service). Stability of supply chain configuration may lie in the effective coordination of stakeholders, products, processes and logistics decisions. Multidimensional coordination is essential for configuring future supply chains. Configuration also involves identifying and developing inter-relationships between the network partners and improving 'value structure' of the product. The configuration of supply chains have typically been studied at two levels. Firstly, the macro level which looks at the system as a whole and aims to find solutions for strategic decision-making. Secondly, the micro level which looks at individual entities and aims at resolving specific problems with the aim of minimising a particular variable. A causal relationship diagram formulates the link between the interactions of the described two levels. Zsidisin and Ritchie (2008) identify that the aggregate supply chain risk is a function of supply chain configuration. Hence, managing risks holistically could be a valid basis for the supply chain configuration. Tang and Tomlin (2008) argue that, with so many disruptions that have happened in recent times, supply chain risk will become an important consideration for all businesses in the future.

All above research in relation to reconfiguring the supply chains encourage to identifying the SC factors and their influence on risks particularly from the industry perspective. It was necessary to understand how SC factors influence the new disruptions through the supply chain network. It was also necessary to understand the dynamic behaviour of risks. For example, the ICT infrastructure has improved the efficiency of global logistics tracking. A sudden disruption to internet data cables deep under sea would disrupt the worldwide information network link causing data loss and chaos. The preliminary assumption undertaken was that, all the identified factors would influence the SC network performance and hence lead to some sort of disruption.

3.2 Secondary data analysis

In order to understand the link between SC factors and risks, the author had access to secondary data collected from several workshops and recent manufacturing sector cases. The secondary data was analysed in conjunction with literature review on SCRM to understand the issues faced from an industry perspective.

3.2.1 Factors identified from workshops

The primary results from a series of workshops held in five countries over a period of three years were used for this analysis. The data was made available by one of the active members of the ‘Next Generation Manufacturing Supply Chains and Digital Economy Research Collaboration’ project undertaken by the academics from UK and Indian universities. This facilitated information regarding supply chain challenges and risks from a practitioner and academic perspective. In the workshops, the participants identified challenges affecting future supply chains. The data from the workshops helped to develop the preliminary sketches of causal hypotheses of influential factors and their interaction with risks.

The outcomes from the series of workshops conducted over a period of three years at different locations like India (2008), Thailand (2008), Turkey (2009), Malaysia (2010) and UK (2009, 2010) were thoroughly studied. The participants of the workshop were asked to identify the challenges facing future supply chains through brainstorming sessions (Ramanathan *et al.,* 2009). On an average, each workshop was attended by 30 participants who represented industry and academic working in the broad domain of operations, marketing, logistics and supply chain. The challenges/issues/factors influencing future supply chains were identified through different workshops as seen in Table 7.

It is observed from Table 7 that, most of the identified factors were repeated at different workshops. These finding provide a generic picture of parameters critically important for existing and future supply chains. These factors at the same time may drive the design of future supply chains and need to be studied carefully from a macro perspective.

Each challenge/factor/issue was considered and classified into different themes. After a careful analysis, the SC influential parameters were organised into six clearly defined ‘future supply chain factors’ for the study.

Workshops conducted (Year)	Bangalore, India and Bangkok, Thailand (2008)	Istanbul, Turkey and Hull, UK (2009)	Loughborough, UK and KL, Malaysia (2010)
Identified future supply chain issues/ challenges/ factors	Green/Environmental supply chain issues with cost effectiveness.	Environment and social issues	Overall sustainability issues
	People skills/ HRM / Talent management	Cost management and optimisation	Emerging economy, Cost management and optimisation
	Digital capabilities / Role of IT	New management models dealing with skills, collaboration and outsourcing	Managing uncertainty, complexity, customer responsiveness and risk
	Demand management / Mass customization	Emerging economy and risk	New technology and ICT
	Supply chain performance management	Managing uncertainty, complexity, customer responsiveness	New management models dealing with skills, collaboration and outsourcing
	Outsourcing and Risk management	New technology and ICT	Transport, distribution and Infrastructure utilisation

Table 7: Factors identified through workshops (Year 2008-Year 2010)

(Source: http://www.nex-gem.co.uk/project_description/project_description.htm)

The key influential issues/factors for future supply chain identified are:

1. **Environmental regulations and sustainable challenges**
2. **Information and Communication Technology (ICT)**
3. **Assets utilization and Servitisation**
4. **Customer expectations and supplier relations**
5. **Skills shortage and training requirements**
6. **Uncertainty and risks**

The six key factors were identified based on their ranking as a potential factor during subsequent workshops. The Associated links to each identified factor was also captured and collated in the form of nodes as seen in the radial tree (Figure 16).

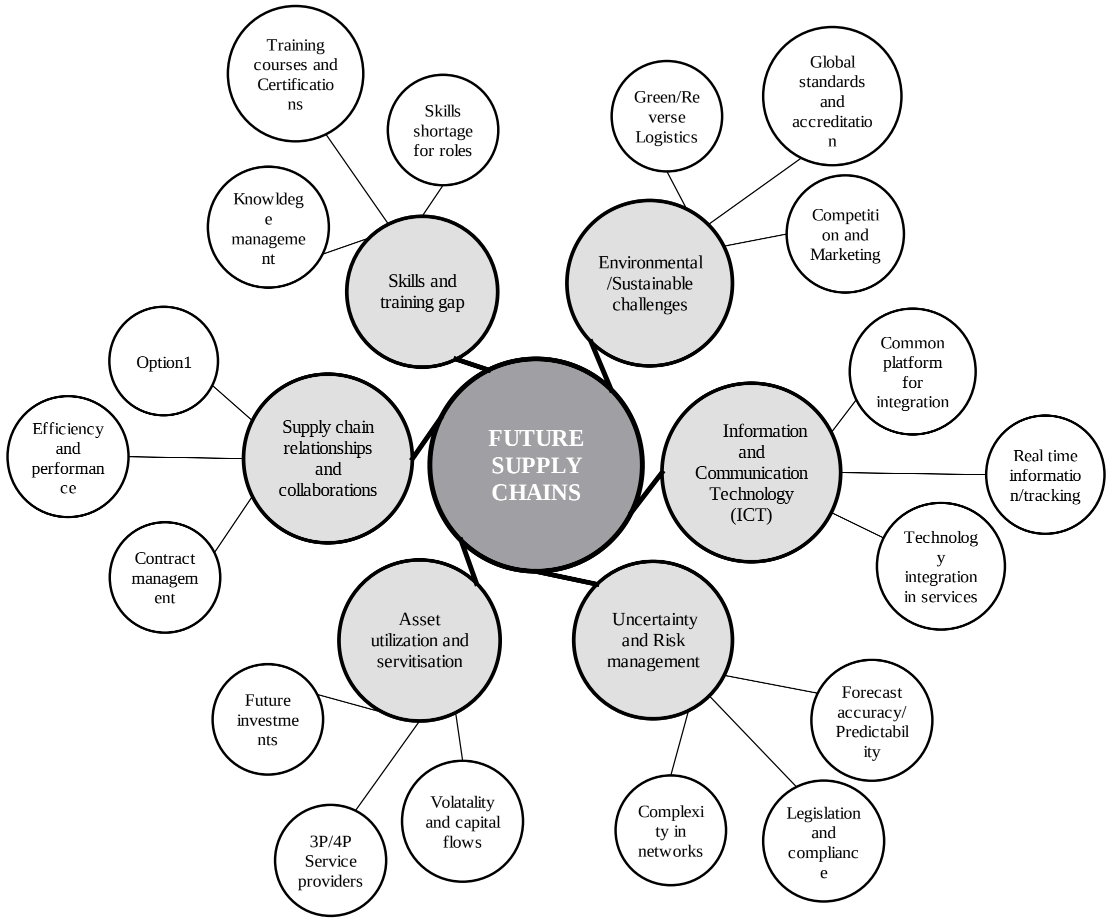


Figure 16: Radial tree for future supply chain factors

These identified factors interact with each other causing a positive as well as negative impact on the supply chain network. In order to understand these interactions, a causal diagram considering all the identified factors was developed as seen in Figure 17. A causal (influence) diagram serves as a preliminary sketch for capturing the interactions of variables. These identified issues/factors were analyzed at a macro level for their impact on risk assessment parameters. For the risk assessment the identified parameters were quality, delivery performance and cost. In the causal diagram the causal linkages between the variables are highlighted as a +/- effect. This shows the supply chain interrelations with different influential factors with respect to risks. From the causal diagram, it is evident that when different factors (challenges) interact, the system is affected by parameters such as cost, inventory, lead-time and service level. This was confirmed based on the number of loops joining towards and away from the risk assessment parameters in Figure 17. At the outset, this may not provide an entirely new significance, as the manufacturing industry and academic community have been dealing with the challenges of cost, quality and lead-time. However, the significance of the study is to understand the interaction of the various factors on each other and to capture the movement of risk through the medium of risk assessment parameters.

It is evident from the causal diagram that the supply chain network consists of a system of systems consisting of a complex association of stakeholders, processes and their dynamic interrelationships. It is difficult to consider so many parameters together to see the overall impact. Oehmen *et al.* (2009) attempted a generic supply chain risk model to identify the possible dynamics of the risk in supply chain.

Sustainability, technology and collaboration were the most important factors identified to drive the future of supply chains. Uncertainty, risks and skill shortage were identified as issues concerning supply chains and asset utilisation/servitisation as possible solutions for future supply chains. It is envisaged that these challenges can provide sufficient tools for managing the supply chain in a more efficient and robust way. However, if each of the factors is not handled appropriately, it will generate further risks within the supply chain network. It is necessary to focus on these challenges to see its impact on creating further risks. It is also important to note that, each individual factor will create its own associated risk whilst combined influence of factors will generate adverse risks.

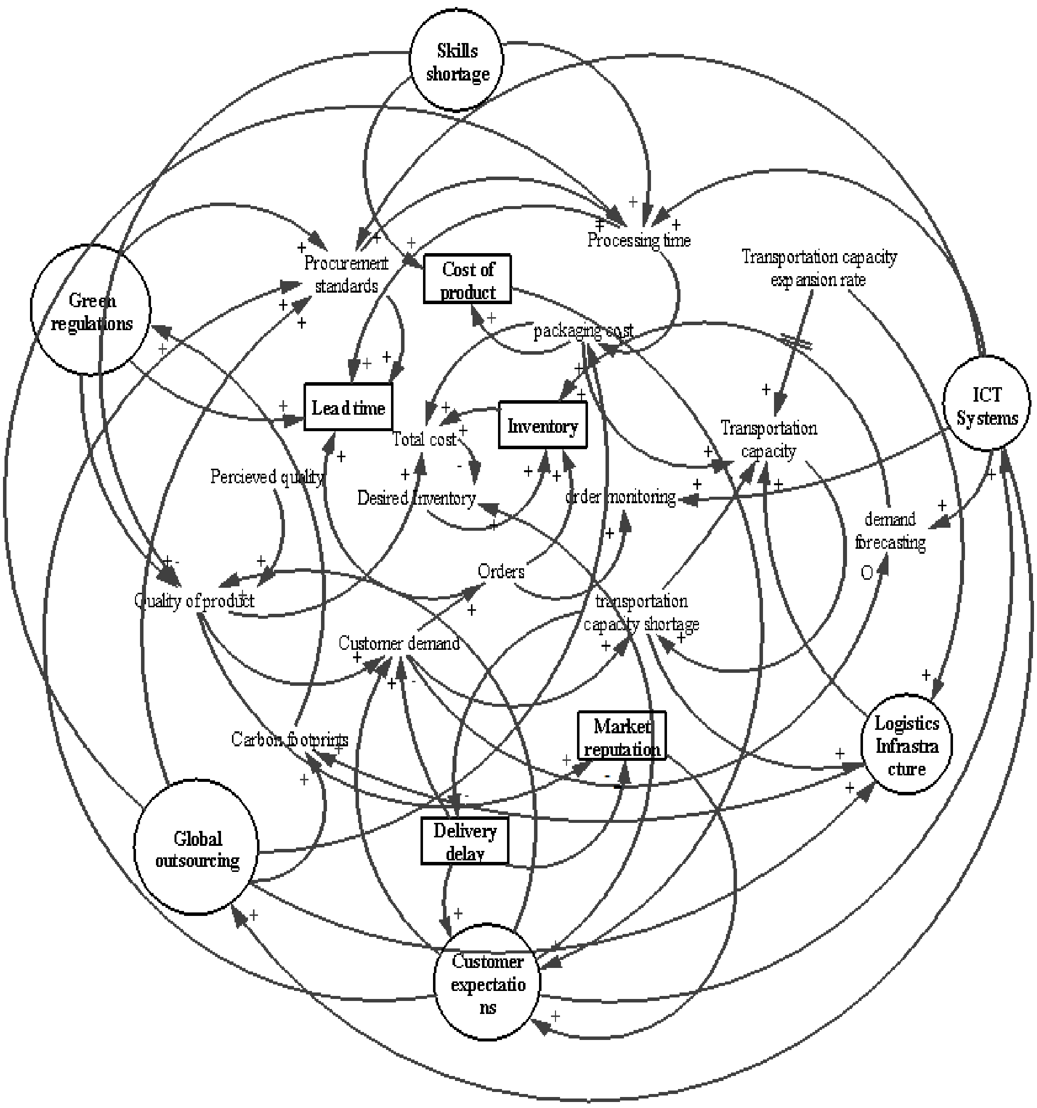


Figure 17: Causal loop diagram for supply chain system

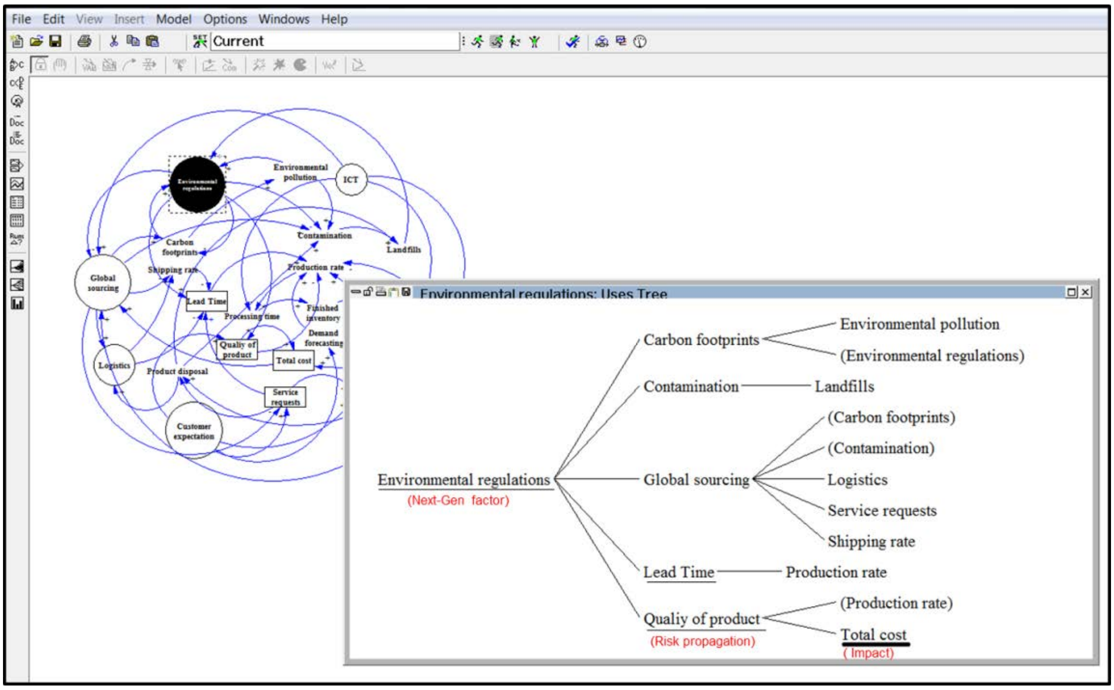


Figure 18: Example of next generation factor loop tree

In the supply chain network there will be more than one challenge propagating at any point of time at each node and hence the complexity of managing the problem space increases. Based on this theory, causal hypotheses are considered for the dynamic and problematic behaviour. This dynamic hypothesis is a working theory showing how the problem arose (Sterman, 2000). Using a causal diagram, interactions between the variables were captured where a change in one variable affects other variables over time that in turn affects the original variable. The feedback loop is a very important element of the causal loop. The iterative feedback diagram depicts that the risk cascades through the medium of risk assessment parameters. Each factor was studied individually through its feedback loops. Figure 18 shows an example of a causal relationship of a future factor with risk assessment parameters captured through a tree diagram. A causal diagram illustrates the causal linkages between the factors and their risk propagations within a supply chain system. The diagram depicts that these future factors have a pronounced effect on quality and lead-time. The overall impact (closing or last loop) was observed to be in terms of total cost and delays for all factors. These preliminary findings from the workshop data clearly show the need for a holistic approach to understand the interactions between multiple factors for studying supply chain risks.

3.2.2 Factors identified from industry cases

In order to seek research gaps from an industry perspective, secondary data from the manufacturing sector was collected and analysed using published information on various industry cases. The cases emanate from the automotive and aerospace sectors. The information for these cases was collected from secondary data sources like newspaper articles and other publications from professional (Consulting firms) firms. This data was available online.

Supply chain factors influencing the disruptions were identified and later compared with the findings from the workshops. It was also necessary to identify the impact of these disruptions to get a better view of the risk profile. Table 8 depicts that the risk impact will lead to an increase in total costs, project delays and loss of reputation. It is important to see that the risk of reputation loss due to quality issues and resultant product recalls in the recent past requires a focus on risk management. Although all the cases shows similar risk influences, it is important to note that the factors affecting next generation supply chains will lead to increased cost, delays with heavy impact on reputation.

Industry	Supply Chain factor	Risk propagation	Risk impact
Airbus A380 (2005) *Ferrari (2008), Wong (2006)*	Global sourcing	1) Distributed Integration dependencies among manufacturing sites and suppliers	1) **Mismatch** of electrical harness between designed and physically appeared routing on aircraft.
	ICT systems	2) Design configuration management problems (CATIA V4/V5)	2) **Costly delays** for two years.
Boeing 787 (2006)	Logistics/Customer expectation	1) Failure of assemble to order manufacturing strategy	1) Problems with spare parts led to **delays** up to 2 years.
Ferrari (2008), Business execution insights (2009)	Global sourcing/Customer expectation	2) Failure by global supplier network to meet targets	2) **Financial loss/Reputation loss** due to cancellation of orders.
JSF F-35 Lockheed Martin (2010)	ICT systems	1) Development is being done concurrently with early production.	1) JSF F-35 **delays** up to 2015 to US Air Force
Market Watch (2010), Government Executive. (2010)	Skill shortage	2) Shortage of professionals leading to longer flight test program.	2) Delays resulting in **heavy cost increases** to JSF program partners.
Toyota/Honda/ Nissan (2010)	Global sourcing	1) Faulty components	1) **Product recalls**
BBC News (2010a)/ (2010b)/ (2010c).	Customer expectations	2) Quality and Safety concerns	2) Heavy **reputation loss**

Table 8: Some instances of supply chain risk propagation

The study identifies a need for a holistic approach towards considering all risk factors as necessary criteria for configuring future supply chains. The instances considered in the analysis are recent occurrences of supply chain failure (product delays and recalls) within the automotive and aerospace sector that interestingly have different supply chain structures and working environments. With reference to the generic causal model, it can be inferred that supply chains are dynamic and as factors change, the risk parameters will modify and propagate. Studying the phenomenon of risk propagation can provide more insights into the fracture points leading to the disruption. It can also provide in depth information about the approximate estimate of the risk impact.

By studying the causal loops individually and holistically, it is observed that studying risk propagation and its effect based on a system response is critical. The systems view of the supply chain and the perspectives developed from the feedback of the causal diagram proves to be a potential approach for handling the supply chain risks. The risk propagation has a cascading effect beginning with increase in lead times, increase in costs and decrease in service levels. This cascading effect of the factors ultimately leads to a decrease in market share and loss of reputation. Although it can be predicted that disruption impacts will eventually lead to reduced profitability in the propagating direction, it is yet difficult to model this phenomenon.

3.3 Research gap for the study

The systematic literature review has provided critical insights into the present and future scope of the SCRM field. A careful study of the identified research gaps provides a fit between SCRM and Systems Engineering. The research gaps identified through an industry case study and SLR are combined together to define the research gaps in the next section.

3.3.1 Evaluating supply chain risk propagation

Although the academic SCRM literature has essential insights on this phenomenon, limited amount of information was located on how to deal with risks or disruptions from a practical perspective (Blackhurst *et al.,* 2005). Out of the seven identified SCRM research gaps, lack of a holistic approach to risk management is clearly a common gap when compared with the secondary data analysis. The attention given for identifying and analyzing the supply chain risks is fairly limited (Rao and Goldsby, 2009). SCRM researchers suggest that an approach to managing risks needs to follow a formal, structured approach to identifying, quantifying and reducing risk (Khan and Burnes, 2007). Kouvelis *et al.* (2006) argues that, the field of SCRM has evolved out of the parent field of SCM. But, very limited work is actually done to address the issue of holistic risk evaluation in the supply chain.

It is also observed from the SLR on SCRM that, both qualitative and quantitative approaches are used to study the SCRM issues. Conceptual as well as empirical methods are used along with case study techniques. Few researchers have used modelling and simulation techniques to understand the intricacies of the SCRM. The secondary data and case studies clearly show that the study looking at the performance of risk and its propagation is essential for effective risk management. Dynamic supply chains need a modelling platform to capture complexity and uncertainty parameters. Systems thinking provides a holistic picture capturing the multidimensional and multilevel perspective. The integrated approach following systems thinking is a suitable research approach to solve the complex intricacies involved in supply chain risks.

Raw materials flows through various processes, geographic and political regions and are transported by different modes of transportation (Stacke and Kumar, 2009; Handfield and Ernest, 2002). All of these are the potential failure points where a supply chain is open to disturbances. *"Modern supply chain trends such as globalization, decentralization and outsourcing make supply chains efficient at the cost of increase in the number of exposure points"* (Stacke and Kumar, 2009). In order to achieve efficiency in such a complex web of inter-connected nodes, the systems have to be holistically studied to identify the fracture points.

The second research gap which overlaps with the SLR and the secondary data analysis is the necessity of understanding the risk propagation and recovery. From the cases it is evident that the movement of risks within the network needs careful modelling to understand their overall effect. Modelling the interaction of multiple SC factors and risks within the network will provide a new way for understanding the behavior of risks. Various reasons such as lower cost, available capacity, quality, technology, delivery time, etc. drive the manufacturers to outsource (Li and Kouvelis, 1999). SCM practices like outsourcing, decentralization, JIT and product customization have increased the number of exposure points in the SC network. A proactive approach to identify nodes of failure is needed in such an uncertain and volatile supply chain environment. The choice of appropriate mitigation strategies depends on various factors such as location, market, culture, operations, suppliers, product and process characteristics, ownership and other several factors. Supply chains could be benefited by developing practical models that can estimate the risks in aspects of supply, operations, inventory, transportation and location (Stecke and Kumar, 2009). Identifying the nodes of failure by developing dynamic models to capture the uncertainty in supply chain would benefit the researchers in the SCRM and to understand the complex phenomenon of supply chain disruptions in a holistic way.

Understanding the phenomenon of supply chain risk propagation is expected to permit better management of supply chains (Wu *et al.*, 2007). It is difficult to determine the overall effect of a particular disruption on each node in the supply chain network. In order to evaluate such complex web of interconnected nodes in the supply chain, the system has to be holistically studied to identify the fracture points and risk propagations within each node. Systems thinking has the ability to deal effectively with problems which are marked by complexity and multiple interactions. The system oriented modelling approach is selected for understanding the risk propagation phenomenon. This systemic approach to supply chain network analysis is expected to help in identifying the interdependent nature of risk factors affecting supply chain nodes.

Supply chain disruptions propagate along the supply chain network in a similar manner to the lifecycle of the product. Risk impacts can propagate not only along the supply delivery direction, but may also backlash up in the route due to the dependence of upstream elements of the network on the impacted route (Cheng, 2008). Propagation of unexpected or undesirable disruptions through the network severely affects the profitability of the whole SC network. Understanding the propagation of disruptions and gaining insight into the operational performance of a supply chain system can lead to a better understanding of disruptions and ways to lessen their effects (Wu *et al*. 2007). The academic literature depicts limited work for evaluating risk propagation in supply chain networks. Failure of one point in the supply chain can cause the entire supply chain system to collapse. All activities in the supply chain are interrelated and interdependent as seen from the link between factors and risks. Complex relationships and dependencies contribute to disturbance propagation in the network (Hallikas *et al.,* 2004). As firms expand their operations globally, their supply chain lengthens with multiple interdependencies making them vulnerable to severe disruptions propagating throughout the network. The mechanism of propagation through the supply chain is complex, from an event at semiconductor plants in Japan, to MTO supply chain dysfunction in the US to unexpected financial breakdown in the global stock markets (Papadakis, 2006).

The impact of risks on entities of the SC network depends on the abilities of the entities to resist and recover from disruption. Undoubtedly, there is a critical need for planning and recovery strategies for the disasters (Bryson *et al.,* 2002). Richey Jr. (2009) has attempted to develop a disaster recovery pyramid based on extensive review of the resource, risk and crisis recovery literature. Risk recovery is expected to stabilize all turbulences and bring the supply chain to normal operations. Research in disruption propagation, examining recovery of a supply chain from risks/disruptions is lacking in literature (Wu *et al.,* 2007; Natarajarathinam *et al.,* 2009). Two of the research gaps followed through SLR compliments with the finding from secondary case analysis attempting to understand the industry perspective. The two clear and evident research gaps within SCRM are utilized to define the research problem and associated research questions in the next section.

3.3.2 Research problem and questions

The research gaps identified through SLR on SCRM along with findings from the secondary data analysis utilizing the SE approach supports the construction of the research problem.

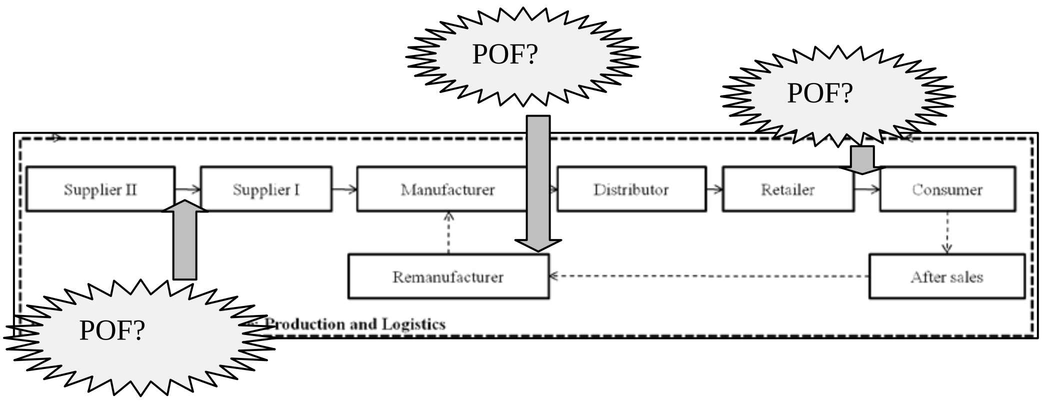


Figure 19: SC system risk propagation zones with points of failure

Supply chain disruption can occur at any node or zone in supply chain network as shown in Figure 19. This disruption is expected to cascades to other parts of network and the propagation would depend on how quickly mitigation strategies are being implemented. The risk while propagating to different levels/zones will make the supply chain network unstable. The cascading effect is felt in terms of additional cost and delays. The research problem intends to measure the risk propagation impact in terms of cost and duration from a (fracture) point in the supply chain to another.

Based on the understanding of the research problem discussed, the following research questions are defined for this research:

1. ***How long will it take a risk to propagate from a fracture node/point to other nodes/points in supply chain network?***
2. ***How to model the risk propagation impact on a complete supply chain network?***

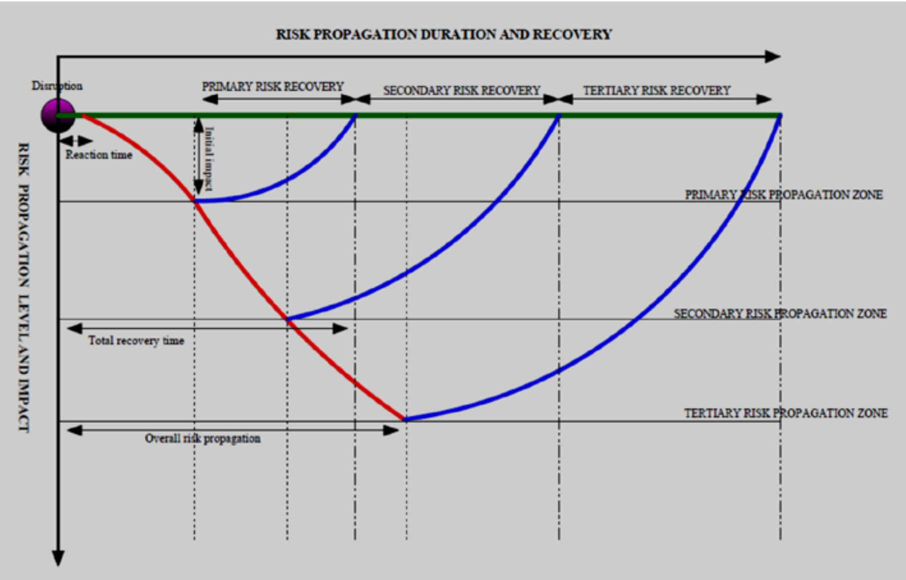


Figure 20: Conceptual representation of supply chain system risk propagation

(Extended from 'Disruption profile' Sheffi and Rice, 2005)

The first research question attempts to capture the phenomenon of risk propagation in terms of movement from one entity/node to another within the supply chain network. The risks may flow beyond the material, information and financial dimension. The research question will explore the cascading phenomenon following a systems approach. The answers obtained from the first question will guide in answering the second research question. The disruption in the network is expected to shift the datum line of supply chain stability (Refer to Figure 20). Risk may initially propagate from the primary zone to secondary and tertiary zone. But at the same time may backlash from secondary or tertiary to primary risk creating another wave of disruption in SC network. Here the zones are different levels of supply chain network. Deep and Dani (2009) portray the primary zone as the critical chain of fulfillment, the secondary zone as the zone that feeds into the primary zone or is the output of the primary zone; and the tertiary zone as the zone that feeds into the secondary zone or is the output of the secondary zone. Measuring the overall effect of disruption in terms of cost and duration is a challenge. Modelling of risk propagation for complete SC network is expected to answer the above research questions associated with the 'risk propagation'. The following research will attempt to find answers for above defined research questions following a systems thinking approach.

Chapter 4 Research Methodology

This chapter discusses different research methodological approaches suitable to achieve the defined research objectives. The investigation of different research paradigms and methods support in developing the research design for study. The systems thinking approach to capture the holistic picture of supply chain risks is identified to be an appropriate research approach. Mixed methods used within the systems thinking approach are broadly discussed to represent its fit with the defined research problem.

Research is a methodological process of collecting, analysing and interpreting the data for making appropriate decisions. The research process must have six important characteristics: *Controlled, Rigorous, Systematic, Valid, Verifiable, Empirical, and Critical* (Kumar, 2010). Theory development in the research requires challenging the prior assumptions, assessing previously un-quantified parameters and innovating new concepts (Fawcett and Waller, 2011). In order to develop a new theory it is essential to first identify the appropriate research methodology suitable for the research. Research methodology is a "*philosophical stance of worldview that underlines and informs the style of research*" (Sapsford and Jupp, 2006). Research methodology is differentiated from research methods in the thesis. According to Greener (2008), former provides a generic approach to the research whereas, latter refers to specific activities designed for generating and analysing the data. Methodology is a theory for directing how research should be undertaken whereas; methods are techniques or procedures for obtaining and analysing the data (Saunders *et al.,* 2009).

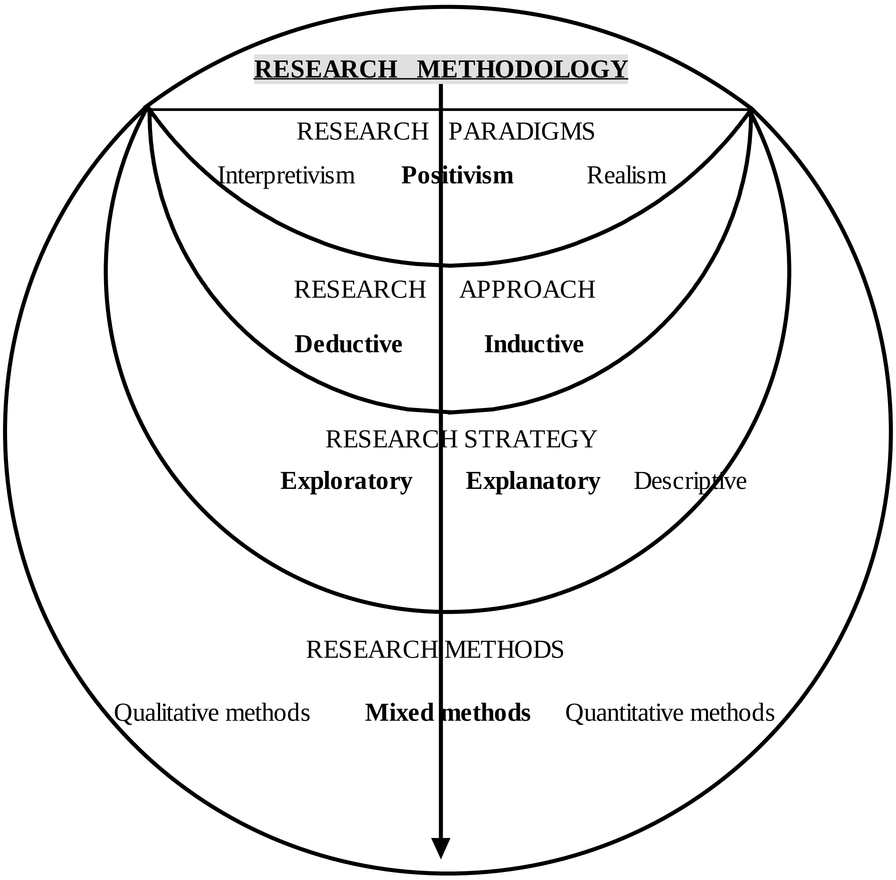


Figure 21: Research methodology approach

(Adapted from Saunders *et al.*, 2009)

There are several research paradigms, approaches, designs and methods for conducting structured research discussed in the academic literature. In this chapter, the relevance of several research dimensions are presented and justified with regards to this research. Figure 21 depicts the different research methodologies used in the social sciences. Appropriate research methodologies found suitable for the research are explained in context with the defined research problem.

4.1 Research paradigms

There are three types of research philosophy paradigms namely interpretivism, positivism and realism (Saunders *et al.,* 2009). These paradigms form the different ways in which it is possible to produce reliable and valid knowledge about the research field. Validity of the research is a degree to which the content adequately represents the universe of all relevant areas under study (Cooper and Schindler, 2003). Paradigms guide researchers in deciding what should be studied and how results should be interpreted. Three types of paradigms are discussed below to provide first-hand information about different paradigms along with identifying the appropriate paradigm for the research discussed in this thesis.

Interpretivism

Interpretivism refers to the challenge of entering the social world of the research by attempting to understand the world from a personal point of view (Saunders *et al.,* 2009). Interpretivists argue that the simple fundamental research laws are insufficient to understand the whole complexity of social phenomena and advocates three principles for interpretivism (Saunders *et al.,* 2009) as,

- A social world is constructed and is given different meanings (subjectively) by people.

- The researcher is part of what is observed or analysed.
- Interests in the specific field drive the research.

Positivism

The positivist paradigm advocates application of quantitative methods to study the research world and adopts a philosophical stand of natural scientists. This paradigm's fundamental assumption is that the research is independent and does not affect the subject of the research (Remenyi *et al.,* 1998). It involves an emphasis on a highly structured methodology to facilitate replication (Gill and Johnson, 1997).

Realism

Realism is similar to positivism where it assumes the scientific approach to the development of knowledge (Saunders *et al.,* 2009). There are two types of realism; one is direct realism and another is critical realism. The difference lies in what we see and what they actually are. First of its kind is called direct realism and other is called as critical realism. Both the realisms are important as direct realism relates to capacity of research to changes and critical realism recognizes the importance of multidimensional, multi-level study to interpret the reality (Prowse, 2008).

Positivists focus on a single strong reality and interpretivist on multiple realities. The realist focuses on multiple perceptions about a single, mind-independent reality (Healy and Perry, 2000). The interpretivist paradigm supports qualitative methods and positivist paradigm supports quantitative methods (Howe, 1998).

From the above discussions, the research problem discussed in thesis suits well with the realism paradigm because it attempts to focus on the importance of multidimensional, multi-level study to interpret the results. The conceptualization and modelling activity can be attempted through qualitative as well as quantitative methods following an interpretivist as well as a positivist paradigm. Business and Management research is often a mixture of both positivist and interpretivist paradigm. Due to the nature of the problem, it may be necessary that interpretivist as well as positivist research paradigm be followed in this research.

4.1.1 Research approach

The research paradigms may not be explicit initially within the design of the research but eventually becomes explicit from the presentation of the finding and conclusion (Saunders *et al.,* 2009). The research approach adopted can be either deductive or inductive.

Deductive

Deductive approach develops a theory or hypothesis and designs a research strategy to test the hypothesis (Saunders *et al.,* 2009). Robson (2002) provides five sequential stages of the deductive approach namely, deducing the hypothesis, expressing it in operational terms, testing operational hypothesis, examining the outcomes and modifying the theory or hypothesis if necessary. This approach makes conclusions based on previously known facts. Deductive approach deducts specific instances starting with a general case during the research. Researchers using deductive approach are likely to work with quantitative data (Hilmola *et al.*, 2005). Three characteristics of the deductive approach identified by Saunders *et al.* (2009) are:

- *Search causal relationship* between variables under study
- *Operationalize* the concepts for the development of a hypothesis
- *Generalize,* implying the necessity to select data of sufficient size for study.

Inductive

In the inductive approach, set of observations are used for data analysis. Inductive theory is a process of building theory more than testing theory as discussed previously in the deductive approach. Inductive approach is the way in which the cause-effect link is made between particular variables (Saunders *et al.,* 2009). Followers of the inductive approach criticise deductive approach for their rigid methodology and for not providing an alternate explanation for the understanding. Inductive approach is suitable when the problem is practical and involves limited access to data or the researcher lacks prior knowledge of the field under study (Easterby-Smith *et al.,* 2002).

It is possible to combine both approaches in same piece of research depending on the nature of research topic. Research on SCRM is relatively new and has a limited literature discussing specific research problems within the broad context of the field. This research has used both inductive as well as deductive approaches. Three characteristics (*search causal relationship, operationalize and generalize*) of deductive approach systematically attempt to understand the causal relationship followed by operationalizing the concepts in the first phase of research leading to an inductive research approach to solve the practical problem in an industry setting through experimentation. Use of inductive approach guides in generating the concepts and later helps in reflecting upon what needs further attention. Similarly, the deductive approach is used in second part of research for data screening and quantitative interpretation of the findings.

4.1.2 Research strategy

Exploratory, descriptive and explanatory are three different types of research strategy to conduct research.

Exploratory

Exploratory research is conducted when no prior information about the research area is known. Exploratory research is believed to support in gathering relevant information on the management problem to define the research questions/hypotheses.

Saunders *et al.* (2009) explains three principle ways of conducting exploratory research as:

- Search of the appropriate literature from the sources.
- Interview the experts in the field for their quality opinion.
- Conduct focus group (formal/informal) interviews.

Exploratory research strategy is believed to be flexible and adaptable but it does not mean it lacks the research direction (Adams and Schvaneveldt, 1991). The exploratory research begins with a bigger research area and later narrows down as the research progresses. The research discussed in thesis follows similar approach beginning with literature review to predict specific research gaps.

Descriptive

Descriptive research strategy falls between exploratory and explanatory research. The research problem is structured, well understood and follows precise rules. It usually attempts to represent the profile of characters, incidences and situations. The strategy demands a clear picture of phenomenon before the data collection activity (Saunders *et al.,* 2009).

Explanatory

The study establishing the causal relationships between variables is termed as explanatory study. The emphasis is put on studying the situation or a problem to identify the relationship between different variables (Saunders *et al.,* 2009).

In terms of the research strategy, exploratory as well as explanatory strategy is followed in order to answer the research questions in this thesis. The SLR on SCRM utilises the exploratory strategy to gather relevant literature followed by an explanatory strategy that attempts to build the conceptual relationship between SC factors with risks to define the research problem/questions. The systems thinking approach for conceptualising and modelling the risk propagation phenomenon is believed to require exploratory as well as explanatory strategy as seen in Figure 21.

4.1.3 Research design

Research design is the overall plan for data collection and analysis. It reveals the research strategy and the priorities of the researcher in the use of methods (Ghauri, 2005). Research strategy drives the choice of appropriate research design for solving the research problem. Two commonly used methods in research design are qualitative methods and quantitative methods.

Different research methods used in the Business and Management research field were studied to identify the suitable research approach or paradigm. The research methods were studied through several training programmes provided by the School of Business and Economics. The comparison of the qualitative and quantitative research methods is presented in Table 9 for a quick understanding of the nature of data requirements and the commonly preferred methodologies. The clear understanding of different research paradigms, approaches and strategy is important for research in business studies. A similar attempt is made in this section to explain them and justify its use for this research.

It is observed that the research discussed in this thesis follows a pragmatic approach by utilising more than one type of research paradigm, strategy and design.

Qualitative Methods	**Quantitative methods**
1. Goal is to sensitize the concepts and develop multiple realities	1. Goal is to test the theory and establish facts
2. Design methods are flexible and generic	2. Design methods are structured and scientific
3. Data is descriptive and intangible	3. Data is quantitative and measurable
4. Sample size can be small	4. Sample size needs to be large
5. Observation methods and interviewing techniques are predominately used	5. Based on the experiments and structured observations.
6. Preferred paradigm by interpretivists	6. Preferred paradigm by positivists

Table 9: Comparison between qualitative and quantitative methods

4.2 Research methods

Qualitative as well as quantitative research methods can be used for collecting and analysing the data. In qualitative research, different methods such as case study, action research, structured/unstructured interviews and ethnography are found to be commonly used. Qualitative research can be employed in the task of generating rich, unstructured information in order to develop hypotheses or measurements to be quantified later (Creswell, 2008). In quantitative research, different statistical methods, simulation methods, experimentation and Operations Research (OR) methods are predominately used to analyse the data. There are several other methods used for qualitative and quantitative research apart from the ones mentioned. The research data is collected and analysed using a variety of qualitative and quantitative techniques depending upon its need and fit in answering the research objectives and questions. Three main methods identified by Cho and Trent (2006) for exploratory data collections are focus groups, observations and structured interviews. Observations include direct, indirect observation or studying primary as well as secondary documents. When qualitative and quantitative research methodologies are combined to answer the research problem, they are commonly referred as ‘mixed methods’.

Qualitative as well as quantitative research methods combined for data collection and data analysis in a single study are becoming increasingly popular (Molina-Azorin, 2012). The combined (mixed) approach frequently results in superior research compared with other mono method design (Johnson and Onwuegbuzie, 2004). The benefit behind the use of mixed methods is that it enables to simultaneously generate and verify theory in same study (Molina-Azorin, 2010). Mixed methods are used in this research for drawing strong inferences, difficult to capture through merely qualitative or quantitative research methods. According to Johnson and Onwuegbuzie (2004), the potential benefits of mixed methods are comprehensive findings, confidence in results, validity of results and holistic understanding of the problem. Mixed methods advocate the use of both inductive and deductive research approach that strengthens the research (Jogulu and Pansiri, 2011). Mixed methods are employed in this research for conceptualizing and modelling the problem under study.

4.3 Research approach for the problem

The generic understanding of the different research methodologies and their fit for the research problem is discussed in the previous section. In this section, the research approach for answering the research problem in context with identified research gaps and suitability of different research methods is discussed. The holistic approach to SCRM was identified to be a possible approach for understanding the complex behaviour of risks. From the SLR it was further deduced that Systems Engineering (SE) tools and techniques are found to be appropriate for a holistic study of risks. SE is an interdisciplinary field of engineering and management that focuses on designing and managing the complex projects. SE signifies as both an approach as well as a discipline in engineering, which utilises the diverse technical, managerial and social disciplines. By providing a systemic (holistic) view of the system, SE helps in forming a structured process from conceptualization to formulation to testing and in most cases, to the implementation (Forrester, 1994).

The SE process consists of fundamental systems engineering activities such as requirements analysis, functional analysis and design synthesis. All these activities are secured by a tool called ‘system analysis and control’ (Systems Engineering Fundamentals, 2001). SE uses different tools and techniques to better comprehend and manage the complexity in the systems. The methodology of SE is a systematic process that starts with identifying the problem to be solved. Subsequently, a causal-loop diagram based on mental models is developed. This helps in identifying the feedback loops that cause the problematic behavior. Later, the system is formally represented in a computer-based mental model. In the end, a mathematical model is deduced and is simulated by using the most likely parameters of the variables. The resulting hypothesis is tested to find various ways to improve the problem. These steps help in viewing the system as an interconnected sub-system. There are enough evidences of the usefulness of SE methodology in the literature (Oehmen *et al.*, 2009). Some of the commonly used tools from SE identified from literature are:

- **System architecture**
- **Systems thinking**
- **System dynamics /Simulation**
- **Statistical analysis**

System architecture conceptually models the structure and behaviour of system. Systems thinking look at broader picture of system and captures macro as well as a micro picture of the system. System dynamics is also referred to as systems thinking by some of the early researchers. Forrester founded Systems thinking in 1956 at MIT. Systems thinking allow people to make their understanding of social systems precise. Systemic thinking is very important during the system conceptualization phase in system dynamics or simulation studies (Forrester, 1961). The process focusses on how the thing being studied interacts with each other in the system and works by expanding its view to take into account large number of interactions. Statistical modelling also comes under the umbrella of different SE tools and techniques.

4.3.1 Systems thinking (ST) approach

Systems thinking approach is a methodological approach that considers all the dimensions of the problem influencing the system. It seeks to understand how these dimensions interact with one another and how they can be brought into an appropriate relationship for the improved results (Sterman, 2000). Systems Thinking (ST) and System Dynamics (SD) aspire for understanding and improving systems. Case studies and Soft OR studies help in developing conceptual or mental models (Forrester, 1994). The complex models emerging from the initial description of the real system are then modeled for the evaluation. Qualitative and quantitative modelling can be used for conceptualizing and analyzing the interdependency of the system. (Luna-Reyes and Anderson, 2003).

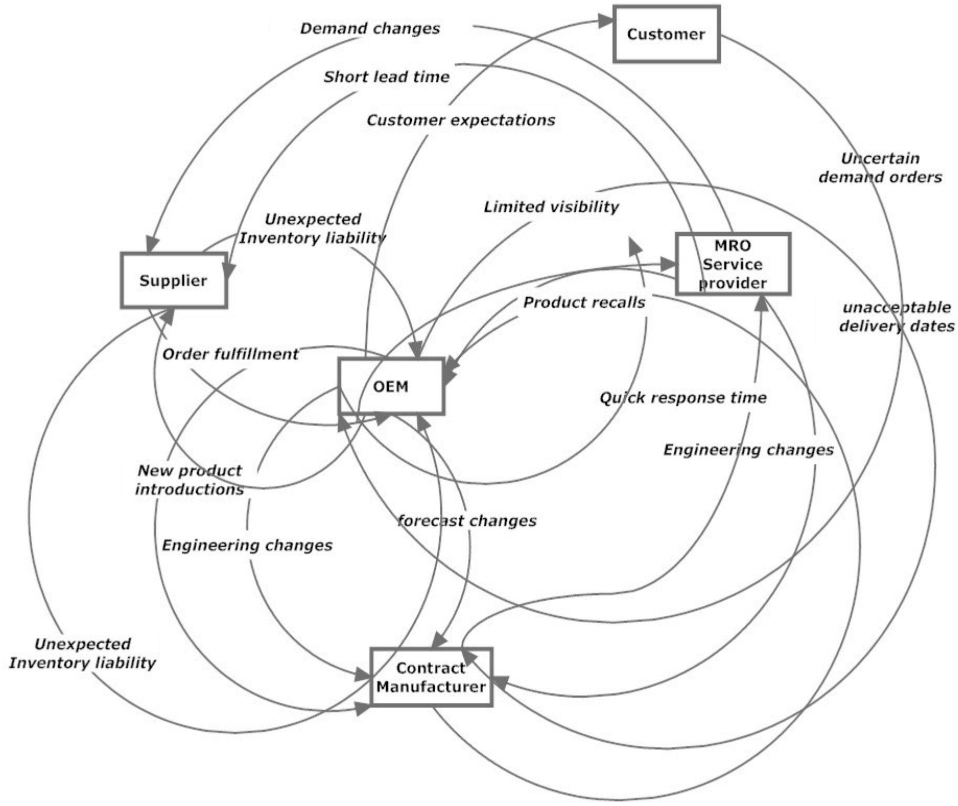


Figure 22: Complex SC network and their interactions

The research gap considering risk propagation and recovery needs a structured approach to understand the complex behaviour of risks. The research question also attempts to check the possibility of capturing the risk impact following modelling behaviour of risks within the supply chain network. The increased complexity within the network due to several SC factors can be observed in Figure 22. The example shows different supply chain stakeholders or entities interacting within the aerospace supply chain network. Due to multiple interactions, the system behaviour is altered leading to risks.

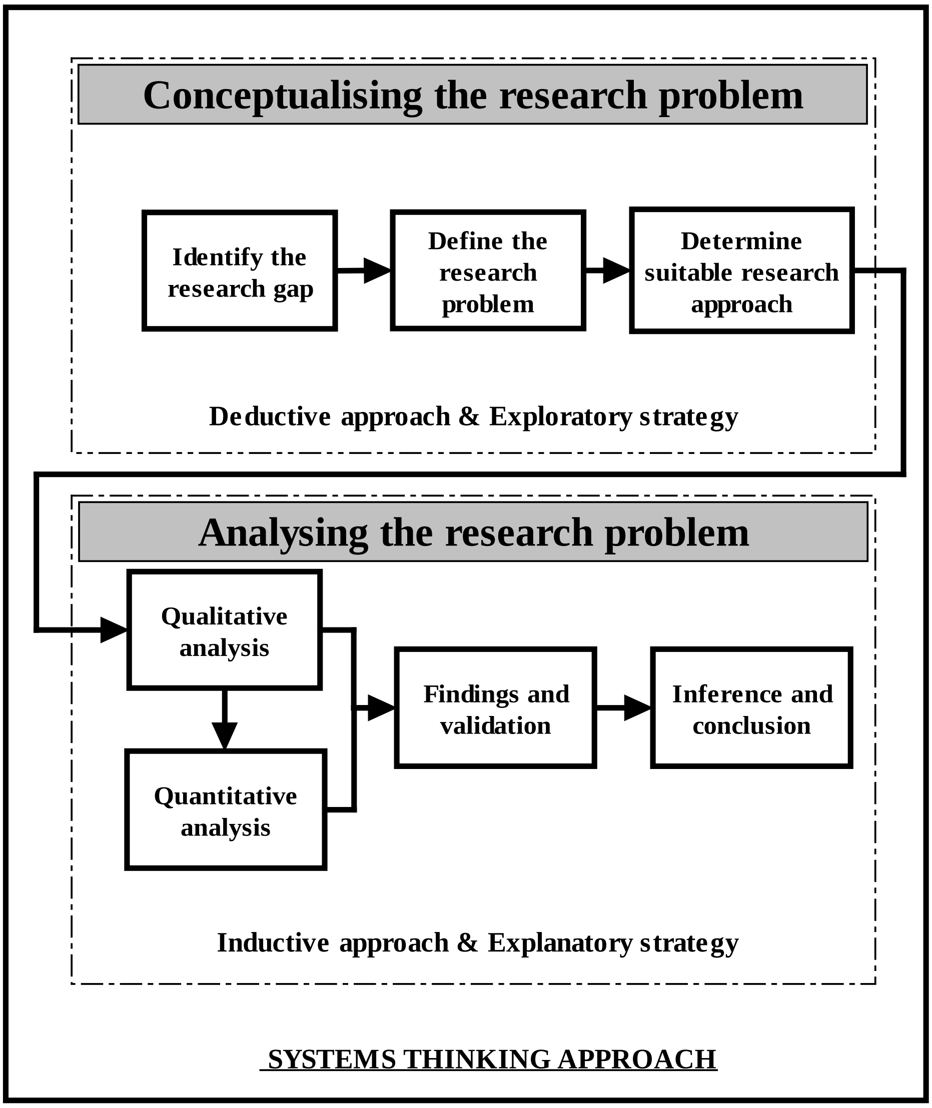


Figure 23: Research approach for the problem

Based on a careful study of different research paradigms discussed in this chapter, a research approach to the defined problem is identified. The research follows a systems thinking approach as the most appropriate approach to the problem as seen in Figure 23. For identifying the research gaps, a deductive approach is followed by systematically reviewing the literature. The exploratory strategy of looking at interactions between several SC factors and risks brings forth gaps from an industry perspective. For conceptualising the research problem and identifying the suitable methodology, a combination of interpretivist as well as positivist approach is followed utilising the potential of both (qualitative as well as quantitative) research methods. A systematic and structured approach utilised during the research problem definition clearly follows systems thinking concepts. After the research problem is conceptualised, the next stage is to analyse the problem. For the analysis of research problem, mixed research methods are used. Several research methods, both qualitative and quantitative can be used during the systems thinking approach. Some of the commonly used research methods are discussed later in this section. Case study approach followed in this study supports in conceptualising the risk propagation phenomenon. Simulation and statistical methods are also used for modelling risk propagation. Inductive approach followed for limited data analysis supports in validating the developed research design and framework for SCRM. Explanatory strategy helps to bring research insights into the behaviour of risks within a supply chain network. The use of systems thinking is intended to develop a new theory into risk propagation modelling following the proposed research approach (Figure 23).

4.3.2 ST research methods

The key benefit of systems thinking is its ability to deal effectively with those types of complex problems that are marked by complexity and multiple interdependencies. Systems thinking approach based research methods have shown positive results in services, human resources and high-technology industries (Senge, 1990). Some of the key characteristics of systems thinking modelling are:

- Captures dynamic and stochastic behaviour

- Ability to represent holistic view of system
- Unique ability to integrate people, process and tools
- Models feedback/inter-relationships of system
- Compatibility of transferring mental model to computer model
- Provides early warnings, suggestions for the system improvement

Systems thinking approach adapts qualitative as well as quantitative methods for solving multidimensional problems. This section focuses on all possible research methods suitable for the data collection and analysis to answer research questions.

Qualitative research methods are commonly used in systems thinking. They support in conceptualizing the system model. Later, quantitative research methods contribute for simulation. Some of the research methods commonly used in systems thinking are provided below:

1. **Interviews:** Interview research is considered a primary method of social science data collection. A number of structured and semi-structured interviews allow the researcher to look for patterns, definitions and understanding of the area studied to develop dynamic hypotheses. Outcomes of interviews are used for developing causal relationships during systemic thinking.
2. **Focus groups:** Information from groups interacting with each other in the research environment is also a source of qualitative data collection method. Discussion emerging out of respondents provides new concepts and critical issues like policies, competencies or causal factors (Luna-Reyes and

Anderson, 2003). Delphi groups an extension of focus groups is a commonly used research method for data collection within systems thinking.

3. **Field observation:** Field observation with or without the observer's participation is another means of qualitative data collection method. This method may involve several ethical issues. It may also involve strict screening of documents collected. Field observation is laborious and time-consuming but provides an in-depth data collection opportunity. This method can be paired with interviews or focus groups depending on need and flexibility during the data collection activity.
4. **Case study:** In exploratory research, case study is commonly used to build a research foundation. Case study is preferred to develop research hypothesis or questions when the researcher lacks clear idea of the problem. Secondary data is used for case study analysis to draw insights and develop a conceptual understanding of the problem.
5. **Experimental approach:** The data collected in this form of experimental approach is usually quantitative. This can be in the form of documents, reports, registers, excel sheets, etc. Statistical, OR modelling and simulation techniques are commonly used to draw the results in this approach.

Some of the other consensus methodologies like Brainwriting, Nominal group technique are also found to be used in systems thinking research. These methods are beyond the scope of the research and hence not discussed in this section.

Simulation, a quantitative research method used during systems thinking use SD models. Currently available software programs are based on fundamental concepts of continuous and discrete event simulations. Continuous event simulation is suitable for the systems in which the variables can change continuously (e.g. typical production system). Discrete event simulation is suitable for the problems where variables change in discrete times such as logistics or disruption. Few of the prominent commercially available software used for modelling and simulation are - *Arena©, iThink©/Stella©, PowerSim© and Vensim©*. A preliminary study of these software programmes is completed to understand the best fit for the research requirement. *Vensim©* a discrete event simulation software is used in developing feedback loops, stock-flow diagrams and simulation models.

The research methodology discussed in this chapter provides a comprehensive understanding of different research paradigms, approaches, methods suitable for the research problem defined. Identified research gaps are integrated with most appropriate research approaches and associated methods. A systems thinking approach is followed in the next chapters to integrate several set of risks and understand their complex behaviour.

Chapter 5 Conceptualizing Risk Propagation

This chapter discusses the conceptual development of risk propagation phenomenon following a systems thinking approach. It discusses secondary case studies from various manufacturing sectors to build the conceptual understanding. The conceptualization phase for risk propagation utilizes two different case studies to build the fundamentals for the modelling stage. The operational (internal) risk based case study looks at secondary data related to recalls in the automotive and food industry whereas, the external risk based case study captures the Japan tsunami disaster. Both case studies combine together to capture the fundamental behaviour of risks and their propagation phenomenon within supply chain networks.

5.1 Risk propagation phenomenon

The research gap identified in chapter 2 and 3 clearly shows that the research on evaluation of risk propagation had been lacking in the past. Large-scale supply chain systems are growing more global and complex. There are many examples of supply chain disruptions in the past, most recent being the Japan tsunami (2011) that has affected the global supply chain. Global outsourcing increases risks in the supply chains because of their vulnerability to several operational and environmental disruptions. It is difficult to determine the overall effect of a particular disruption on each node in the supply chain network. In order to evaluate such complex web of interconnected nodes in SC network, systems have to be holistically studied to identify the fracture points and risk propagation within each node.

In this chapter, the supply chain risk propagation phenomenon is captured following a systems thinking approach. A system based modelling approach attempts to develop a conceptual framework for evaluation of risk propagation and recovery time from the disruption. The secondary case studies build on the systemic approach as utilized to identify the interdependency of risk influencing factors affecting the SC in chapter 3.

In the next section, a conceptual risk propagation model is developed to build the proposition. Two case studies have been conducted to conceptualize the preliminary understanding. The research utilises inter-linkages and interrelationships from case studies to develop the conceptual model for risk propagation. The cases on recalls from Automotive and Food industry (for operational or internal risk) and Japan tsunami (for external risks) are holistically analysed from various dimensions of risk propagation and recovery perspective. The generalized cascading effect of supply chain risks is predicted along with their estimated recovery durations.

5.2 Secondary case studies

In this section, risk propagation phenomenon is conceptualised through two separate case studies. The first case study relates with operational (internal) type of risks observed in supply chain network where the secondary data related to vehicle and food recalls are analysed for understanding the risk propagation behaviour. The second case study focuses on external risk influencing the supply chain network, the famous and most recent natural disaster is considered for the analysis.

5.2.1 Automotive and food recalls

Vehicle recalls is a measure of automotive supply chain efficiency (Bates *et al.*, 2007) and recently there have been many recalls, globally affecting the reputation of automotive leaders. Automotive industry vehicle recalls were selected for the study to understand the extent of the risk propagation in terms of different zones, levels and impact. Table 10 and Table 11 provide some of the findings of the secondary data analysis to understand the phenomenon of risk propagation in a better way. Earlier studies attempting to understand the impact of recalls on supply chains have found limited influence on customer demand for new vehicles (Reilly and Hoffer, 1983). However, the supply chains are growing larger and longer; thus affecting the market share along with the brand reputation. Although the indirect cost of recalls is difficult to quantify, some of the prominent impacts of recalls on business have been delays in launch of new models, reduction in customized or new model variants and lengthy reworks running over a number of years. Ford automaker suffered component safety

Automotive manufacturer	Year	Product/Component	Risk Propagation	Risk Impact
Ford	2002	Engine	Recalled over 600,000 Focus cars due to engine fires and other difficulties.	Similar 11 safety recalls for the Ford Focus, since it was launched in 1999 compromising the brand value.
	2006	Engine	Recall of 1.2 million trucks and SUVs over concerns about potential engine fires.	Heavy financial losses in particular year.
	2011	fuel tank straps	1.2 million Recalls due to possible corrosion of the fuel tank straps which secure it to the vehicle after prolonged exposure to road de-icing chemicals.	Expected additional cost for replacement.
GM	2005	seat belt	Recall of more than two million vehicles in the US for seat belt design problems.	Over and above net loss of $1.1bn for the first three months of 2005: 2% share fall on same day of announcement.
	2010	power steering	Recalling 1.3 million small cars in North America because of a power steering problem.	GM blamed the fault on a supplier.
Toyota	2009	Electrical system	690,000 cars made in China recalled because of faulty electrical window switches.	Believed to be short term impact.
	2009	accelerator pedals	Toyota recalled four million cars after fears that the accelerator pedal could get stuck on the floor mat.	Reputation loss due to heavy recall.
	2010	Engine control system	1.1 million Corolla and Matrix models over an engine control system fault, defects.	A record fine of $32.4m (£20.8m) in the US in addition to $16 agreed previously.
	2010	accelerator pedals	Recalling up to 1.8 million cars across Europe, including about 220,000 in the UK, following an accelerator problem.	
	2011	Power supply circuits	Recall of more than 110,000 hybrid vehicles over concerns about a problem with the power supply circuit.	Questions about Toyota's quality controls. Danger of losing its position as world leader.
	2011	Fuel leakage	Recall nearly 1.7 million vehicles worldwide over concerns about a possible fuel leakage.	
Honda	2009	Airbag	Honda has announced it is recalling 440,000 vehicles in the US due to an airbag defect.	Heavy recall cost for replacing the components.
	2010	Breaks	410,000 cars in the US recalled because of complaints about their brakes.	
	2010	Switch defects	Recall of 646,000 cars globally to fix a switch defect that could cause a fire.	
Nissan	2008	Steering mechanism	Recalled 70,000 cars built because of a fault that could cause a steering malfunction.	Heavy cost in recall all over the world with exchange for free defective parts
	2010	Engine ignition	Recalling 2.1 million vehicles worldwide because of an ignition problem leading to engine stall while running.	
Chrysler	2004	Gearbox	Is recalling 2.7 million cars over concerns about the safety of their gearboxes.	Heavy recall cost for replacing the components.
	2011	Steering mechanism	11351 cars unit recalled due to possibility of missing or incorrectly installed steering column pivot rivet.	

Table 10: Automotive recalls in recent years

recalls damaging its brand identity. Millions of vehicles recall in the US by General Motors led to huge loss to the organisation. Honda, Nissan and Chrysler automakers had to face heavy recall repair cost. Toyota had a heavy impact on reputation due to multiple recalls for their car models. All of the above is evident from Table 11, where most of recalls are primarily associated with the quality problems initially neglected in the supply chain network later affecting the end customers in terms of service. Vehicle recalls undoubtedly is a costly business for the automakers, suppliers as well as distributors. The knock-on effect of risks within their operations is felt across the supply chain network. The propagation of unexpected or undesirable disruptions through the network severely affects the profitability of the automotive supply chain. Similar to Auto industry recalls, the food industry recalls also have had an equal impact in terms of cost and delays in short term, and on service value and brand reputation in long term perspective. Table 11 captures the major food recalls in the last decade. It can be observed that all of the food recalls have influenced cost, service level or lead-time.

Year	Product	Risk propagation	Affected parameter: Risk impact
2001	chicken	Thousands of frozen chicken steaks over fears they may have been made with meat unfit for human consumption.	**Service level:** Supermarkets recalls the products with immediate effect.
2001	Coffee	Nestlé coffee jars recalled after a customer found metal shavings in one of them.	**Cost and Service level:** Recall of about 250,000 jars of entire batch production.
2001	Chocolate bars	Confectionery manufacturer Mars found insects in the flour that had been used to make the snacks.	**Cost:** Destroyed three million Twix chocolate bars.

2004	pasta sauce	Several complaints about the sauce's taste and smell by customers.	**Cost and Service level:** Dolmio precautionary recalled a batch of 2,000 of pasta sauce pouches after receiving complaints.
2005	Food dye	50 food products have been taken off shop shelves after they were contaminated with an illegal food dye causing cancer.	**Cost:** Immediate product withdrawal notice as a precautionary measure by FSA.
2005	Chicken	Seven of chicken products diagnosed of a salmonella scare.	**Cost**: Supermarket Waitrose has recalled all chicken products.
2007	Pet food	Cans and pouches of dog and cat food after several animals died during taste testing.	**Cost and Delays:** Company issued a product recall for 40 brands of cat food and 51 brands of dog food overall 60 million in quantity.
2007	Thickening agent	Thickening agent following reports it had been contaminated with the poison dioxin.	**Cost and Service level**: Recalling efforts to retrieve the affected batches of guar gum already sent to its customers.
2008	Milk powder	Milk powder killed four infants and sickened more than 6,000 others were tainted with melamine.	**Cost and Service level**: Mass recall of China milk produce; 10% of liquid milk from three of China's dairies.
2010	Shrek glasses	Fast food chain McDonald's identified painted designs on Shrek glasses containing the toxic metal cadmium.	**Cost and Service level**: Recalled 12 million drinking glasses and asking customers to stop using the glasses and stop selling later.
2010	eggs	Nationwide outbreaks of salmonella poisoning in a number of states.	**Cost and Service level**: Recall to 380 million eggs. Authorities recommend discarding or returning any potentially affected eggs with immediate effect.
2011	Meat	Salmonella outbreak that has killed one person and made dozens ill.	**Cost and Delays:** Recall of 18,000 tons of turkey. Plant has been suspended until the source of the outbreak is confirmed.

Table 11: Food recalls in recent years

5.2.2 Japan tsunami disaster

A case study of Japan tsunami (2011) was conducted to understand the length and breadth of risk propagation phenomenon as observed due to external risks. The cascading effect of disruption was analysed from several risk propagation dimensions. Secondary data in the form of literature from different electronic sources like articles, newspapers, magazines and reports were used to analyze holistically the case from a risk propagation and recovery perspective. The Japanese tsunami was selected as an appropriate and recent natural disaster with a large cascading effect and its inherent global extent of risk propagation. Several case studies on natural disasters like SARS in china (2003), Hurricane Katrina in US (2005) and Indian ocean tsunami (2004) has been studied in the past.

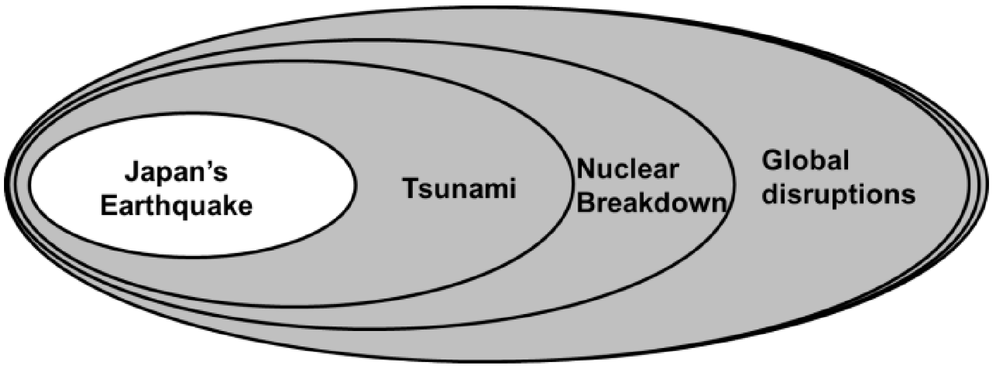


Figure 24: Cascading effect: Japan tsunami, 2011

It is found that 90% of the world's earthquakes occur along the "*Ring of fire*" (Khilyuk *et al.*, 2000). Japan lies on one of these three seismic belts and hence has witnessed many earthquakes in the past. One such that struck on the 11th March 2011 was higher on the Richter Scales (8.9) and had a wider cascading effect in terms of disruptions as seen in Figure 24. The earthquake caused a tsunami, resulting in damage to the local nuclear power plant with a fear of expected nuclear radiation in the environment creating massive chaos in the global market. Studying such disruption in the supply networks for various risk propagation levels and dimensions is the major focus of this case discussion. It is expected that this study will provide the platform for developing the system based model to test the validity of risk propagation phenomenon.

5.3 Conceptualization of risk propagation

In this section we develop a conceptual understanding of possible risk propagation zones and dimensions following a systems thinking approach. In conventional supply chains, physical goods, finance and information resource follow a unidirectional flow. Goods flow from the raw material supplier to the end customer whereas; the financial flow tends to follow in the opposite direction. Information flow follows a bidirectional flow between supplier and customer along with other network stakeholders. Figure 19 (Chapter 3) represents a closed loop supply chain including after sales service and remanufacturing entities considered. Similar supply chains are commonly found in the manufacturing industry. Automotive, electronics and aerospace sectors follow the network represented in Figure 19. In the case of any natural or man-made disruption /shock, it is expected to affect the core supply chain nodes first. This region is defined as a primary zone of risk propagation comprising of sourcing, production and logistics activities. Other interrelated areas associated with supply chains are likely to be affected over a period of time following a 'snow ball effect'.

Risk propagation cascading into critical service support entities such as R&D, Finance and Information technology (outside the primary zone) is defined as a secondary risk. Whereas, the tertiary risk propagation zone is expected to lie outside supply chain network indirectly impacting the system with a long-term effect.

<u>Proposition 1</u>: Risk propagation flow is multidimensional and not unidirectional

It is assumed that the risk propagation is not unidirectional and does not just flow in the direction of goods, finance and information flow. Hence this research is further developed with a proposition that, the risk propagation is multidimensional and does not just include three conventional resource flows namely, infrastructure,

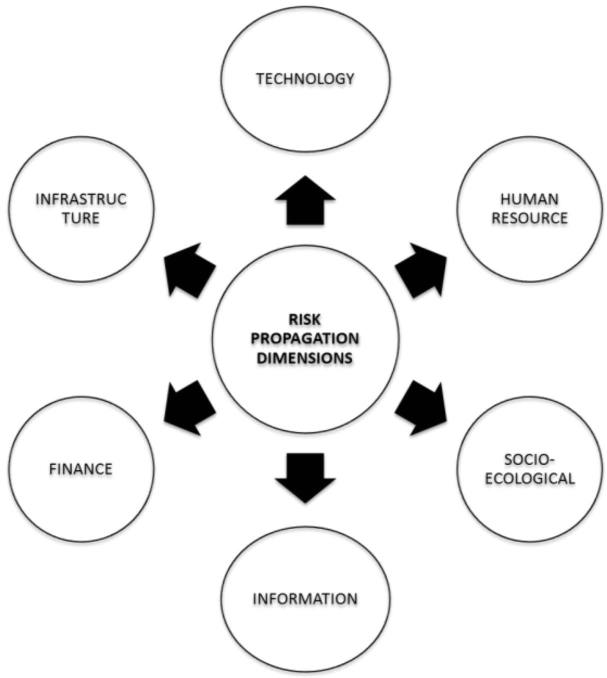


Figure 25: Conceptual multidirectional wheel of risk propagation

information and financial dimension. The cascading effect flows beyond this and takes into consideration other resources or factors like human resource, technology, socio-economics, etc. The reason to include these six factors is justified through the case study analysis. Figure 25 shows the conceptual multidirectional wheel of risk propagation. We holistically analyze the Japanese tsunami case study based on zones (Figure 19) and dimensions (Figure 25) of risk propagation in the following section.

1. Physical/Infrastructure Disruption

Physical damage and human fatalities are typical immediate consequences of any natural disaster. According to Bloomberg, physical or infrastructural damage caused by the Japanese earthquake followed by the tsunami has been estimated from $250 billion to as much as $309 billion (Ujikane, 2011). Direct damage caused by the earthquake and tsunami swept at least 10 kilometers inside northern region of Japan. The Japanese ports considered to be the lifeline of supply chains from east to west were heavily damaged. 2,300 Nissan vehicles awaiting shipment were destroyed at the port of Hitachi, consumed by fire and pileup (Web source, 30 March 2011). All major ports were closed with intense effect on the global logistics services. These transportation challenges caused major global disruption. The spilling effect of the earthquake and tsunami further led to a nuclear power plant breakdown in Fukushima. The Nuclear crisis and electricity shutdown forced many companies to shut down their plants to reduce demand on the already broken electrical grid.

2. Financial Disruption

Japan’s stock market (benchmark Nikkei 225) plunged by 6.2 percent the day after the disaster, hitting a two and half month low (Ikeda, 2011). Nuclear power related business was hardest hit due to the fear of a nuclear crisis. This was closely followed by the semiconductor and automotive business. Japan's central bank pumped a record $184 billion into money market accounts to encourage bank lending (Web source, 16 March 2011). The VDAX-NEW volatility index, one of Europe's major barometers of investor anxiety, surged 18 percent hitting its highest level in last 8 months indicating the global impact of disaster (Reuters, 2011). Three sectors namely Automotive, Electronics and Steel industry were identified by global supply chain analysts as most affected business areas. Automotive companies like Toyota, Honda, Nissan, Mazda, Suzuki and Mitsubishi had to close their plants for varying periods. Table 12 shows immediate reaction to supply chain disruption classified in various business sectors based on inputs from global news sources and reports released immediately after the disaster. The disaster severely affected Japan's steel and nuclear production capacity with a further expected rise in steel and energy demand for damage restoration work. It was predicted that the global consumer market will see the hike in prices of all affected products.

3. Technology Disruption

Technology is critical to the changing risk background. Stability and integrity of e-services is fundamental for effective risk management. Apple delayed the launch of its new products as Japan recovered from the disaster. In high-tech production of wafer chips, a split second loss of power could completely damage a large volume of goods (Kelly *et al.*, 2011). These examples show the importance of technology in the supply chain. Risk associated with intellectual property rights highly depend on technology and unfortunately there was no clue of its security after the disaster.

4. Information Disruption

The lack of communication due to a complete shutdown of the supply network had a massive impact on Information security. Information and data security are largely under the control of the organisation (Finch, 2004) and hence, information was completely exposed until organisations restarted their operations after disaster. It took two weeks to assess the impact of disaster with continued uncertainty due to nuclear radiation fear. Getting suppliers from Japan online to assess the damage and finding alternate suppliers for key components was the most challenging activity for procurement managers across the globe. These problems further escalated due to information distortion below top suppliers (Tier II and III suppliers).

Business sector	Company/ Industry	Immediate reaction to Japan SC disruption*
Automotive	Toyota	Halts production of 12 plants in Japan by slashing output by 40,000 vehicles.
	Nissan	Halts production at four plants.
	General Motors	Suspends production at assembly plant in USA due to part shortage.
Electronics/ Semiconductor	Sony Corp.	Operations at 10 Sony group sites and facilities suspended.
	Canon Inc.	Fifteen employees injured.
	Panasonic Corp.	Several workers with minor injuries.
	Texas Instruments	Manufacturing plants in Japan damaged.
	Sanyo	Stopped production lines and evacuated employees for safety.
	Toshiba	Partial production with reduced electricity supply.
	Fujifilm Corp.	Halts production lines at a plant in Japan.
Other	Japan Nuclear power	Two nuclear power plants of Japanese government under emergency.
	Nippon Steel Corp	Steelwork's facilities in Japan completely damaged.
	Sumitomo Metal Industries	Suspended production at its steelwork plant in Japan.
	Japan shipbuilding	Declared 'force *majeure'* on delays of new ship building deliveries.

Table 12: Immediate reactions to supply chain disruption

(Source: Inputs from global news sources between 12th March and 31st March 2011.)

5. Human Resource Disruption

As per the Japan National Police Agency, 27,000 people are estimated to be killed and more than 146,000 buildings (homes, offices, factories) being destroyed are reported (Web source, 25 March 2011). Barclay's capital estimated the impact of earthquake in Japan affecting the economy to 6.2% of GDP, 6.8% of population and 6.5% of overall household life insurance (Web source, 16 March 2011). Human resource is considered to be a key to any supply chain. Automotive and Electronics manufacturers scrambled to find alternate suppliers to mitigate delays from disabled Japan suppliers. Many global companies removed their expatriate employees from Japan, which clearly affected productivity heavily. It can be visibly made from Table 12 that the most of the companies halted their production not due to issues with their infrastructure but due to the unavailability of human resource and power shortage after the natural disaster.

6. Social and Ecological Disruption

The economic disparity is interconnected with corruption, organized crimes and global imbalance contributing to global social fragmentation (Global Risks, 2011). The Japanese tsunami limited the economic opportunities for people and this also propagated to long-term risk of brain drain and skills depletion for Japan's supply chain. Skills shortage is identified as one of the major factors affecting the next generation supply chains. Water, food and energy security are essential for social stability, if not provided creates social unrest. A months-long period of social unrest caused due to lack of food, water, housing and transportation affected the already disrupted Japanese supply chain.

The process of rebuilding power generated by nuclear reactors was lengthy and was expected to complicate the industrial output for months along with long-term risk of radiation exposure. The nuclear crisis of Japan also expected to raise oil prices globally, further depleting the environment. Higher radiation levels were detected in water and food in and around broken nuclear plant region. US Food and Drug

Administration banned imports of certain food items from Japan as immediate action to evade radiation (Nato *et al.*, 2011). The Japanese food supply chains along with other business sectors expected to bear long-term effects on global consumer purchasing habits and food safety regulations.

The systems thinking approach to supply chain risk propagation used in this case study on Japan's natural disaster provides some critical insights. It is observed from a multi-dimensional study of risk propagation that the supply chain risks are associated and cascade in zones as earlier represented in Figure 19.

The earlier assumption of unidirectional risk propagation is false and proves the proposition that the risks propagate in all directions leaving both short-term and long-term impact.

5.4 Directions for modelling risk propagation

Based on the evidence captured via the multidimensional wheel of risk propagation for the Japan tsunami disaster, the emergence of risks is plotted on earlier defined zones. Figure 26 shows the holistic picture of risks identified from the case study and their approximate risk propagation durations observed over a period of three months after the disaster. Supply chain risks are noticed to originate and propagate faster in primary zone and later initiate propagations in other zones with comparatively short-term impact in secondary zone and long-term impact in tertiary zone.

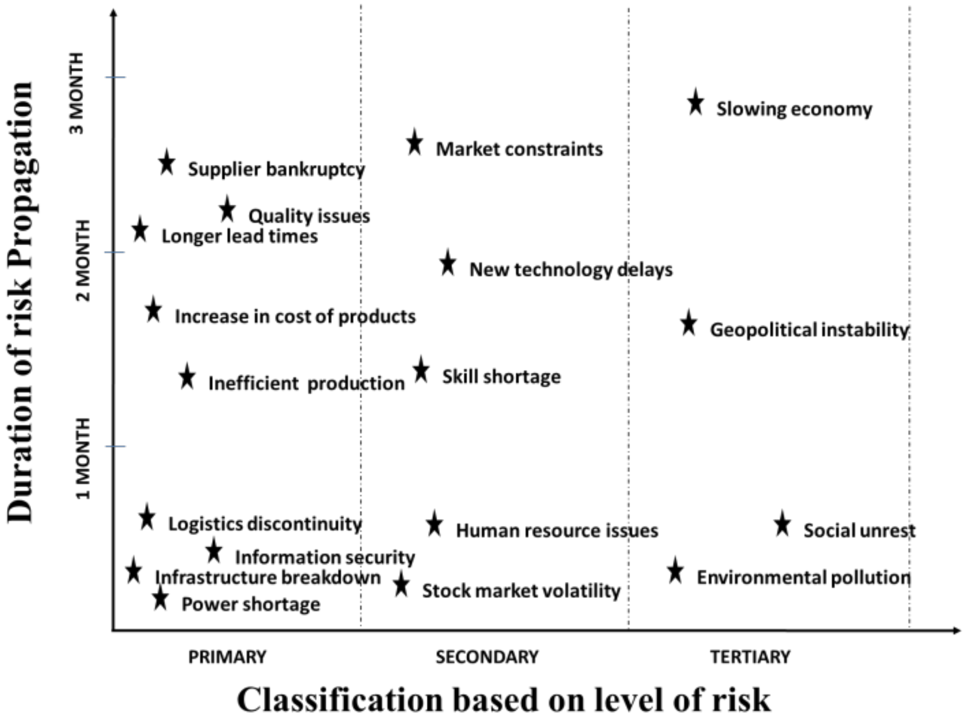


Figure 26: Duration of risk propagation observed from case study

Figure 27 shows the identified zones and the drivers associated with each zone. Here the drivers are different operational areas within SC network. It is important for supply chain managers to analyze contingency/recovery from disasters for its global suppliers and logistics partners. Finding the right safety stock levels and identifying dual/multi suppliers for critical components to mitigate supply chain disruptions is equally important. It is clear from the case study that, the problem escalated to such an extent due to globalization, JIT and Lean manufacturing practices. 'Near sourcing' instead of global sourcing and diversification of supplier and production bases could be a possible solution for effective supply chain risk management in such uncertain environments. It is interesting to find that, global risk propagation follows the '*Pareto principle'* where 20% of product shortages create 80% of global supply chain disruptions. Such event driven risks have long-term impact due to their tendency to inflate and create cascading shocks affecting the complete network of supply chain.

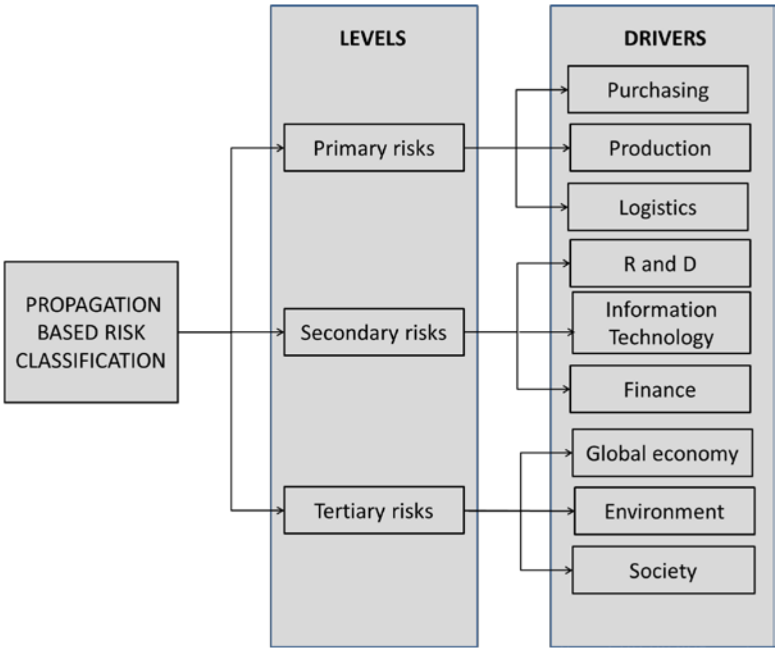


Figure 27: Risk propagation based classification levels

The conceptual levels and multi-dimensional risk propagation model guide to simulate the supply chain system behavior for natural disruptions and to proactively measure the risk propagation impact in terms of cost and duration. Earlier preliminary case study findings depict that the risk impact is in terms of cost and delays and further escalates to impact the long term dimensions like service level and brand reputation. These findings have been validated in the secondary case study. Systems thinking approach to supply chain risks has identified the risks and their approximate duration for a typical disruption like the Japan tsunami. Through systems thinking a conceptual understanding of the risk propagation has been developed in this chapter.

This understanding is further developed by modelling risk propagation to capture risk behavior and its impact on complete supply chain network.

Risk propagation cost impacts and time durations are found to vary for different industry sectors like Retail, Electronics, Food and Heavy manufacturing. Comparison with other past disasters also shows the similar propagation and recovery performance. Efficient risk management strategies will improve readiness of the supply chain network. However, in order to implement these robust strategies an appropriate knowledge of the extent of risk propagation is essential. A case study of Japan tsunami is used to validate the conceptual framework by assessing the effect of disruption on supply chain performance for various industry sectors. The cascading effect of Japan's nuclear crisis on supply chain is also captured. Numerous automakers, including General Motors, Ford, Toyota and Honda closed factories or scheduled downtime for plants due to shortages of parts coming from Japan (captured in Table 12). A need for rethinking on mitigating strategies like JIT, Lean manufacturing has been identified by systems thinking for quick recovery of SC's. The phenomenon of risk propagation conceptualised in this chapter is followed for building the fundamental platform for risk modelling (discussed in the next chapter).

Chapter 6 Modelling Risk Propagation

The chapter builds the risk propagation modelling approach from conceptual thoughts generated in the previous chapter. Following a systems thinking approach the 'Framework for SCRM', 'Supply chain risk model' and 'Research design' are proposed for quantitative modelling of risk behaviour. A collaborative case study is used to model the complex behaviour of risks and validate the framework. The research discussed in this chapter was an experimental study conducted at a collaborating organisation for six-month duration. The developed models capture the failure point(s) and the cascading impact of the risk propagation within the network.

6.1 Framework for modelling risk behaviour

Modelling the broad domain of SCRM is difficult due to the complexity of the SC network incorporating several stakeholders, processes and interactions. To compromise between model complexity and reality it is important to define the scope of the model in a way that it reflects the key real-world dimensions without making it too complex to solve (Min and Zhou, 2002). Supply chain modelling is difficult when the model has to take into account uncertainty. Blackhurst *et al.* (2004) attempt a network based modelling approach to capture uncertainty in the large-scale supply chains. Similar supply chain modelling frameworks with uncertainty factors considered have been presented in the past by some of researchers (e.g. Escudero *et al.*, 1999; Swaminathan *et al.*, 1998; Gjerdrum *et al.*, 2001). Supply chain modelling with uncertainty is gaining popularity with researchers (Cheung and Powell, 1996; Van Landeghem and Vanmaele, 2002). Chaudhuri *et al.* (2012) suggest that the assessment of supply chain risks should start during the new product development process due to the growing uncertainty in supply chains. Wu *et al.* (2006) and Wang *et al.* (2012) use analytical hierarchy process to model supply chain risk assessment. Other multidisciplinary approaches have been attempted for building models for supply chain risk analysis in the literature. Multi-stage influence diagram (Liu, 2009), Monte carlo approach (Klibi and Martel, 2012), Interpretive structural modelling (Diabat *et al.,* 2012), Partial least square method (Kern *et al.,* 2012) and several other methods from MS/OR (e.g. Bryson *et al.,* 2002) have been utilized by academics to test models for supply chain risk assessment. All the above researchers tend to look at individual characteristics rather than the chain in its entirety. This research attempts to cover this particular gap where the supply chain network risks are considered holistically by developing a framework for modelling risk propagation.

In this section, the conceptual framework for SCRM is introduced following a systems perspective. The systematic development of the framework was achieved following standard risk management processes; risk identification, risk assessment and risk mitigation as seen in Figure 28. The reason for developing a framework was to propose a methodology for SCRM by capturing micro activities involved in each stage. Though the proposed framework follows processes that are identical to a standard risk management process, the difference lies in its approach to the problem where systems thinking principles develop the framework for a holistic risk management study. The conventional risk management process does not specify multiple activities involved in each stage of risk management. To capture the intricacies involved, two stages were developed for each process during data experimentation. Each stage in the conceptual framework for supply chain risk management was improved through a continuous feedback loop system.

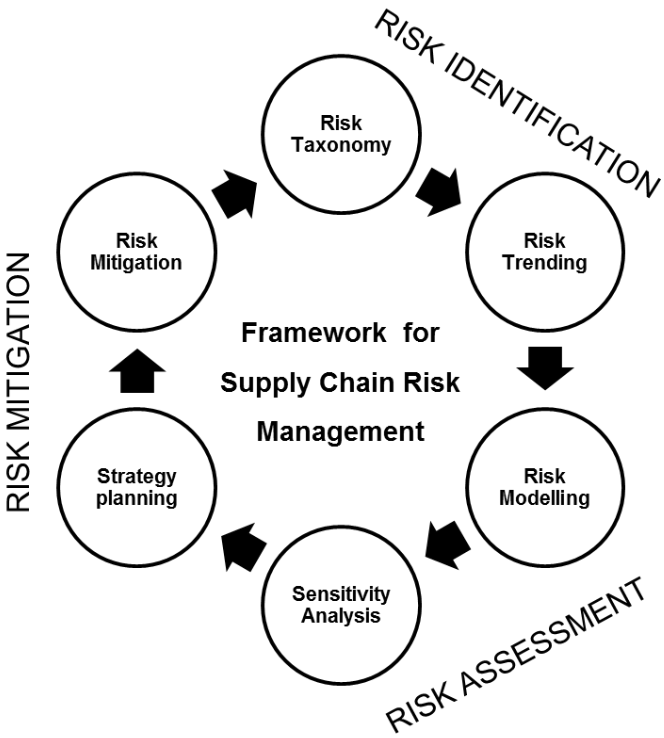


Figure 28: Framework for supply chain risk management

Risk taxonomy is the first stage in the framework where the risks are identified and classified from the pool of risks. Risks trending, the second stage in the risk identification process is for predicting the operational boundaries of the risk variables.

Risk assessment process is the major focus of our research and hence presented exhaustively in this as well as in the next chapter. Risk modelling and sensitivity analysis are two activities identified for the risk assessment process. Both theses stages attempts to evaluate the overall performance of the risks.

The risk mitigation process is classified into two stages as strategic planning and risk mitigation. Strong inferences drawn from risk trending, risk modelling and sensitivity analysis provides directions for the risk mitigation. New risk mitigation strategies identified from the study are utilized for future projects.

The systematically developed framework for SCRM (Figure 28) is believed to capture the overall nature of risks through a structured study. All the activities described in the conceptual framework are structurally followed for modelling supply chain risks in the later part of this research by validating its practicality with the collaborative case study. The methodically designed framework for SCRM is expected to capture the overall nature of risks. All different stages from the framework are discussed systematically for predicting the overall behaviour of risks in the following section.

6.1.1 ST for risk classification

Risk classification is the first stage during any risk management activity. Most of the researchers and practitioners in SCRM follow risk identification as the only activity for risk classification process; but that does not capture a holistic picture of risks in terms of identification, classification and general behaviour. Every system is different in its operation and hence the involved complexity in it. Risk taxonomy and risk trending are two stages introduced during the risk classification process in the proposed framework.

1. Risk Taxonomy

Risk taxonomy can be defined as the method for facilitating the methodical and repeatable identification of risks associated within a given system (Carr *et al.*, 1993). This particular activity is important and needs to be comprehensive and consistent for the best process output. The first stage of the framework for SCRM is to identify and classify the risks based on causal (relational) attributes.

There exists several risk classifications in the SCRM literature as discussed in Chapter 2. Risk itself is termed as disruption, vulnerability, uncertainty, disaster, peril and hazard in SCRM literature. The SLR on SCRM, identified that the risks classification should not just be based on the sources of risks. The literature of ERM and systems thinking considers the concept of 'system of systems' where the enterprise or a larger system like the one similar to supply chain is considered from a strategic (macro) as well as an operational (micro) perspective. In order to achieve this, the risks are classified based on multi-dimensional causal relationships. This is not just limited to classifying the risks based on its risk sources but also taking into account other important interdependent factors such as work activities and business practices undertaken at an organisation. For developing appropriate risk taxonomy, the literature from ERM as well as SCRM was considered. Blome and Schoenherr (2011) remark that although SCRM and ERM are often perceived as separate functions, SCRM is still an important element of ERM. Supply chain risk management to a certain extent is comparable with project/enterprise risk management as all of them consist of several nodes of network-interconnected working together for a single objective. Hence, the approach to risk classification is built on the principles of ERM and SCRM literature.

"*Enterprise risk management is defined as a process applied in terms of strategy setting across the enterprise, designed to identify and manage potential events that may affect the organisation to provide reasonable assurance regarding the achievement of set objectives*" (COSO, 2004).

The aligning link between ERM and SCRM processes has received very limited attention in the existing research literature (Blome and Schoenherr, 2011) however, the research on risk management has evolved into numerous distinctive fields like financial risk management, healthcare risk management, project risk management, supply chain risk management, etc. (Harland *et al.*, 2003; Handfield and McCormack, 2007). The 'enterprise architecture' based classification from Burtonshaw-Gunn (2008) was adopted for identifying supply chain risks as it provides a systematic approach to selecting and recording unclassified behaviour of risks. Enterprise architecture is further classified as business and system architecture as previously seen during the classification. The business architecture represents the most important work activities and assets in an organisation along with the organisations core business practices as the primary set of requirements (Burtonshaw-Gunn, 2008). 'POLDAT' is abbreviation for Process, Organisation and Location, Data, Applications and Technology. These six attributes are '*spheres of change*' that help in identifying the commonalities between activities, issues, solution fits within a system (Burtonshaw-Gunn, 2008). These six risk attributes constitute the portfolio of risks based on causality found in the enterprise or supply chain. American Computer Services Corporation first used 'POLDAT'- a hexagonal model developed for the process improvement (Burtonshaw-Gunn, 2008). The use of the process improvement model for risk classification is expected to provide the systematic approach for capturing the risk behaviour within SC network.

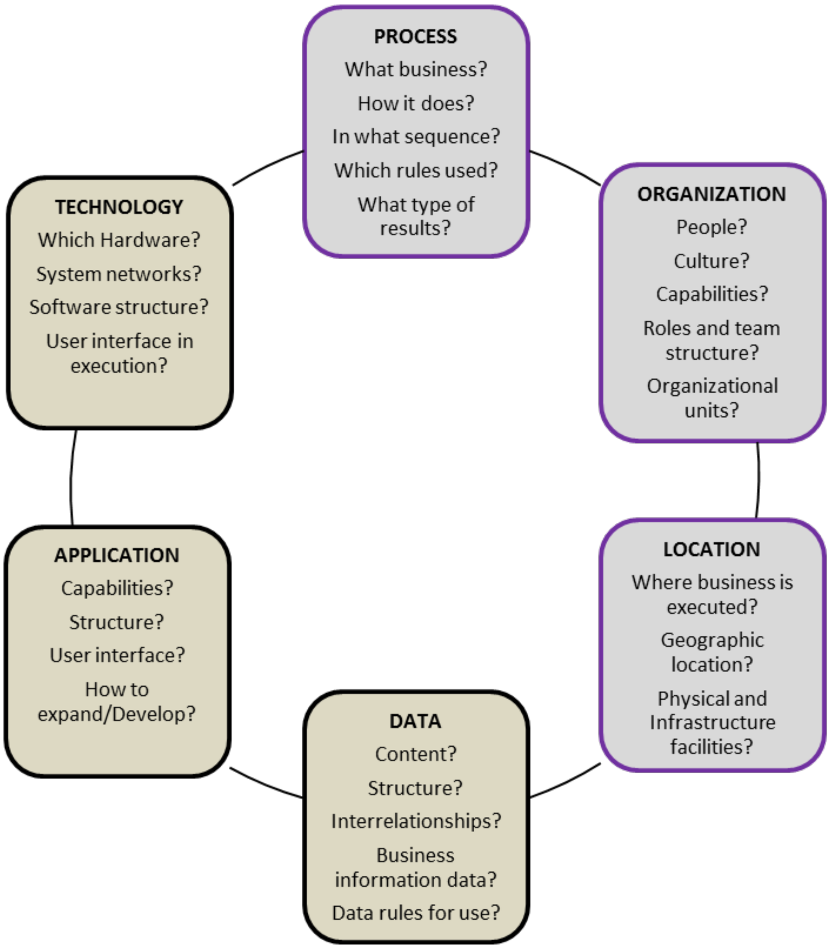


Figure 29: Enterprise based POLDAT methodology

(Source: 'The essential management toolbox: Tools, models and notes for Managers and Consultants. S A Burtonshaw-Gunn, 2008).

Following the classification based on the enterprise architecture discussed above, risks were classified based on business and system architecture attributes. Business and System architecture together comprises of six attributes referred to as 'POLDAT'. Business architecture comprises of Process, Organisation and Location attributes whereas System architecture comprises of Data, Application and

Technology attributes. Risks are selected from the pool of risks by comparing questions associated with POLDAT attributes. Figure 29 shows the comparing questions associated with each attribute in business and systems architecture.

2. Risk Trending

It is important to understand the fundamental or generic behaviour of risks before understanding the overall risk performance. The classified risks are then analysed to draw a preliminary understanding of the risk profile i.e., identifying (upper and lower limit) 'zones of operation' observed for each risk variable. It is understood that every project is expected to behave independently and may have different operational limits. However, the risk is a financial liability (McCarthy, 1996) and hence it is important to define the limitation of liability. The operational limit also represents the worst-case scenario for driving insurance policies and project budgets. Upper and lower limits of probability of the event and its impact in terms of cost and delay are crucial parameters for the risk assessment process as they define the boundary of the system under study. Quality (of products and services), cost and delivery offered by the organisation are the most important key performance indicators affecting the business performance (Ghobadian *et al.*, 1994; Atkinson, 1999). At the same time cost, customer responsiveness, quality and flexibility are most important supply chain modelling performance measures (Beamon, 1999). Quality and service associated with the customer responsiveness measure is assumed to be the function of either cost or delay (delivery time) in this risk assessment process. Gunasekaran *et al.* (2004) identified that the quality and service can be improved or controlled by additional cost or time.

The two stages for risk classification are formed to capture the bigger picture associated with the risk classification process.

6.1.2 ST for risk assessment

Following the proposed framework for SCRM, the risk assessment process also involves the activities in two folds. The risk modelling activity focuses on the design of risk models and conducting the assessment. The risk modelling assessment conducted during this stage is superseded by sensitivity analysis. Sensitivity analysis is the study of how the variation in the output of a mathematical model can be attributed to different variations in the inputs of the model (Saltelli *et al.,* 2008). This is conducted in order to study the behaviour of risks from all possible directions. The analysis looks at the variation in one or more than one parameter changes affecting the complete system.

1. Risk Modelling

The analysis conducted during the risk classification process provides the directions towards important considerations necessary for modelling risks. In order to model the risk propagation phenomenon, it was essential to build the model for capturing the overall impact of disruption. The Supply Chain Risk (SCR) model forms the building block for conducting the risk assessment process. Findings from the previous case study were combined at this stage for modelling the SCR model. The model is believed to be capable of capturing the overall impact in terms of cost and delay along with the failure point(s).

The developed SCR model is like a ‘system’ combining the risk theory and practical mechanism required for the risk modelling. The model as seen in Figure 30 considers a risk event triggered with an anticipated probability. With this given probability, it is expected to have a low or high impact on the supply chain system. In order to define the impact created by the risk event, a control feedback is provided which will calculate the impact just once (as high or low) depending on several parameters considered in the modelling. Although a risk event is assumed to be disrupting only once, in reality the risk impact propagates over periods and levels as seen in the previous chapter. The developed model is not designed to capture the cascading phenomenon of disruptions into levels and is limited to capturing risk propagation in periods.

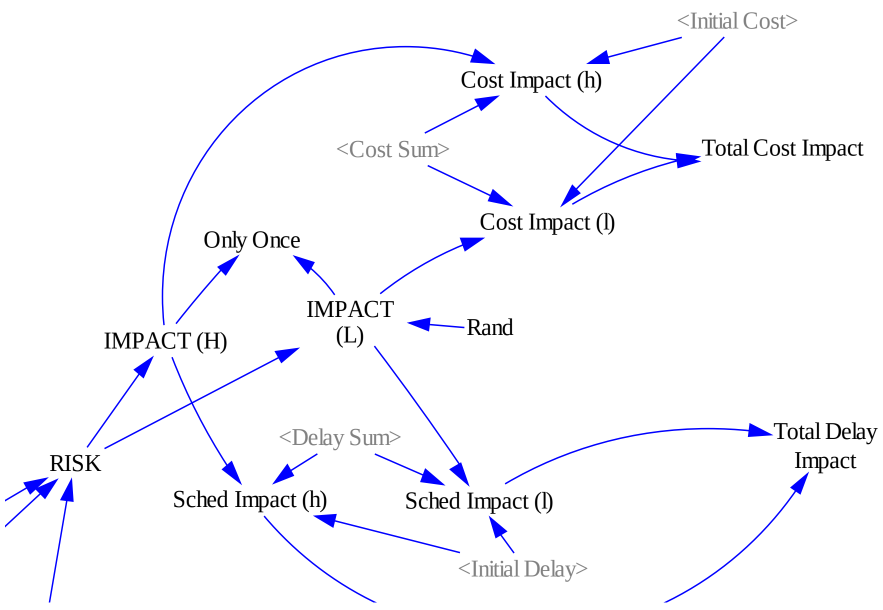


Figure 30: Supply chain risk model

The system model can either trigger a low or high impact condition for varying risk probability. This provides a condition for the risk to occur at a reduced impact providing early warning for disruption and for possible mitigation action. At the high condition of impact, the probability reaches 100% (or more) and remains unchanged indicating the full extent of disruption, providing no opportunity for the risk mitigation. ‘'Risk' is an input to the model taking into account different sets of risk attributes and parameters. The input requirements for the model to function are a combination of risk attributes and the anticipated values of probability, cost and delay at the start of project. The model then considers the combination of risk attributes and their behavioural patterns to model the overall impact. Random integers are fed during this stage into the model to control the impact. The impact of the risk event could be high or low depending on the forces acting during risk propagation. This is presented in the model as high or low with a constraint that either one occurs during each risk event. The modelling of risk propagation is further expanded to capture the impact in terms of cost and schedule. The model later considers two scenarios for cost and schedule (as high and low). The accumulative impact in terms of cost and schedule over different periods is calculated as total cost impact and total delay impact respectively.

For the smooth functioning of the model, projected or anticipated values for initial probability, initial cost and initial time (delay) need to be provided to activate the system. The system model automatically considers the previous parameters for measuring the impact for next period. The overall cost and time (delay) accumulated over the period is represented as total cost and delay impact. Based on this underpinning concept, risk modelling is performed to predict the behaviour of risks in a SC network. Application of SCR model and associated analysis is provided in next chapter using the collaborative case study data.

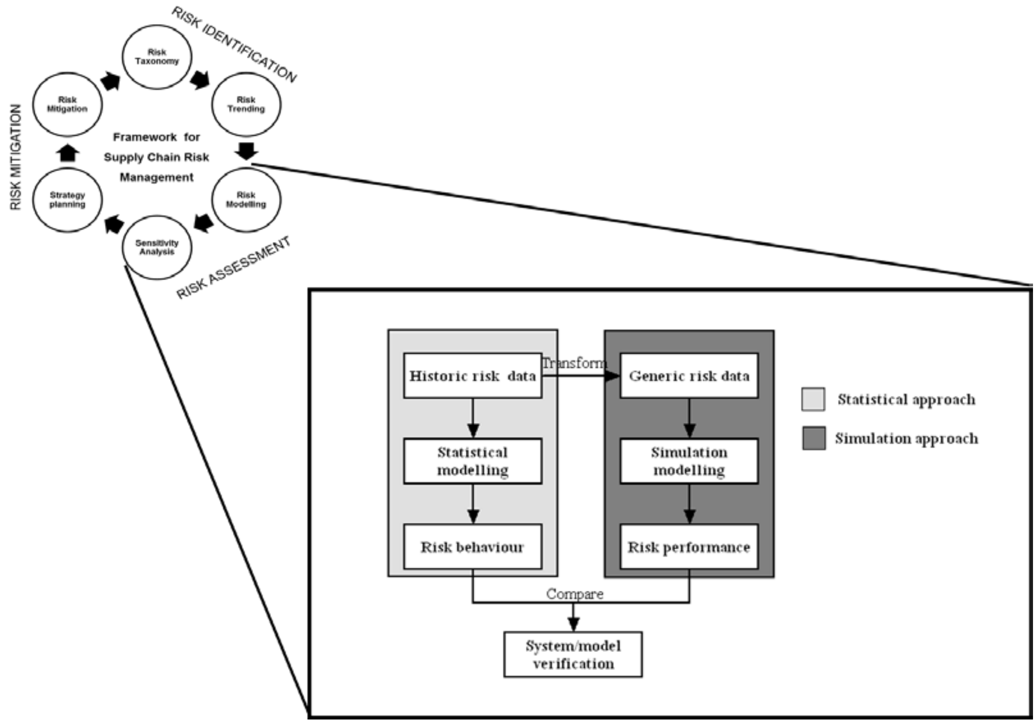


Figure 31: Research design for risk assessment

2. Sensitivity Analysis

Sensitivity analysis supports in the modelling process in two different stages. Parameter sensitivity analysis is used for validating the variation level in modelling parameter assumptions. This helps to reduce the error tolerance within the model. Identifying the variables that have a significant impact on model performance requires a robust or re-addressed input relationship. The second stage is called as evidence sensitivity analysis, which forms the later stage during the sensitivity analysis. This is conducted when it is found that the modelling representation is providing expected response to the modelling assumptions. This stage is used when first stage of sensitivity analysis is accepted and forms subsequent stage of sensitivity analysis. Evidence sensitivity analysis can be extended to become the succeeding modelling prediction analysis for the micro-level analysis.

For a systematic, holistic and quantitative risk assessment process, a research design is proposed as seen in Figure 31. Detailed information regarding conceptual research design for the risk assessment process is explained later in the chapter.

6.1.3 ST for risk mitigation

The risk mitigation process closes the loop in the framework for SCRM. The risk mitigation process is divided into strategy planning and risk mitigation stages. With the help of risk modelling and sensitivity analysis, risk managers can develop their strategies for the set of risk attributes instead of dealing with each risk independently. The modelling platform is expected to provide a unique ‘early warning system’ for unpredictable risk events for effective risk control and mitigation. The system also can be used during risk recovery by reactively providing the understanding of the most influential risk attribute and their inter-relationship in cascading the risk(s). This information is vital for reactive strategy planning and risk mitigation process for quick recovery from the disruption.

1. Strategy Planning

Strategy planning is an important stage in the risk mitigation process as it draws interpretations and adds new knowledge to the overall risk management process.

Strategy can be described as the planning and configuring of the organisation for future stakeholder's expectations (Mangan *et al.,* 2012). Strategy planning in SCRM follows a top-down as well as bottom-up approach. Anderson *et al.* (2007) identifies seven generic key actions for successful supply chain management as defined in the supply *chain management review* journal:

1. Customer segmentation
2. Customize logistics network
3. Listen and align to market demand
4. Product differentiation
5. Reduce total cost of ownership
6. Development of technology driven supply chain strategy
7. Adopt channel-spanning performance measure

These actions are very much related to some of the common strategies currently being used in supply chain management. Product differentiation, Just in Time, Vendor Managed Inventory, and Postponement are effectively used not just to make supply chains efficient but also to mitigate the risks within the SC network.

The system feedback obtained during the risk identification and risk assessment process guides in developing appropriate supply chain strategies to mitigate risks. The understanding drawn from past projects and risk events can further develop the ability in deciding the right strategy for different risk conditions. For proactive as well as reactive risk mitigation, agility, flexibility, responsiveness and preparedness are ideal generic strategies (Ponomarov and Holcomb, 2009). Based on the fundamental understanding of risk behaviour, risk managers can leverage on agility or flexibility to develop their proactive mitigation strategies. Risk management options can vary depending on the decision-making capacity of the risk managers. Manuj and Mentzer (2008) suggest risk management strategy options as avoidance, control, sharing and transfer. Risk avoid option is suitable for known-known risks like quality risk. Quality related risks are identifiable and known to impact in poor product service and recalls. This is a known risk with known effect and hence can be avoided with appropriate risk mitigation strategy.

2. Risk Mitigation

The risk mitigation approach can be either proactive or reactive but the choice of risk mitigation option could vary depending upon the nature of risk and decision-making capacity. Risk transfer, risk sharing, risk avoid (control) and risk accept are the decision making options and they depend very much on the behaviour of the risk as well as on risk managers decision making capability within the organisation.

In the next section, the research design of risk assessment is proposed for capturing the holistic picture of behaviour of risks with help of different modelling platforms developed.

6.2 Research design for risk assessment

The research design implemented for the risk assessment is based on the application of systems thinking concepts. The systems thinking approach provides a structured development process from conceptualisation to the end of system life cycle

(Forrester, 1961; Forrester 1994; Sterman, 2000). Tools like simulation/system dynamics and different algorithm modelling have the potential to capture static as well as the dynamic behaviour of supply chains. Following the systems thinking approach, a systematic experimental research design for risk assessment is developed and implemented in this section.

The research design for modelling supply chain risks primarily focuses on the risk assessment process in the developed framework for SCRM. Empirical research designs use statistical analysis, OR modelling and simulation techniques to draw the results (Luna-Reyes and Anderson, 2003). Figure 32 shows the developed research design for modelling supply chain risk propagation phenomenon. It implements two distinctive approaches for evaluating the complex risk behavioural performance. The left side is termed as ‘statistical approach’, for behavioural risk assessment and right side is termed as ‘simulation approach’ for exploring the risk performance. Both modelling platforms run parallel to each other during risk assessment process and are combined later to extract comprehensive results.

The historical risk data can be analysed following a statistical approach and generic risk data can be analysed using the System Dynamics (SD)/ simulation approach. Forrester advocated the use of computer simulation instead of mathematical models to learn about the system’s modes of behaviour and design policies to improve the system performance (Lane, 2007; Vennix, 1996). Richardson and Pugh (1981) suggest that system dynamics considers ‘feedback’ and ‘delay’ in the system behaviour and hence the system structure is very important to understand system behaviour. The reason for the two modelling approaches or structures used was to test

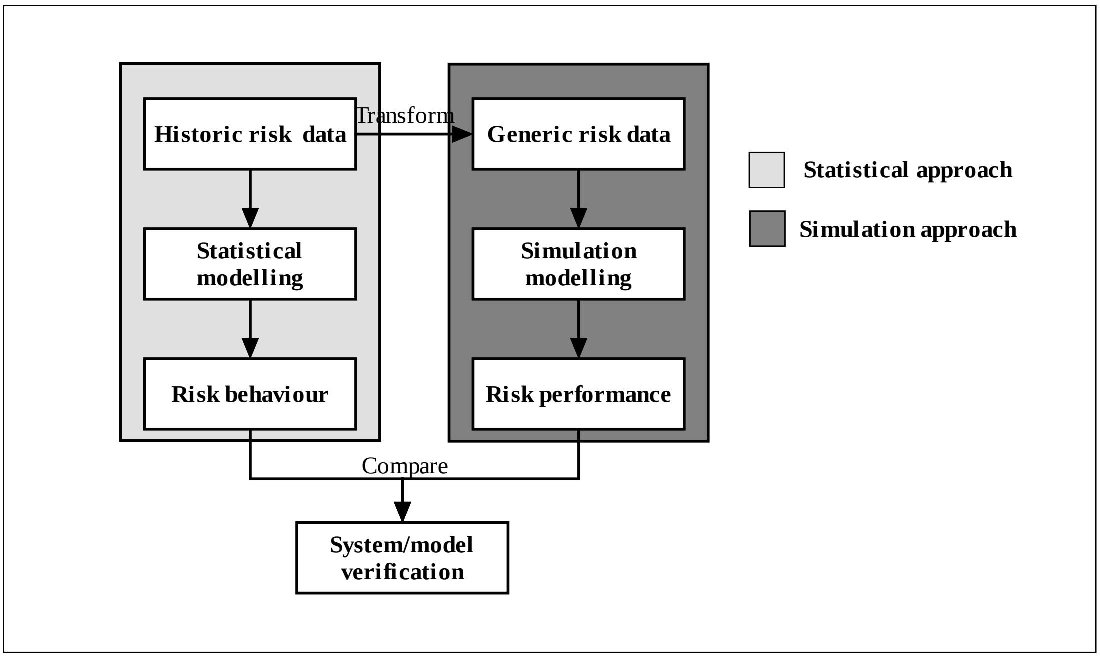


Figure 32: Research design

and validate statistical as well as empirical relationships between supply chain risks. Two distinct approaches were believed to facilitate critical insights through cross-comparison and combination of the results, as it is difficult to comprehend it individually. The SD simulation model for measuring the overall risk performance can be modelled using simulation platform named Vensim©, a commercial discrete event simulation software. The findings from the two different risk assessment approaches are collated and compared for comprehensive risk assessment.

6.3 Collaborative case study

In order to test the proposed modelling platform for risk propagation, a joint collaborative project between Loughborough University and a reputed Aerospace and

Defence organisation was developed for modelling risks in the supply chain network. The objectives of the project were set through several meetings between Loughborough University and Aerospace and Defence organisation before the start of the project. Several informal interviews were conducted to understand the research gap in supply chain modelling from industry perspective. The need to move from a traditional risk management approach to optimised risk management approach was one such finding identified through the interviews. The knowledge gap in identifying, classifying the risks and analysing them based on their impact was also found to be lacking in industry. The commonalities observed in terms of industry requirements and identified research problem provided the necessary directions for modelling and validating the risk propagation within supply chain network. This collaborative project generated the ideal platform for experimental research whilst working with the risk manager and system engineers from the organisation. The data collected from the collaborating organisation was utilized to validate the proposed modelling platform for risk propagation. The modelling platform consisting of the framework for SCRM, Supply Chain Risk (SCR) model and quantitative research design for risk assessment were tested in an industry environment through a collaborative case study.

Earlier build concepts associated with risk propagation were also utilized during this experimental testing. As an output from this collaborative case study, the participating organisation was looking for a systematic approach for risk modelling for their future complex projects.

6.3.1 Preliminary data analysis

A reputed Aerospace and Defence organisation from UK was used as a platform to model and test the supply chain risk propagation phenomenon. This organisation is a global leader in aerospace and defence with more than 107,000 employees worldwide. The company delivers a variety of products and services for multiple customers for their air, land and naval defence support. The organisation also builds advanced electronics, security, information technology solutions and associated support services. This collaborating organisation has its supply chain network spread across the world. The typical nature of supply chain activities for this organisation involves design, manufacture, delivery and after sale maintenance of the product. Several informal meetings were held with the organisation to discuss the research problem and to understand further the gap in supply chain risk modelling from industry perspective. The case study was initially developed with the preliminary data analysis as a 'proof of concepts' to see if the data is appropriate for interpreting the conceptualized phenomenon. Inversely, it also supported in the preliminary validation of the developed concepts.

The data collection for the experimental approach can be in a wide variety of formats. This can be in the form of documents, reports, registers, spread sheets, audio/video recordings etc. Qualitative as well as quantitative data was collated from different internal projects conducted within the collaborating organisation. The project data inherently represents a product development environment within a supply chain. Some of the data was in the form of the risk register and other relevant data was collected over a period of active association. The quantitative risk register data was supported with qualitative data in the form of informal interviews and the secondary data made available from company in form of reports and internet sources. Initially the project risk data was thoroughly studied and transformed into a form required for the experimentation as seen in Figure 33. Inputs from the informal discussions with the risk managers were further integrated to comprehend their understanding of possible risk impacts and severity of the events. The reports made available supported in recording the events and their impact in terms of cost and delay over the running of the complete project. For a comprehensive study of behaviour of the risks, the available data was screened by filtering confidential information associated with the collaborating organisation to form a 'Risk data register' (Figure 33). Two other people from the collaborating organisation were also actively involved in this experimental study for providing guidance and support during the different stages of the research. In order to bridge the findings made from the qualitative and quantitative data sources, the Delphi method was utilized for arriving at a common consensus. The Delphi method is a commonly used research method for data dissemination and learning. The Delphi method is used to obtain a reliable consensus of a group of experts with a controlled feedback system (McKenna, 1994). This structured technique is believed to work well when the objective is to improve the understanding of the problems and solutions (Skulmoski *et al.*, 2007). Thus, the data available in different (qualitative and quantitative) forms was transformed into ‘quantitative’ historical risk data. This transformed risk data comprised of 30 risk events called ‘risk scenarios’ each having the description of the event discussing the type of risks observed and their probability, cost and delay changes over different stages/nodes in the project/network.

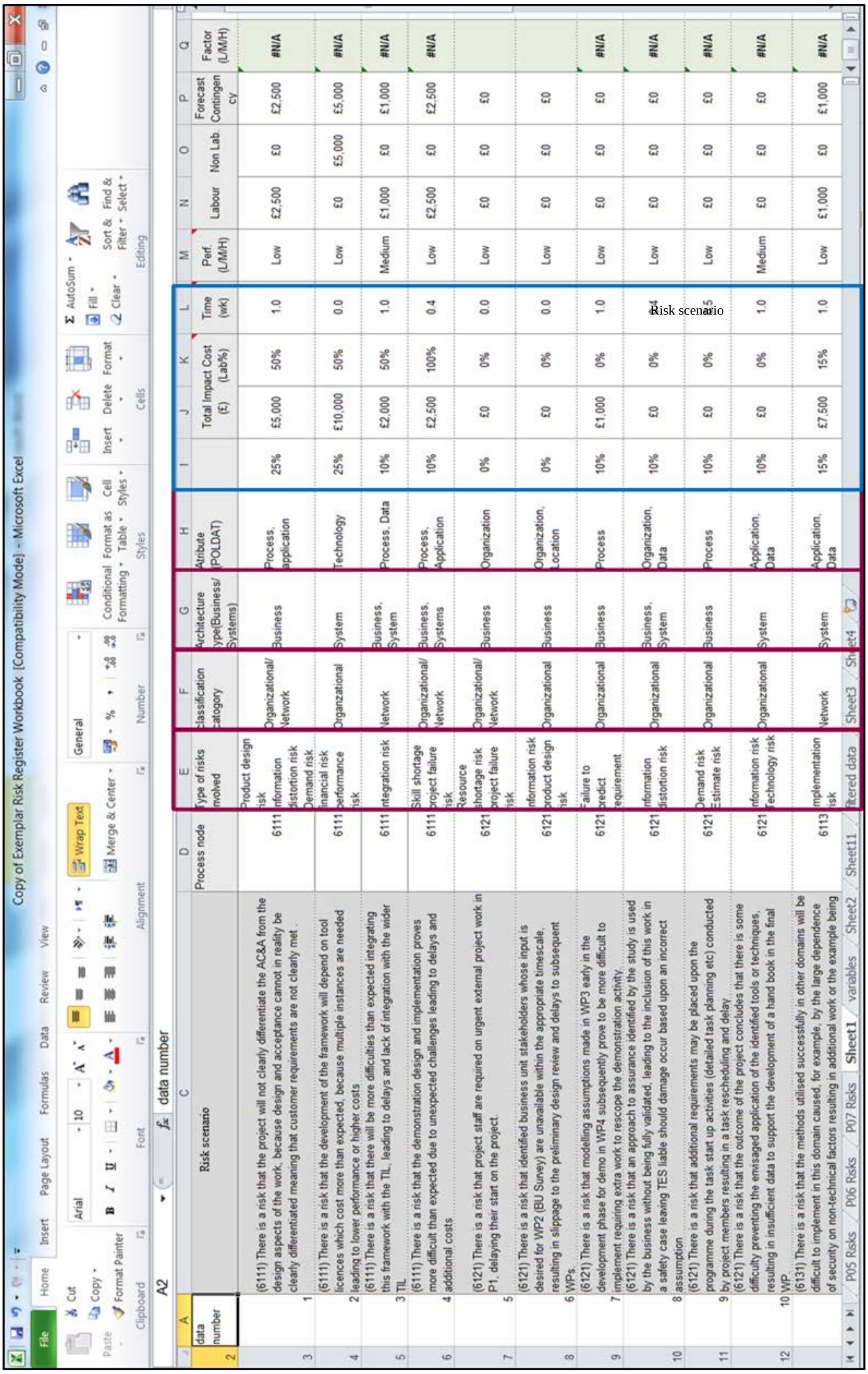


Figure 33: Risk data Register: Risk scenario and parameters

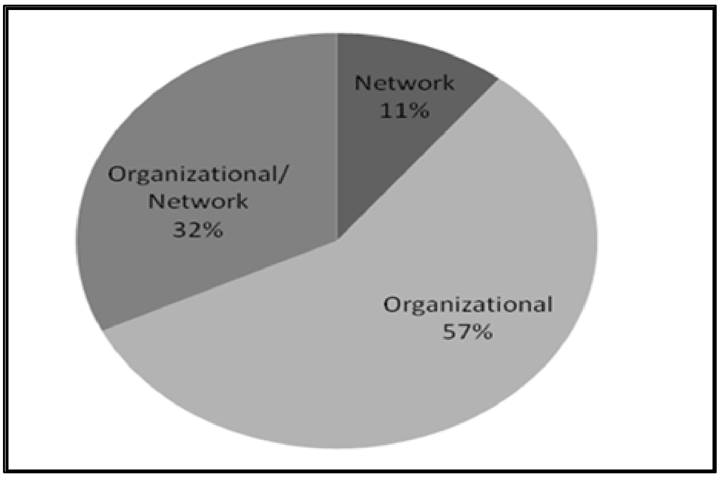


Figure 34: Risks: Based on classification

The proposed framework for SCRM was implemented to test its viability on the above data. To understand the fundamental behaviour of the risks during risk propagation a preliminary analysis was conducted. The basic intension of this study was to identify the static behaviour of risks expected for each risk parameter while interacting in the supply chain network. The data trending activity also involved classifying the risks following a standard risk classification as Organisational and External (or network) for a basic and mutual understanding of the risks. Using this fundamental approach to risk classification, it is observed from the pie chart shown in Figure 34 that the organisation and/or business related risks share half of all observed risks in the given database. External (network) and/or system related risks are mainly associated with organisational /business risks and form the latter half of the section. Few risk scenarios comprised of both kinds of risks and were identified separately and studied to look for interdependency and mutual impact in the latter part of the research.

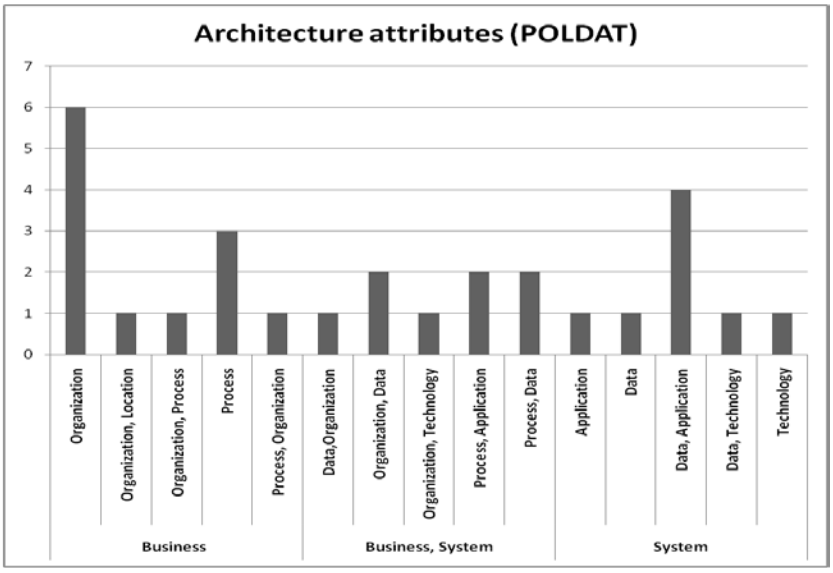


Figure 35: Classification: Business and Systems risks

During several meetings with the collaborative partner, it was decided to follow the enterprise architecture based classification for the future part of this research. The set of questions represented under each attribute in Figure 29 were applied to the different risk scenario's from the risk register to classify the risks. Based on this predefined risk taxonomy, some of the commonly observed risks identified from the risk scenarios are presented in Table 14 (Chapter 7). The nature of risks identified for each risk attribute is associated with either process or practice. Few risk events comprised of more than one type of risk attribute. In such cases, each risk was assumed independent with no appropriate distributions considered. This provides a good measure for classifying the risks as well as provides a direct indication towards particular process needing attention for an impending disaster.

The use of POLDAT classification as proposed earlier provided a systematic approach to selecting and recording performance of the risks. It identifies whether the risk is associated with the organisation, department or activity. It provides a basis of comparison with the same activities undertaken in different locations (attributes defined in Figure 29 and discussed extensively during the risk classification process). Following POLDAT classification, business and systems architecture related risks are further classified into its constituent architecture type as seen in Figure 35. A preliminary observation from Figure 35 shows that the business architecture related risks arise mainly from process and organisation based risk attributes. Whereas the system related risks comprise of data, application and technology based attributes. POLDAT classification is believed to follow the systemic approach for classifying the risks from different risk scenarios from a pool of risks.

The risks were identified from 30 different risk scenarios and later classified based on the developed risk taxonomy by referring to their association with different sources, activities and practices in organisation using POLDAT attribute based risk classification. In order to capture the fluctuation over a period or phase in a given supply chain network, a preliminary analysis using historical risk data was conducted.

The behavior of individual risk parameters namely probability, cost and time (delay) were captured as seen in Figure 36. The plot is drawn by considering the average values of individual risk parameters for 30 risk scenarios analyzed. The period-wise distribution for risk parameters depicted interesting perspectives. The average probability vs. periods plot showed that application, process and data attribute related risks had unusually high probability of occurrence. It is also interesting to see the drastic reduction in probability of risk in period/node three, whereas other parameters cost and duration had a drastic change in period/node four. In terms of cost, the technology and application attribute related risks showed the highest impact. The time parameter showed a random behaviour in terms of duration (delay).

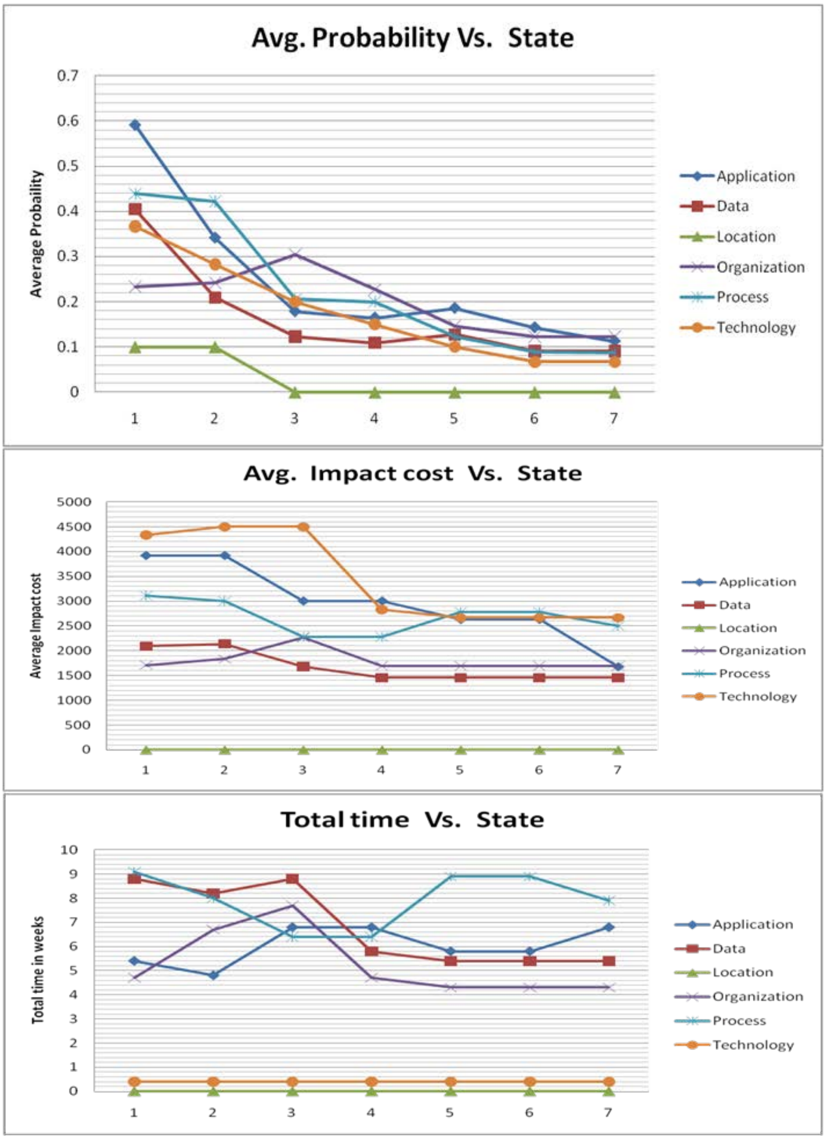


Figure 36: POLDAT phase-wise behaviour

The preliminary data analysis was mainly looking for plausible relationships or associations of different parameters interacting within the system. The preliminary study also focussed on identifying the trend/behaviour of particular risks attribute, important for consideration in the next level of analysis. The secondary analysis was followed using the preliminary analysis as a 'building block' and further looked at degree of correlation between different risk parameters.

6.3.2 Secondary data analysis

The secondary data analysis of the risk data was conducted for two purposes. One was to predict the distribution pattern of the risk parameters and other to predict the degree of correlation with other risk parameters. Different approaches were identified from the literature for predicting the distribution pattern of risk variables. All the approaches used for identifying the distribution pattern of risk parameters are discussed in this section. Some of the approaches (although discussed) did not provide the anticipated output and hence had to be rejected during the course of the research.

1. Multi axis chart

The multi axis chart is a three-axis chart commonly used for Engineering and Project management related data representations. The data from 30 risk scenarios was plotted by considering the average probabilities with average impact in terms of cost

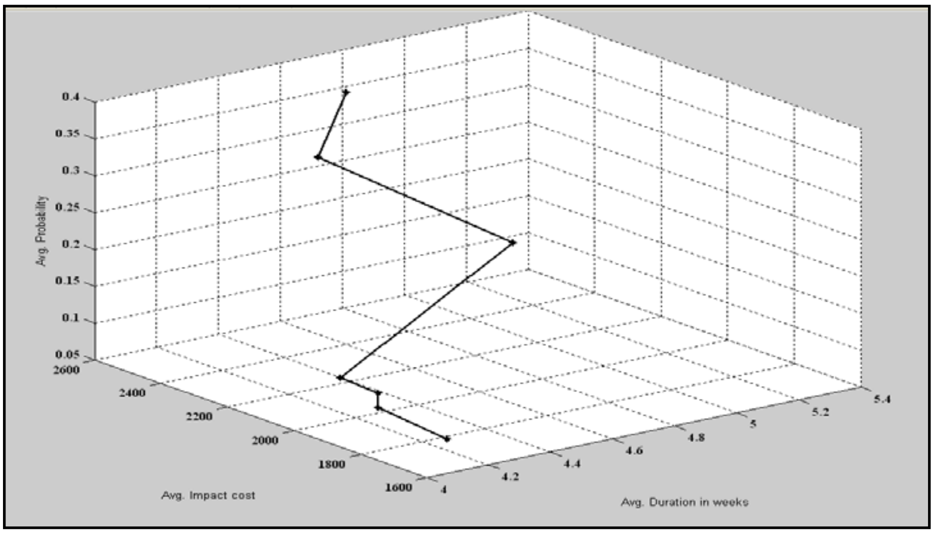


Figure 37: POLDAT general behaviour

and delay to see if there exists any significant correlation between probability and its impact. This would essentially provide the most common observed behaviour for disruptions during the project. Figure 37 does not bring any significant findings but represents the generic behaviour of risks for average values of probability, cost and delays on three-axis plot.

2. *Forecasting approach*

Can risks be forecasted similar to demand using the past data? Attempting to answer this particular question, forecasting concepts were used to predict the distribution pattern. Different forecasting methods are depicted in the literature to predict demand quantity (e.g. Aviv, 2002). The most commonly used and robust approach for periodic forecasting is the Holt–Winters exponential smoothing approach. The demand, in this case is the risk for the next rolling horizon, is forecasted based on the previous horizon. The Holt-Winters model used in this section of research is based on three smoothing factors- level, trend and seasonality (Winters, 1960). Using the Holts-Winters model, the risk is forecasted for the next horizon.

Accuracy of forecasting is identified by its tracking signal value. Past risk data was fed to the forecasting model. Figure 38 shows the overlapping of actual data with the forecasted data in the central part of graph. This is to check the validity of the forecasted data. Accuracy of the forecast is checked using ‘tracking signal’ value and it is found to be greater than 4 which is a poor sign of forecasting accuracy. The maximum limit for acceptability of forecasted value is 4 (Jacobs *et al.,* 2011). The forecasted vs. actual risk overlap provided no confidence for the next horizon. The forecasted vs. actual risk did not overlap as seen in Figure 38 and was a clearly a bad measure for predicting the behavior of the risk.

TIME SERIES FORECASTING
Curve fitting and model validation

MODEL TYPE: Seasonal
Level sm. const. = .80 Seasonal sm. const. = .40

Prd no.	Period label----------	Actual	Forecast	Trend	Sea-sonal	Error
15	Week 15	2,010.00	2,674.71		1.19	-664.71
16	Week 16	2,050.00	2,190.11		1.22	-140.11
17	Week 17	2,000.00	1,635.37		.96	364.63
18	Week 18	2,000.00	1,666.84		.83	333.16
19	Week 19	2,050.00	1,933.37		.83	116.63
20	Week 20	2,020.00	2,026.67		.83	-6.67
21	Week 21	2,100.00	2,266.17		.93	-166.17
22	Week 22	1,708.00	2,667.19		1.16	-959.19
23	Week 23	1,833.00	1,980.32		1.21	-147.32
24	Week 24	2,269.00	1,495.99		.97	773.01
25	Week 25	1,692.00	1,826.44		.84	-134.44
26	Week 26	1,692.00	1,703.32		.83	-11.32
27	Week 27	1,692.00	1,686.05		.83	5.95
28	Week 28	1,692.00	1,884.29		.92	-192.29
29	Week 29	3,111.00	2,089.23		1.12	1,021.77
30	Week 30	3,000.00	3,137.33		1.20	-137.33
31	Week 31	2,277.00	2,518.81		1.00	-241.81
32	Week 32	2,277.00	1,939.38		.84	337.62
33	Week 33	2,277.00	2,202.07		.83	74.93
34	Week 34	2,277.00	2,252.89		.83	24.11
35	Week 35	2,500.00	2,508.97		.92	-8.97
36	Week 36	4,333.00	3,133.28		1.15	1,199.72
37	Week 37	4,500.00	4,281.46		1.20	218.54
38	Week 38	4,500.00	3,690.13		.99	809.87
39	Week 39	2,833.00	3,692.91		.85	-859.91
40	Week 40	2,666.00	2,966.59		.84	-300.59
41	Week 41	2,666.00	2,710.24		.83	-44.24
42	Week 42	2,666.00	2,950.25		.92	-284.25

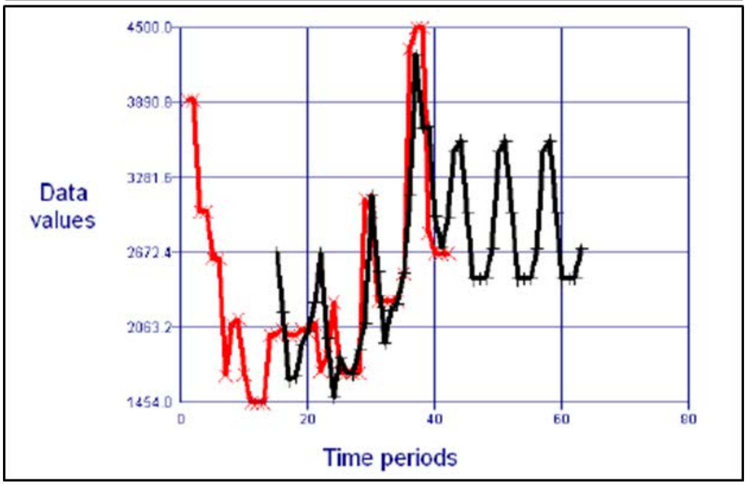


Figure 38: Forecasting technique

3. Scatter diagram

The scatter diagram is a collection of points showing the relationship between dependent and independent variables. Using 30 risk events data scenarios, three important risk performance variables namely probability, cost and time (delay) were studied for any possible correlation. The scatter points with the best fitting curve was plotted to observe the 'degree of correlation' between these variables.

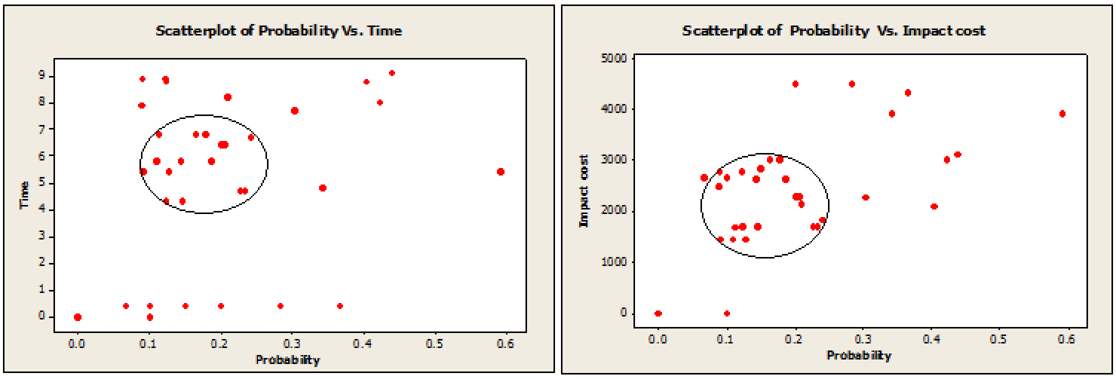


Figure 39: Scatter diagram

Probability vs. cost and probability vs. delay scatter plots were developed to find if there is significant correlationship between probability and impact (in terms of cost and delay). One of the important observations from the scatter plot was that there is 'no correlationship' between all the three risk parameters as seen in Figure 39. Based on this preliminary finding a proposition was developed to further analyse the results.

<u>Proposition 2</u>: Probability, cost and duration are independent of each other for a given set of risks.

It was interesting to find the pockets of accumulations in a specific range for probability, cost and time distribution. This range provided us with a most preferred operating range of risk parameters for a given dataset. The developed proposition was checked for its authenticity through other approaches used during secondary analysis.

4. Best fitting curve

The scatter plot depicts that there is no correlation between the three risk parameters. In order to cross-verify, we used the best curve fitting approach to the given data points. The behaviour of cost and time with respect to probability were plotted for all the risk scenarios. The scatter points obtained as seen in Figure 39 were later analysed for obtaining possible correlations between different risk performance variables. Minitab©, a commercial statistical and process management software was used for generating the risk trending results. The best fitting curve attempts to obtain the possible degree of correlation, providing useful information for resource allocation during the project planning activity. With a 95% confidence interval, the best curve fit for the given set of data was drawn. Quadratic curve equation as seen in Figure 40 captures the points. However, based on the 'goodness of the fit' the curve fitting has to be rejected due to lower value of R^2. R^2 ('coefficient of determination') is a statistical measure of how well the regression line approximates the real data points and is a measure of the 'goodness of fit' for the estimated regression equation (Anderson *et al.*, 2007).

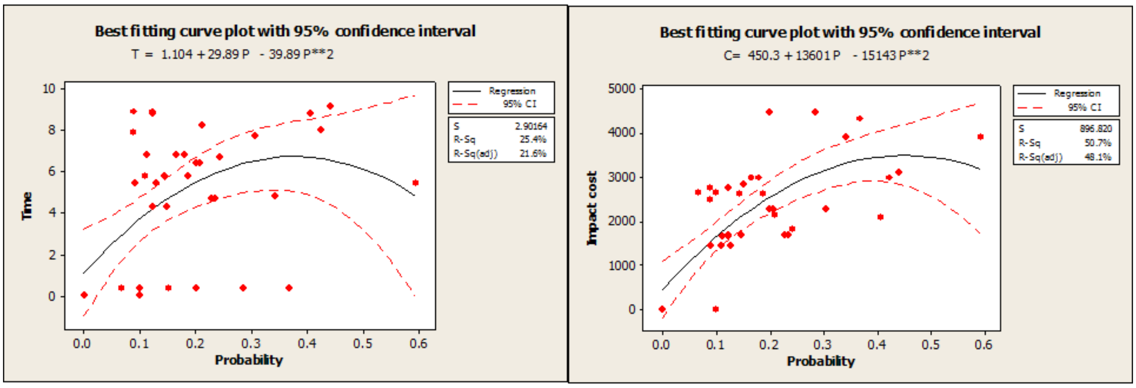


Figure 40: Best fitting curve

Lower values of R^2 were found for probability versus time and probability versus cost data points. Goodness of fit indicates whether it is reasonable to assume that a random sample comes from a specific distribution. None of the best-fit procedure is guaranteed to generate a correct solution for arbitrary relationships. This is evident from the Figure 40 and hence the proposition holds true. Analysis concludes that, the probability, cost and duration are independent of each other for given set of risks in the project.

5. Probability density function approach

It is crucial to predict the right probability distribution fit for transforming historic risk data into generic risk data for further risk assessment. Another approach was utilised to predict the behaviour by identifying the probability distribution pattern of the risk performance variables. A commercial data analysis and simulation software provided by Mathware named Easyfit© was used to generate a probability density function and later to produce the random numbers. Figure 41 shows the snapshot of the Easyfit software used for identifying the best probability distribution function based on goodness of fit test. Following group consensus, check for 'goodness of fit' for risk distributions was undertaken using a Chi-Squared test. 'Goodness of fit' tests whether data taken as a whole is uniform and consistent (Oakshott, 1997). The Chi-Squared test is used to determine if a sample comes from a population with a specific distribution (Anderson *et al.*, 2007). The identified probability distribution pattern for each risk attribute over a period was later used to generate the random numbers for generic risk data.

No universal best-fit procedure is guaranteed to provide a correct solution for the random relationships (Ortells, 2011). As discussed previously, this analysis was conducted with an intension to see if there is any significant correlation between the three risk performance variables. Probability density function approach was found to provide the behavioural trend or pattern through an equation as seen in Figure 42.

Probability, cost and times (delay) were observed to be behaving independently of each other for the given set of risk events and this was confirmed through earlier approaches. This means that even with the high probability of an event, there may be less likelihood of impact on either cost or time (delay) and vice-versa. With this crucial finding, further modelling of supply chain risks was developed. The assumption that the risk variables behave independently and do not influence each another was set for the later part of the research.

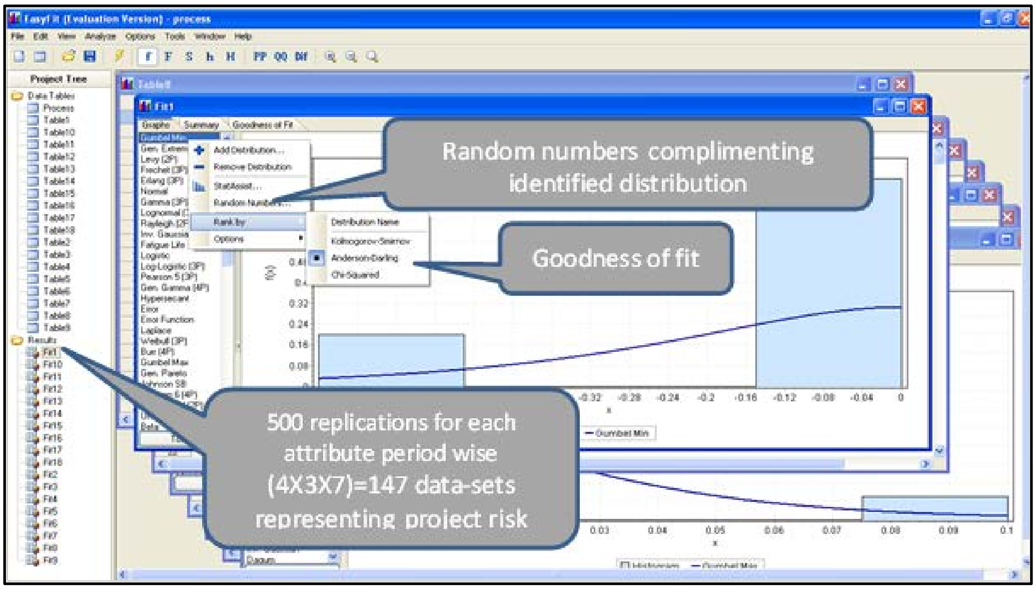


Figure 41: Snapshot: Distribution fit and random number replications

These small but crucial findings were presented to the collaborating partner and further discussed during the focus group meetings. Other statistical findings made by a statistical consultant in the focus group also complimented our findings. Hence, the risk behaviour for the project was assumed independent for future risk modelling. Risk parameters behave independently and each has a distinct risk profile and distribution. Predicting risk profiles is essential for replicating risk behaviour in form of random numbers during risk modelling.

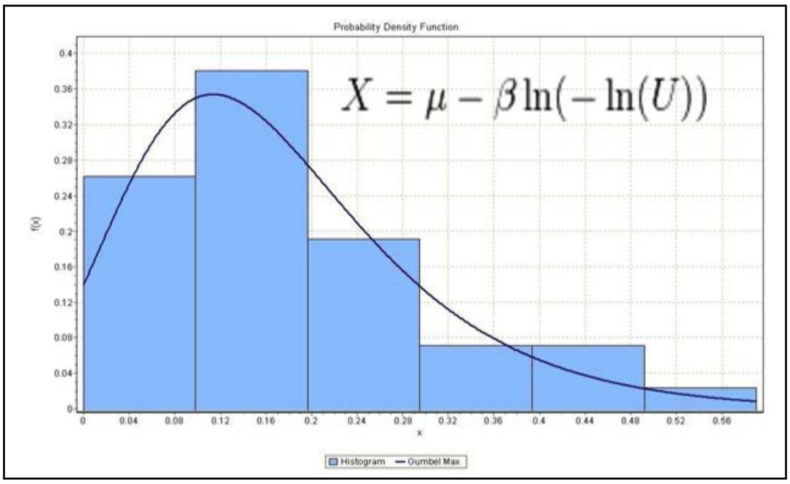


Figure 42: Probability density function

It can be inferred from the primary and secondary analysis that it is fundamentally important to predict the static behavior of risks before looking at modelling the dynamic behavior of risks. The results not only justify this through multiple approaches but also supports in developing a robust process for the risk modelling and analysis. The primary and secondary data analysis supports an important aspect of the systems thinking approach, where the problem is holistically studied to capture important patterns, interactions and trends. The understanding built on the above study was utilized to develop the next stage of the risk propagation modelling.

Chapter 7 Assessing Risk Propagation

The chapter validates the risk modelling theory developed in the previous chapter. The statistical and simulation model systematically follows SCRM framework, supply chain risk model and research design for assessing the holistic behaviour of risks. The sensitivity analysis compliments and supersedes the risk modelling activity for drawing comprehensive results. Attribute and parameter based sensitivity analysis provides a dynamic analysis of the behaviour of risks within the SC network. The combined results support in demonstrating the validity of the developed theory for modelling the risk propagation.

7.1 Risk classification

The questions represented in each attribute (refer to Figure 29) were applied to the different risk scenario's from the risk register to classify the risks as seen during secondary data analysis. For the risk trending activity, a 3D plot was used to represent the operating envelope for probability, cost and duration for the analysed project data. Figure 43 shows the static behaviour of the identified risks classified using POLDAT with their operating zones for different risk scenarios. The static behaviour provides first-hand information on the set of risks needing priority during the mitigation stage.

The historical risk data was later studied to predict the probability distribution pattern of the risk performance variables. Different approaches for identifying the probability distribution are discussed in the academic literature. It was identified earlier that, it is important to predict the right probability distribution fit for transforming the historic risk data into generic risk data for further risk analysis.

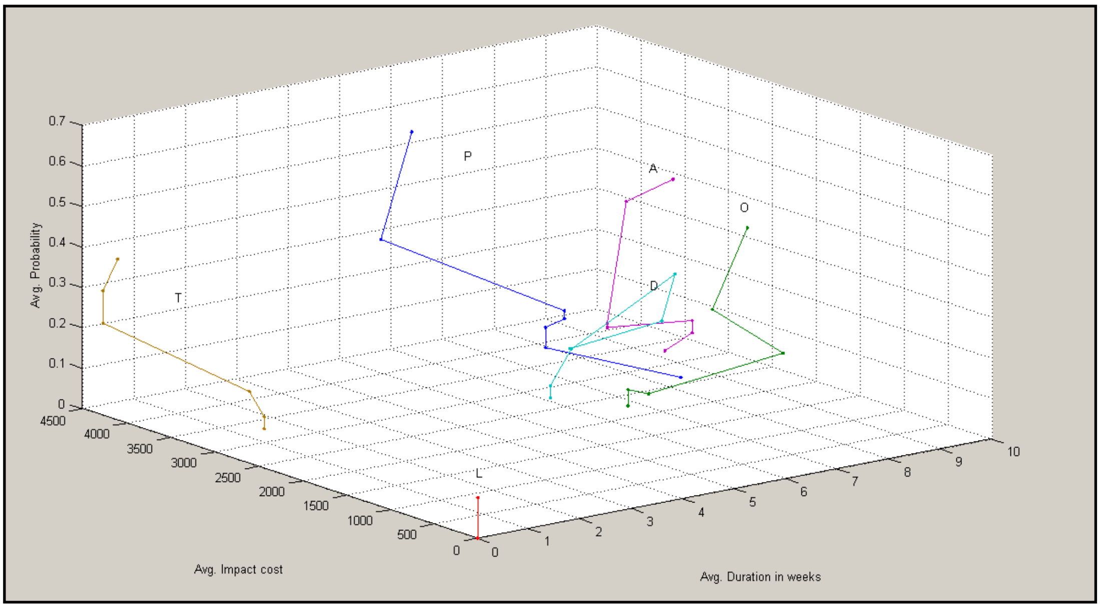


Figure 43: Risk trending: Static behaviour of risks (POLDAT)

The qualitative data on the risk trending behaviour was collected from two risk managers working in the collaborating organisation through informal discussion. Other qualitative data related to number of stages, their expected duration and risk operational limits for other past projects was collected through informal discussion with the risk managers. A focus group consisting of two researchers from SCRM and three practitioners from the Systems Engineering domain provided consensus for the observed risk trending behaviour. This was followed in three stages; the first focus group meeting did not derive any consensus but helped the group in synchronizing with the problem under study. The second and third meetings led to a consensus on the relationship of risk parameters. The focus group further supported in defining the boundaries of the system under study and suggested directions for the risk modelling. Earlier, the preliminary analysis on risk trending provided a single but very important consideration into the behaviour of risks. Modelling of risks during the risk assessment process was conducted with the proposition that the three risk performance variables namely probability, cost and time (delay) are functionally independent and do not influence one another directly.

7.2 Risk assessment

In this section, the framework for SCRM is tested for the risk assessment process. The validation for applicability of SCR model and research design for risk assessment is provided following the risk modelling and sensitivity analysis stages described below.

7.2.1 Risk modelling

The developed SCR model and research design are synchronized together during the risk modelling activity. The functioning of risk modelling is fundamentally based on the developed SCR model and follows the proposed research design for quantitative assessment. The developed SCR model is a ‘system’ combining the risk theory and a working mechanism for the risk modelling. The proposed research design is tested in the following section. Statistical modelling focuses on risk behaviour and simulation modelling looks at the risk performance.

Statistical modelling

Statistical modelling was conducted on the lines of the supply chain risk modelling theory discussed earlier. As discussed previously in Chapter 6, in order to develop a generic risk data set from the historical risk data, it is important to find the best probability distribution for the set of the data. Probability distribution was used for predicting the basic behaviour of risks during the risk identification process and was further used to extrapolate the historic risk data by reproducing random numbers. Random numbers are generated to replicate the randomness occurring in the stochastic environment system (Oakshott, 1997). The generated random numbers for the given probability distribution were used to replicate the real world risk conditions experienced in any industry within a standard supply chain network. This also gave the opportunity to generalize the risk behaviour for any project in order to overcome the limitations of the historic risk data. The generated random numbers were checked through a hypothesis testing for a sample size to prove that the random numbers generated for an identified risk probability distribution were not significantly different each time. This was done by generating five sets of random numbers for a single risk probability distribution and plotting them to see if there is significant difference every time the random numbers are generated for a given probability distribution. The process of random number generation is represented in Figure 41 (in the previous chapter).

The model is provided with input parameters as a set of risk attributes and initial expected probability, cost and delay to begin its working. Table 13 shows the process map of the activities for calculating the worst, average and best-case scenarios from the given set of risk data.

- The best case is the most ideal risk scenario where the event does not occur (mathematically represented as negative).
- The average case is the most likely outcome from the risk scenario for the risk event.
- The worst case is the predicted risk performance providing the approximate period and impact expected for the given risk event, if it occurs.

Modelling process chart	Description of the activity
1. Data decomposition	Risk scenarios/events are classified into POLDAT attributes.
2. Distribution Curve fitting	In order to predict behaviour over a period, identify the distribution fit for set of data.
3. Check for *Goodness of fit*	Chi square test: Goodness of fit tests indicates whether it is reasonable to assume that a random sample comes from a specific distribution.
4. Generate random numbers	Generate a random sample based on identified probability distribution.
5. Calculate: Median of sample size	This will give 'Normal case scenario' for risk predictability.
6. Calculate: 10 Percentile of sample size	This will give 'Best case scenario' for risk predictability.
7. Calculate: 90 Percentile of sample size	This will give 'Worst case scenario' for risk predictability.
8. Calculate risk propagation impact	Calculate the risk propagation by estimating initial (at the start of project) parameters for probability, Cost and Time (Delay).

Table 13: Process map for evaluating risk propagation

Statistical modelling is performed based on these three possible outcomes for the risk behaviour as best case (lower line), average case (middle line) and worst case (top line) as seen in Figure 44. In the statistical modelling the 'negative probability'

(Feynman, 1987) concept is utilized to understand three paradoxical cases. Negative probability thus can have a complementary probability greater than unity (Bartlett, 1945). Although practically unrealistic, in theory the overall risk probability may sometime overshoot above the 100% threshold mark due to combination of different mutually inclusive risk attributes.

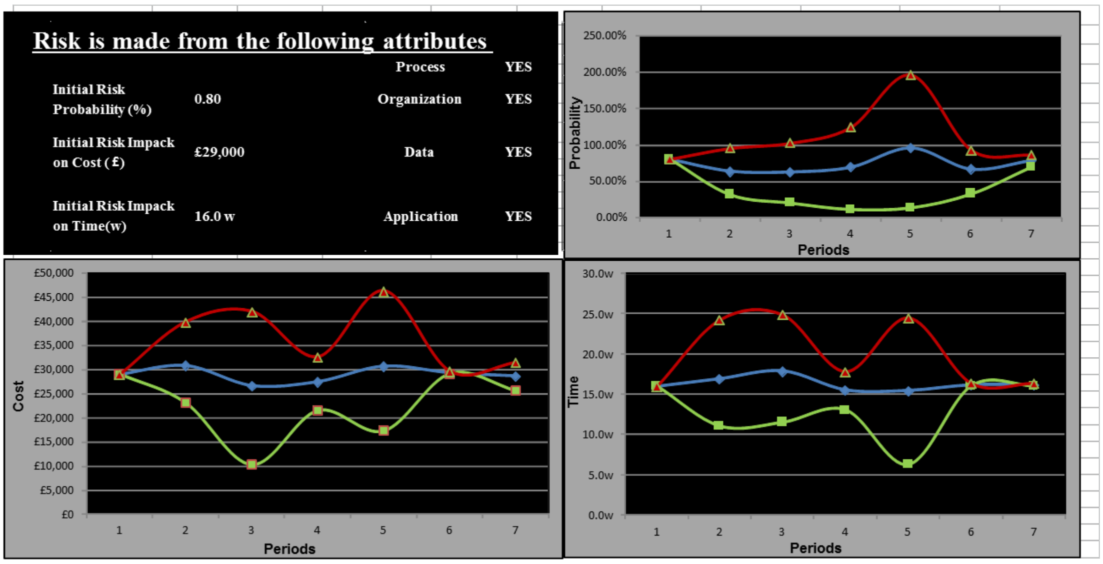


Figure 44: Statistical model for risk trending

The risk behaviour is plotted over periods representing three case-estimated changes in the risk profile from its given initial condition for probability, cost and time respectively. For the example considered in Figure 44, risk behaviour is captured with three possible outcomes showing cost, delay and probability changes during different periods when all four risk variables (process, organisation, data and application) are activated (shown as ‘yes’). The screenshot depicts the behaviour for this run when the cumulative impacts of all risks are taken into consideration. The three risk performance parameters behave independently as reflected in the statistical model.

Simulation modelling

The objective of the simulation modelling is to capture the dynamic interactions of different risk attributes in a supply chain. SD modelling captures the dynamics of different variables within SC by representing them into stocks and flows. The conceptual or mental model is transformed into a computer based simulation model by a structured development process. In the generation of a SD model, there are conceptually two components in consideration: structure and parameters. The structure provides the qualitative aspects of the problem domain. Whereas, the parameters provide the quantitative measures in the process of generating systems based models. Following the systems approach for the SCRM framework and SCR model, a causal loop diagrams is obtained capturing the inter-dependencies of risk attributes and performance variables.

Figure 45 shows the structure of the simulation model for one risk attribute (Organisation). All six attribute combine together to form a macro-structure for the simulation model. It follows three possible outcomes similar to the statistical model. Best, average and worst case is captured as a phase output. Probability of event and expected impact in terms of cost and delays is also captured as the output from the model. SD model shown in Figure 46 is based on the stock and flow representation of risk attributes and periods interacting with varying risk variables. The stock and flow diagram developed in Vensim© (Commercial software), takes into consideration the SCR model theory, all six risk attributes and their associated likelihood of impact over periods as seen in the Figure 45. The system model was provided with the initial anticipated probability, cost and time (delay) parameters to activate the simulation run similar to the statistical modelling. The model was fed with the information on risk attributes associated with the event as seen in top left side of the SD model in Figure 46.

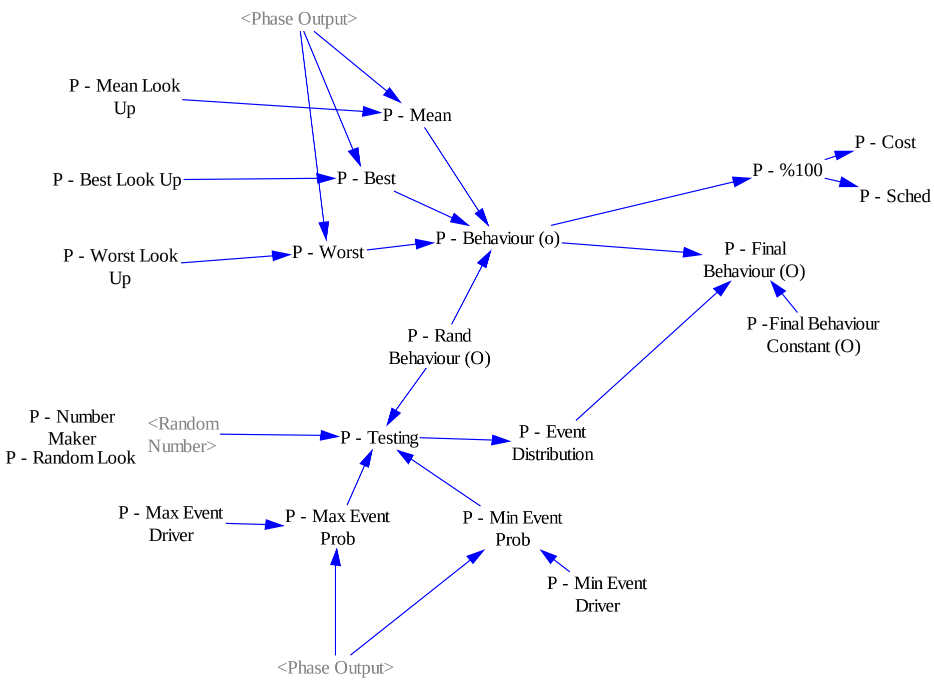


Figure 45: Structure of the simulation model

An example of a risk event is considered for analysing the risk performance as seen in Figure 46. The risk event consists of Process (P), Organisational (O), Data (D) and Application (A) risk attributes with initial estimated probability of risk event to occur as 80% and the expected impact in terms of cost and delay. The simulation that was run for 200 iterations shows that the predicted risk occurs approximately in 3-4 week with 100% probability threshold estimation. It also shows that there is a slight increase in time (delay) for the project with no deviation to cost over the periods. This implies that although the set of risks disrupts the network in terms of increased delay, it does not substantially influence the cost parameter. The dynamic system thus estimates the impact for single risk event and the risk behaviour is expected to change due to changing circumstances in SC network like emergence and accumulation of new risks or events, lack of recovery planning, etc. Considering all such parameters will provide exact information of total delay and cost impact over the lifecycle of the project or network. The aspect of having no impact on the cost within the suggested example is relevant only for the scenario when the attributes have a certain profile. This may be different at different interactions of the attributes. The advantage of this system is visible when the interdependency between the attributes can be studied at different interactions and probability levels.

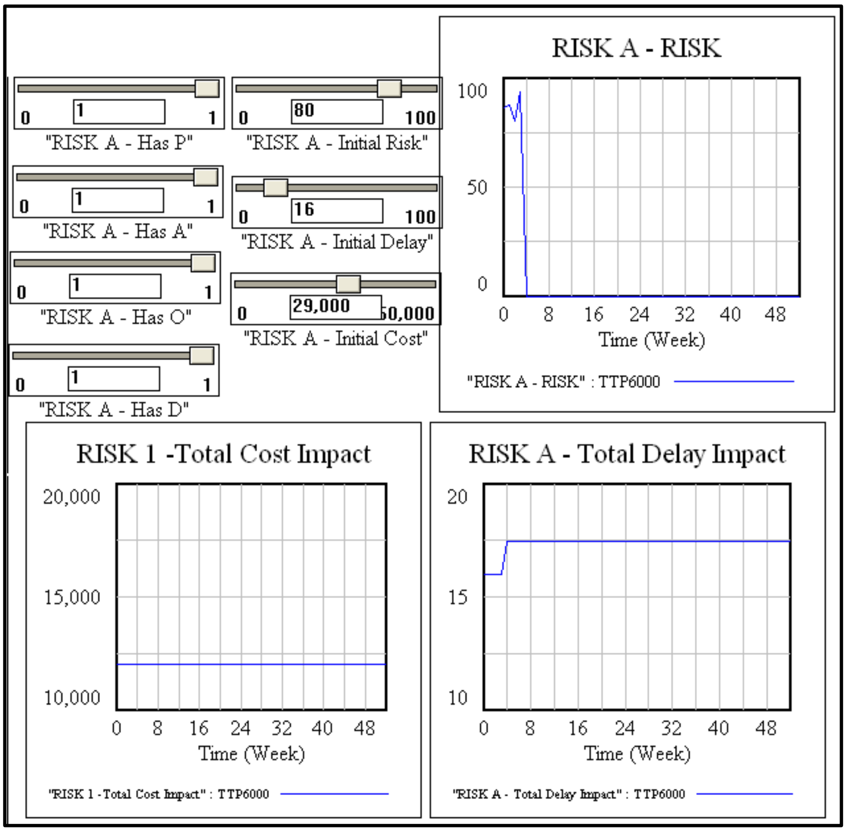


Figure 46: Simulation model for risk performance

The modelling platform predicts the possible point of failure apart from estimating the total impact for any risk event. The risk variables show independent nature of behaviour, which is evident from the statistical as well as simulation results. However, it is also clear that the risk variables when considered together create a different set of risk propagation failure points and this brings out the systemic approach of considering the interaction of the different variable to create the risk profile of the system. The results are approximate but provides the risk managers with sufficient understanding of fracture points and its overall impact for a given risk conditions.

7.2.2 Sensitivity analysis

Sensitivity analysis is the study of variation in the output due to different variations in the inputs. "*Sensitivity analysis of risk models can be used to identify the most significant exposure or risk factors and aid in developing priorities for risk mitigation*" (Christopher and Patil, 2002). Sensitivity analysis forms the support activity for risk modelling in the risk assessment process. It supports the risk modelling process in two stages as parameter/variable sensitivity analysis and evidence sensitivity analysis. Both sensitivity analysis stages have been systematically conducted with appropriate examples in the following section.

Variable sensitivity analysis

The behavioural pattern of business and system enterprise risk attributes are analysed for change in the cost and delay over a period during variable sensitivity analysis. It is interesting to observe that the business attribute risks (P+O) comprise of process and organisation risks tends to impact in cost more than delays. Business attribute risks tend to influence more in overall cost as seen in Figure 47. This may be due to the initial investment involved in process and organisational process improvement to resist the oncoming disruption. Data and application risks tend to emanate in later stages of SC network and hence tend to affect less in terms of cost. Overall impact in terms of delays is observed to affect equally, the business as well as system attribute based risks. However, it is observed that the system attribute risks tend to cascade the delays into multiple nodes within a network.

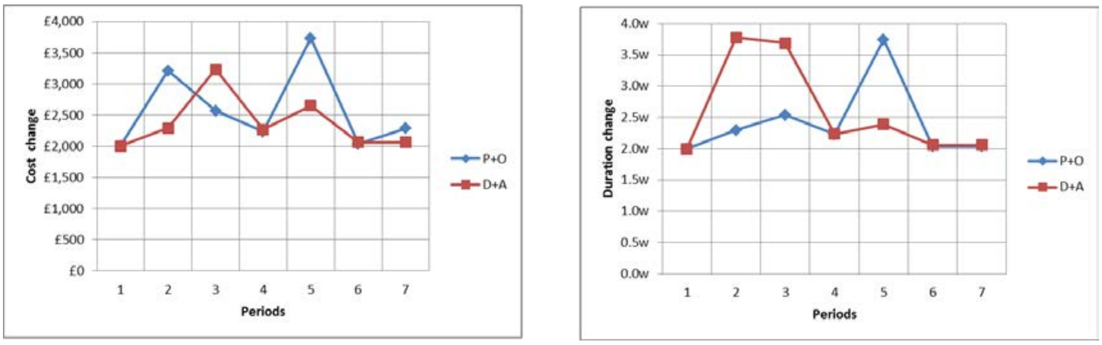


Figure 47: Variable sensitivity analysis (Cost and Delay)

Different conditional probabilities are plotted to observe the variation in impact in the statistical model as seen in Figure 48. The example shows two different initial risk probabilities and their behaviour over the period. The left side of the example shows the behavioural change in probability from initial predicted 10% whereas, the example on the right side shows the change from initial predicted probability of 50%. At the lower initial probability (10%), business and system attribute risks tend to behave equally. However, System attribute risks tend to increase drastically when compared with the business attribute risks. No specific reason for this behaviour is known; but it might be possible to predict this during evidence sensitivity analysis. Variable sensitivity analysis conducted at this stage provides the macro picture of risk impact by reacting to the working model. In the systems model, the variable sensitivity analysis can be analysed to see the behavioural change of risk probability with varying possibilities.

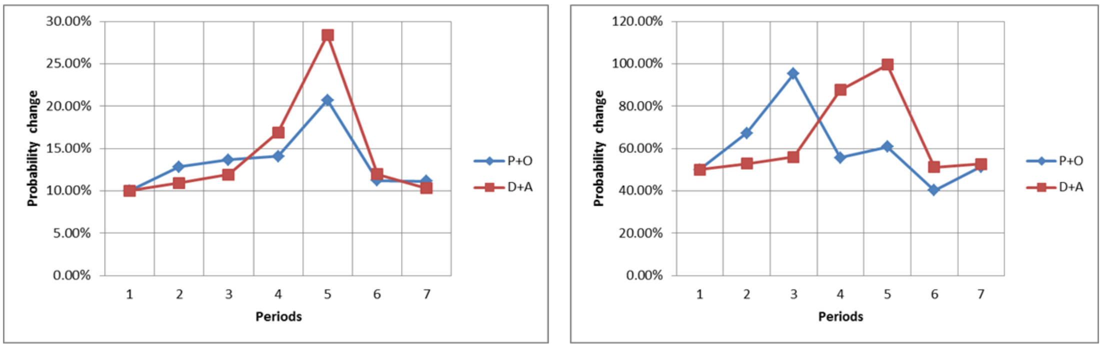


Figure 48: Variable sensitivity analysis (Probability)

Figure 49 shows the example of variable sensitivity analysis conducted in a systems model. On the left side, the initial probability set as 10% and behaviour is observed with varying possibilities. The varying possibilities show the fluctuations for given initial probability. On right side, the initial probability is set as 25% and behaviour is predicted with varying possibilities. Results may not be 100% accurate

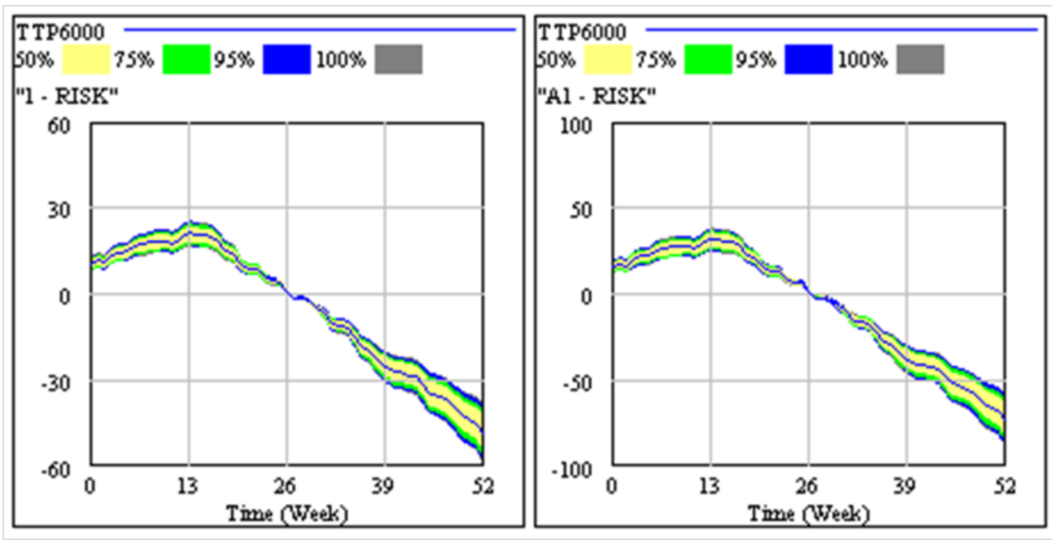


Figure 49: Systems variable sensitivity analysis (Probability)

for the examples taken but provides the range of possibilities in sensitivity analysis following a systems approach. Variable sensitivity analysis provides the stepping-stone for the evidence sensitivity analysis discussed in the next section for prediction of failure point and overall performance of risks while interacting together.

Evidence sensitivity analysis

The behavioural performance of risk attributes at a failure point is predicted through evidence sensitivity. Since both platforms provided similar results for predicting the behaviour of risk assessment parameters, evidence sensitivity can be conducted on the model. Figure 50 shows the example of evidence sensitivity for capturing the behaviour of risks under a multi interaction scenario. It also helps to predict the point of failure and its movement based on number of risks involved during the disruption. The difference in behavioural patterns of risk attributes individually and cumulatively can be observed in the example. Due to the difference in the set of risks observed in each attribute, the risks propagate its impact over a limited period. This is represented by a sudden surge in the probability. When the different set of risk attributes are combined the pattern of behaviour is changed based on a number of interacting risk attributes.

The example showed in Figure 50 shows one or more risks combined to represent the cumulative effect on the point of failure. As more and more risks are combined the probability of the event to occur reduces, but it is difficult to predict whether there would be shift in the failure point due to the accumulation of risks in the model. It is however projected that the failure point will occur earlier due to accumulation of risks within a system. The combination of risks and initial probability can be varied in evidence sensitivity analysis to analyse further the complex behavioural patterns.

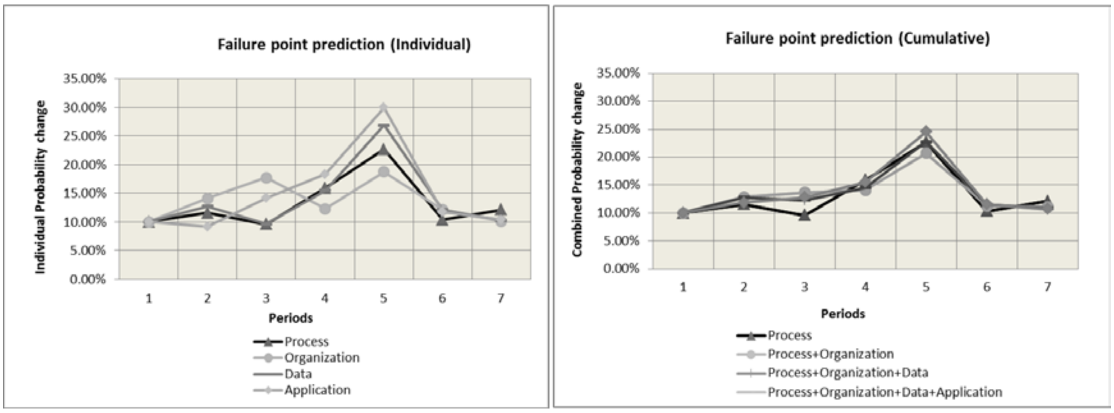


Figure 50: Example of evidence sensitivity analysis

The system thinking based modelling and sensitivity approach to the risk assessment process was created to elicit results through an iteration of statistical and simulation testing. The examples of variable and evidence sensitivity analysis are used to observe the behaviour of risk attributes and the occurrence of failure point for varying risk parameters. These examples support in verifying the theory behind the SCR model and validate the proposed research design for risk assessment.

7.3 Risk mitigation

Following some of the earlier discussed risk mitigation strategies and options, set of risks in the POLDAT attribute form were identified for classification during the risk mitigation activity as seen in Table 14. For each risk type, probable or most suitable mitigation strategy is suggested based on the discussion with risk managers from the collaborating organisation and the literature survey. The suggested strategies are generic in its form and can be applied for similar risks observed in any other risk attribute.

Risk attribute	**Commonly observed risks**	**Mitigation strategy**	**Decision option**
Process	• Product design risk • Information distortion risk • Demand risk • Quality risk	• Product standardization • ERP/SCM tools • Postponement/ Strategic stock • Process Standardization.	Risk transfer Risk sharing Risk avoid Risk share
Organisational	• Financial risk • Skill/performance risk • Poor management	• Risk sharing contracts • Outsourcing/trainings • Mentoring	Risk sharing Risk accept Risk avoid
Location	• Supply risks • Safety risk • Geopolitical risk • Supply risk	• Diverse supply base • Stricter guidelines • Alternate options • Sustainable logistics models • Multi/Dual/Contract sourcing	Risk transfer/ sharing Risk avoid Risk transfer Risk sharing
Data	• IP risk • Data contamination risk	• Contractual agreements • Data Management	Risk sharing Risk avoid
Application	• Integration risk	• Common platforms	Risk sharing
Technology	• Technology risk • IT failure	• Cloud database • Data backups	Risk transfer Risk avoid

Table 14: Risk mitigation strategies and decision options

The behavioural rationale in risk mitigation decision making can provide interesting insights related to the risk mitigation process but are beyond the scope of this research. Reactive risk mitigation experience will further improve the risk identification and assessment processes by forming a close-loop feedback system for the effective SCRM. The proposed holistic systems based risk modelling approach is methodically experimented at the collaborating organisation. The inductive approach was followed due to limited data availability in this case study. Explanatory strategy justifies the theory developed and tests the risk propagation phenomenon following mixed research methods.

7.4 Findings and insights

The systems thinking based modelling approach has provided a broader picture of risk behavioural performance. Statistical trending and likelihood of non-normal behaviour of associated risk attributes is represented in the best, average and worst-case scenarios and clearly defines the expected zone of operation of the risk performance variables. The SD simulation platform represents the dynamic nature of risk attribute behaviour well beyond the overall project period through iterative and predictive process. Both the modelling platforms show the expected probability of the event occurring approximately at same time for the same input conditions. Predicted impact in terms of cost and time for the given example are observed to be fluctuating over the period in the statistical modelling; whereas are found to be stable in the simulation results. This is due to the iterative nature of the SD simulation/systems modelling where consistent fluctuations for the limited periods are neutralized over the long periods. This also draws an important inference that the statistical model is slightly constrained and is limited to specific project periods while providing the clear picture of risks. On the other hand, the SD simulation model identifies the general behaviour of risks. Such generic, unbiased results can provide a better view of risk performance for risk managers. The risk modelling approach has helped in investigating the behaviour of risks beyond the conventional supply chain risk assessment commonly followed through the identification of the probability vs. likelihood of impact for different risks. Practitioners as well as researchers can comprehend this combined approach better for predicting the dynamic behaviour of risks.

Chapter 8 Conclusions and Future Research

The chapter combines the research findings on conceptualising and modelling the risk propagation phenomenon. The chapter goes back to the defined research objectives and research questions to justify the outcome of the research. Different scenarios captured from multi-interactive nature of risks are analysed in detail in this chapter and interpreted to develop further understanding into intricate behaviour of risk propagation. The chapter also focuses on limitations and future opportunities arising from this research.

8.1 Conclusions from research objectives

Research development can be evaluated based on pre-set research objectives and research goals. Following were the objectives defined by RSSE and SBE for this research project (as discussed earlier in Chapter 1):

1. **To establish the current research links between SE approach and supply chain modelling.**
2. **To understand the complex behaviour of supply chain risks due to disruptions.**
3. **To design a methodology for measuring behaviour of supply chain risk dynamically.**
4. **To test the developed research with industry collaborators and disseminate the research outcome widely.**

The first objective focussed at linking the current research on SE with supply chain modelling. Establishing this relationship between Systems engineering and supply chain risk modelling was attempted through systematic literature review of SCRM and SE field. Different research methods within management are also discussed extensively in relation to problems in the broad domain of supply chain modelling. The integrating link between supply chain management, risk management and systems engineering is provided following different risk management theories. A summary and synthesis of SCRM, answers the first objective defined in this thesis.

The second objective focussed on understanding the complex behaviour of supply chain risks due to disruptions. The structured literature survey of SCRM identified seven independent research gaps. Risk propagation and recovery was one of such research gaps, which were verified later through a case study. The case study was conducted for looking at complex links between supply chain factors and risks with causal loop diagraming. The case study identified that the risk impacts in terms of cost and delay for the short term and on reputation and share value in the long-term. The exploratory study finds this link through a conceptual model for supply chain risk. The findings are retrospectively validated through secondary data from two manufacturing sectors. The findings from the literature review and case study are overlapped for formulating two research questions (discussed earlier in Chapter 2).

The third objective aims to design a methodology for measuring behaviour of supply chain risk dynamically. The phenomenon of risk propagation is holistically studied through multidimensional perspectives. Operational risk and external risk based case studies helped in conceptualizing the risk behaviour and their propagation. Systems thinking approach has helped to identify approximate risk propagation durations for a typical disaster like Japan tsunami (2011). This was later attempted following a systems thinking approach to propose a framework for SCRM. The research on measuring the behaviour of risks dynamically was tested successfully with the collaborating industry partner through an experimental study. The data collected and provided by the collaborating partner was also extensively used to build the risk propagation-modelling concepts. Here the research design for quantitative risk modelling is tested following statistical and simulation modelling platforms. The risk propagation impact on the overall supply chain network is captured following systematic framework for SCRM, holistic SCR model and quantitative research design for supply chain risk modelling.

The forth objective was aimed at two important aspects of this research. One was to test the developed research with industry collaborators and other to disseminate the research outcome widely through conference presentations and journal publications. The first aspect was successfully completed with support from the collaborating partner. The developed framework for SCRM, Research design and SCR model were successfully implemented and tested for its authenticity. The outcome of this research was appreciated by the managers from collaborative organisation and was later published into a reputed journal for dissemination. Other forms of dissemination were used to transfer the knowledge acquired through this research. The research was presented at numerous internationally reputed conferences for constructive feedback. The research was also presented through several workshops and poster competitions. Formal as well as informal feedbacks from different dissemination platforms were used to improve the general quality of the research. The part of this research has been already published in two reputed peer reviewed academic journals in supply chain and logistics management.

8.2 Contribution to the research

The research believes to contribute to the theory by developing a holistic and systematic risk management procedure for measuring overall risk behaviour. Following systems thinking concepts, different frameworks and models for capturing risk propagation phenomenon were developed. The frameworks and models proposed were tested by experimenting with the collaborating organisation on a real case problem. Supply chain risk model is a ‘system’ for holistic risk assessment and this was cross verified and validated through two separate modelling platforms. The system based risk model provided true risk behaviour in a dynamic and accessible way.

Systems thinking approach is predominately used for the exploratory nature of this research. By implementing mixed (qualitative and quantitative) research methods, the research is strengthened by providing a collective understanding of the problem supported with comprehensive results. During the whole process of research, systems thinking was justified to be the most appropriate approach for capturing the complete behaviour of risks. The developed frameworks and models for the SCRM have provided the systematic process for measuring the overall behaviour of risks for proactive risk management. The developed approach to the SCRM is believed to benefit the practitioners in capturing the behaviour of the supply chain systems holistically. The developed SCR model is novel and is validated through cross-comparison of the fundamental analysis results. Systems thinking has provided visibility into capturing the holistic and dynamic picture of the system behaviour. The research combines risk modelling theory and practice together to add to current research on the SCRM.

Exploratory as well as explanatory research based on case studies has provided interesting insights into modelling risk behaviour within supply chain network. It has also provided with an excellent opportunity to develop the new concepts contributing to the theory. Mixed research methods were found to be appropriate for the nature of the research. Qualitative methods such as case study, Delphi/focus groups and secondary data analysis were followed. In quantitative methods, it was attempted through statistical and simulation techniques. The interpretivist paradigm supported in using qualitative methods and positivist paradigm supported in using quantitative methods during this study. The research is expected to benefit academicians as well as supply chain practitioners for a holistic understanding of the risk propagation phenomenon.

8.2.1 Primary research contribution

The major contributions of this research are depicted in Table 15. One of the important contributions of this research is that it conceptualised the phenomenon of risk propagation. The development of the multi-dimensional wheel and zones for risk propagation discussed in the chapter 5 builds the foundation for modelling the risk propagation phenomenon. Researchers have studied several case studies on natural disasters in the past to draw interesting findings. The Japanese tsunami (2011) was selected as an appropriate and recent natural disaster with a large 'cascading effect'. With its inherent global extent of risk propagation, it encouraged us to choose the Japanese tsunami as an appropriate case study. Understanding the impact of disruption to the global supply chain was another motive behind this research. Data from different business sectors was collected and studied together for conceptualising the phenomenon of risk propagation. The systems thinking approach was utilised to develop a concept for risk propagation. The data analysis led to identification of primary, secondary and tertiary risk levels for risk propagation. The risk propagation impact measuring parameters were identified to be cost and time (delay). Quality, another identified parameter was believed to be a function of either cost or time. The conceptualisation of the risk propagation phenomenon supported in the next stage of research for defining the boundaries of disruption within the SC network and defining risk assessment parameters for modelling.

Most important research contribution from this research is the holistic, systematic and quantitative modelling approach for supply chain risk assessment. Research provides a structured approach for quick and comprehensive understanding of risk behaviour as well as performance. The SCR model based statistical modelling provides a brief picture of the risk behaviour whereas, simulation modelling provides slightly detailed picture of the risk performance. Secondary analysis results like failure point estimation and zones of operation of the risk attributes were found to be same in both modelling platforms validating the working of SCR model. Quantitative research methods for risk modelling has helped in not just capturing the fracture points in supply chains, but also provided other interesting insights into the behaviour of portfolio of risks difficult to capture through other qualitative techniques.

Extensive sensitivity analysis is attempted to draw intricate results difficult to capture through conventional risk assessment methodology. The developed supply chain risk model is limited to capturing risk propagation only in periods. Hence, the next stage of research will consider modelling risk propagation over zones along with periods. Some of the developed frameworks and proposed models are in an infancy stage and needs further validation. Future research will focus on micro-level analysis of risk propagation and recovery phenomenon conceptualized and developed in this project.

The theory behind modelling supply chain risk propagation is validated through experimentation with collaborating organisation. The framework and models proposed for modelling supply chain risks is believed to bridge the gap between theory and practice.

8.2.2 Secondary research contribution

One of the secondary contributions of the thesis is the SLR of SCRM through a transparent, unbiased and systematic way to identify key seven research gaps. The

SLR methodology was found to be driven by a methodical process and provides a strong evidence base. The process is not just systematic but open and unbiased in drawing the definitive inferences. SLR supported with modern knowledge management tools allows a multi-dimensional analysis of the field to reveal patterns that are less clear in conventional literature study. Use of modern knowledge management tools for SLR is a novel approach used in SCRM research. The identified seven distinctive research factors are expected to provide researchers with new hypothesis for future work. The factors in themselves can provide individual research areas within the area of SCRM. All the identified research gaps relate to industry impact and it is essential for future academic research. It is important to provide industry with proactive and reactive management models to manage SCRM and this will be possible by taking a holistic approach to understanding the challenges that supply chains face. The data analysis conducted during SLR is based on evolved typologies and suggests a major growth of SCRM from a nascent to an established stage over the past decade. The secondary contribution of the thesis is believed to have established firm insights and clearly identified gaps and future directions into SCRM field. The identified seven distinctive research agendas are expected to provide significant benefit to researchers and managers by providing a quick greater understanding across the length and breadth of the SCRM field.

Another contribution of the thesis is the identification of the link between several supply chain factors and their influence on risks. The exploratory research was based on the application of systems thinking for understanding demands of the next generation supply chains. Factors affecting next generation supply chains are identified through literature review and several workshops. A causal diagram shows

Research Contribution	Gap addressed in the existing research
Primary research Contribution	
Conceptualisation of multi-dimensional wheel and zones for risk propagation.	One of the primary contributions of this thesis is that it identified six dimensions for risk propagation beyond conventional flow of resources (material, finance and information) into technology, human resource and socio-economic dimensions. In terms of zones, the risk propagates not just through the network chain but also cascades from one zone to another with an increased impact. The risk propagation impact measuring parameters were identified as cost and time (delay). Quality and service, other identified parameters were believed to be either function of cost or time.
Development of framework for SCRM, SCR model and research design for holistic risk assessment.	Key contribution of the thesis is the development and testing of framework for SCRM following systems thinking perspective. This framework consists three parts risk identification, risk assessment and risk mitigation process with two stages associated with each process for data experimentation. Each stage in the conceptual framework is improved through a continuous feedback loop system. The developed SCR model for risk modelling captures the impact in terms of cost and time (delay) and the possible failure point due to disruption. Holistic research design for risk modelling provides behavioural performance of risks.
Secondary research Contribution	
Research identified seven research gaps in SCRM field with support of SLR and modern knowledge management techniques.	One of the secondary contributions of the thesis is that it conducted SLR of SCRM through transparent, unbiased and systematic way to identify key seven research gaps. The research gaps are identified following text mining tools and techniques to bring new perspective difficult to capture through conventional literature review process.
Identified the link between several supply chain factors and their influence on risks.	Another secondary contribution of the thesis is that, it identified six factors influencing supply chain configuration. Sustainability, technology and collaboration were factors identified to drive the future of supply chains. Risk management, skill shortage and total cost management as issues concerning supply chains. Asset utilisation and servitisation as possible solutions for next generation supply chains.

Table 15 : Primary and secondary contributions

the causal linkages between the factors and their risk propagations within a supply chain system. A conceptual model has been developed based on the causal diagram that depicts the identified challenges, risk propagation directions and their future impact on supply chain networks. This is an important finding as it presents a holistic approach towards considering all factors as necessary criteria for configuring next generation supply chains. The conceptual model is retrospectively validated using secondary data analysis for two cases (industry sectors). The instances considered in the analysis are recent occurrences of supply chain failure (product delays and recalls) within Food, Automotive and Aerospace sector, which interestingly have different supply chain structures and working environments. The case study research has modelled a framework to configure next generation supply chains, which is expected to contribute for further research in SCM.

8.3 Research limitations

No research is believed to be through without discussing its limitations. The research discussed in this thesis had its limitations in many ways. Some of the limitations of this research are discussed below.

The thesis begins with a systematic literature review approach to SCRM. Although SLR is found to be better than conventional literature review in its rigour and unbiased nature, it was found to be very laborious in its approach. The SLR of 120 quality articles was conducted following an extensive systematic research methodology. Although the process of SLR is driven by a methodical process and provides a strong evidence base, it was found to be time consuming due to integration and validation of modern knowledge management tools forming a multi-dimensional analysis. An evident weakness of the SLR methodology is that it sacrifices too much of efficiency but never the less captures the best from literature given the explosion of academic publications in today's e-world. Data analysis of research conducted was limited between year 2000 and 2010 by systematic identification, screening, extraction and synthesis of quality data sources. This in a way was focussed on the developments in past decade but was also constrained due to limitation in range of years for study. It was found that some of the quality journals had been neglected due to restriction on the year of publication. The same restriction was applied to journal selection and only ABS ranked publications from OM/OR/MS field were selected for the SLR analysis. This may look like a distillation of thoughts already accepted among particular section of the research community but raised questions on the other good quality journals being neglected during the analysis. An evident weakness of the methodology is that it puts greater stress on efficient data analysis and may be weak in deciphering future challenges.

The primary and secondary case analysis utilised for conceptualising the phenomenon of risk propagation looks at limited industry sectors. This may not be a major constraint as the holistic study attempts to captures the operational (internal) as well as external risks from the secondary data. During risk propagation modelling, statistical modelling is found to be constrained by the data limitation and provided accurate results only for the limited period of the project. On the other hand, Simulation modelling provides dynamic and predictive assessment of risk performance variables capturing holistic behaviour. The overall results obtained through conventional and systems approach for risk assessment were collated and cross verified. Systems approach also permitted the sensitivity analysis for in-depth and dynamic micro-level assessment, found lacking in statistical modelling further limiting its application for complex analysis. Systems approach was identified to be better than statistical approach for the risk assessment but this cannot be justified based on the collaborative case alone.

8.4 Future research directions

The research currently lacks micro level sensitivity analysis to predict the behaviour of risks for different combinations of risk attributes. The research in the future intends to investigate ‘evidence sensitivity’ to bring forward some of the intricate behavioural patterns associated with each risk attribute. The risk model is tested and validated based on single case study and further studies in different sectors will improve the robustness of SCRM framework. One of the main future research areas associated with risk propagation modelling is the ability to understand how the risk profile changes because of different risk variables. Future research will focus on micro-level interaction of risks while studying risk propagation and recovery phenomenon.

Throughout the analysis, it was evident that sustainability and risk management requires a prominent consideration when configuring future supply chains. The research surrounding supply chain risks and sustainability have identified that non-conformance to the sustainability criteria can introduce various risks within the supply chain; which in turn will affect the brand and market value. Hence, sustainability and risk management play a prominent role in future supply chains practices. Sustainable development can be defined as "*a development that meets the needs of the present without compromising the ability of future generations to meet the needs*" (World Commission on Environment and Development, 1987). Environmental regulations, economic parity and social stability are identified as major pillars of the global sustainable development by several authors in the past. Economic parity helps in reduced corruption and illegal practices. Social stability is concerned with poverty, injustice and human rights. Environmental and social equality is believed to be interdependent on economic equality. From a triple bottom line approach, sustainability is seen in three different dimensions as the natural case (environmental), business case (economic) and societal case (social) (Dyllick and Hockerts, 2002). According to Shrivastava (1995), Sustainability is "*the potential for reducing long-term risks associated with resource depletion, fluctuations in energy costs, product liabilities, and pollution and waste management*". Stonebraker *et al.* (2009) have suggested that, the scholarly literature generally avoids the interrelationship of environmental costs and supply chain risk with the potential for supply chain disruption (fragility). A central thrust, focus or integrated model of supply chain and environmental risk is still lacking (Anderson, 2006; Kleindorfer and Saad, 2005). In the opinion of the author, risk is not a single entity and can be classified based on 'pillars of sustainability' into three different perspectives as economic risks, social risks and environmental risks. Figure 51 shows the interdependence of risks influencing sustainable supply chain management. It is quite evident that, sustainability and risks are very much unified and are important considerations for configuring future supply chains. It is apparent from above study that two factors, sustainability and risk management must be integrated together for future research in supply chain management in general and SCRM in particular.

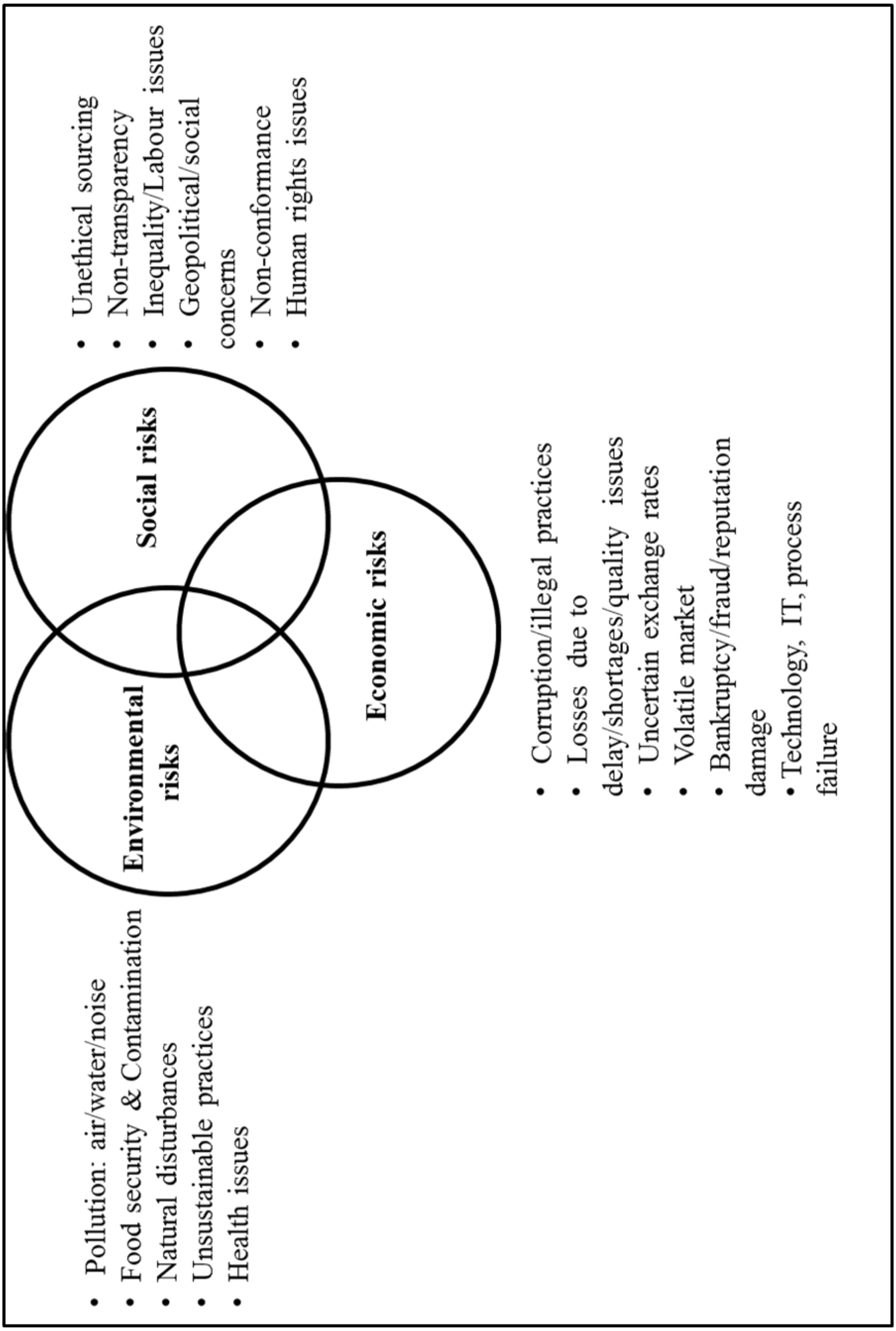


Figure 51: Risks for sustainable supply chain management

During the research, it was observed that the decision to choose the right risk strategy is crucial. The behavioural dimensions into the use of risk mitigation strategy could provide dimensions for bounded rationality in decision-making. The behavioural aspect of managers dominates such decisions but studies looking at similar bounded, rational decision-making would provide more insights into decision-making. The research on developing practices for unbiased or rational decision making is another unexplored area in SCRM.

Another possible area for future research is the use of technology and related models for disaster risk management. ICT is expected to make a big impact on SCRM. More and more supply chain and logistics organisations are networking through use of modern technologies. Accurately identifying risks and providing timely information is crucial for the disaster management (Kovacs and Spens, 2009). It has become vital for disaster relief operations to proactively identify and mitigate the risks. Mitigation, preparedness, response and recovery are four stages during any disaster management (Van Wassenhove, 2006). Each stage faces different challenges in terms of information gathering, interpretation and dissemination for quick relief operations. The research could look at capturing various activities involved during disaster management cycle. ICT based models for disaster risk management have huge potential in reducing the overall impact of disruption.

The thesis concludes with a famous quote by Alan Kay, a noted computer scientist (1982) "*The best way to predict your future is to invent it*". Future research in broad domain of logistics and supply chain management is expected to be driven by technology and innovation to create new approaches, techniques and strategies to improve the overall performance of the SC system.

References

ABS Journal Guide. (2011), Association of Business Schools Academic Journal Quality Guide: Version 4, available at: http://www.associationofbusinessschools.org/node/1000257 (accessed 25 September 2012).

Adams, G. R. and Schvaneveldt, J. D. (1991), *Understanding research methods*.

Agrell, P. (2004), “Risk, information and incentives in telecom supply chains”, *International Journal of Production Economics*, Vol. 90 No. 1, pp.1-16.

Altay, N. and Green, W. (2006), “OR/MS research in disaster operations management”, *European Journal of Operational Research*, Vol. 175 No. 1, pp. 475-493.

Ananiadou, S., Rea, B., Okazaki, N., Procter, R. and Thomas, J. (2009), “Supporting Systematic Reviews Using Text Mining”, *Social Science Computer Review,* Vol. 27 No. 4, pp. 509-523.

Anderson, D. J. Sweeney, T. A. Williams, J. Freeman. and Shoesmith, E. (2007), *Statistics for Business and Economics*, Thomson, UK.

Anderson, D. R. (2006), “The critical importance of sustainability risk management”, *Risk Management*, Vol.53 No.4, pp. 66-74.

Atkinson, R. (1999), “Project management: cost, time and quality, two best guesses and a phenomenon, it’s time to accept other success criteria”, *International Journal of Project Management*, Vol. 17 No. 6, pp. 337-342.

Autry, C. W. and Bobbitt, L. M. (2008), “Supply chain security orientation: conceptual development and a proposed framework”, *The International Journal of Logistics Management*, Vol. 19 No.1, pp. 42-64.

Aviv, Y. (2002), “Gaining benefits from joint forecasting and replenishment processes: The case of auto-correlated demand”, *Manufacturing and Service Operations Management*, Vol. 4 No. 1, pp. 55-74.

Babich, V. (2006), “Vulnerable options in supply chains: Effects of supplier competition”, *Naval Research Logistics*, Vol. 53 No. 7, pp.656-673.

Badger, D., Nursten, J., Williams, P., and Woodward, M. (2000), “Should all literature reviews be systematic?”, *Evaluation and Research in Education*, Vol. 14 No.3, pp. 220-230.

Barbarosoglu, G. (2002), “An interactive approach for hierarchical analysis of helicopter logistics in disaster relief operations”, *European Journal of Operational Research*, Vol. 140 No.1, pp.118-133.

Bartlett, S. (1945), "Negative probability", *Mathematical Proceedings of the Cambridge Philosophical Society*, Vol. 41 No. 1, pp. 71-73.

Bates, H., Holweg, M., Lewis, M., and Oliver, N. (2007), "Motor vehicle recalls: Trends, patterns and emerging issues", *Omega: The International Journal of Management Scienc*e, Vol. 35 No. 2, pp. 202-210.

BBC News (2011), As it happened: Japan earthquake on Monday, Available at: http://news.bbc.co.uk/1/hi/programmes/9424985.stm (assessed on March 16, 2011).

BBC News, (2010a), California sues Toyota for faults, available at: http://news.bbc.co.uk/1/hi/world/americas/8565637.stm (accessed 19 April 2012).

BBC News, (2010b), Honda recalls 384,000 US vehicles, available at: http://www.bbc.co.uk/news/business-10921161 (accessed 19 April 2012).

BBC News, (2010c), Nissan recalls 540,000 vehicles, available at: http://news.bbc.co.uk/1/hi/8547475.stm (accessed 19 April 2012).

Beamon, B. M. (1999),"Measuring supply chain performance", *International Journal of Operations and Production Management*, Vol. 19 No. 3 pp. 275-292.

Beamon, M. B. (1998), "Supply Chain Design and Analysis: Models and Methods", *International Journal of Production Economics*, Vol.55 No.3, pp. 281-294.

Ben-Asher, J. Z. (2008), "Development program risk assessment based on utility theory", *Risk Management*, Vol. 10 No. 4, pp. 285-299.

Bennett, J., Lubben, F., Hogarth, S., and Campbell, B. (2005), "Systematic reviews of research in science education: rigour or rigidity?" *International Journal of Science Education*, Vol. 27 No. 4, pp. 387-406.

Bimrose, J., Barnes, S-A. and Brown, J. (2005), A Systematic Literature Review of Research into Interventions for Higher Education, *Higher Education*, (November).

Blackhurst, J. , Craighead, C. W., Elkins, D. and Handfield, R. B. (2005), “An empirically derived agenda of critical research issues for managing supply-chain disruptions”, *International Journal of Production Research*, Vol. 43 No.19, pp. 4067-4081.

Blackhurst, J., Wu, T., and O'grady, P. (2004), “Network-based approach to modelling uncertainty in a supply chain”, *International Journal of Production Research*, Vol. 42 No. 8, pp. 1639-1658.

Blome, C. and Schoenherr, T. (2011), “Supply chain risk management in financial crises-A multiple case-study approach”, *International Journal of Production Economics*, Vol. 134 No. 1, pp. 43-57.

Blos, M. F., Quaddus, M., Wee, H. M., and Watanabe, K. (2009). Supply chain risk management (SCRM): a case study on the automotive and electronic industries in Brazil. *Supply Chain Management: An International Journal*, Vol. 14 No. 4, pp. 247-252.

Bogataj, D. and Bogataj, M. (2007), “Measuring the supply chain risk and vulnerability in frequency space”, *International Journal of Production Economics*, Vol. 108 No.1, pp.291-301.

Braunscheidel, M. J. and Suresh, N.C. (2009), “The organisational antecedents of a firm’s supply chain agility for risk mitigation and response”, *Journal of Operations Management*, Vol. 27 No. 2, pp. 119-140.

Brun, A., Caridi, M., Salama, K. and Ravelli, I. (2006), “Value and risk assessment of supply chain management improvement projects”, *International Journal of Production Economics*, Vol. 99 No. 2, pp.186-201.

Bryson, K., Millar, H., Joseph, A. and Mobolurin, A. (2002), “Using formal MS/OR modelling to support disaster recovery planning”, *European Journal of Operational Research*, Vol. 141 No. 3, pp. 679–688.

Burtonshaw-Gunn S. A. (2008), *The essential management toolbox: Tools, models and notes for Managers and Consultants*, United Kingdom.

Business Execution insights, (2009), “Business Execution Lessons learned from Boeing 787 delays", available at:http://businessexecution.wordpress.com/2009/07/01/business-execution-lessons-learned-from-boeing-787-delays/ (accessed 19 April 2012).

Cachon, G. P. (2004), “The Allocation of Inventory Risk in a Supply Chain: Push, Pull, and Advance-Purchase Discount Contracts”, *Management Science*, Vol. 50 No.2, pp.222-238.

Carr, M., Konda, S., Monarch, I., Ulrich, C. and Walker, C. (1993), Taxonomy based risk identification (CMU/SEI-93-TR-6, ADA266992), Software Engineering Institute, Carnegie Mellon University, Pittsburgh, PA.

Carter, C. and Easton, P. (2011), "Sustainable supply chain management: evolution and future directions", *International Journal of Physical Distribution and Logistics Management*, Vol. 41 No. 1, pp. 46-62.

Carter, C. and Rogers, D. (2008), “A framework of sustainable supply chain management: moving toward new theory”, *International Journal of Physical Distribution and Logistics Management*, Vol.38 No.5, pp. 360-387.

Carter, M. W. and Price, C.C. (2001), *Operations Research: A Practical Introduction*, USA.

Cavinato, J. L. (2004), “Supply chain logistics risks: From the back room to the board room”, *International Journal of Physical Distribution and Logistics Management*, Vol. 34 No. 5, pp.383-387.

Centre for Reviews and Dissemination, University of York and Akers, J. (2009), *Systematic reviews: CRD's guidance for undertaking reviews in health care*. Centre for Reviews and Dissemination.

Chaabane, A., Ramudhin, A., & Paquet, M. (2012), "Design of sustainable supply chains under the emission trading scheme", *International Journal of Production Economics*, Vol. 135 No. 1, pp. 37-49.

Chandra, C. and Grabis, J. (2007), *Supply chain configuration: concepts, solutions and applications*, Springer Verlag, Berlin, Heidelberg, New York.

Chase, R. B., Jacobs, F. R. and Aquilano, N.J. (2006), *Operations Management for Competitive Advantage*, 11th edition, McGraw-Hill, New York, NY.

Chaudhuri, A., Mohanty, B and Singh, K. (2012), "Supply chain risk assessment during new product development: a group decision making approach using numeric and linguistic data", *International Journal of Production Research*, Vol. 51 No. 10, pp. 2790-2804.

Chen, F.Y. and Yano, C. A. (2010), “Improving Supply Chain Performance and Managing Risk Under Weather-Related Demand Uncertainty”, *Management Science,* Vol. 56 No.8, pp.1380-1397.

Chen, H., Fuller, S.S. and Friedman, C. (2001), *Knowledge Management, Data Mining, And Text Mining in Medical Informatics*, Springer, pp.3-33.

Cheng, S. K. and Kam, B. H. (2008), "A conceptual framework for analysing risk in supply networks", *Journal of Enterprise Information Management*, Vol. 21 No. 4, pp. 345-360.

Cheung, R.K.M. and Powell, W.B. (1996),” Models and algorithms for distribution problems with uncertain demands”, *Transportation Scie*nce, Vol.30 No.1, pp.43-59.

Childerhouse, P., Hermiz, R., Mason-Jones, R., Popp, A. and Towill, D. R. (2003), “Information flow in automotive supply chains- identifying and learning to overcome barriers to change”, *Industrial Management and Data Systems*, Vol. 103 No. 7, pp. 491–502.

Chiong, R. (2009), *Nature-Inspired Algorithms for Optimisation, Series in Studies in Computational Intelligence*, Vol. 193, Springer, Berlin.

Cho, J. and Trent, A. (2006), “Validity in qualitative research revisited”, *Qualitative research*, Vol. 6 No. 3, pp. 319-340.

Chopra, S. and Sodhi, M. (2004), "Managing Risk To Avoid Supply Chain Breakdown", *MIT Sloan Management Review*, Vol. 46 No.1, pp. 53-61.

Chopra, S., Reinhardt, G. and Mohan, U. (2007), “The Importance of Decoupling Recurrent and Disruption Risks in a Supply Chain”, *Naval Research Logistics*, Vol. 54 No. 5, pp. 544–555.

Chopra, S., Sodhi, M.S. (2004), Managing Risk To Avoid Supply Chain Breakdown, *MIT Sloan Management Review*, Vol. 46 No. 1, pp. 53–61.

Chraighead, C. W., Elkins, D., Blackhurst, J. V., Hendricks, K. B., Handfield, R. B. and Singhal V.R. (2005), “An empirically derived agenda of critical research issues for managing supply-chain disruptions”, *International Journal of Production Research*, Vol. 43 No. 19, pp. 4067-4081.

Christopher, F. H. and Patil, S. R. (2002), “Identification and review of sensitivity analysis methods”, *Risk analysis*, Vol. 22 No. 3, pp. 553-578.

Christopher, M. and Lee, H. (2004), “Mitigating supply chain risk through improved confidence”, *International Journal of Physical Distribution and Logistics Management*, Vol. 34 No. 5, pp. 388-396.

Christopher, M., Peck, H. (2004), Building the Resilient Supply Chain. *The International Journal of Logistics Management*, Vol. 15 No. 2, pp. 1–13.

Christopher, M., Peck, H. and Towill, D. (2006), “A Taxonomy for Selecting Global Supply Chain Strategies”, *The International Journal of Logistics Management*, Vol. 17 No.2, pp.277-287.

Cigolini, R. and Rossi, T. (2010), “Managing operational risks along the oil supply chain”, *Production Planning and Control*, Vol. 21 No.5, pp.452-467.

Clarke, M. and A. D. Oxman (Eds) (2001), *Cochrane Handbook for Systematic Reviews of Interventions*, The Cochrane Collaboration. Oxford Library.

Colicchia, C. and Strozzi, F. (2012), "Supply chain risk management: a new methodology for a systematic literature review", *Supply Chain Management: An International Journal*, Vol. 17 No 4, pp.403 - 418.

Colicchia, C., Dallari, F., and Melacini, M. (2010). Increasing supply chain resilience in a global sourcing context. *Production Planning and Control*, Vol. 21 No. 7, pp. 680-694.

Cooper, D. R. and Schindler, P. S. (2003), *Business research methods.*

COSO, (2004), *Enterprise Risk Management-Integrated Framework, The Committee of Sponsoring Organisations of the Treadway Commission*, 2004, executive summary report.

Cousins, P. D., Lamming, R.C. and Bowen, F. (2004), “The role of risk in environment-related supplier initiatives”, *International Journal of Operations and Production Management*, Vol. 24 No.6, pp. 554-565.

Craighead, C.W., Blackhurst, J., Rungtusanatham, M.J., Handfield, R.B. (2007), “The severity of supply chain disruptions: design characteristics and mitigation capabilities”, *Decision Sciences*, Vol. 38 No.1, pp.131–156.

Creswell, J. W. (2008), *Research design: Qualitative, quantitative, and mixed methods approache*s, SAGE Publications, Incorporated.

Cruzes, D., Basili, V., Shull, F., and Jino, M. (2007), “Automated Information Extraction from Empirical Software Engineering Literature: Is That

Possible?” in *First International Symposium on Empirical Software Engineering and Measurement*, pp. 491-493.

Dani, S. (2008), "Predicting and Managing Supply Chain Risks", in *Supply Chain Risk: A Handbook of Assessment, Management and Performance*, Ritchie, R.L. and Zsidisin, G. (Eds), Springer.

Dani, S. and Deep, A. (2010), “Fragile food supply chains: reacting to risks”, *International Journal of Logistics Research and Applications*, Vol. 13 No.5, pp.395-410.

Datta, P.P., Christopher, M. and Allen, P. (2007), “Agent-based modelling of complex production/distribution systems to improve resilience”, *International Journal of Logistics Research and Applications*, Vol. 10 No.3, pp.187-203.

Davies, P. (2000), *The relevance of systematic reviews to educational policy and practice*, Oxford Review of Education, Vol. 26, pp. 365–378.

Deep A., Dani S. (2009), “Risks: A Scenario Planning Perspective”, Paper-011-0371, in *POMS 20th Annual Conference,* Orlando, Florida, USA, May1-4, pp 21

Denyer, D. and Tranfield, D. (2009), Producing a systematic review, in *The Sage Handbook of Organisational Research Methods*, Buchanan, D. and Bryman, A. (Eds), Sage Publications Ltd, London.

Diabat, A., Govindan, K. and Panicker, V. (2012), "Supply chain risk management and its mitigation in a food industry", *International Journal of Production Researc*h, Vol. 50 No.11, pp. 3039-3050.

Dyllick, T. and Hockerts, K. (2002), "Beyond the business case for corporate sustainability", *Business Strategy and the En*vironment, Vol.11 No.2, pp. 130–41.

Easterby-Smith, M., Thorpe, R. and Lowe, A. (2002), *Management Research: An Introduction* (2nd Edition), London, Sage.

Ellegaard, C. (2008), "Supply risk management in a small company perspective", *Supply Chain Management: An International Journal*, Vol. 13 No. 6, pp. 425-434.

Ellis, S.C., Henry, R.M. and Shockley, J. (2009), "Buyer perceptions of supply disruption risk: A behavioural view and empirical assessment", *Journal of Operations Management*, Vol. 28 No. 1, pp.34-46.

Ermoliev, Y.M., Ermolieva, T. Y., MacDonald, G. J., Norkin, V. I. and Amendola, A. (2000), "A system approach to management of catastrophic risks", *European Journal of Operational Research*, Vol. 122 No.2, pp.452-460.

Escudero, L. F., Galindo, E., García, G., Gomez, E., and Sabau, V. (1999), "Schumann, a modelling framework for supply chain management under uncertainty", *European Journal of Operational Research*, Vol. 119 No. 1, pp. 14-34.

Faisal, M.N., Banwet, D.K. and Shankar, R. (2007), "Quantification of risk mitigation environment of supply chains using graph theory and matrix methods", *European Journal of Industrial Engineering*, Vol. 1 No. 1, pp. 22-39.

Fawcett, S. E., and Waller, M. A. (2011), "Making sense out of chaos: why theory is relevant to supply chain research", *Journal of Business Logistics*, Vol. 32 No. 1, pp. 1-5.

Ferrari, B. (2008), Boeing and Airbus Product Delays- Lessons in Supply Chain Risk Management, available at: http://www.theferrarigroup.com/images/Boeing_and_Airbus_Lessons_in_Supply_Chain_Risk_Mgt.pdf (accessed 5 October 2010).

Feynman, R. P. (1987), *Negative probability*, Quantum implications: essays in honour of David Bohm, pp. 235-248.

Finch, P. (2004), “Case study supply chain risk management”, *Supply Chain Management: An International Journal*, Vol. 9 No. 2, pp. 183-96.

Forbes, (2012), Ranking the World's Most Sustainable Companies, available at: http://www.forbes.com/sites/jacquelynsmith/2012/01/24/ranking-the-worlds-most-sustainable-companies/ (accessed 20 March 2012).

Forrester, J. W. (1958). Industrial Dynamics: A Major Breakthrough for Decision Makers. *Harvard Business*, *Review*, 36 (4):37-66.

Forrester, J. W. (1961), *Industrial Dynamics*, Productivity Press, Portland, OR.

Forrester, J. W. And Senge, P. (1980), “Tests for Building Confidence in Systems Dynamics Models”, *TIMS Studies in the Management Sciences*, Vol. 14, pp. 209-228.

Forrester, J.W. (1994), “System dynamics, systems thinking, and soft OR”, *System Dynamics Review*, Vol. 10, pp. 245–256.

Gan, X., Sethi, S.P. and Yan, H. (2004), “Coordination of Supply Chains with Risk-Averse Agents”, *Production and Operations Management*, Vol. 13 No. 2, pp.135-149.

Garavelli, A. C. (2003), "Flexibility configurations for the supply chain management", *International Journal of Production Economics*, Vol. 85 No. 2, pp. 141-153.

Gaudenzi, B. and Borghesi, A. (2006), “Managing risks in the supply chain using the AHP method”, *The International Journal of Logistics Management*, Vol. 17 No.1, pp.114-136.

Geary, S., Childerhouse, P. and Towill, D. (2002), "Uncertainty and the Seamless Supply Chain", *Supply Chain Management Review*, July/August, pp. 52-61.

Geoffrey, W.H and Robert, S.S (1997), “Risk Analysis Techniques”, *Disaster Recovery Journal*.

Georgiadis, P., Vlachos, D., and Iakovou, E. (2005), “A System Dynamics Modelling Framework for the Strategic Supply Chain Management of Food Chains”, *Journal of Food Enginee*ring, Vol. 70 No. 3, pp. 351-364.

Ghauri, P. G. K.(2005), *Research methods in business studies, a practical guide*, Essex: Pearson education limited.

Ghobadian, A., Speller, S. and Jones, M. (1994), "Service Quality Concepts and Models", *International Journal of Quality and Reliability Management*, Vol. 11 No. 9, pp. 43-66.

Giaglis, G. M., Minis, I., Tatarakis, A. and Zeimpekis, V. (2004), "Minimizing logistics risk through real-time vehicle routing and mobile technologies: Research to date and future trends", *International Journal of Physical Distribution and Logistics Management*, Vol. 34 No. 9, pp.749 - 764

Gill, J and Johnson, P. (1997), *Research methods for Managers* (2nd Edition), London, Paul Chapman.

Giunipero, L.C. and Eltantawy, R.A. (2003), “Securing the upstream supply chain : a risk management approach”, *International Journal of Physical Distribution and Logistics Management*, Vol. 34 No. 9, pp.698-713.

Gjerdrum, J., Shah, N., and Papageorgiou, L. G. (2001), “A combined optimization and agent-based approach to supply chain modelling and performance assessment”, *Production Planning and Control*, Vol. 12 No. 1, pp. 81-88.

Gjerdrum, J., Shah, N., and Papageorgiou, L. G. (2001). A combined optimization and agent-based approach to supply chain modelling and performance assessment. *Production Planning and Control*, Vol. 12 No. 1, pp. 81-88.

Global Risks. (2011), An initiative of the risk response network, *World Economic Forum*, Sixth edition, 2011, pp. 10-11.

Goh, M., Lim, J.Y.S. and Meng, F. (2007), “A stochastic model for risk management in global supply chain networks”, *European Journal of Operational Research*, Vol. 182 No. 1, pp.164-173.

Gordon, L.A., Loeb, M.P. and Tseng, C-Y. (2009), “Enterprise risk management and firm performance: A contingency perspective”, *Journal of Accounting and Public Policy*, Vol. 28, No. 4, pp. 301-327.

Government Executive. (2010), “Navy acknowledges schedule for F-35 fighter is slipping”, available at: http://www.govexec.com/story_page.cfm?articleid=44784&oref=todaysnews (accessed 19 April 2012).

Greener. S. (2008), *Business Research Methods*.

Gunasekaran, A., Patel, C. and McGaughey, R. E. (2004), "A framework for supply chain performance measurement", *International Journal of Production Economics*, Vol. 87, No. 3, pp. 333-347.

Hale, T. and Moberg, C.R. (2005), “Improving supply chain disaster preparedness: A decision process for secure site location”, *International Journal of Physical Distribution and Logistics Management*, Vol. 35 No. 3, pp.195-207.

Hallikas, J., Karvonen, I, Pulkkinen, U., Virolainen, V-M. and Tuominen, M. (2004), “Risk Management Processes in Supplier Networks”, *International Journal of Production Economics*, Vol. 90 No. 1, pp. 47-58.

Handfield, R. B. and Ernest L. N., (2002), Supply chain redesign: Transforming supply chains into integrated value systems, *FT Press*, pp. 371-372.

Handfield, R. B. and McCormack K. P. (2007), *Supply Chain Risk Management: Minimizing Disruption in Global Sourcing*, Boca Raton, FL: Taylor and Francis.

Harland, C., Brenchley, R. and Walker, H. (2003), “Risk in supply networks”, *Journal of Purchasing and Supply Management*, Vol. 9 No. 2, pp. 51-62.

Healy, M., and Perry, C. (2000), “Comprehensive criteria to judge validity and reliability of qualitative research within the realism paradigm”, *Qualitative market research: An international journal*, Vol. 3 No. 3, pp. 118-126.

Hendricks, K B and Singhal, V. R. (2003), “The effect of supply chain glitches on shareholder wealth”, *Journal of Operations Management*, Vol. 21 No. 5, pp.501-522.

Hendricks, K. B., Singhal, V. R. and Zhang, R. (2009), “The effect of operational slack, diversification, and vertical relatedness on the stock market reaction to supply chain disruptions”, *Journal of Operations Management*, Vol. 27 No. 3, pp.233-246.

Hilmola, O. P., Hejazi, A., and Ojala, L. (2005), “Supply chain management research using case studies: a literature analysis”, *International Journal of Integrated Supply Management*, Vol. 1 No. 3, pp. 294-311.

Hilmola, P., Helo, P. and Holweg, M. (2005), "On the outsourcing dynamics in the electronics sectors: the evolving role of the original design manufacturing", *Working paper*, Cambridge.

Hoenig, D. (2009), “An empirical analysis of supply chain risk management in the German automotive industry”, *International Journal of Production Economics*, Vol. 131 No. 1, pp. 242-249.

Howe, K. R. (1998), “The interpretive turn and the new debate in education”, *Educational Researcher*, Vol. 27 No. 8, pp. 13-20.

Hubbard, D. (2007), *How to Measure Anything: Finding the Value of Intangibles in Business*, John Wiley and Sons, pp. 46.

Hubbard, D. (2009), *The Failure of Risk Management: Why It's Broken and How to Fix It*, John Wiley and Sons.

Hult, G.T.M. and Craighead, Christopher W. (2010), “Risk Uncertainty and Supply Chain Decisions : A Real Options Perspective”, *Decision Sciences*, Vol. 41 No. 3, pp.435-458.

Hung, K.T. and Ryu, S. (2008), “Changing risk preferences in supply chain inventory decisions”, *Production Planning and Control*, Vol. 19 No. 8, pp.770-780.

Ikeda, A. (2011), Japanese Stocks Rise; Topix Has Biggest Weekly Gain since July, *Bloomberg*, March 25, 2011.

Jacobs, F. R., Berry, W. L., Whybark, D. C., and Vollmann, T. E. (2011), *Manufacturing planning and control for supply chain management*, McGraw-Hill.

Jia, F. and Rutherford, C. (2010), “Mitigation of supply chain relational risk caused by cultural differences between China and the West”, *The International Journal of Logistics Management*, Vol. 21 No. 2, pp.251-270.

Jiang, B, Baker, R. C. and Frazier, G. V. (2009), “An analysis of job dissatisfaction and turnover to reduce global supply chain risk : Evidence from China”, *Journal of Operations Management*, Vol. 27 No. 2, pp.169-184.

Jiang, B, Belohlav, J. and Young, S. (2007), “Outsourcing impact on manufacturing firms’ value: Evidence from Japan”, *Journal of Operations Management*, Vol. 25 No. 4, pp. 885-900.

Jogulu, U. D., and Pansiri, J. (2011). “Mixed methods: a research design for management doctoral dissertations”, *Management research review*, Vol. 34 No. 6, pp. 687-701.

Johnson, R. B., and Onwuegbuzie, A. J. (2004), “Mixed methods research: A research paradigm whose time has come”, *Educational researcher*, Vol. 33 No. 7, pp. 14-26.

Jonsson, P. (2000), “Towards a Holistic Understanding of Disruptions in Operations Management”, *Journal of Operations Management*, Vol. 18 No. 6, pp. 701-718.

Juttner, U. (2005), “Supply chain risk management - Understanding the Business Requirements from a Practitioner Perspective”, *The International Journal of Logistics Management*, Vol. 16 No.1, pp.120-141.

Juttner, U., Peck, H. and Christopher, M. (2003), “Supply chain risk management: outlining an agenda for future research”, *International Journal of Logistics Research and Applications*, Vol. 6 No. 4, pp.197-210.

Kainuma, Y., and Tawara, N. (2006). A multiple attribute utility theory approach to lean and green supply chain management. *International Journal of Production Economics*, Vol. 101 No. 1, pp. 99-108.

Kaya, M. and Özer, Ö. (2009), “Quality Risk in Outsourcing : Non contractible Product Quality and Private Quality Cost Information”, *Naval Research Logistics*, Vol. 56 No.7, pp. 669-685.

kelly, T., Reynolds, I., Sugiyama, k. and Topham, J. (2011), Disaster shows flaws in Just-In-Time production, *Thomson Reuters*.

Kern, D., Moser, R., Hartmann, E. and Moder, M. (2012), "Supply risk management: model development and empirical analysis", *International Journal of Physical Distribution and Logistics Management*, Vol. 42 No. 1, pp. 60-82.

Khan, O. and Burnes, B. (2007), “Risk and supply chain management: creating a research agenda”, *The International Journal of Logistics Management*, Vol. 18 No. 2, pp.197-216.

Khan, O., Christopher, M. and Burnes, B. (2008), “The impact of product design on supply chain risk: a case study”, *International Journal of Physical Distribution and Logistics Management*, Vol. 38 No. 5, pp. 412-432.

Khilyuk, L.F., Chilingar,G.V., Robertson, J.O. and Endres, B. (2000), Gas Migration-Events Preceding Earthquakes, *Gulf Publishing Company*, Houston, TX, 2000.

Kim, Y.G., Jeong, D., Park, S-H. and Baik, D-K. (2006), “Simulation of Risk Propagation Model in Information Systems”, in *International Conference on Computational Intelligence and Security*, 2006, IEEE Guangzhou, pp. 1555–1558.

Kirkwood. C. W. (1998), *Systems Dynamics Methods*, College of Business Arizona State University, USA.

Kleindorfer, P.R. and Saad, G.H. (2005) “Managing disruption risks in supply chains”, *Production and Operations Management*, Vol. 14 No.1, pp. 53–68.

Klibi, W. and Martel, A. (2012), "Scenario-based Supply Chain Network risk modelling", *European Journal of Operational Research*, No. 223 No. 3, pp. 644-658.

Knemeyer, A.M., Zinn, W. and Eroglu, C. (2009), “Proactive planning for catastrophic events in supply chains”, *Journal of Operations Management*, Vol. 27 No. 2, pp.141-153.

Kotov, V. (1997), Systems of Systems as Communicating Structures, *Hewlett Packard Computer Systems Laboratory* ,Paper HPL-97-124, pp. 1-15.

Kouvelis, P., Chambers, C. and Wang, H. (2006), "Supply chain management research and production and operations management: review, trends, and opportunities”, *Production and Operations Management* , Vol. 15 No. 3, pp.449–469.

Kovacs, G. and Spens, K. (2009), “Identifying challenges in humanitarian logistics”, *International Journal of Physical Distribution and Logistics Management*, Vol. 39 No. 6, pp. 506-528.

Kuhn, T. S. (1970), *The structure of scientific revolutions*, 2nd edition, Chicago, University of Chicago Press.

Kull, T. and Closs, D. (2008), “The risk of second-tier supplier failures in serial supply chains: implications for order policies and distributor autonomy”, *European Journal of Operational Research*, Vol. 186 No. 3, pp.1158-1174.

Kumar, R. (2010), *Research methodology: a step-by-step guide for beginners*, Sage Publications Limited.

Laeequddin, M., Waheed, K. A. and Sahay, V. (2009), “Supply chain partners’ trust building process through risk evaluation : the perspectives of UAE packaged food industry parties”, *Supply Chain Management: An International Journal*, Vol. 14 No. 4, pp. 280-290.

Lai, G., Debo, L. and Sycara, K. (2009), “Sharing inventory risk in supply chain: The implication of financial constraint”, *Omega: The International Journal of Management Science*, Vol. 37 No. 4, pp. 811-825.

Lambert, D.M. and Pohlen, T.L. (2001), “Supply Chain Metrics”, *The International Journal of Logistics Management*, Vol. 12 No.1, pp.1-19.

Lane D.C. (2007), “The Power of the Bond between Cause and Effect: Jay Wright Forrester and the field of system dynamics”, *System Dynamics Review*, Vol. 23 No. 203, pp. 95-118.

Lee, R.P. and Johnson, J.L. (2010), “Managing Multiple Facets of Risk in New Product Alliances”, *Decision Sciences*, Vol. 41 No. 2, pp.271-300.

Lemmer, B., Grellier, R. and Steven, J. (1999), “Systematic review of non-random and qualitative research literature: Exploring and uncovering an evidence base for health visiting and decision making”, *Qualitative Health Research*, Vol. 9 No. 3, pp. 315–328.

Leopoulos, V. N. and Kirytopoulos, K. A. (2004), “Risk management: a competitive advantage in the purchasing function”, *Production Planning and Control*, Vol. 15 No. 7, pp.678-687.

Levary, R.R. (2007), "Ranking foreign suppliers based on supply risk", *Supply Chain Management: An International Journal*, Vol. 12 No. 6, pp.392-394.

Lewis, M. (2003), "Cause, consequence and control: towards a theoretical and practical model of operational risk", *Journal of Operations Management*, Vol. 21 No. 2, pp. 205-224.

Li, C. L. and Kouvelis, P. (1999), 'Flexible and risk-sharing supply contracts under price uncertainty', *Management Science*, 45, pp. 1378-1398.

Li, J., Wang, S. and Cheng, T.C.E. (2010). "Competition and cooperation in a single-retailer two-supplier supply chain with supply disruption", *International Journal of Production Economics*, Vol. 124 No. 1, pp.137-150.

Liston, P., Byrne, J., Byrne, P.J. and Heavey, C. (2007), "Contract costing in outsourcing enterprises: Exploring the benefits of discrete-event simulation", *International Journal of Production Economics*, Vol.110, pp. 97–114.

Liu, Z. and Nagurney, A. (2011), "Supply chain outsourcing under exchange rate risk and competition", *Omega: The International Journal of Management Science*, Vol. 39, pp.539-549.

Liu, Z., Lai, M., Zhou, T. and Zhou, Y. (2009), "A supply chain risk assessment model based on multistage influence diagram," In *6th International Conference on Service Systems and Service Management*, Xiamen, China, pp.72-75.

Lockamy, A. and McCormack, K. (2010), "Analysing risks in supply networks to facilitate outsourcing decisions", *International Journal of Production Research*, Vol. 48 No. 2, pp.593-611.

Luna-Reyes, L.F. and Andersen, D.L. (2003), "Collecting and analyzing qualitative data for system dynamics: methods and models", *System Dynamics Review*, Vol.19 No.4, pp. 271-296.

Mangan, J., Lalwani, C., and Butcher, T. (2008), *Global logistics and supply chain management*,. Wiley, London.

Mantel, S., Tatikonda, M. and Liao, Y. (2006), "A behavioral study of supply manager decision-making: Factors influencing make versus buy evaluation", *Journal of Operations Management*, Vol. 24 No. 6, pp. 822-838.

Manuj, I. and Mentzer, J.T. (2008), "Global supply chain risk management strategies", *International Journal of Physical Distribution and Logistics Management*, Vol. 38 No. 3, pp.192-223.

Manuj, I., Mentzer, J.T. and Bowers, M.R. (2009), "Improving the rigor of discrete-event simulation in logistics and supply chain research", *International Journal of Physical Distribution and Logistics Management*, Vol. 39 No. 3, pp.172-201.

Market Watch, (2010), Lockheed, Pentagon soothe partners over F-35 delays- Next-generation warplane falls behind schedule, raising concerns, available at: http://www.marketwatch.com/story/lockheed-pentagon-calm-f-35-partners-over-delays-2010-03-04 (accessed 19 April 2012).

Matook, S., Lasch, R. and Tamaschke, R. (2009), "Supplier development with benchmarking as part of a comprehensive supplier risk management framework", *International Journal of Operations and Production Management*, Vol. 29 No. 3, pp. 241-267.

Mauricio F. B., Mohammed Q., Wee, H.M. and Watanabe, K. (2009), "Supply chain risk management (SCRM): a case study on the automotive and electronic industries in Brazil", *Supply Chain Management: An International Journal*, Vol. 14 No. 4, pp. 247 – 252.

McCarthy, D. (1996), “Liability and Risk”, *Philosophy and Public Affairs*, Vol. 25 No. 3, pp. 238-262.

McKenna, H. P. (1994), “The Delphi technique: a worthwhile research approach for nursing?” *Journal of Advanced Nursing*, Vol. 19, No. 6, pp. 1221-1225.

Millar, H., Joseph, A., and Mobolurin, A. (2002), “Using formal MS/OR modelling to support disaster recovery planning”, *European Journal of Operational Research*, Vol. 141 No. 3, pp. 679-688.

Min, H. and Zhou, G. (2002) "Supply chain modelling: past, present and future", *Computers and Industrial Engineering*, Vol. 43, pp. 231-249.

Minegishi S, Thiel. D. (2008), “System Dynamics Modelling And Simulation Of A Particular Food Supply Chain”, *Simulation Practice And Theory*, Vol. 8, pp. 321–339.

Mingers, J. and White, L. (2010), "A Review of the Recent Contribution of Systems Thinking to Operational Research and Management Science", *European Journal of Operational Research*, Vol. 207 No. 3, pp. 1147-1161.

Molina-Azorin, J. F. (2012), “Mixed Methods Research in Strategic Management Impact and Applications”, *Organisational Research Methods*, Vol. 15 No. 1, pp. 33-56.

Mudrageda, M. and Murphy, F.H. (2006), "Designing Safety Space in a Supply Chain to Handle System-Wide Disruptions", *Naval Research Logistics*, Vol. 54 No. 3, pp. 258– 264.

Nagurney, A., Cruz, J., Dong, J. and Zhang D. (2005), "Supply chain networks, electronic commerce, and supply side and demand side risk", *European Journal of Operational Research,* Vol. 164 No. 1, pp.120-142.

Narasimhan, R. and Talluri, S. (2009). "Perspectives on risk management in supply chains", *Journal of Operations Managemen*t, Vol.27 No.2, pp. 114–118.

Natarajarathinam, M., Capar, I. and Narayanan, A. (2009), "Managing supply chains in times of crisis: a review of literature and insights", *International Journal of Physical Distribution and Logistics Management*, Vol. 39 No. 7, pp.535-573.

Nato, D., Cooper, W. and Donnelly, J. M. (2011), Japan's 2011 Earthquake and Tsunami: Economic Effects and Implications for United States, *Congressional Research Service*, March 25, 2011.

Neiger, D., Rotaru, K. and Churilov, L. (2009), "Supply chain risk identification with value-focused process engineering", *Journal of Operations Management*, Vol. 27 No. 2, pp. 154-168.

Norrman, A and Lindroth, R. (2004), Categorization of Supply Chain Risk and Risk Management, in *Brindley C. (Ed.) Supply Chain Risk*, London, UK: Ashgate, pp. 14-28.

Norrman, A. and Jansson, U. (2004), “Ericsson’s proactive supply chain risk management approach after a serious sub-supplier accident”, *International Journal of Physical Distribution and Logistics Management*, Vol. 34 No.5, pp.434-456.

Oakshott, L. (1997), *Business modelling and Simulation*, Pitman publishing, London.

Oehmen, J., Ziegenbein, A., Robert, A., and Schönsleben, P. (2009), “System-oriented supply chain risk management”, *Production Planning and Control*, Vol.20, No.4, pp. 343-361.

Ojala, M. and Hallikas, J. (2006), “Investment decision-making in supplier networks: Management of risk”, *International Journal of Production Economics*, Vol. 104 No. 1, pp. 201-213.

Oke and Gopalakrishnan, M. (2009), “Managing disruptions in supply chains : A case study of a retail supply chain”, *International Journal of Production Economics*, Vol.118 No. 1, pp. 168-174.

Ortells, L.E., (2011), “Spatial Fuzzy Clustering with Simultaneous Estimation of Markov Random Field Parameters and Class”, *PhD thesis, Illinois Institute of Technology Telecom BCN*, Polytechnic University of Catalonia.

Oseibryson, K. and Ngwenyama, O. (2006), “Managing risks in information systems outsourcing: An approach to analyzing outsourcing risks and structuring incentive contracts”, *European Journal of Operational Research*, Vol. 174 No. 1, pp. 245-264.

Pai, R.R., Kallepalli, V.R., Caudill, R.J. and Zhou, M-C. (2003), "Methods toward supply chain risk analysis", in *Systems, Man and Cybernetics, 2003. IEEE International Conference*, Vol.5, pp. 4560- 4565.

Papadakis, I. S. (2006), "Financial performance of supply chains after disruptions an event study", *Supply Chain Management: An International Journal*, Vol. 11 No. 1, pp. 25-33.

Pawar, K S. and Lalwani C S., (2010), Introduction, Configuring Future Supply Chains, in *the Proceedings of the 15th International Symposium on Logistics*, Kuala Lumpur, Malaysia - 4-7 July 2010, pp. 5.

Peck, H. (2005), "Drivers of supply chain vulnerability: an integrated framework", *International Journal of Physical Distribution and Logistics Management*, Vol. 35 No. 4, pp. 210-232.

Peck, H. (2006), "Reconciling supply chain vulnerability, risk and supply chain management", *International Journal of Logistics Research and Applications*, Vol.9 No. 2, pp.127-142.

Peck, H. and Christopher, M. (2004) "Assessing and managing risk in the global supply chain", *Logistics and Supply Forum*.

Perry, M. (2007), "Natural disaster management planning: A study of logistics managers responding to the tsunami", *International Journal of Physical Distribution and Logistics Management*, Vol. 37 No. 5, pp. 409-433.

Petersen C. G., Aase. G. R. and Heiser. D. R. (2011), “Journal ranking analyses of operations management research” *International Journal of Operations and Production Management* Vol. 31 No. 4, 2011 pp. 405-422.

Petticrew, M., and Roberts, H. (2006), *Systematic Reviews in the Social Sciences: A Practical Guide*, Oxford: Blackwell.

Pierreval. H, Bruniaux, Caux (2007), "A Continuous Simulation Approach For Supply Chains In The Automotive Industry", *Simulation Modelling Practice And Theory*, Vol.15 No. 2, pp. 185-198.

Ponomarov, S. Y., and Holcomb, M. C. (2009), "Understanding the concept of supply chain resilience", *The International Journal of Logistics Management*, Vol. 20 No. 1, pp. 124–143.

Ponsporrata, a, Berlangallavori, R. and Ruizshulcloper, J. (2007), “Topic discovery based on text mining techniques”, *Information Processing and Management*, Vol. 43 No. 3, pp. 752-768.

Prowse, M. (2008), Locating and extending livelihoods research, *Brooks World Poverty Institute Working Paper*, pp. 37.

Pyke, D. and Tang, C. (2010), “How to mitigate product safety risks proactively? Process, challenges and opportunities”, *International Journal of Logistics Research and Applications*, Vol. 13 No. 4, pp. 243-256.

Ramanathan, R., Lalwani, C., Burns, N., Adil, G. K., Pawar, K. and Shah, J. (2009), Future Manufacturing Supply Chains: Issues and Challenges, in *Proceedings* *of the 14th International Symposium on Logistics*, Istanbul, Turkey - 5-8 July 2009, pp. 21.

Rao, S. and Goldsby, T.J. (2009), "Supply chain risks: a review and typology", *The International Journal of Logistics Management*, Vol. 20 No.1, pp.97-123.

Ravindran, A. R., Bilsel, R. U., Wadhwa, V. and Yang, T. (2010), "Risk adjusted multi-criteria supplier selection models with applications", *International Journal of Production Research*, Vol. 48 No. 2, pp.405-424.

Reilly, R. J., and Hoffer, G. E. (1983), "Will retarding the information flow on automobile recalls affect consumer demand?", *Economic Inquiry*, Vol. 21 No. 3, pp. 444-447.

Remenyi, Dan, Williams, Brian, Money, Arthur and Swartz, Ethné (1998), *Doing Research in Business and Management, An Introduction to Process and Method*, London: Sage.

Reuters, (2011), DAX Volatility index hits 8-1/2 month high, *Best growth stock*, March 15, 2011.

Richardson, G. P., and A. L. Pugh, III. (1981), *Introduction to System Dynamics Modelling*, Portland (OR): Productivity Press.

Richey Jr, R. G. (2009), "The supply chain crisis and disaster pyramid: A theoretical framework for understanding preparedness and recovery", *International Journal of Physical Distribution and Logistics Management,* Vol. 39 No. 7, pp.619 - 628.

Ritchie, B. and Marshall, D. (1993), *Business Risk Management*, Chapman and Hall, London.

Ritchie, B. and Brindley, C. (2007), “Supply chain risk management and performance: A guiding framework for future development”, *International Journal of Operations and Production Management*, Vol. 27 No. 3, pp.303-322.

Robson, C. (2002), *Real world research*, 2nd Ed, Blackwell, Oxford.

Ross, A. M., Rong, Y. and Snyder, L. V. (2008), "Supply Disruptions With Time-Dependent Parameters", *Computers and Operations Research*, Vol. 35, pp. 3504 – 3529.

Rousseau, D.M., Manning, J. and Denyer, D. (2008), “Evidence in management and organisational science: assembling the field's full weight of scientific knowledge through syntheses”, *The Academy of Management Annals*, Vol. 2 No. 1, pp. 475-515.

Rowe, W.D. (1980), *Risk assessment: approaches and methods*, in Conrad, J. (Ed.), Society, Technology and Risk Assessment, Academic Press, London.

Saltelli, A., M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, and S. Tarantola. (2008), *Global Sensitivity Analysis: The Primer*, Chichester, England: John Wiley and Sons.

Sanchez-Rodrigues, V. and Naim, A.P. and M.M. (2010), “Evaluating the causes of uncertainty in logistics operations”, *The International Journal of Logistics Management*, Vol. 21 No. 1, pp. 45-64.

Sapsford, R. and Jupp, V. (Eds.). (2006), *Data collection and analysis*, SAGE Publications Limited.

Satty, T. L. (1990), “How to Make a Decision: The Analytic Hierarchy Process”, *European Journal of Operations Research*, Vol.48, pp. 9-26.

Saunders, M. N., Saunders, M., Lewis, P., and Thornhill, A. (2009). *Research Methods for Business Students*, Pearson Education India.

Scheller-Wolf, A. and Tayur, S. (2009), “Risk sharing in supply chains using order bands- Analytical results and managerial insights”, *International Journal of Production Economics*, Vol. 121 No. 2, pp.715-727.

Senge P. (1990), *The fifth Discipline, Pegasus Communications*, New York, NY.

Sheffi, Y. (2001), “Supply Chain Management under the Threat of International Terrorism”, *The International Journal of Logistics Management*, Vol. 12 No. 2, pp.1-11.

Sheffi, Y. and Rice, J. (2005), “A supply chain view of the resilient enterprise”, *MIT Sloan Management Review*, Vol. 47 No. 1, pp. 41-49.

Sheffield, J., Sankaran, S and Haslett, T. (2012),"Systems thinking: taming complexity in project management", *On the Horizon*, Vol. 20 No. 2, pp.126-136.

Shi, D. (2004), “A review of enterprise supply chain risk management”, *Journal of systems science and systems engineering*, Vol.13 No.2, pp. 219-244.

Shin, K., Shin, Y., Kwon, J. H., and Kang, S. H. (2012), “Risk propagation based dynamic transportation route finding mechanism”, *Industrial Management and Data Systems*, Vol. 112 No. 1, pp. 102-124.

Shrivastava, (1995), “The role of corporations in achieving ecological sustainability”, *Academy of Management Review*, Vol.20 No.4, pp. 936-60.

Sinha, P. J., Whitman, L. E. and Malzahn, D. (2004), “Methodology to mitigate supplier risk in an aerospace supply chain’’, *Supply Chain Management: An International Journal*, Vol. 9 No. 2, pp.154-68.

Skipper, J.B. and Hanna, J.B. (2009), “Minimizing supply chain disruption risk through enhanced flexibility”, *International Journal of Physical Distribution and Logistics Management*, Vol. 39 No. 5, pp. 404-427.

Skulmoski, G. J., Hartman, F. T., and Krahn, J. (2007), “The Delphi method for graduate research”, *Journal of Information Technology Education*, Vol.6 No. 0, pp. 1–21.

Smeltzer, L. R. and Siferd, S. P. (1998), “Proactive supply management: the management of risk”, *International Journal of Purchasing and Materials Management*, Vol. 34 No. 1, pp. 38-45.

Sodhi, M. S., and Tang, C. S. (2012), Strategic approaches for mitigating supply chain risks, *Managing Supply Chain Risk*, Springer, New York.

Sodhi, M. S., Son, B.-G., and Tang, C. S. (2012), “Researcher’s perspectives on supply chain risk management”, *Production and Operations Management,* Vol.21 No.1, pp. 1-13.

Sodhi, M.S. (2005), “Managing Demand Risk in Tactical Supply Chain Planning for a Global Consumer Electronics Company”, *Production and Operations Management*, Vol. 14 No. 1, pp. 69 -79.

Sounderpandian, J., Prasad, S. and Madan, M. (2008), “Supplies from developing countries: Optimal order quantities under loss risks”, *Omega: The International Journal of Management Science,* Vol. 36 No. 1, pp.122-130.

Spekman, R. E. and Davis, E.W. (2004), “Risky business: expanding the discussion on risk and the extended enterprise”, *International Journal of Physical Distribution and Logistics Management*, Vol. 34 No. 5, pp. 414-433.

Srai, J. S. and Gregory, M. (2008), “A supply network configuration perspective on international supply chain development”, *International Journal of Operations and Production Management*, Vol.28 No.5, pp. 386.

Stecke, K. E. and Kumar, S. (2009), “Sources of Supply Chain Disruptions, Factors That Breed Vulnerability, and Mitigating Strategies”, *Journal of Marketing Channels*, Vol.16 No.3, pp.193-226.

Steel, R. G. D. and Torrie, J. H. (1960), *Principles and Procedures of Statistics*, New York, NY.

Stefanovic, D., Stefanovic, N. and Radenkovic, B. (2009), "Supply network modelling and simulation methodology”, *Simulation Modelling Practice and Theory*, Vol. 17 No. 4, 743-766.

Sterman, J. D. (2000), *Business Dynamics: Systems Thinking and Modelling for a Complex World*, Irwin/McGraw-Hill, USA

Stonebraker, P. W., Goldhar, J. and Nassos G. (2009), "Weak links in the supply chain: measuring fragility and sustainability", *Journal of Manufacturing Technology Managemen*t, Vol.20 No.2, pp. 161-177.

Svensson, G. (2000), "A conceptual framework for the analysis of vulnerability in supply chains", *International Journal of Physical Distribution and Logistics Management*, Vol. 30 No. 9, pp.731-750.

Swaminathan, J. M., Smith, S. F., and Sadeh, N. M. (1998), "Modelling Supply Chain Dynamics: A Multiagent Approach", *Decision Sciences*, Vol. 29 No. 3, pp. 607-632.

Systems Engineering Fundamentals, (2001), *Supplementary Text, Prepared By The Defence Acquisition University Press Fort Belvoir*, Virginia 22060-5565.

Tang, C. (2006a), "Perspectives in supply chain risk management", *International Journal of Production Economics*, Vol. 103 No. 2, pp.451-488.

Tang, C. (2006b), "Robust strategies for mitigating supply chain disruptions", *International Journal of Logistics Research and Applications*, Vol. 9 No. 1, pp.33-45.

Tang, C. and Tomlin, B. (2008), "The power of flexibility for mitigating supply chain risks", *International Journal of Production Economics*, Vol. 116, No. 1, pp.12-27.

Tang, O. and Nurmaya Musa, S. (2010), "Identifying risk issues and research advancements in supply chain risk management", *International Journal of Production Economics*, Vol. 133 No. 1, pp.25-34.

Tapiero, C. (2007), “Consumers risk and quality control in a collaborative supply chain”, *European Journal of Operational Research*, Vol. 182 No. 2, pp. 683-694.

Tomlin, B. (2006), “On the Value of Mitigation and Contingency Strategies for Managing Supply Chain Disruption Risks”, *Management Science*, Vol. 52 No. 5, pp. 639-657.

Tomlin, B. (2009), “Disruption-Management Strategies for Short Life-Cycle Products”, *Naval Research Logistics*, Vol. 56 No. 4, pp. 318-347

Torgerson, C. (2003), *Systematic reviews*, London: continuum.

Towill, D. R. (2005), "The impact of business policy on bullwhip induced risk in supply chain management", *International Journal of Physical Distribution and Logistics Management*, Vol. 35 No. 8, pp. 555–575.

Towill, D. R., Naim M. M., Wikner J. (1992), “Industrial Dynamics Simulation Models in The Design Of Supply Chains”, *International Journal of Physical Distribution Logistics Management*, Vol. 22 No. 5, pp. 3–13.

Tranfield, D., Denyer, D. and Smart, P. (2003), "Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review", British Journal of Management, Vol.14 No. 3, 207-222.

Trkman, P. and Mccormack, K. (2009), “Supply chain risk in turbulent environments- A conceptual model for managing supply chain network risk”, *International Journal of Production Economics*, Vol. 119 No. 2, pp. 247-258.

Tummala, R. and Schoenherr, T. (2011),"Assessing and managing risks using the Supply Chain Risk Management Process (SCRMP)", *Supply Chain Management: An International Journal*, Vol. 16 No. 6 pp. 474 – 483.

Ujikane, K. (2011), Japan Sees Quake Damage Bill of Up to $309 Billion, Almost Four Katrinas, *Bloomberg news report*, March 23, 2011.

Urciuoli, L. (2010), "Supply chain security—mitigation measures and a logistics multi-layered framework", *Journal of Transportation Security,* Vol. 3 No. 1, pp. 1-28.

Van Landeghem, H and Vanmaele, H. (2002), "Robust planning: a new paradigm for demand chain planning", *Journal of Operations Management*, Vol. 20 No. 6, pp. 769-783.

Van Wassenhove, L. N. (2006). "Blackett memorial lecture- Humanitarian aid logistics: Supply chain management in high gear", *Journal of the Operational Research Society*, Vol. 57 No. 5, pp. 475–489.

Vanany, I., Zailani, S. and Pujawan, N. (2009), "Supply chain risk Management: Literature review and Future research", *International Journal of Information Systems and Supply Chain Management*, Vol. 2 No. 1, pp.16-33.

Vennix, J. A. M. (1996), *Group Model Building: Facilitating Team Learning Using System Dynamics*, Chichester: John Wiley and Sons.

Vlachos, D., Georgiadis, P. and Iakovou, E. A. (2007), "System Dynamics Model for Dynamic Capacity Planning Of Remanufacturing In Closed-Loop Supply Chains", *Computers and Operations Research*, Vol. 34, pp. 367–394.

Vorst, J. G. A. J., Beulens, A. J. M., Wit, W. and Beek, P. (1998), “Supply Chain Management in Food Chains: Improving Performance by Reducing Uncertainty”, *International Transactions in Operational Research*, Vol. 5 No.6, pp. 487-499.

Vorst, J.G.A.J, and Beulens, A. J. M. (2002), “Identifying sources of uncertainty to generate supply chain redesign strategies”, *International Journal of Physical Distribution and Logistics Management*, Vol. 32 No. 6, pp.409-430.

Wagner, S. M. and Bode, C. (2006), "An empirical investigation into supply chain vulnerability", *Journal of Purchasing and Supply Management*, Vol. 12 No. 6, pp. 301–312.

Wagner, S. M. and Neshat, N. (2010), "Assessing the vulnerability of supply chains using graph theory", *International Journal of Production Economics*, Vol. 126 No. 1, pp. 121–129.

Wagner, S. M., Bode, C. and Koziol, P. (2009), “Supplier default dependencies: Empirical evidence from the automotive industry”, *European Journal of Operational Research*, Vol. 199 No. 1, pp.150-161.

Wakolbinger, T. and Cruz, J. M. (2011), “Supply chain disruption risk management through strategic information acquisition and sharing and risk-sharing contracts”, *International Journal of Production Research*, Vol. 49 No. 13, pp. 4063-4084.

Wang, C. X. and Webster, S. (2007), “Channel Coordination for a Supply Chain with a Risk-Neutral Manufacturer and a Loss-Averse Retailer”, *Decision Sciences*, Vol. 38 No. 3, pp.361-389.

Wang, X., Chan, H., Yee, R., Diaz-Rainey, I. (2012), "A two-stage fuzzy-AHP model for risk assessment of implementing green initiatives in the fashion supply chain", *International Journal of Production Economics*, Vol. 135 No. 2, pp. 595-606.

Williams, Z., Lueg, J. E. and LeMay, S. A. (2008), “Supply chain security: an overview and research agenda”, *The International Journal of Logistics Management*, Vol. 19 No. 2, pp.254-281.

Wilson, M. C. (2007), “The impact of transportation disruptions on supply chain performance”, *Transportation Research Part E: Logistics and Transportation Review*, Vol. 43 No.4, pp. 295-320.

Winters, P. R. (1960), “Forecasting sales by exponentially weighted moving averages”, Management Science, Vol. 6 No. 3, pp. 324-342.

Wong K. (2006), What Grounded the Airbus A380?, available at: http://www.cadalyst.com/management/what-grounded-airbus-a380-5955 (accessed 19 April 2012).

World Commission on Environment and Development. (1987), *Our Common Future*, Oxford University Press, New York.

Wu, D. and Olson, D. (2008), “Supply chain risk, simulation, and vendor selection”, *International Journal of Production Economics*, Vol. 114 No.2, pp. 646-655.

Wu, T., Blackhurst, J. and Chidambaram, V. (2006), “A model for inbound supply risk analysis”, *Computers in industry*, Vol. 57 No. 4, pp.350–365.

Wu, T., Blackhurst, J. and O'grady, P. (2007), "Methodology for supply chain disruption analysis", *International Journal of Production Research*, Vol. 45 No. 7, pp.1665-1682.

Xiao, T. and Yang, D. (2008), "Price and service competition of supply chains with risk-averse retailers under demand uncertainty", *International Journal of Production Economics*, Vol.114 No.1, pp.187-200.

Yang, J., Qi, X. and Yu, G. (2005), "Disruption management in production planning", *Naval Research Logistics*, Vol. 52 No.5, pp.420-442.

Yang, Z., Aydin, G., Babich, V. and Beil, D. (2008), 'Supply Disruptions, Asymmetric Information, and a Backup Production Option", *Management Science*, Vol. 55 No. 2, pp.192-209.

Yin, R. K. (1984), *Case Study Research: Design and Method*, Sage, Beverly Hills, California.

Yu, H., Zeng, and Zhao, L. (2009), "Single or dual sourcing: decision-making in the presence of supply chain disruption risks", *Omega: The International Journal of Management Science*, Vol. 37 No. 4, pp. 788-800.

Zsidisin, G. A. (2003a), "A grounded definition of supply risk", *Journal of Purchasing and Supply Management*, Vol. 9 No. 5, pp. 217-24.

Zsidisin, G. A. (2003b), "Managerial Perceptions of Supply Risk", *Journal of Supply Chain Management*, Vol. 39 No. 1, pp.14-26.

Zsidisin, G. A. and Ritchie, B. (2008), *Supply Chain Risk: A Handbook of Assessment, Management and Performance*, Edited Book, 103-120.

Zsidisin, G. A., Ellram, L. M., Carter, J. R. and Cavinato, J. L. (2004), “An analysis of supply risk assessment techniques”, *International Journal of Physical Distribution and Logistics Management*, Vol. 34 No. 5, pp. 397- 413.

Zsidisin, G. A., Panelli, A., and Upton, R. (2000), “Purchasing organisation involvement in risk assessments, contingency plans, and risk management: an exploratory study”, *Supply Chain Management: An International Journal*, Vol. 5 No. 4, pp. 187-198.

Appendix

Journal publications:

1. **<u>Supply Chain Risk Management: Present and Future Scope</u>**

The International Journal of Logistics Management, Vol. 23 No. 3, pp. 313-339.

Abstract:
Purpose – This paper examines supply chain risk management (SCRM) from a holistic systems thinking perspective by considering the different typologies that have evolved as a result of earlier research. The purpose of this paper is to identify important strategic changes in the field and to outline future requirements and research opportunities in SCRM.

Design/methodology/approach – The systematic literature review (SLR) methodology employed by this research was used to evaluate and categorise a literature survey of quality articles published over a period of ten years (2000-2010). Additionally, the findings from the SLR have been strengthened through cross validation against results obtained from an associated text mining activity.

Findings – The SLR methodology has provided a rich, unbiased and holistic picture of the advances in the field of SCRM. Consequently, important new research areas have been identified based on a multi-perspective descriptive and thematic data analysis. In addition, the analysis, based on evolved typologies, indicates a growth of SCRM from a nascent to a fairly established activity over the past decade.

Practical implications – The systematic approach undertaken for the literature review will provide future researchers and managers with an insightful understanding of the scope of the SCRM field. Also, the literature review provides important clues on new research directions for SCRM through identification of gaps in current knowledge.

Originality/value – The holistic approach to SCRM was found to be an important missing link in earlier literature surveys. The outcome of the SLR reported in this paper has provided critical insights into the present and future scope of the SCRM field. The identified research insights, gaps and future directions will encourage new research techniques, with a view to managing the risks in the globalized supply chain environment.

2. **A Systems Approach for Modelling Supply Chain Risks**

Supply Chain Management: An International Journal, Vol. 18 No. 5, pp. 523-538.

Abstract:
Purpose- With increasing exposure to disruptions, it is vital for supply chains to manage risks proactively. Prediction of potential failure points and overall impact of these risks is challenging. In this paper, systems thinking concepts are applied for modelling supply chain risks. The aim of this research is to develop a holistic, systematic and quantitative risk assessment process for measuring the overall risk behaviour.

Design/methodology/approach- A framework for Supply Chain Risk Management (SCRM) is developed and tested using an industrial case study. A systematically developed research design is employed to capture the dynamic behaviour of risks. Additionally, a system based supply chain risk model is conceptualized for risk modelling. Sensitivity modelling results are combined for validating the supply chain risk model.

Findings- The systems approach for modelling supply chain risks predicts the failure points along with their overall risk impact in the supply chain network. System based risk modelling provides a holistic picture of risk behavioural performance which is difficult to realise through other research methodologies commonly preferred in the SCRM research.

Practical implications- The developed framework for SCRM is tested in an industry setting for its viability. The framework for SCRM along with the supply chain risk model is expected to benefit practitioners in understanding the intricacies of supply chain risks. The system model for risk assessment is a working tool, which could provide a perspective of future disruptive events.

Originality- A holistic, systematic and quantitative risk modelling mechanism for capturing overall behaviour of risks is a valuable contribution of this research. The paper presents a new perspective towards using systems thinking for modelling supply chain risks.

Conference Publications:

3. **A Framework for Managing Risks in the Aerospace Supply Chain Using Systems Thinking**

5th International Conference on System of Systems Engineering, IEEE, 22-24 June, 2010, Loughborough University, UK. pp. 1-6.

Abstract:
Impact of globalization, technological and environmental changes, has radically influenced supply chain risks and mitigating strategies. Since uncertainty is an intrinsic element of the aerospace supply chain system, this paper analyses the uncertain variables (risks) in aerospace supply chain using a 'systems of systems' approach. Complexity and interdependent nature of the aerospace supply chain requires different levels of mitigation strategies. In this paper, utility theory and a proactive approach to risk management is considered. Effect on quality and delivery are two important monitoring parameters when analysing risks within the aerospace supply chain system. This is depicted with the help of cases. The paper concludes by identifying the benefits of mitigating strategies for future sustainable systems.

4. **Managing Risks in Next Generation Supply Chains: A Systems Approach**

15th International Symposium on Logistics, 4-7 July 2010, Kuala Lumpur, Malaysia. pp. 488-495.

Abstract:
Supply chain risk management follows three basic processes to manage supply chain risks: Identify, Assess and Mitigate. This paper considers a systems perspective towards managing these risks. It presents variables that may affect Next Generation Supply Chains and applies a System dynamics modelling approach (Oehmen, *et al.*, 2009) towards depicting the causal linkages of these variables with future supply disruptions. To understand the interdependencies within these factors and the risk propagation on account of these factors it was decided to adopt a systems perspective. This perspective is based upon application of a causal loop diagram, which considers the interdependencies between the factors affecting next-generation supply chains. The causal linkages between the variables are then highlighted with regards to the supply chain process and the nodes, and the causes of future risks are identified.

5. **Supply Chains Risks: A Systems Thinking Perspective**

10th International Research Seminar on Supply Chain Risk Management, ISCRiM, 6-7 September 2010, Loughborough University, UK. pp. 51-55.

Abstract:
This paper considers a systems perspective towards managing these risks. It presents variables that may affect next generation supply chains and applies a causal loop model towards depicting the causal linkages of these variables with future supply disruptions. The causal linkages between the variables are then highlighted with regards to the supply chain process and the nodes, and the causes of future risks are identified. From the causal loop diagram the risk propagation is derived in a form of risk framework

6. Systems Thinking for Sustainability and Supply Chain Risks

15th Logistics Research Network Annual Conference, 8- 10 September 2010, Harrogate, UK. pp. 230-237.

Abstract:
Sustainable Supply Chain Management (SSCM) is defined as the 'Strategic achievement and integration of an organisation's social, environmental, and economic goals through the systemic coordination of key inter-organisational business processes to improve the long-term economic performance of the individual company and its value network' (Carter and Rogers, 2008). Following the same concept, we analyze sustainable supply chains from a risk management perspective through systemic coordination (feedback loops). For supply chain traceability and risk mitigation we use a systems thinking approach to analyse two different closed loop supply chain systems, one with component supplier and other with contract manufacturer. The research presents a Sustainable Supply Chain Risk Management (SSCRM) sourcing decision framework.

7. **Supply Chain Risk Management: An Analysis of Present and Future Scope**

16th International Symposium on Logistics, 10-12 July 2011, Berlin, Germany. pp. 245-254. ***(Best doctoral paper award)***

Abstract:
Supply chain risk management has increasingly attracted researchers as well as practitioners in recent years. Literature reviews on this topic have provided a good platform for beginners in the field of SCRM. However this paper assumes that the SCRM researcher will benefit from a systematic literature review in which the SCRM field is studied holistically based on different typologies. The study considers papers published over a period of ten years and depicts the prominent strategic changes in SCRM research analysed from numerous perspectives. The outcome of this systematic literature review has provided insights into the present and future scope of SCRM field. This research expects to provide researchers and managers a quick but insightful understanding of the length and breadth of the SCRM field. The identified research insights, gaps and future directions will encourage new research techniques to manage risks in the globalized supply chain environment.

8. Systems Thinking for Modelling Risk Propagation in Supply Networks

5th International Conference on Industrial Engineering and Engineering Management, IEEE, 6-9 December, 2011, Singapore. pp. 1685-1689.

Abstract:
Large scale systems like supply chains are growing more global and complex. Quantifying supply chain risks is challenging due to their uncertain nature. Understanding of the risk propagation is expected to provide new directions for effective supply chain risk management. Using systems thinking approach for

modelling risk propagation in supply chain, we have developed a conceptual understanding of risk propagation levels and dimensions. A case study of the Japanese tsunami (2011) has been analysed and presented in a multi-dimensional perspective to validate the conceptual development of risk propagation. Key supply chain risks and their approximate risk propagation durations are identified for a typical natural disaster disrupting global supply chain network. Case study has validated the classification of risks based on their propagation zones in supply network.

9. Risk Modelling for Creating Economically Sustainable Supply Chains

17th Logistics Research Network Annual Conference, 5-7 September 2012, Canfield University, UK, pp. 1-6.

Abstract:
In today's global environment there is an increased emphasis on economic, ecological and social sustainability in business practices and theory (Svensson, 2000). With increasing exposure to disruptions, it has become vital for supply chains to maintain working capital for staying resilient. Economic sustainability is believed to be critical from a 'triple bottom line' perspective (Carter and Rogers, 2004) for the survival of the organisation. Effective management of risks affecting organisations can have a positive impact on economic sustainability. Proactively measuring the risk propagation in terms of potential failure points and impacts is lacking in the literature (Wu et al., 2007). Systems thinking concepts are applied in this research for conceptualizing, modelling and evaluating supply chain risks. The research attempts to provide a holistic, systematic and quantitative risk modelling approach for creating economically sustainable supply chains.

Working paper:

10. Configuring Future Supply Chains using a Systems Approach.

Abstract:
Purpose- Supply chains are consistently reconfiguring themselves to meet changing global demands. The paper attempts to utilise a systems thinking approach for understanding various factors that are expected to influence next generation supply chains.

Design/methodology/approach- The research is conducted in two phases. In the first phase, an extensive literature review and feedback from international workshops on supply chain management is utilised to identify the factors that would affect next generation supply chains. Additional information regarding supply chain issues is driven from the study of different industry sectors. In the second phase, a conceptual model of supply chain risk and framework for next generation supply chains is developed and retrospectively validated with secondary data analysis.

Findings- The paper is able to identify the factors expected to influence future supply chains. A framework for configuring next generation supply chains presents sustainability and risk management as the important considerations for future supply chain design.

Practical implications- The next generation factors are expected to generate a cascading effect through quality and supply chain disruptions on market share and brand reputation. Supply chains need to shift their focus on long term sustainability by proactively mitigating the risks is evident from the study. The identified next generation factors are believed to be critical for the survival of companies in competitive global market.

Originality/value- The paper attempts to present a novel perspective towards using systems thinking for configuring next generation supply chains. The paper presents a focus on supply chain design from a short term to a long term perspective and presents the strategic elements for influencing this.

Workshop presentations:

Preliminary research work was also presented at the following two international workshops:

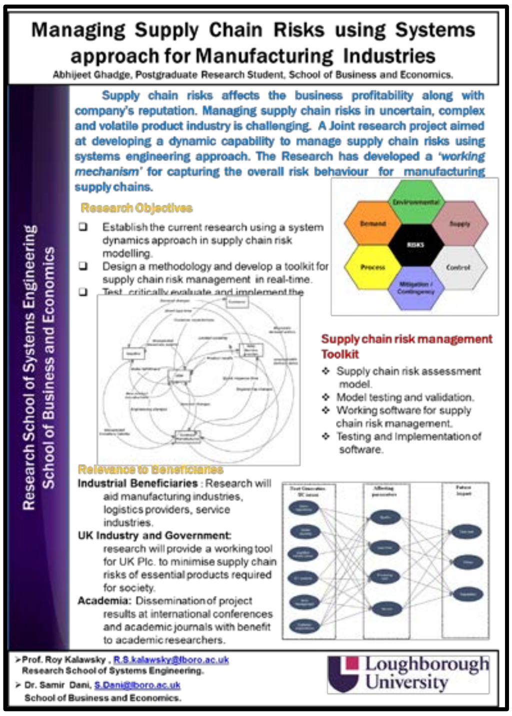
1. **Next Generation Manufacturing Supply Chains and Digital Economy Research Collaboration (NEX-GEMS)** project conference held at Loughborough University, UK, 2010.

2. **International Supply Chain Risk Management Network (ISCRiM) conference** held at Loughborough University, UK, 2010.

3. A **guest lecture on 'Supply Chain Risk Management'** was delivered to MSc. Operations Management students on 3rd May 2012 at the university.

Poster presentations:

Attempts were made to advertise the project information through a poster competition held in university during first and third year. The posters prepared and presented at different competitions are attached.



POSTERS PRESENTED