Risk Modelling and Simulation of Chemical Supply Chains using a System Dynamics Approach

Chaoyu Li

A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy

April 2016

Abstract

A chemical supply chain (CSC) presents a network that integrates suppliers, manufacturers, distributors, retailers and customers into one system. The hazards arising from the internal system and the surrounding environment may cause disturbances to material, information and financial flows. Therefore, supply chain members have to implement a variety of methods to prepare for, respond to and recover from potential damages caused by different kinds of hazards. A large number of studies have been devoted to extending the current knowledge and enhancing the implementation of chemical supply chain risk management (CSCRM), to improve both safety and reliability of the CSCRM systems. However, the majority of existing risk management methods fail to address the complex interactions and dynamic feedback effects in the systems, which could significantly affect the risk management outcomes. In order to bridge the gaps, a new CSCRM method based on System Dynamics (SD) is proposed to accommodate the need to describe the connections between risks and their associated changes of system behaviour. The novelty of this method lies not only on providing a valid description of a real system, but also on addressing the interactions of the hazardous events and managerial activities in the systems. In doing so, the risk effects are quantified and assessed in different supply chain levels. Based upon the flexibility of SD modelling processes, the model developer can modify the developed model throughout the model life cycle. Instead of directly assessing different risks and providing arbitrary decisions, the obtained numerical results can offer supportive information for assessing potential risk reduction measures and continuously improving the CSC system performance. To demonstrate the applicability of the newly proposed method, a reputed specialty chemical transportation service provider in China is used and analysed through modelling and simulating the chemical supply chain transportation (CSCT) operations in various scenarios. It offers policy makers and operators insights into the risk-affected CSC operations and CSCRM decision-making processes, thus helping them develop rational risk reduction decisions in a dynamic environment.

Acknowledgements

The completion of this thesis represents the culmination of three years of hard work. It has been a long journey with a number of ups and downs along the way but I have not had to make this journey alone. Over the three years that have gone into completing this work I have been fortunate to be accompanied by an extraordinary range of wonderful people. Each of these people has made the journey easier for their being involved.

The first person that I would like to thank is my principal supervisor, Dr Jun Ren. His guidance was invaluable, which enabled me to develop a strong understanding of the subject and supported me to complete this thesis. I owe him lots of gratitude for all he has done.

Secondly, I owe special thanks to my second supervisor, Professor Jin Wang. I could have not completed my PhD without his help and support. He also offered me a great opportunity to be part of the EU funded REFERENCE project to advance my knowledge in risk modelling and decision making, and also extended my network in the research community. I also would like to thank my co-supervisor, Professor Ian Jenkinson for the assistance that he offered to me in gaining a greater understanding of their specialist areas.

Also, I would like to thank the other members of my supervisory board, Professor Xinping Yan and Dr Di Zhang at Wuhan University of Technology, China, for their support and comments on the thesis.

No set of acknowledgments would be complete without mentioning family. My mother and father have provided me with over twenty years of support in which they have helped me through a broad variety of challenges. I have absolutely no doubt that without their presence in the background I would never have completed this work.

This thesis is dedicated to my family.

Table of Contents

List of Figures

List of Tables

Abbreviations

AHP	Analytic Hierarchy Process
B2B	Business-to-Business
BE	Bullwhip Effect
CEFIC	European Chemical Industry Council
CI	Chemical Industry
CM	Cost Management
CP	Consequence Probability
CPL	Capacity planning
CS	Consequence Severity
CSC	Chemical Supply Chain
CSCRM	Chemical Supply Chain Risk Management
CSCT	Chemical Supply Chain Transportation
DP	Distribution Planning
ETA	Event Tree Analysis
EU	European Union
EUCI	European Union Chemical Industry
FCA	Fuzzy Comprehensive Assessment
FMEA	Failure Model and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Study
IPM	Inventory Planning/Management
IS	Information Sharing
LO	Likelihood of a Hazardous Event Occurrence
OSCO	Optimising Supply Chain Operations

PDF	Planning and Demand Forecasting
PR	Processes Redesign
PRA	Preliminary Risk Analysis
PP	Production Planning
RCP	Replenishment control policies
REACH	Registration, Evaluation, and Authorization of Chemicals
RL	Reverse Logistics
RM	Relationship Management
SCM	Supply Chain Management
SCRM	Supply Chain Risk Management
SD	System Dynamics
S.D.	Standard Deviation
SI	System Information
SMEs	Small and Medium-size Enterprises
SO	Structure Optimisation
SS	Supplier Selection
WHO	World Health Organization
WIP	Work-in-Process

CHAPTER 1 INTRODUCTION

Summary

This chapter gives a brief introduction to research background that helps to understand the research necessity from the academic and practical viewpoint. The thesis outline is provided to explain the different stages in chemical supply chain risk management (CSCRM), followed with the hazard identification, risk analysis and risk reduction. It is particularly innovative that the qualitative method is applied to capture and conceptualise the chemical supply chain (CSC) risks and a quantitative method is used to model and simulate the risk effects in the supply chain level. Meanwhile, the challenges in the research have been specified to demonstrate the deliverables to the knowledge and to indicate the achievements against the defined objectives.

1.1 RESEARCH BACKGROUND

The Chemical industry (CI) is playing a key role in modern world economy, which comprises more than 70,000 product lines and a number of geographic markets. The CSCs are the networks of the CI that integrates suppliers, manufacturers, distributors, retailers and customers in one system (Tsiakis and Papageorgiou, 2008). Due to the geographic dispersion of the supply chain members, huge volumes of chemical materials often need to be purchased, and transported across the national boundaries by air, road, railway, pipeline or ship. Meanwhile, multiple manufacturing recipes can be applied for converting raw materials to finished products in batch, continuous or semi-continuous operation modes. These distinct features require highly coordinated material, information and finance flows to perform as per expectations.

However, the CSC appears to be complex and volatile (Pasman and Rogers, 2012; Kirschstein, 2015; Li *et al*., 2015). The complexity may reduce the efficiency, while the volatility brings uncertainties to CSC operations. These are regarded as the sources of risks, which should be managed during the operations (Simangunsong, Hendry and Stevenson, 2011). A risk is defined as the potential for an incident or accident, which can interrupt the operational process and have a negative impact on the system performance (Waters, 2011). In the CSC, the risks are the threats in terms of some unpleasant things, such as financial instability, global sourcing, and unstable regional situations, arising from the uncertainties and disruptions among the internal system, and the surrounding environment that damage the system performance and cause unexpected losses (Mckinnon and Braithwaite, 2005). Apart from the general risks addressed in the supply chain, each CSC has its distinct risk features. The hazardous characteristics of chemical substances, such as being flammable, toxic and explosive, could result in the significant risk consequence on the CSC systems. As well, it threatens the surrounding environment and endangers human health (Bonvicini, Leonelli and Spadoni, 1998; Papageorgiou, 2009). In response, governments and authorities have introduced a substantial body of legislation, regulatory guidance and recommendations to ensure the safety of CSC operations (Furuhama *et al.*, 2011; Fisk, 2014; Scruggs *et al.*, 2014). It is essential for the CSCs to provide low pollution and energy-efficient services and products for the framework of today's society in terms of the responsibility for environmental protection (Verboven, 2011). Meanwhile, the majority of fossil fuels are sourced from dangerous and unstable areas of the world. It leads to CSCs experiencing a higher probability of terrorist attack (Mullai, 2009). The academics and practitioners are highly concerned about the environment issue, especially after the hurricane Katrina, Indonesia tsunami and the Tohoku earthquake. When major disruptions occur, many CSCs tend to break down and take a long time to recover (Rao and Goldsby, 2009; Ehlen *et al.*, 2014). To deal with these undesired risks, it is essential to broadly outline the sources of risks across the supply chain network following the structured method.

CSCs are becoming more and more vulnerable, it is therefore important to effectively predict and control the risks through a coordinated approach under the challenges of uncertainty, complexity and regulatory oversight across the global economy (Christopher and Lee, 2004; Thun and Hoenig, 2011). Both academia and CSC operators appreciate the need to improve the safety and reliability of the CSC not only at the operational level but also at the strategy level, to identify the hazards, analyse their associated risks and manage the unacceptable ones (Mckinnon and Braithwaite, 2005). However, it still remains to be further investigated as to how hazard identification can be conducted, how the causal relations and feedback effects can influence the risk effects in a CSC, how the risk modelling method plays a role in CSCRM and how the advantageous risk reduction decisions can be made.

1.2 RESEARCH QUESTIONS

The research questions are generated to ensure that the research objectives are met and the methodological points are specified, which are shown as:

- What are the risks in the CSC?

In theory, a risk is defined as a potential for an incident or accident, which brings undesired effects (Waters, 2011). In the CSC, the risks arise from the uncertainties and disruptions among the internal system, and the surrounding environment that interrupt the operational process and cause unexpected losses in terms of financial, service level and reputation aspects. It is therefore significant to ensure that all the risks have been recognised across the supply chain network.

- What is a CSCRM framework that can be implemented to deal with the CSC risks?

The framework describes the overall plan and reveals the priorities of the research. Managing CSC risks should first understand the sources of risks, and then facilitate risk management in a proper way. The knowledge gathered by means of the literature review will contribute to developing a framework, which facilitates the risk management approaches and suggests the structured steps to achieve the research objectives.

- What are the hazards or sources of risks associated with a CSC and how to identify these hazards?

An unforeseen hazard is a threat that can interrupt the CSC operations and has negative impact on the CSC performance, it is therefore essential to identify hazards in the CSC. To extend the understanding of the risks from an industrial perspective, a rigorous approach is required to strengthen the knowledge base in hazard identification and provide a comprehensive CSC risk portfolio.

- What are the appropriate methods for analysing and evaluating the risks associated with the identified hazards within the changeable system and how to implement the proposed methods?

Although the proposed analytical approaches seem more promising, the formulation of a risk analysis technique is a rather difficult task within the changeable system. A novel method is required to accommodate the need to describe the causal relations between the hazardous events and their associated changes of CSC behaviour. The risks should be analysed that take into consideration the complex interactions and dynamic feedback effects among the system.

- What is the appropriate method for reducing the unacceptable risks on system thinking and how can it be used to manage the CSC risks?

Risk reduction measures aim at reducing occurrence likelihood of undesirable events and/or mitigating possible consequence severity. Before practically applying it, the reduction outcomes should be estimated to ensure that the provided approach does indeed address the research objectives.

1.3 RESEARCH AIM AND OBJECTIVES

The primary purpose of this research is to propose an integrated method by using both qualitative and quantitative techniques to identify hazards, analyse and reduce the risks associated with the identified hazards in the supply chain level. Due to the insufficient hazard identification studies specific to CSCs, this research combines the distinct CSC risk features with sources of general supply chain risks to the established CSC risk taxonomic diagram.

In the previous studies, various methods and different techniques are applied to accommodate the need to analyse and evaluate the risks. However, little has been done to address the dynamic interactive relations among the variables influencing the system operations, which could significantly affect the risk management results. It is imperative to develop a methodology that can obtain and represent the complex relationships using multiple sources of data to address the dynamic risk impacts in CSC systems.

In order to achieve the research aims, the objectives are addressed as follows:

- To understand the technical challenges in carrying out hazard identification, risk assessment and risk reduction through conducting a literature review;
- To propose a novel framework to capture, conceptualise, analyse and reduce the risks in the CSC and hence to strengthen the knowledge base in CSCRM;
- To develop conceptual models to support the proposed framework;
- To conduct simulations to investigate the significant risks and explore the risk reduction outcomes in CSC systems;
- To conduct case studies to test the proposed methods. A real CSCT case is provided to examine the developed CSCRM method for hazard identification, risk assessment and risk management.

1.4 THE CHALLENGES OF CONDUCTING THE RESEARCH (THE STATEMENT OF PROBLEM)

In recent years, “global”, “complex”, “uncertain” and “hazardous” are the words frequently used to describe the CSC system. These characteristics contribute to the risks in both internal systems and the external environment and lead to the uncertainties and disruptions to the CSC operations. Instead of offering a holistic CSCRM framework, the majority of the studies were carried out to analyse several specific kinds of risks. It is important to credit the publications that had developed conceptual or analytical models to investigate the risks in the CSC. Ferrio and Wassick (2007), You, Wassick, and Grossmann (2009), Tong, Feng and Rong (2011), Oliveira *et al*. (2013) and Cai (2014) applied stochastic programming methods to investigate schedule and reschedule problems under demand uncertainty, so as to enhance the service level and reduce the waste in CSCs. La ńez, Puigjaner and Reklaitis (2009), Carneiro, Ribas, and Hamacher (2010), Oliveira and Hamacher (2012), and Ruiz-Femenia *et al.* (2013) provided retrofit actions to deal with the investment optimisation problems in the CSC. Recently, an alternate viewpoint on the CSC operations reaches a consensus that environmental standards should be improved to minimise the hazardousness to the environment. Mont, Singhal and Fadeeva (2006), Bruinen de Bruin *et al.* (2007), Furuhama *et al.* (2011), Zhu, Cordeiro and Sarkis (2013), Fisk (2014) and Scruggs *et al.* (2014) offered alternative viewpoints to manage policy related risks effectively and efficiently toward the increasing challenges in CSCRM. However, there is a need to provide a generally applicable method for analysing and managing multiple types of risks in the supply chain level.

In practical terms, it is difficult to have a clear understanding of the complex CSC structure, operating procedures, and other aspects with available quantitative data. To provide risk information, past experience and expert judgement are frequently employed to describe the risk consequences and the behaviours of the CSC operations (Tse, 2012). However, the majority of existing methods are restricted by using the combination of qualitative and quantitative data in risk management research (Kaggwa, 2008). A novel method is required to conduct risk analysis and risk reduction using multiple sources of data in the research.

Besides, the developed risk management systems are presented as static models and the simple algebraic equations are frequently adapted to represent the relationship between the system components (Leveson, 2004). It ignores the feedback effects among the logical loops emerging from the causal relations, which govern the system behaviour change over time and lead to the dynamic of system behaviours over time (Fernandes, Barbosa-Póvoa and Relvas, 2011). Meanwhile, the addressed relationships between each functional node are not simply proportional. The nonlinear relationships exist as the norm rather than the exception. It is imperative to develop a methodology that can obtain and represent both the linear and nonlinear relationships, so as to address the dynamic CSC operations.

The identified research gaps indicate the valuable points of the additional work. It is challenging to provide a novel CSCRM method employing both qualitative and quantitative data/information to manage changeable CSC risks taking into consideration the complex interactions between the hazardous events and their associated changes of system behaviour.

1.5 ACHIEVEMENT OF THE RESEARCH

A CSC is usually an extremely complex system in which multiple interdependent variables lead to the dynamic system behaviour. Uncertainties, disruptions, and hazardous characteristics of chemical substances pose significant challenges to the CSC operations. It is difficult to address the dynamic risk effects caused by the inherent relations and the complex feedback effects using the majority of the existing risk analysis methods. In this research, a system dynamics (SC) based CSCRM method is provided that encapsulates the hazards addressed in the literature, assesses their associated risks and suggests the beneficial risk reduction approaches. The applied SD modelling technique takes into account the complex interactions between a CSC and hazardous events, dynamic feedback loops in the developed system, and the uncertain nature of the risks, which is capable of demonstrating the CSC system operations and predicting dynamic behaviours as the system changes under different risk circumstances. It combines the theory, the method and the risk reduction analysis to investigate the dynamic risk effects in a complex system and provide useful insights not only in engineering but also in broad fields, such as policy making, planning, and management.

In the hazard identification stage, the achievement of the research is the identification of the hazards in the whole CSC network. To broadly outline the sources of CSC risks, a risk diagram is developed in a hierarchical structure that classifies the identified hazards into nine risk categorises: supply risks, operational risks, demand risks, security risks, political risks, policy risks, macroeconomic risks, and natural environment risks. It provides a risk portfolio for further hazard identification research in a certain CSC.

In the risk analysis stage, a noteworthy study is to introduce a systematic methodology for the quantitative analysis of the risks instead of assessing the risks based on the expert knowledge or limited historical data. The provided SD-based risk analysis is a scenario-based analytical method within a complex system. It quantifies the system behaviours with an interactive procedure that integrates risk scenarios. Revealing the gap between the expectation and the real-time performance in different risk scenarios quantitatively assesses the risk effects in the developed CSC system and suggests the further risk reduction activities.

To fit in with the risk reduction measures, the developed SD model can be modified through appropriately amending the inputs, re-defining the cause and effect relationships, and modifying the model structure. Developed risk reduction measures aiming at reducing occurrence likelihood of undesirable events and/or mitigating possible consequences are forecasted to suggest the rational risk reduction decisions.

1.6 SCOPES AND OUTLINE OF THE THESIS

The research scopes are set up to surround the core of the thesis, which offer an integrated method to identify the CSC hazards, analyse the observed risk factors and provide an advantageous risk reduction method in the CSC. The proposed method considers the dynamic feedback loops in the developed system and the uncertain nature of the risks. It is particularly innovative, when being used to support risk management in a dynamic environment, compared to the traditional static risk analysis methods largely based on the experts' knowledge or the limited historical data. The research gives a perspective to policy makers and operators, an insight into the dynamic CSC and suggests advantageous CSCRM packages on the system thinking. A graphical flowchart is presented in **Figure 1.1** for outlining the structure of the thesis followed with the identification of research gap, development of research, model validation, case study and conclusion. The thesis layout is highlighted and explained as follow.

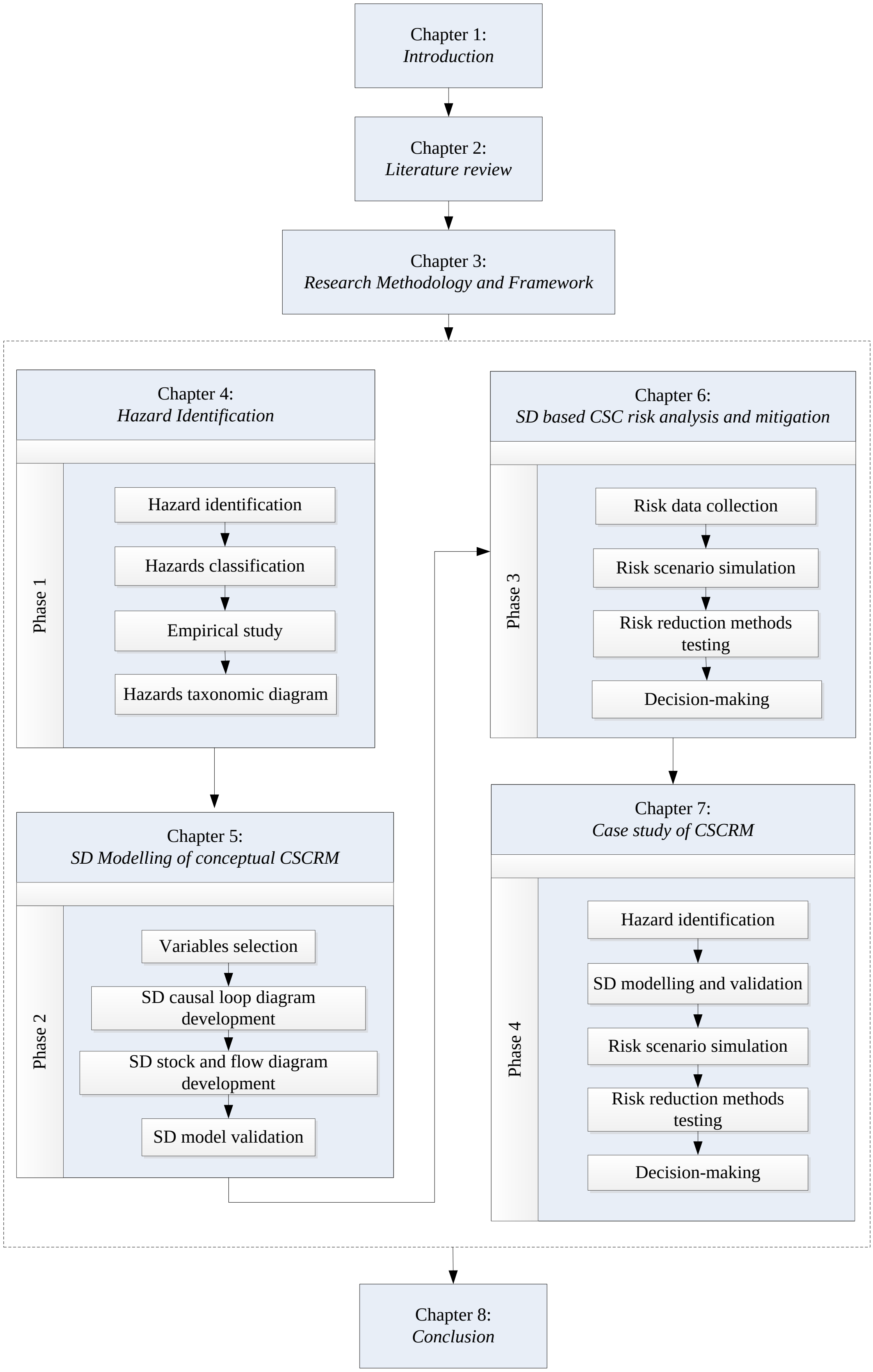


Figure 1.1. The structure of the thesis

This thesis is compiled in eight chapters. Following the discussion of the research process as presented in ***Chapter 1***, ***Chapter 2*** offers a first attempt at broadly understanding the risk perspectives in CSCs, and discussing the state-of-the-art CSCRM research. Thematic analysis is conducted to gather the fragmental information, so as to provide a systematic description of the research. A classification tree for the CSCRM literature review is developed to thematically describe the sub-divided risk classifications, research methodologies, risk management procedures, and CSCRM strategies. It finds that practically conducting CSCRM is a fertile area emerging from growing challenges. The distinctive gaps existing in current literature provide a future research agenda.

In ***Chapter 3***, the research methodology, research strategies and research methods are presented and discussed. It lays down the foundation for the study through indicating the main philosophical views behind the research methodologies. A CSCRM diagram is provided to reveal the overall plan and the priorities of the research. Furthermore, the chapter describes the methodologies of questionnaire survey and a SD modelling method, which are employed to capture, conceptualise, analyse and reduce the CSC risks.

To strengthen the knowledge base in hazard identification in the CSC, ***Chapter 4*** aims to broadly outline and decompose the unstructured hazards from the CSC perspective. Following the rigorous approaches, the questionnaire survey and online survey are developed to make inferences about the attitudes and opinions from the experts. The hazards are addressed and the importance of these identified hazards to the CSC system is obtained providing a portfolio of CSC risks.

The SD method is employed to model and simulate the CSC risks on system thinking. ***Chapter 5*** discusses the conceptual development of the CSC model and its associated risk model. Interactions between the CSC and the hazardous events are formalised that combine the risk theory and risk generation mechanism. The major interdependences and feedback mechanisms are addressed that demonstrate the changes of system behaviours arising from the hazardous events within the system boundaries. To establish sufficient confidence in the built model, a validation is carried out to test and verify the correspondence of the model structure and the robustness of the model's behaviours.

SD is a scenario based modelling and simulation method to predict the system behaviours under certain conditions. ***Chapter 6*** develops risk scenarios to assess diverse risks and explore possible risk reduction measures using the proposed method. The design of CSC conceptual models (shown in ***Chapter 5***) is adapted to fit in with the established scenarios. It is capable of addressing the system performance as the developed model changes under different risk circumstances. The expert intervention is applied to generate risk scenarios and corresponding risk reduction scenarios in the methodology. Through benchmarking the system behaviour in different scenarios, the risk generation mechanism is simulated and the risk effects are addressed.

Chapter 7 demonstrates the application of the provided SD-based CSCRM method. A case study is conducted to understand and improve the developed SD models and proposed CSCRM approach. The developed CSCT sub-model is adapted to simulate CSCT operations, as well predict the dynamic behaviours as the model changes under different risk scenarios. Establishing upon the flexibility of the SD modelling, the developers can use the different input values and amend the developed model structure throughout the life cycle specifically in design and operations phases. The obtained numerical results offer policy makers and operators insights into the risk-affected CSC operations and CSCRM decision-making processes, thus helping them develop rational risk reduction decision in a dynamic environment.

Chapter 8 summarises the research findings on the hazard identification, risk analysis and risk reduction in all previous chapters. The research findings have been disseminated through academic publications in research journals and at international conferences making contributions to academic and industrial areas for the further research on CSCRM. The limitations of the proposed research are outlined and the opportunities arising from the proposed methods are suggested for future improvements and applications.

CHAPTER 2 LITERATURE REVIEW

Summary:

This chapter presents the process of carrying out a rigorous and structured literature review. The fragments of isolated investigations are gathered within the research domain to provide critical insights into addressed hazards, proposed risk management methods and implemented risk reduction strategies in CSCRM. The identified research gaps indicate the valuable points of additional work, which are used to clarify the research problem in the proposed study.

2.1 OVERVIEW OF THE CHEMICAL INDUSTRY AND CHEMICAL SUPPLY CHAIN

The CI is playing a key role in modern world economy, which produces a wide variety of chemical products to help maintain life at a productive and comfortable level (Massey *et al*., 2012). To satisfy the various customer needs, the CSC connects suppliers, manufacturers, distributors, retailers and customers together to provide sourcing, manufacturing, logistics, storage and other services. However, the majority of chemical substances have hazardous characteristics, which threaten the surrounding environment and endanger human health (Papageorgiou, 2009). The disruptions and uncertainties arising from globalisation, complexity and vulnerability interrupt the operations and damage the CSC performance. These kinds of undesired events, which are regarded as the origin of risks, are determined by the hazardous characteristics of chemical products. To overcome the challenges of uncertainty and complexity in the CI and the CSC, it is necessary to make great efforts to reduce risks and improve the service through a coordinated approach.

2.1.1 Current chemical industry (CI)

The CI converts raw materials, such as oil, natural gas, and water, into different products including basic chemicals, commodity chemicals, polymers and speciality chemicals. The produced chemicals are widely used in automotive industry, construction industry, communications industry, energy industry, food industry, medical industry and other essential industries, which help maintain life at a productive and comfortable level. It is hard to find an industry or any single economic sector that can work effectively without chemicals (Massey *et al.*, 2012).

In the financial aspect, the CI is regarded as one of the major contributors to national and global economies. The European Chemical Industry Council (2012) announces that "The European chemical industry plays a key role in ensuring that by 2050 over 9 billion people live well, within the resources of the planet". In last fifty years, the CI has shown rapid and dramatic growth around the world. The value of global chemicals produced and shipped around was $4.12 trillion while it was US$171 billion in 1970 (Massey, *et al.* 2012). The performances of chemical companies are different because there are wide gaps between the top and bottom companies. Meanwhile, the economic development level determines the global chemical production map. The newly emerging economies are likely to produce commodity chemical products. In contrast, the developed economies are enjoying the comparative advantage of speciality chemicals (Burgess *et al.*, 2002).

Generally, the chemical products can be categorised into 5 groups: polymers, petrochemicals, consumer chemicals, basic inorganics and specialities. **Figure 2.1** shows European Union Chemical Industry (EUCI) sales by sectorial breakdown in 2010 and 2011. Specifically, polymer is a kind of large molecule chemical, which ranges from synthetic plastic to natural biopolymer. Petrochemical derives from petroleum and other fossil fuels, which is defined as the essential part of the CI. Large volumes of polymers and petrochemicals are produced, which account for the majority of EU chemicals sales. Consumer chemicals, such as soaps, detergents, perfumes, cosmetics and pesticide, are produced by polymers or petrochemicals that represent 12.8% and 12.3% of total EU chemical substance sales in 2010 and 2011. Basic inorganic products are synthesised from inorganic and organometallic compounds and applied in in every aspects of the CI, including catalysis, materials science, pigments, surfactants, coatings, medicine, fuel, and agriculture. In EU, the sales of basic inorganic chemicals take up around 13.5% of the sales in the CI. The specialities are particular chemical substances, which can be used as the auxiliaries for the other industries. Therefore, speciality chemicals are the largest market in terms of sales, which accounts for more than 25% of sales.

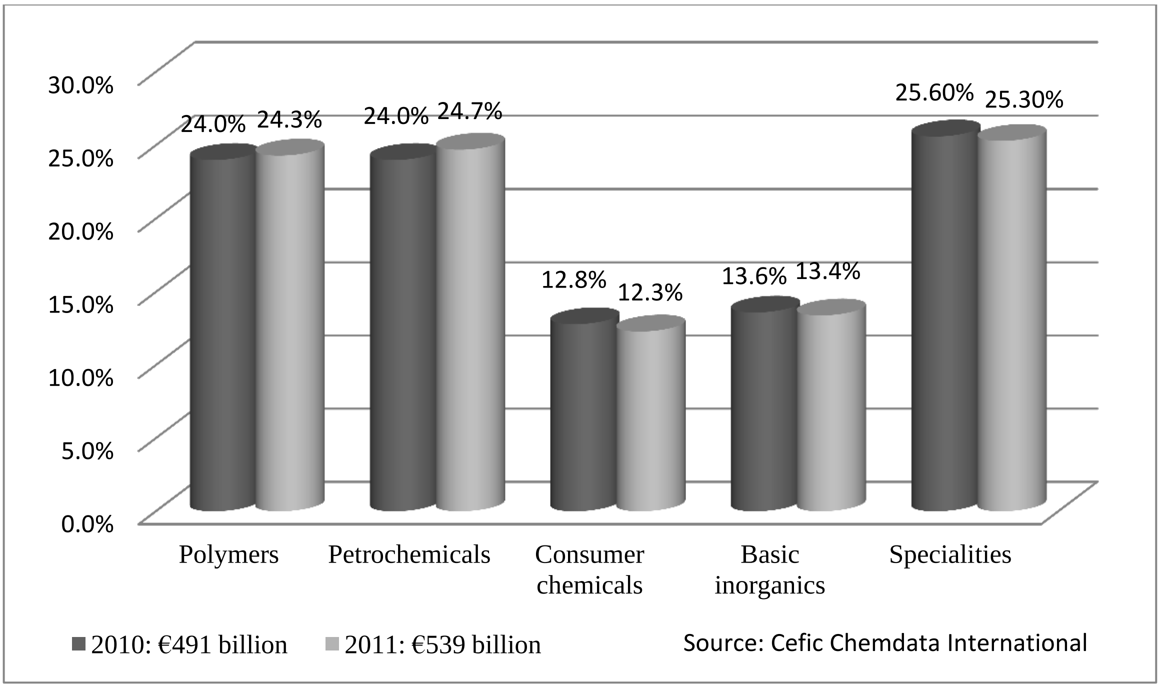


Figure 2.1. EU chemicals industry sales by sectorial breakdown in 2010 and 2011

During the operations, the CI achieves more profit in sales by improving product design and flexibility but it is still facing many challenges in terms of cost reduction and environmental friendliness (Iles and Martin, 2013). The public criticises the pollution and waste produced by the CI, especially in China. Not only the public but also the governments have drawn attention to the environmental issue. In response, more rigorous policies and legislation are introduced to reduce the environmental damage and improve the industrial ecology. The chemical organisations have to reposition so as to fully meet the market requirements. As well, novel technologies and competitive strategies are implemented to provide desired products and services with low cost and high profit (Bartels, Augat and Budde, 2006). Risk management is recognised as the one of the core elements of value creation in such a challenging environment, which offers a method to deal with the unexpected challenges.

2.1.2 The global and vulnerable CSCs

In practice, CSCs have multiple interdependent entities and numerous nonlinear interactions that are complex and dynamic (Tsiakkouri, 2010). A traditional CSC is a push system, which continuously produces low margin and high throughput products based on the schedule and plan, while special types of CSC are driven by customer orders to manufacture high value and low throughput chemical substances. To provide a graphic illustration, a conceptual CSC network is shown in **Figure 2.2**.

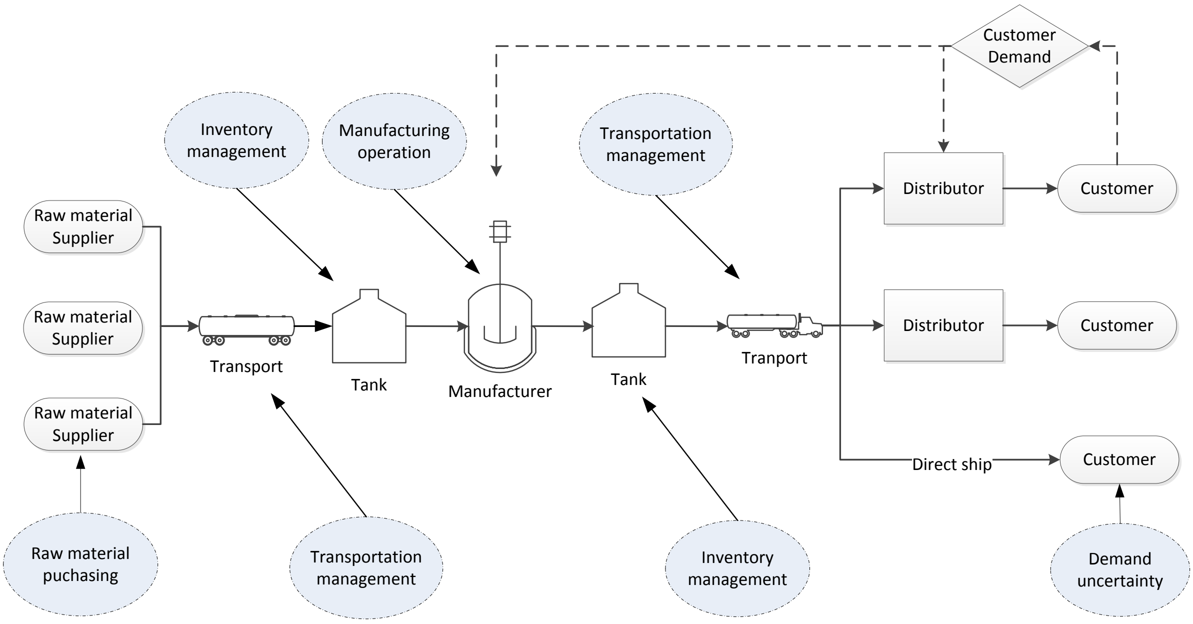


Figure 2.2. A conceptual CSC network

The CSC operations involve sourcing, conversion, logistics, and storage activities to provide required products and services to the customers. The CSC engages in developing effective strategies to sustain competitive advantages in the vulnerable environment (Liu and Nagurney, 2011). The geographic dispersion of supply chain members determines that huge volumes of materials often need to be purchased and transported from remote areas and unstable regions by multiple transportation modes. For instance, the United States imports crude oil from the gulf region by ships; China purchases tons of natural gas and oil from Russia every year through pipelines; Japan imports fossil fuels from the Middle East due to the limited domestic energy resources. To reduce the risk and achieve the desired performance, different sourcing strategies are applied to purchase the required products from upstream members. However, European Chemical Industry Council (CEFIC, 2012a) indicated that unexpected events, such as financial instability, policy change and unstable regional situations, can interrupt the operational process and bring negative impacts on the CSC systems. A majority of fossil fuels are sourced from unstable areas of the world, so that the flows of the CSC are likely to be affected by natural catastrophes, war, economic downturns and political upheaval. For instance, the earthquake and tsunami which happened in Japan resulted in the shortages of necessary chemicals all over the world (Park, Hong and Roh, 2013). In 2012, super storm Sandy interrupted the CSC operations because of the shut-down of ship terminals, flooded warehouses and labour shortage. These hazardous events caused tremendous losses in terms of cost, service level, and reputation aspects. During the manufacturing, different chemical products are formulated though blending, reaction and other activities according to the recipes. Multiple materials are added following the specific procedures at a particular time. The complex and vulnerable operational process destroys the efficiency of the CSC operations and brings the risks to the CSC system (Applequist, Pekny and Reklaitis, 2000; Pasman and Rogers, 2012). In addition to the risks existing in the operational processes, the requirements of environment protection restrain the development of the CI. The public is sensitive towards every chemical company in terms of the environmentally friendly movements (Verboven, 2011). To take environmental responsibility, it is essential for the CSCs to produce low-pollution and energy-efficient products and services.

In spite of the risk-related challenges, CSCs have to deliver a competitive business performance so as to survive in such an emulous industry (Manuj and Mentzer, 2008a). It is estimated that a reduction of the CSC operations cost by 10% can create three times the profit improvement (Garcia-Flores and Wang, 2002). Therefore, both academics and CSC operators appreciate the efforts to improve the safety and reliability of the CSC.

2.1.3 The unique characteristics of CSCs

Compared with the automotive supply chain, general retail supply chain and other supply chains, the unique characteristics of the CSCs are associated with the strategic planning and operational activities, including extensive trading, highly security required, sensitivity to energy prices, restriction of environment regulations and high capital investment (Adhitya and Srinivasan, 2010). These distinctive characteristics enable the CSCs to exhibit complex structures and particular ways of operating. In order to offer a structured description, the features of the CSCs are presented according to the stage of CSC operations:

- Opportunistic raw material purchasing

In the CSC, the exchanges of chemical raw materials are extensive and the trades take place in all parts of the world on a 24×7 basis. Therefore, the opportunistic buying is necessary because of the price fluctuation (Gebreslassie, Yao and You, 2012). To obtain more profits, chemical companies take advantage of every cost saving opportunity to make a good purchasing decision. However, there is an option arguing that highly discounted raw materials may lead to finished products at low prices when the customer demand remains at a certain level. The effective purchase decisions should be made through evaluating the difference between market requirements and sourcing cost so as to maximise the profit of investment (Koji and Macgregor, 2008).

- Complex manufacturing process

The chemical products are formulated by different kinds of feedstock and reaction equipment based on the recipe (Mele, 2011). The manufacturing is a complex network in terms of numbers of restrictions in chemical manufacturing operations, such as the amount of reaction materials, reaction time, and sequence of material adding. A slight change of manufacturing activity could lead to a huge difference of final products so the complexity results in the difficulties of finding out the root cause for quality issues. To guarantee the effective and efficient production, the production planning and management are required to reduce the waste and prevent the disruption during the manufacturing process.

- High inventory level

In order to catch the brisk demand, most chemical manufacturers implement make-to-stock strategies (Sharda and Akiya, 2012). It compels the companies to maintain a relatively high level of inventory.

Meanwhile, the products are manufactured in batch, continuous or semi-continuous operation mode. This kind of manufacturing feature leads the inventory level to increase in a specific period of time. It is a big challenge for the CSCs to manage the complex inventory system to optimise the inventory level in the whole system.

- Complex container management

In the inventory system, the containers and tanks are set up within each operation unit used to store the raw materials, work-in-process (WIP), by-products and finished products. The immiscibility of chemicals determines that the substances with different identities cannot be mixed during storage (Karimi, Sharafali and Mahalingam, 2005). Meanwhile, the movement of inventory is accomplished through one of five modes: pipeline, bulk tankers, parcel tankers, tank containers, or drums. To transport large quantities of a single product, pipeline and bulk tankers are widely applied, especially in the petrochemical industry. Parcel tankers are designed to carry an assortment of liquids with up to 42 tank compartments, so that multiple chemical substances can be simultaneously transported. Tank containers, also referred to as ISO tanks, intermodal tanks, or IMO portable tanks, differ from other modes, which can be used for intermodal transportation by road, rail, and ship (Karimi, Sharafali and Mahalingam, 2005). To address the beneficial container modes and ensure the operations of the container chain, container management is required to improve the service level. However, empty repositioning is a challenging point given imbalanced global trade flows. Since CSCs provides global service, material flows are not balanced geographically. Decision-makers and operators have to correct geographic and temporal imbalances in the container chain to improve the utilisation and efficiency through a coordinated approach (Erera, Morales and Savelsbergh, 2005; Manuj and Mentzer, 2008b).

- Vulnerable transportation operations

Obviously, safety, efficiency and sustainability have become the critical principles to the CSC transport management (Reiskin, White and Johnson, 1999). Due to the geographic dispersion of the supply chain members, multiple transportation modes are used to support the transfer in various materials and high technical, expensive and sophisticated transportation equipment is employed during the whole transportation processes. However, unforeseen and potentially disruptive events pose significant challenges to the operations in terms of difficulty prediction and risk control (Srinivasan and Karimi, 2002). Hazardous characteristics of chemical substances, uncertainties and disruptions pose significant challenges to CSC shipment as well as the surrounding environment, which potentially threaten ecological balance and endanger human health (Bonvicini, Leonelli and Spadoni, 1998; Papageorgiou, 2009).

- The alternative customer orders

In CSCs, the chemical composition are not specified by a certain value but described by a range of values with the words such as ‘at least’, ‘no more than’ or ‘less than’. Therefore, it is significant for CSC members to understand the rules of products substitution. The disparate orders can be classified and combined by properly selecting the product attributes, so as to benefit from large-scale production (Bartels, Augat and Budde, 2006).

2.2 REVIEW METHODOLOGY

In order to construct a thorough understanding of current research, reviewing literature is a vital part of the research because it serves as a foundation and guidance to build the proposed study. On a positive note, the proper review of papers will help to identify the gaps and to find out what further efforts should be taken to bridge the gaps. Before undertaking any research, it is essential to collect, select and analyse *‘what is already known’* through conducting a scientific literature review to find out a new research topic.

To illustrate the existing studies systematically and structurally, the taxonomic diagrams provide an elaborate guideline of CSCRM. The review methodology is shown in **Figure 2.3**.

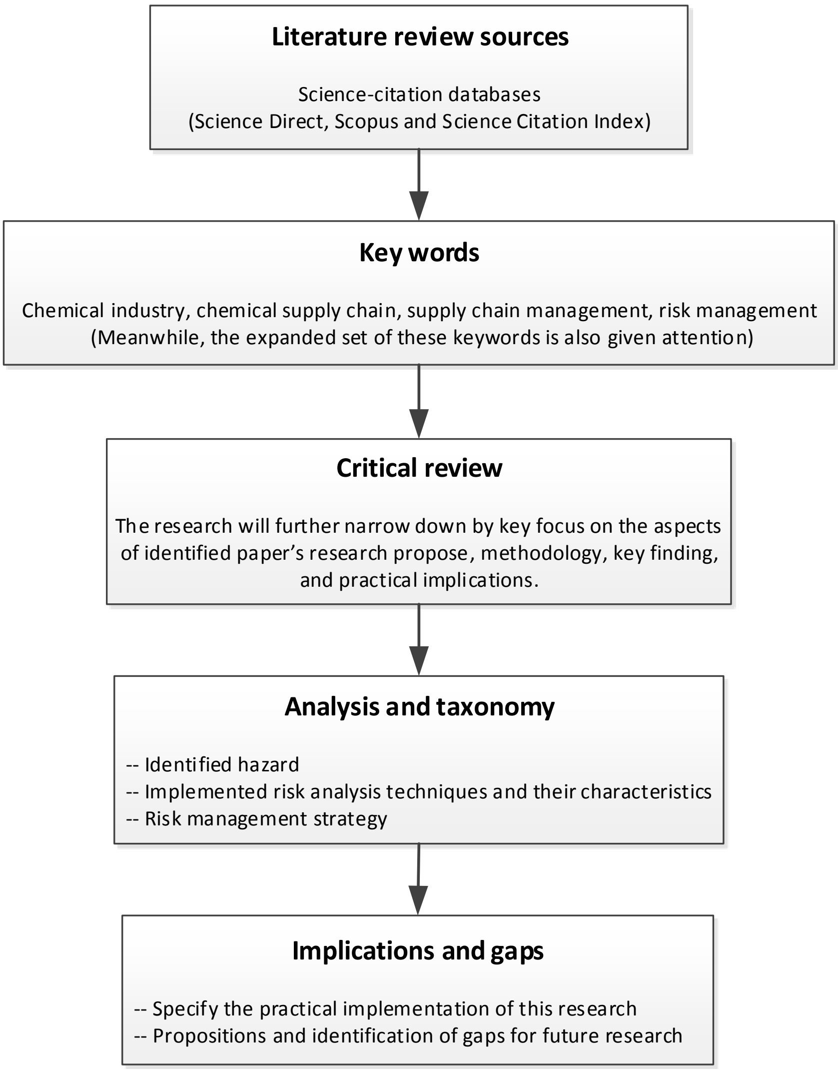


Figure 2.3. Methodology of literature review

An overview of the literature context provides the current status of CSCRM research holistically. The specific papers are selected which are highly relevant to the proposed study in terms of the research scope, methodology, and methods. Then, the literature search narrows down and focus on the research purpose, methodology, key findings, practical implications and gaps in identified papers. From an in-depth review, the taxonomic diagrams of identified hazards, risk analysis methods and risk reduction strategies are developed to graphically describe the findings of the literature review.

2.3 OVERVIEW OF CSCRM LITERATURE

Although it is a fact that the concept of SCRM has attracted researchers' attention for the last fifteen years, very limited literature actually addressed the risk management issue from the CSC perspective (Khan and Burnes, 2007). There were 993 papers involving SCRM published by the end of 2005 compared with 9,687 papers by the end of 2015. Especially in 2015, there are 2,425 papers published dealing with SCRM problems. However, insufficient studies employed existing methods or proposed novel methods to manage the risk from industrial practice. There were only 502 articles in 49 journals found analysing CSCRM problems by the end of 2015. **Figure 2.4** presents the year-wise distribution of identified papers.

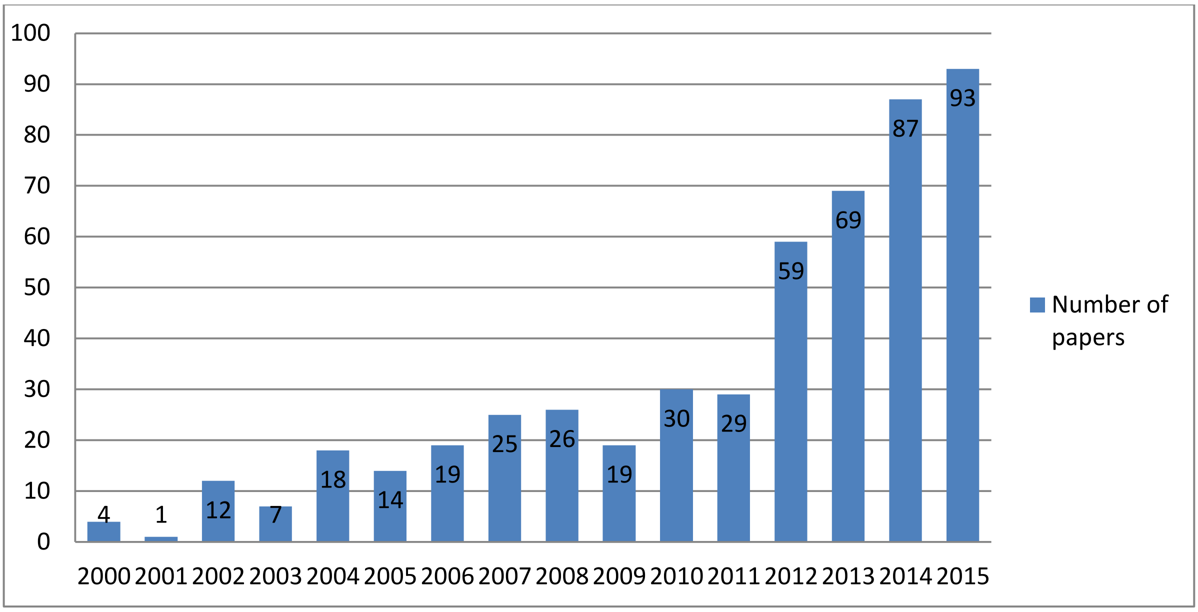


Figure 2.4. Year-wise distribution of identified papers

In the past fifteen years, the researchers have sought to not only manage the risks to improve the reliability of local company, but also provide a coordinated approach to manage the risk in national/international SC. It is observed that the CSC risk has been given attention by the researchers since 2001. Because of 9/11 attacks, the CSC operations were seriously damaged and experienced tremendous losses in service level, financial, and reputation aspects. After that, more and more academics and practitioners have realised the importance of CSCRM. There are a number of studies provided every year contributing to the knowledge of CSCRM, so that the total number of published papers increased to 204 in the year of 2011. In addition to terrorist risks, environment issues are other important factors in CSCRM. Since 2012, the scientific papers have grown exponentially when the environment issue attracts the attention from the governments and public. In this period, many studies have focused on the CSC planning, optimisation under uncertainty and hazardous material substitution analyses.

In an attempt to classifying the papers based on the journals, the top 10 high quality journals are selected, as shown in **Figure 2.5**. The bar chart illustrates the number of published articles of each journal, while the red line is used to represent the impact factor of each journal. The top 4 journals are "*Computers and Chemical Engineering*", "*European Journal of Operational Research*", "*Journal of Industrial and Engineering Chemistry Research*" and "*International Journal of Production Economics*", which encompassed 22, 11, 11 and 11 papers respectively.

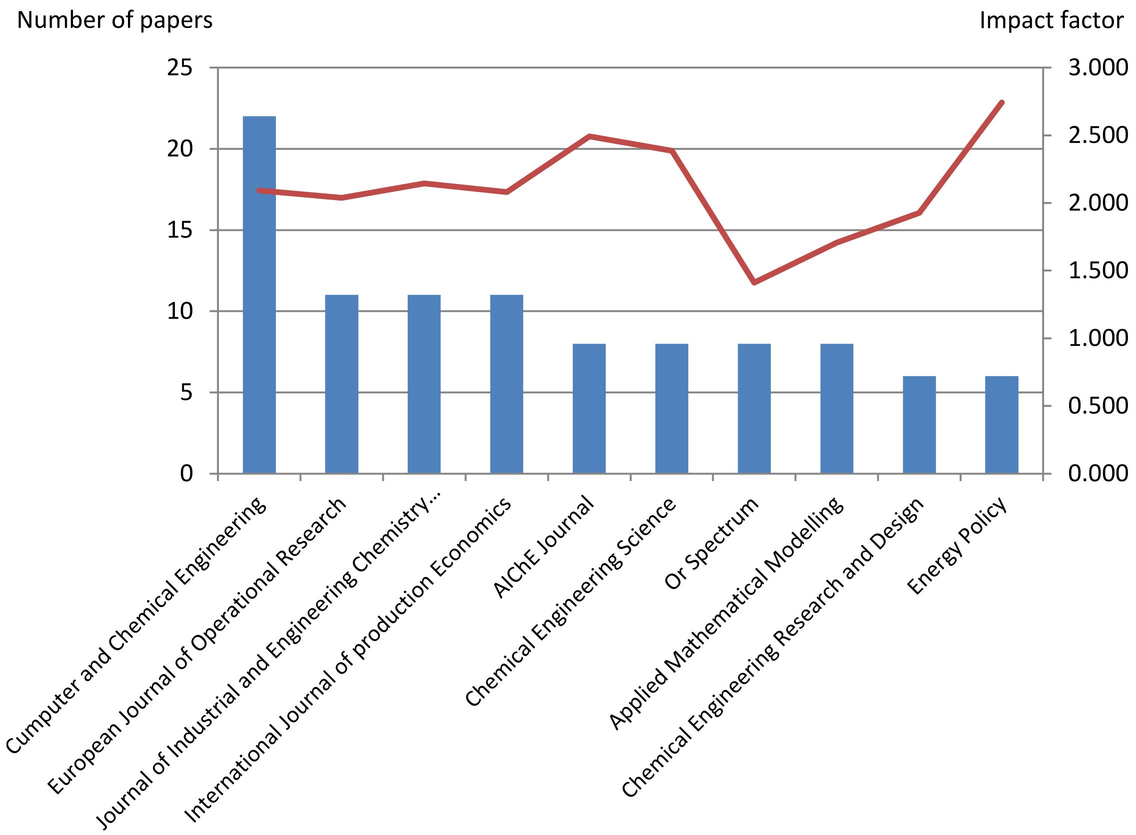


Figure 2.5. Published articles categorised by journals in top 12

To define the concept of SCRM, three structural steps are identifying the hazards, analysing the risk effects and reducing the unacceptable risks (Rao and Goldsby, 2009; Colicchia and Strozzi, 2012). In this research, the identified papers are categorised by the research scope of each paper by structural steps mentioned above. To do so, the papers concerning hazard identification, risk analysis and risk reduction process were reviewed along with the other papers. **Figure 2.6** describes the number of papers categorised by the associated research area.

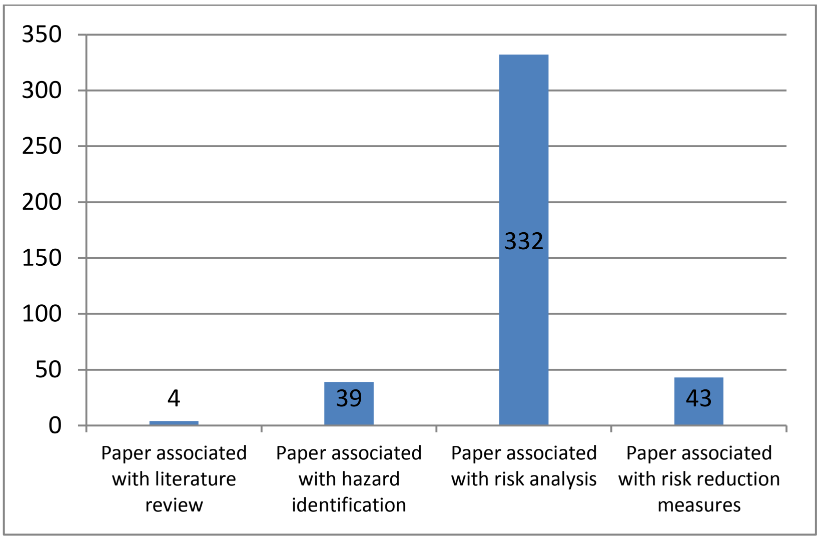


Figure 2.6. The number of papers categorised by the associated research areas

Note that there is some overlap between addressed the number of papers categorised by the associated research areas. There are 31 papers deal with more than one structural step in the CSCRM research. In particular, there is limited attention on literature review while only 4 review papers could be found. In these 4 papers, the studies concentrated on the specific types of issues instead of comprehensively reviewing the CSCRM concept. For instance, An, Wilhelm and Searcy (2011) observed the significance of incorporating SCRM through conducting a literature review in biofuel and petroleum-based fuel supply chain. Nikolopoulou and Ierapetritou (2012) provided a review paper about optimal design of sustainable CSC. Tsai (2013) reviewed the studies associated with environmental distributions and risk management of phenols pertaining to the endocrine disrupting chemicals in Taiwan. Compared with other sequential steps, the majority of the recent studies focused on the stage of risk analysis. In CSCRM research, it is difficult to have a clear understanding of the complex system structure, operating procedures, and aspects associated with available quantitative data. Hence, past experience is employed to judge the risk consequence and descriptive words are used to illustrate the behaviours of the CSC operations (Tse, 2012). The reviewing result shows that the qualitative, quantitative and hybrid risk analysis techniques were implemented to conduct CSCRM supported by multiple kinds of data. However, it is also observed that many studies in CSCRM are carried out to analyse a specific type of risk rather than assessing CSC risks as a whole. A further analysis of the proposed risk analyse techniques is required under a broader context for a more exhaustive variety of disruptive events in the CSC. In order to achieve the objectives of the research, risk reduction should be carried out to minimise the unacceptable risks. Though there are a number of reported studies involving the risk reduction measures, few papers actually address this issue by a practical method. Furthermore, the identified papers were refined by setting exclusion criteria that selected in the field of CSCRM. There were 152 quality papers selected which implemented the SCRM method in CSCs dealing with the different kinds of risks, of which the 30 most citied papers were shown in **Table 2.1**.

Table 2.1. 25 most cited papers categorised by associated research area in risk management

Paper Citation	Hazard Identification	Risk Analysis	Risk Reduction
Applequist, pekny and Reklaitis (2000)		X	
Lohse *et al.* (2003)			X
Frier (2003)			X
Lasschuit and Thijssen (2004)			X
Van Wyk and Baerwaldt (2005)	X	X	X
Kleindorfer and Saad (2005)	X	X	X
Mont, Singhal and Fadeeva (2006)	X		
Bruinen de Bruin *et al.* (2007)			X
Adhitya, Srinivasan and Karimi (2007)	X	X	X
You, Wassick and Grossmann (2009)		X	
Adhitya, Srinivasan and Karimi (2009)	X		
La ńez, Puigjaner and Reklaitis (2009)			X
Foerstl *et al.* (2010)		X	X
Carneiro, Ribas and Hamacher (2010)		X	
Bassett and Gardner (2010)		X	
Liu *et al.* (2011)		X	

Liu, Liu and Chang (2011)		X
Tong, Feng, and Rong (2011)	X	
Gebreslassie, Yao and You (2012)	X	X
Oliveira and Hamacher (2012)	X	
Asamoah, Annan and Nyarko (2012)	X	
Ruiz-Femenia *et al.* (2013)	X	
Oliveira *et al.* (2013)	X	
Leppelt *et al.* (2013)	X	
Ehlen *et al.* (2014)	X	X

Hazard identification, risk analysis and risk reduction are three main steps in SCRM. As shown in Table 2.1, there are three papers found dealing with the whole risk management procedure, while other studies focus on a specific research area. The reported studies are most likely to discuss the risk analysis research that involved 17 of 25 papers. Both qualitative and quantitative methods are adapted to address the risk consequence not only in operational level but also in strategic level. As well, various risk reduction strategies and associated methods are suggested to enhance the studying of CSCRM when 11 of 25 papers offer theoretical or practical methods to evaluate risk management decisions that might improve CSC system performance.

To provide a meaningful analysis, the study is narrowed down by focusing on each paper's research purpose, methodology, key findings, practical implications and gaps therein. **Table 2.2** provides a summary of 25 key papers in terms of the title, authors, publication year, focus, method type and key findings.

Table 2.2. A quick summary of 25 key research papers

No	Paper Citation	Focus	Method type	Key finding
1	Risk and uncertainty in managing chemical manufacturing supply chains (Applequist, pekny and Reklaitis, 2000)	Evaluating uncertainties in planning and design phase	Quantitative	Evaluating risk premium to find out financial trade-off between risk and investment in a CSC during design and planning procedures.
2	Never Change a Running Process? Substitution of Hazardous Chemicals in Products and Processes: Definition, Key Drivers and Barriers (Lohse *et al.*, 2003)	Investigating the main driving factors and barriers of hazardous substitution	Qualitative	Suggesting that legislation, quality benefit, environmental and health concerns are the key drivers of chemical substitution and encouraging conducting co-operation, information sharing and regulatory pushing to enforce hazardous substitution.
3	Hazard and exposure considerations related to chemical risk assessment (Frier, 2003)	Discussing the analytical aspects of hazard analysis, exposure assessment and data requirements	Qualitative	Pointing out reliable information and systematic methods are still required to conduct hazard analysis and exposure assessment under introduced legislation.
4	Supporting supply chain planning and scheduling decisions in the oil and chemical industry (Lasschuit and Thijssen, 2004)	Introducing the optimised decision making toolset known as GMOS/NetSim	Qualitative	Suggesting an optimisation process is a one of the significant parts in CSCRM. GMOS/NetSim is a good method to conduct strategic planning in global supply chain, which has been used in oil, chemical and gas business.
5	External risks and the global supply chain in the chemicals industry (Van Wyk and Baerwaldt, 2005)	Managing external risks in strategic level under global environment	Qualitative	Developing an integrated risk management framework to manage the external risks in CSCs and suggesting five managerial policies to strengthen risk management.
6	Managing disruption risks in supply chain (Kleindorfer and Saad, 2005)	Managing disruption risks in CSC	Qualitative	Building a conceptual framework, which integrated the risk assessment and risk reduction to manage the CSC risks, and conducting case study based on the collected data.
7	Chemical management services in Sweden and Europe (Mont, Singhal and Fadeeva, 2006)	Providing an overview of the chemical management services strategy in Europe	Qualitative	Analysing advantages and disadvantages of chemical management service in Europe and suggesting that joint efforts are needed to seek for economic and environment benefits.
8	Risk management measures for chemicals in consumer products: documentation, assessment, and communication across the supply chain (Bruinen de Bruin *et al.*, 2007)	Analysing risk management measures method	Qualitative	Conducting conceptual analysis in risk management measures used in chemicals risk assessment under the requirements of REACH and developing a standard for establishing risk management measures categorisation.

(Continued)

No	Paper Citation	Focus	Method type	Key finding
9	Heuristic rescheduling of crude oil operations to manage abnormal supply chain events (Adhitya, Srinivasan and Karimi, 2007)	Managing disruptive risks in a refinery supply chain through employing optimal rescheduling method	Quantitative	Proposing a heuristic rescheduling method to manage the disruptions and pointing out the factors affecting schedule resilience.
10	Supply chain risk identification using a HAZOP-based approach (Adhitya, Srinivasan and Karimi, 2009)	Using HAZOP-based approach to identify risks	Qualitative	Providing HAZOP-based hazard identification approach to identify the risks in a refinery supply chain and suggesting the possible cause, consequences, safeguards and reduction actions of captured risks.
11	Risk management for a global supply chain planning under uncertainty models and algorithms (You, Wassick and Grossmann, 2009)	Managing planning risk under demand and freight rate uncertainty in tactical level	Quantitative	Developing a stochastic programming approach for the mid-term planning of global CSC, which considered the production, inventory, time, transportation and service level.
12	Financial and financial engineering considerations in supply chain and product development pipeline management (La ńez, Puigjaner and Reklaitis, 2009)	Discussing financial considerations in enterprise-wide decision problems	Hybrid	Indicating that the enterprise-wide decision problems must be formulated with realistic detail not just in the technical aspects but also in the financial components.
13	Managing supplier sustainability risks in a dynamically changing environment sustainable supplier management in the chemical industry (Foerstl *et al.*, 2010)	Analysing and mitigating supplier sustainability risks in CI	Qualitative	Exploring sustainability risk assessment and risk reduction methods and conducting case study to demonstrating proposed method.
14	Risk management in the oil supply chain: A CVaR approach (Carneiro, Ribas and Hamacher, 2010)	Proposing an integrated risk management method for strategic planning	Quantitative	Developing a strategic method to evaluate and optimise investment planning in oil supply chain.
15	Optimizing the design of global supply chains at Dow AgroSciences (Bassett and Gardner, 2010)	Optimising the network design in global CSC	Quantitative	Presenting a novel method to optimise network design of global CSC. Both strategic and tactical improvements are highlighted to support decision making.
16	Transportation risk assessment of chemical industry supply chain based on a dual model (Liu *et al.*, 2011)	Assessing transportation risk in CSC	Quantitative	Analysing the features of chemical products and using dual model to analyse both the internal and external CSC transportation risks.
17	A study on a framework of chemical industry supply chain risk management based on 3S and the internet of things (Liu, Liu and Chang, 2011)	Integrating internet technology with risk management	Qualitative	Using internet technology to conduct CSCRM and briefly stating the implementation procedures.

(Continued)

No	Paper Citation	Focus	Method type	Key finding
18	Planning under demand and yield uncertainties in an oil supply chain (Tong, Feng and Rong, 2011)	Optimising planning problem under uncertainties	Quantitative	Describing a novel mathematic method to optimise planning under demand uncertainty and product yield fluctuation which takes into account the reduction of the total cost, risk of customer dissatisfaction and inventory violation.
19	Design under uncertainty of hydrocarbon bio-refinery supply chains: Multi-objective stochastic programming models, decomposition algorithm, and a comparison between CVaR and downside risk (Gebreslassie, Yao and You, 2012)	Optimising the design of bio-refinery supply chain under uncertainty	Hybrid	Identifying the hazards in bio-refinery supply chain and presenting a novel modelling and algorithm approach to support decision-making activities through analysing the value-at-risk in the supply chain.
20	Optimization of the Petroleum Product Supply Chain under uncertainty: A case study in Northern Brazil (Oliveira and Hamacher, 2012)	Optimising the investment under uncertainty	Quantitative	Proposing a two-stage stochastic model to simulate the investment planning in the petroleum product supply chain and applying proposed method in real case study.
21	AHP approach for supplier evaluation and selection in a pharmaceutical manufacturing firm in Ghana (Asamoah, Annan and Nyarko, 2012)	Evaluating supplier selection	Hybrid	Indicating that the evaluation and selection of suppliers should be integrated into a company's core strategic decisions.
22	Multi-objective optimization of environmentally conscious chemical supply chains under demand uncertainty (Ruiz-Femenia *et al.*, 2013)	Evaluating demand uncertain risk in terms of economic and environment performance	Quantitative	Developing a stochastic multi-scenario mixed-integer linear program (MILP) to manage demand uncertainty which maximises the expected profits and minimises the environmental impacts.
23	A Lagrangean decomposition approach for oil supply chain investment planning under uncertainty with risk considerations (Oliveira *et al.*, 2013)	Evaluating investment planning problem under demand uncertainty	Quantitative	Presenting a quantitative risk analysis approach to deal with oil supply chain investment planning problem under demand uncertainty and indicating that expected shortfall could be an efficient method to reduce the possibility of high cost.
24	Sustainability management beyond organizational boundaries-sustainable supplier relationship management in the chemical industry (Leppelt *et al.*, 2013)	Managing sustainable supplier relationship in the CSC	Qualitative	Reviewing sustainable supplier relationship management introduced by sustainability leaders and examining the neglected impacts through conducting case studies.
25	Chemical supply chain modelling for analysis of homeland security events (Ehlen *et al.*, 2014)	Investigating how a supply chain can adapt to and recover from risks	Quantitative	Applying SD method to capture the dynamic, disaggregates, and decentralised nature of large chemical supply chains and investigate how developed model can adapt to and recover from risks.

2.4 THEMATIC ANALYSIS

Thematic analysis is a kind of qualitative research technique, which is commonly used in a literature review to emphasise, analyse and illustrate a specific research question. Indeed, there is substantial amount of effort on extending current knowledge in terms of managing the potential risks in the CSC. However, most of the research spread out across multiple disciplines and concentrate on various risk issues. Thematic analysis seeks to gather the fragmental information to provide a comprehensive and systematic description in the proposed research. A classification tree for the CSCRM literature review is developed to thematically illustrate the sub-divided risk classification, research methodology, risk management procedure, and risk management strategy, shown in **Figure 2.7**.

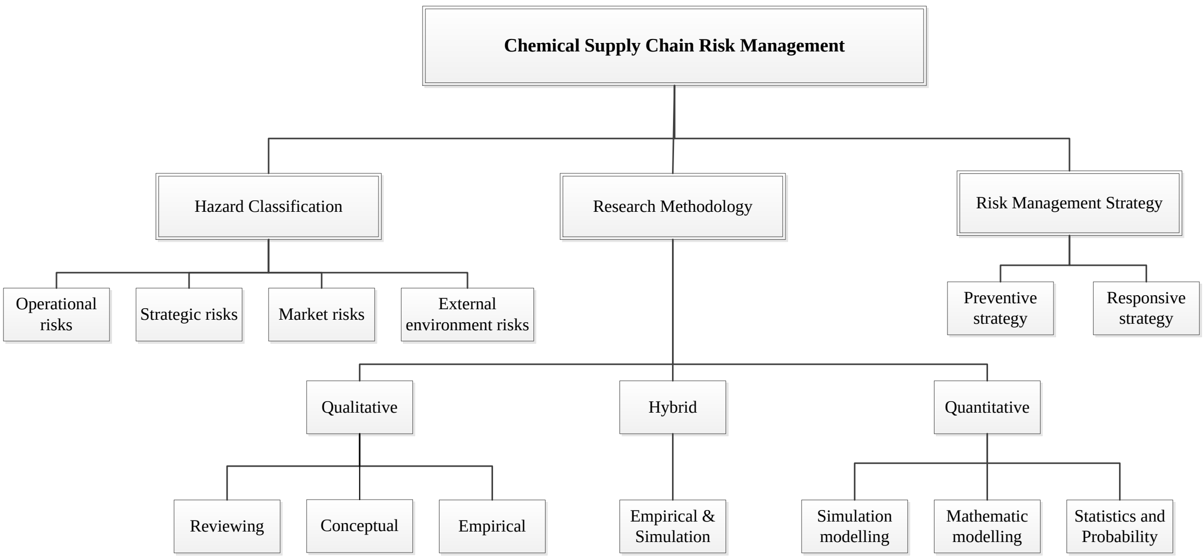


Figure 2.7. Classification tree for CSCRM literature review

Risks appear in a huge variety of forms and impact on diverse points in CSCs. To structured identify the captured hazards, a risk classification method is provided to categorise the risks into operational, market, strategic and external environment aspects in Section 2.4.1. After identifying all the hazards, CSC managers adopt risk analysis methods to assess the risks and screen out the unacceptable ones. There are different tools and techniques for CSCRM that can be used in this regard. As described in Section 2.4.2, the applied methods have been classified into three groups, which are qualitative, quantitative and hybrid. Based on the determined risk management strategy, risk reduction procedure is carried out to preventively or responsively deal with the unexpected hazardous events on system thinking.

2.4.1 Hazard identification of CSCRM

Hazard identification is an essential and significant step in SCRM. A list of risks is produced to indicate the risks that affect the CSC operations (Jereb, Ivanuša and Rosi, 2013). Common listing, taxonomy, scenario based process mapping and objective based process mapping are commonly used for identifying and classifying hazards. Brainstorming is employed to define the possible risks according to the knowledge of experts, while risk mapping techniques are used to systematically identify hazards in the system or surrounding environment.

Even though there is a substantial amount of literature dealing with CSCRM, the attention on systematic hazard identification and classification from an industrious perspective is fairly limited. An overview of the CSCRM studies is discussed in the previous section but it is necessary to provide a clear and distinct analysis to capture the risks within the CSC. To provide a structured description of identified hazards, a risk classification method is adapted from Singhal, Agarwal and Mittal (2011). It categorises the risks into operational, market, strategic and external environment aspects. Each aspect and its attributes are explained in detail below. Meanwhile, a taxonomic diagram is established to structurally present the identified sources of risks in the examined literature.

- Operational risks

Operational risks appear and reside in operational characteristics, which refer to the possibility of an event occurring in internal SC that may cause product damage, service delay or reputation damage (Marley, Ward and Hill, 2014). In the literature, the risks associated with operational process have been analysed, which include supply process disruptions, inventory stock-out/unnecessary, improper container management, demand uncertainties, improper planning, lack of/ failure of information system, lead-time concern, and security risks. A schematic view of operational risks is graphically illustrated in **Figure 2.8**.

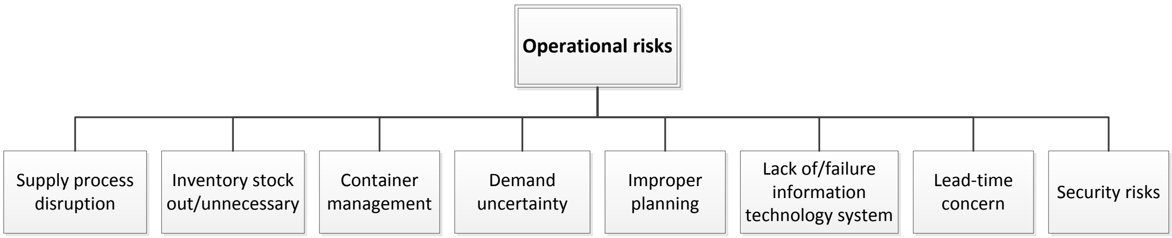


Figure 2.8. A schematic view of operational risks

.

Specifically, the occurrence of supply process disruption accompanies the movement of materials (Christopher and Peck, 2004). In the CSC, tremendous volumes of chemical substances need to be sourced and transported along the network. The unexpected event interrupts the supply activities and results in negative effects. García-Flores and Wang (2002) considered the supply uncertainty in their developed agent-based models to support the CSC management.

Inventory risks belong to the risks arising from the requirement of reducing inventory cost and improving service level (Manuj and Mentzer, 2008a; Laínez, Puigjaner and Reklaitis, 2009). In the CSC, Business-to-Business (B2B) sales are mostly conducted between the supply chain members, so that the feature of high inventory dominates the operational process. In the operations, the chemicals are commonly stored in tanks or other containers. It is difficult to monitor and manage the containers to ensure that they meet the industry standards (Van Wyk and Baerwaldt, 2005). The quality a largely amount of containers exacerbates the vulnerabilities of the CSC because it is difficult to be measured and monitored during the operations.

According to the literature review results, demand uncertainty, planning problem and reschedule management are frequently analysed together (Adhitya, Srinivasan and Karimi, 2007). The majority of CSCs involve strongly diversified sources, multiple products and a long list of markets. It puts a huge pressure to satisfy dynamic customer requirements within narrower time-windows because the demands are uncertain. Therefore, planning management is another interesting research topic that aims for scheduling and controlling system operations. Planning risk arises from improper planning that leads to unexpected losses. To deal with planning risks, the risk management tool is regarded as a helpful method to reduce the possibility of high cost in various viewpoints, such as physical, financial and information aspects (Oliveira, *et al.*, 2013). Applequist, Pekny and Reklaitis (2000) offered a new technique to evaluate the risks in supply chain design and plan stage. It applied the risk premium construct for estimating an equilibrium point between investment and benefit. You, Wassick and Grossmann (2009) developed a stochastic programming model incorporating the production process, inventory level, transportation models, lead-time, customer demand fill-rate and risk measures in one system. Using the same method, Carneiro, Ribas and Hamacher (2010), Tong, Feng and Rong (2011) analysed the planning problem under demand uncertainty in the oil supply chain.

Security risks refer to third parties who intend to steal proprietary data, knowledge or interrupt the supply chain operations. Manuj and Mentzer (2008a) indicated that the security risks include infrastructure damage and information leakage due to spying, system crash, public and private utility services disruptions and criminal activities. In the global environment, the CSCs can be easily attacked by terrorists. Therefore, security risk is of high concern to the CSC operators, especially after 9/11 terrorist attack (Adhitya and Srinivasan, 2010). In order to estimate the potential impacts of man-made and natural disasters on chemical plants, Ehlen *et al.* (2014) developed an agent-based model to analyse the security events.

Furthermore, a hazardous event could not only disrupt the physical flow, but also affect the information exchanging in the supply chain system. Information technology is provided to support to avoid defaults and to generate the trust between the members (Liu, Liu and Chang, 2011; Wakolbinger and Cruz, 2011).

- Strategic risks

The strategic risks represent the risks related to supply chain strategic characteristics that influence the whole supply chain context (Barbosa-PÓvoa, 2012). Preliminary studies suggested that the focus of CSCRM shifted from operational risks towards more tactical and strategic risks due to globalisation and complexity. Generally, the proposed studies are following a structured approach to assess the strategic risks of improper network design, lack of information sharing, lack of relationship management, and unsuitable location of facilities (Carsano, Vecchietti and Montagna, 2011; Awudu and Zhang, 2012). **Figure 2.9** describes a schematic view of strategic risks, which were analysed in the literature.

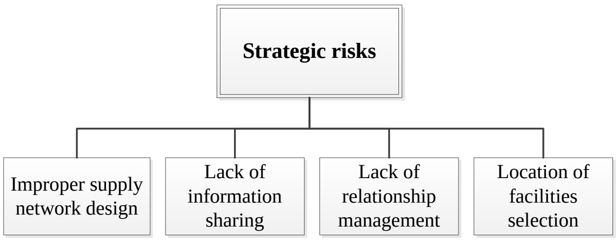


Figure 2.9. A schematic view of strategic risks

Compared with other industries' supply chain, a CSC can be enormously long and complex. The various intermediate links in the CSC systems are exposed to various risks, which have a tremendous impact on supply chain performance (Craighead *et al.*, 2007). The design of the CSC structure is required to be optimised to provide a more robust and reliable network in the changeable environment. Bassett and Gardner (2010) give the credit of network optimisation studies that offer different optimal platforms for CSCM and CSCRM. Mathematic programming has been frequently employed to deal with the problems in this subject. Corsano, Vecchietti and Montagna (2011) demonstrated a proposed mathematic programming model in Dow AgroSciences for sustainable design while considering the recycling process. It suggested that the application of network optimisation could improve CSC performance in terms of cost, time and reputation, which can be regarded as a great help to business (Naraharisetti, Karimi and Srinivasan, 2011).

Additionally, La ńez, Puigjaner and Reklaitis (2009) suggested a computational framework to explore how relationships will affect the supply chain operations. In order to support this viewpoint, conceptual or analytical models are built to investigate the problem in supplier and customer relationships. Foerstl *et al.* (2010) integrated the supplier sustainability risk assessment and corresponding response process in one system to manage the supplier relationship in the CSC. Similarly, Leppelt *et al.* (2013) empirically analysed the sustainable supplier relationship management theory, which is introduced by sustainability leaders in the CI all over the world. It investigated both advantages and neglected impacts of making sustainable supplier relationship development and provides a scientific supplier relationship management framework to enhance the operational performance of the CSC.

- Market risks

Market risks fall into a broad category of the market fluctuations that affect the supply chain behaviours across the industry (Christopher and Lee, 2004). Although the CI is a mature industry, its market environment is still full of uncertainties (Bartels, Augat, and Budde, 2006). Within the CSCRM context, the identified risk components of market risks cover price fluctuation, exchange rate arbitrage, various customer requirements and requirement of hazard products substitution. A schematic view of market risks is presented in **Figure 2.10**.

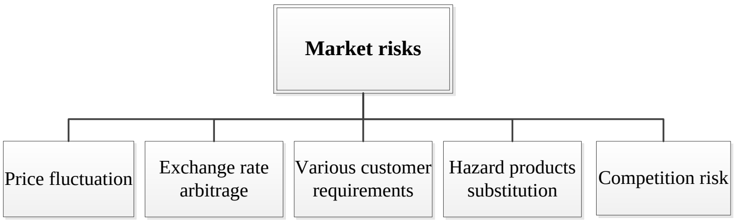


Figure 2.10. A schematic view of market risks

Price fluctuation risk is known as economic risk which refers to an economic fluctuation accompanied by the economic activity changes (Oxelheim and Wihlborg, 1987; Rao and Goldsby, 2009). Inflation or changes in the prices will result in the price fluctuation, so the CSC has to take price variation into consideration when making operational decisions. This is beneficial for allowing the CSC to exploit cost benefits from the price fluctuation and exchange rate arbitrages in the global market (Gebreslassie, Yao and You, 2012).

Competitive risk derives from the uncertainties interrelated with dynamic customer demands and expresses in comparison between the existing products and services and potential entrants (Miller, 1991). The actions are taken by firms to satisfy various requirements and to maintain the market share.

However, the environmental awareness challenges the CSC operations and profitability in these years. CSCs have to change its traditional conception in operations to adapt to the new requirement of incorporating environmental concern along with the economic criteria (Sarkis, Zhu and Lai, 2011). The requirements of hazardous chemicals substitution indeed contribute to the competition that forces the CSCs to provide alternative produce and services to the market (Acar and Gardner Jr, 2012).

- External environment risks

Globalisation and complexity pose significant challenges for CSC operations because they can be the sources of risks which arise from the internal system or the surrounding environment. Compared with internal risks, the external environment risks, such as terrorism, natural disaster and political issues, are much more likely to disrupt the CSCs (Kleindorfer and Saad, 2005). Special attention in the CSC design stage should be given to systematically identify, assess and control the environment risk factors at the beginning. In CSCRM literature, external environment risks refer to a broad term of undesired events surrounding the external environment (Daniel, *et al.*, 2004). The studies focus on minimizing the risk of political instability, policy changes, environment protection problems, frequent natural disasters, and social challenges. **Figure 2.11** describes a schematic view of external environmental risks.

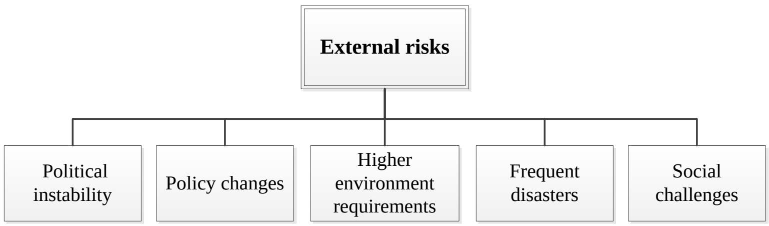


Figure 2.11. A schematic view of external environmental risks

A political risk is described as the uncertainty and instability when a major change happens in a political regime (Barry, 2004). In the global CSC, huge volumes of fossil fuel are exploited from unstable regions of the world due to the geographically uneven dispersion. The wars in Afghanistan (2001), Iraq (2003), and Libya (2011) sent the feedstock prices soaring. After the 9/11 terrorist attacks, terrorism is of the highest concern and the CSC has had to incur higher operating cost in response to the terrorist threat (Kleindorfer and Saad, 2005). These kinds of disturbances affect the supply activities and result in tremendous loss. Therefore, the CSC managers adopt various risk analysis methods to evaluate the political risk in the respective regions before making a business decision.

Manuj and Mentzer (2008b) pointed out that both political risk and policy risk are frequently experienced during the operations. It is significant to fully understand policy risks, such as tax policy, laws, regulations and the available policy material before getting down to business (Ting, 1988; Schildhouse, 2006). Recently, the governments and public have been concerned about the environmental problems of CSC operations. There are more and more legislation, industrial best practices, regulatory guidance, recommendations, *etc*., introduced to protect against the pollution and other environmental concerns, introduced to protect human health and the environment from significant risks and making contributions to a diverse, sustainable and economic environment. Therefore, the CSC has to adapt its products and services toward a more sustainable environmental risk assessment (Zhu, Cordeiro and Sarkis, 2013; Ruiz-Femenia *et al.*, 2013). Coinciding with the requirements of the European policy of REACH (Registration, Evaluation, and Authorization of CHemicals), Bruinen de Bruin *et al.* (2007) developed a table of criteria which incorporates the environment issues and risk factors to support CSCRM.

Meanwhile, the natural disasters and the climate changes are frequently experienced in real life and mostly analysed in the literature. The natural environment uncertainty brings catastrophic consequences that not only affect the CSC operations, but also damages the world economy (Peng, Peng, Chen, 2014). Therefore, it is imperative to develop a method that can be used to simulate the CSC operations under the disruption and address the dynamic risk effects in the supply chain level.

The literatures in CSCRM develop a generic understanding that initiates risk components in different sectors. A detailed synthesis of the literature in these disciplines provides empirical evidences of hazard identification in the CSC, which enables the authors to develop a typological diagram to illustrate the under-investigated risk components. **Figure 2.12** incorporates the preceding discussion of identified hazards and structurally illustrates the supply chain risk classification framework proposed by Singhal, Agarwal and Mittal (2011). This taxonomic diagram can serve as a fundamental guide for future CSCRM research.

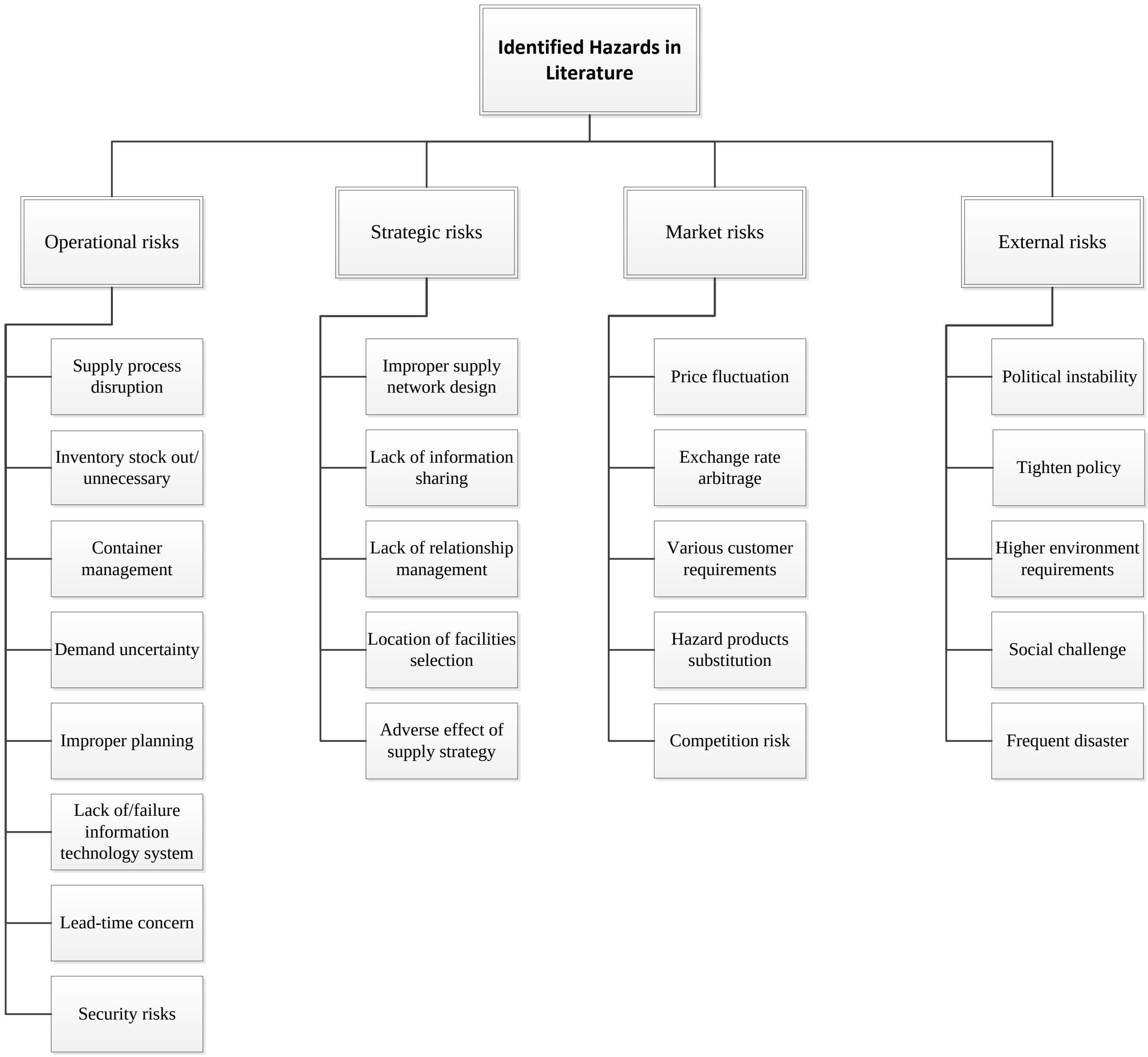


Figure 2.12. A typological diagram of CSC risks

2.4.2 Implemented risk analysis techniques and their characteristics

In CSCRM research, a large number of studies have been devoted to extending current knowledge and enhancing the implementation of CSCRM. The various methods are provided to conduct risk analysis and risk reduction using multiple sources of data, such as numerical data, expert judgement, and interviews (Kaggwa, 2008; Sodhi, and Tang, 2012). To provide a structural analysis, an overview is discussed that categorises the implemented methods into qualitative, quantitative and hybrid aspects:

- Qualitative research methods

Generally, qualitative methods investigate the risk issues from theoretic and empirical perspectives that the studies are carried out to enhance the CSCRM theory (Wagner and Bode, 2006). In the CSCRM research, qualitative methods can be classified into three kinds of approaches, which are literature review, conceptual analysis and empirical study. A schematic view of qualitative research methods addressed in the literature is illustrated in **Figure 2.13**.

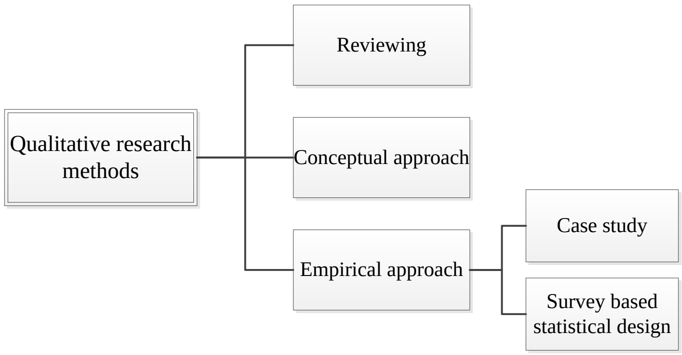


Figure 2.13. A schematic view of qualitative research methods addressed in the literature

Literature review provides a whole picture of associated issues in the past works, which serves as a base and guide to proposed study. The proper review of research papers will help to identify what has been done and what further efforts should be taken to improve the CSCRM. Cohen and Kunreuther (2007) emphasised the contribution of Paul Kleindorfer in CSCRM discipline and provided a novel framework to manage the disruption risks in the CSC. You, Wassick and Grossmann (2009) reviewed scientific articles for tactical planning of a global multi-product chain under uncertainty.

Conceptual technique refers to the method used to describe and enhance the fundamental concepts, it also provides a theoretical framework to future research. It is important to credit the previous publications that have developed conceptual models to investigate various kinds of risks in the CSC. Lohse *et al.* (2003) conceptualised the basic risk issues in hazardous chemicals substitution. Van Wyk and Baerwaldt (2005) conducted a conceptual analysis to manage the various disruption risks in the CSC. Facing the challenges of introduced policy, a conceptual framework is provided to investigate policy risk in the supply chain level (Bruinen de Bruin, *et al.*, 2007). Adhitya, Srinivasan and Karimi (2009) provided a qualitative method to identify the hazards in a refinery supply chain.

The empirical approach is an integral method that gains the knowledge through analysing the direct and indirect information from case study, accident data, industrial survey and interview. In a detailed synthesis of the literature, it is found that a case study has been undertaken to investigate various topics in the proposed subject, such as optimising investment planning in Northern Brazil (Oliveira and Hamacher, 2012), sustainable supplier relationship management in the CI (Leppelt *et al.*, 2013), and a case study of CSC risk analysis based on Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Assessment (FCA) mode (Lu, 2015). Industrial survey is another method of empirical analysis (Meric *et al*, 2002). Sodhi, Son and Tang (2012) investigated the researchers' perspectives on SCRM and indicated the gaps needed to be closed with the help of questionnaire survey.

- Quantitative research methods

The attention paid to and the research conducted on the risk quantification is increasingly growing as time goes on. Therefore, a variety of concepts and methods have been developed to quantitatively analyse CSC risks and support risk management decision making (Marhavilas, Koulouriotis and Gemeni, 2011; La ńez and Puigjaner, 2012). The proposed approaches can be broadly categorised into mathematical modelling, computational simulation, and statistics and probability analysis groups, as described in **Figure 2.14**.

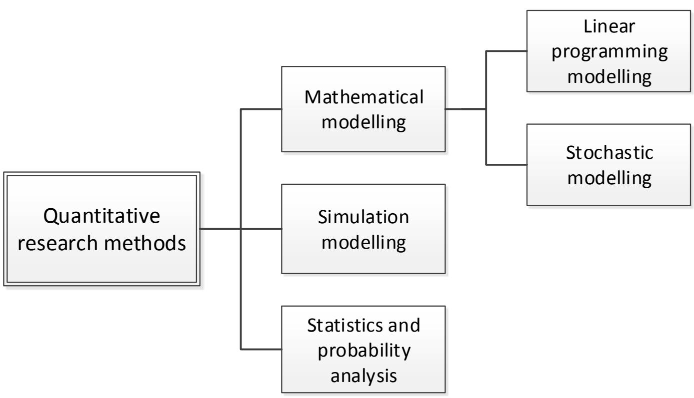


Figure 2.14. A schematic view of quantitative research methods addressed in the literature

Mathematic modelling methods are most discussed in the literature, which consist of multi-objective programming, linear and nonlinear programming, and other quantitative mathematical programming methods. The studies have been devoted to quantitatively analyse the CSC risks in terms of time, financial, quality and reputation aspects (Pai *et al.*, 2003; Tummala and Schoenherr, 2011). In particular, Oliveira *et al.* (2013) applied the multi-objective mathematic modelling method to weight the risk reduction investments and benefits on the finance side, so as to find the optimised decision making under demand uncertainty. To measure the planning risk under demand uncertainties, the stochastic programming models are developed to represent both linear and nonlinear relationships in the CSC system (Guillén-Gosálbeza and Grossmann, 2010; Tong, Feng and Rong, 2011; Gebreslassie, Yao and You, 2012). In contrast, mixed-integer programming models are frequently used to optimise network design of the global CSC. Bassett and Gardner (2010) highlighted the advantages of strategic and tactical improvements for network optimisation.

Simulation modelling approach is a systematic technique for understanding the interactive impacts of the risks under different scenarios. Principally, agent-based simulation, discrete event simulation and SD simulation are widely used to investigate the causal relations between supply chain system and hazardous events for various risk settings. Gao, Shang and Kokossis (2009) developed agent-based models to simulate the dynamic behaviours of a CSC, so as to quantitatively estimate the compromised risk management decisions. Ge *et al.* (2004), Janamanchi and Burns (2007) and Campuzano, Mula and Peidro (2011) conducted discrete event simulation to analyse the dynamic risk effects. However, agent based simulation and discrete event simulation present the developed supply chain models as static (Leveson, 2004). It ignores that the information feedback governs the change of system behaviours which could significantly affect the risk management outcomes. On the contrary, a SD method represents the system operations and assesses the risks under the concept of dynamics. It is employed to address the feedback effects among the logical loops emerging from the interactive relationships (Tako and Robinson, 2014).

Furthermore, some research about the CSCRM has been conducted based on statistical and probability analysis. It is a quantitative method used in hypothesis testing (Hung and Ryu, 2008). Foerstl *et al.* (2010) investigated several hypotheses of managing the supply risks in the CSC to enhance the operational performance. Ghadge (2013) indicated the benefits of utilising statistics and probability analysis method to assess operational and tactical risks.

- Hybrid research methods

Tang and Musa (2011) indicate that there is a huge potential for developing a hybrid technique to capture the complex and dynamic behaviours of risks. It is an integrated method, whereby both qualitative and quantitative techniques are applied to deal with the risk analysis and risk reduction. Vilko and Hallikas (2012) conducted a questionnaire survey to comprehensively identify and empirically evaluate the risks contained in the cargo flows between the Gulf of Finland and Finnish mainland. Then, a simulation model has been constructed to simulate the possibility, consequence and the subjective value of risks.

Even though hybrid methods are the techniques of interest in the SCRM research, very limited study actually provides a hybrid method incorporating the risk issues from industrial practice (Ritchie and Brindley, 2007). Aqlan and Ali (2014) suggested that the hybrid risk management methods, such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Failure Model and Effects Analysis (FMEA), Failure Mode, Effects and Criticality Analysis (FMECA), have huge potential to be implemented in CSCRM. Specifically, FTA provides a method for cause analysis in depth based on a particular accident, which is often used in system-level risk assessment. The inherent logical relationships can be qualitatively or quantitatively analysed. The ETA method logically develops a decision tree model to explore the possible outcome following an initiating event where the risks are presented based on probable subsequent events and final result events. FEMA is a kind of technique for failure analysis, which has been widely used in SCRM, while FMECA is an extension of FMEA used to analyse the possibility of failure modes and the severity of their consequence (Tuncel and Alpan, 2010; Lavastre, Gunasekaran and Spalanzani, 2012). AHP provides a comprehensive and rational framework for structuring a hazards hierarchy and quantifying hazards weight, for overall CSC risk, which helps decision-makers to expand their understanding of the hazards through risk ranking (Asamoah, Annan and Nyarko, 2012). Furthermore, many techniques are integrated in described methods to fill the gap in criticality analysis requirement and to enhance the risk management performance, such as fuzzy logic (Yang, Bonsall and Wang, 2008; Wulan and Petrovic, 2012), grey theory (Yang and Chen, 2006), Monte Carlo simulation (Hekimoğlu and Barlas, 2010; Olson and Wu, 2011), Bayesian nets (Yang, Bonsall and Wang, 2008), Markov models (Bilsel and Ravindran, 2012), neural networks (Wu and Olson, 2013) and Evidential Reasoning (Yang and Xu, 2002; Yang, Bonsall, and Wang, 2010). The following are descriptions of the hybrid approaches addressed, shown in **Figure 2.15**.

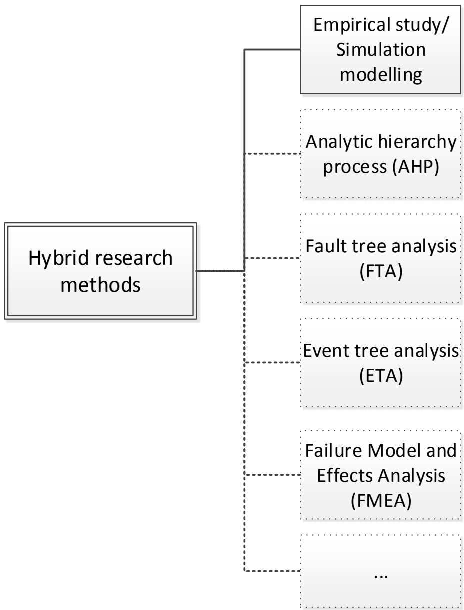


Figure 2.15. A schematic view of hybrid methods addressed in the literature

As shown in **Figure 2.16**, the taxonomic diagram of implemented CSCRM methods is developed which represents the whole picture of the research methods used in the literature. Although the proposed approaches seem more promising, the formulation of a comprehensive and systematic CSCRM technique is a rather difficult task. Researchers have a difficult experience to accurately infer the behaviours of complex systems and address the dynamic risk effects in the supply chain level. The identified research gaps indicate the valuable points of additional work that provides a novel risk management method employing limited qualitative and quantitative data/information to manage a more exhaustive variety of CSC risks. It should address the complex interactions and dynamic feedback effects among the developed system and hazardous events, which could significantly affect the outcomes of CSCRM.

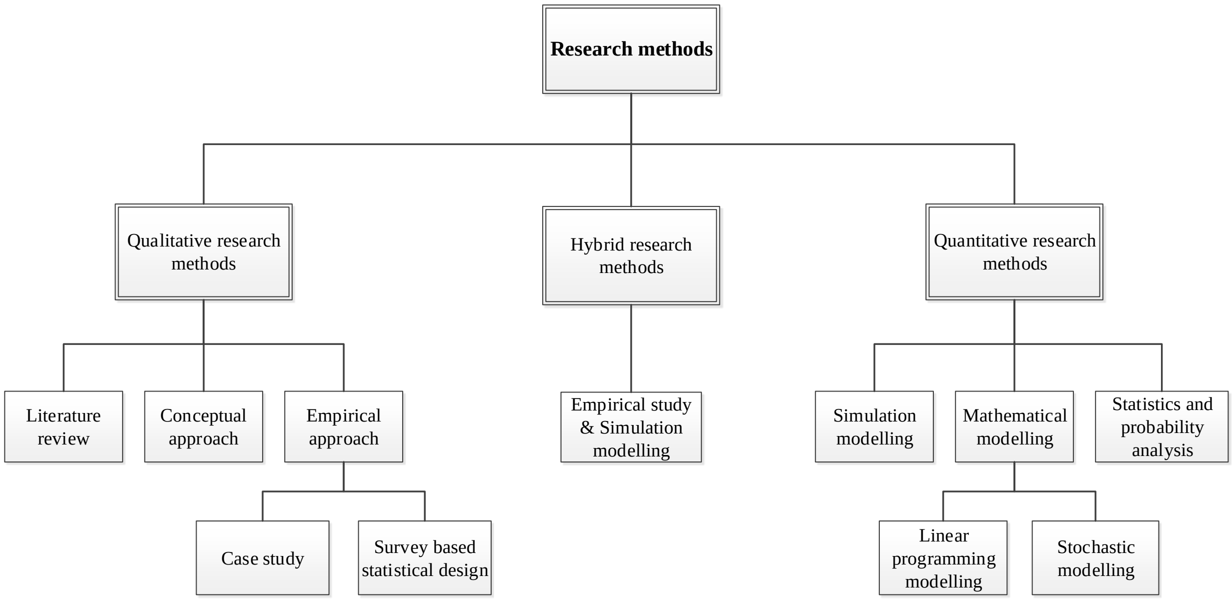


Figure 2.16. A schematic view of sources of CSCRM methods addressed in the literature

2.4.3 Risk management Strategy

Risk management techniques represent the methods proposed by researchers to address the primary research objectives in CSCRM, whereby actions are taken from the view of the outcomes of risk assessment (Lynch, 2012). Ponomarov and Holcomb (2009) indicate that agility, flexibility and preparedness are the main principles in the CSCRM. Efforts have, therefore, intended to provide a structural method to reduce the risks. The risk management mechanisms are based upon the applied strategies that can be preventive or responsive. The goal of the proactive strategy is to build a robust supply chain to ensure that the hazardous event occurrence likelihood can be reduced (Knemeyer, Zinn and Eroglu, 2009). The occurrence of hazardous events, however, cannot be eliminated no matter how much effort and investment is spent. The adaption of a reactive procedure is suggested to reduce the risk when it indeed affects the supply chain operations due to the unmanageable risks which have frequently occurred. **Figure 2.17** presents the risk management strategies and their associated approaches addressed in the literature.

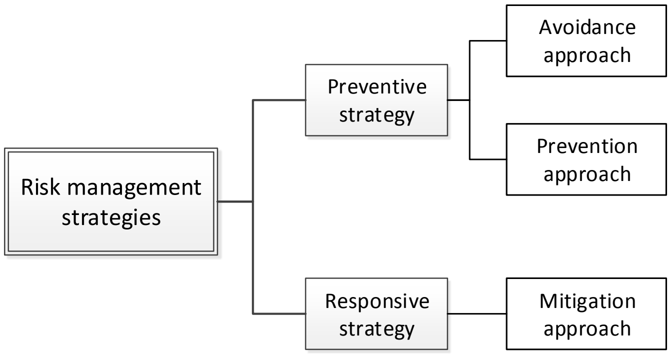


Figure 2.17. CSCRM strategies and their associated approaches addressed in the literature

Specifically, an avoidance approach is the extreme case that is employed to significantly reduce the likelihood of end unbearable threat. Meanwhile, a collaborative relationship among the members is formed to construct the risk tolerance in advance. In the CSCRM research, there are a number of preventive approaches suggested, such as sustainable supplier relationship management combining the SCRM framework with information technologies (Liu, Liu and Chang, 2011), and coordinating of information sharing (Lohse *et al.*, 2003). In contrast, reactive risk management approaches are applied to minimise the risk effects, such as developing an emergency response plan (Kleindorfer and Saad, 2005), reducing the risk through improved confidence (Christopher and Lee, 2004), and improving resilience of network (Christopher and Peck, 2004).

A novel risk management method is required to explore the potential effects of risk reduction methods and to analyse the risk criteria against the risk management incentive, so as to suggest the beneficial CSCRM decision making in further research (Woodruff, 2005; Thun, Drüke, and Hoenig, 2011; Bandaly *et al.*, 2012; Micheli, Mogre and Perego, 2014).

2.5 STATE-OF-ART OF PROPOSING SYSTEM DYNAMICS (SD) METHOD TO SUPPORT SUPPLY CHAIN RISK ANALYSIS

Forrester (1961) first proposed a SD methodology for the adoption of qualitative as well as quantitative methods to solve multidimensional problems. Qualitative methods are used in conceptualizing the system model and quantitative methods contribute to SD modelling and simulation. An SD model emerging from the initial description of the real system is developed by two pairs of basic concepts: resources-information and levels-rate. It combines the theory, methods and philosophy in control engineering and non-linear dynamic system discipline that has been widely applied to investigate economic, management, engineering patterns and other issues distinct from the general system control method (Lyneis and Ford, 2007).

In terms of risk management discipline, SD has been firstly applied to manage risks in project management. There are many SD models developed to evaluate the interaction between project performance and various aspects of decision-making processes in project management (Ford and Bhargav, 2006). Recently, SD modelling technology has been used to deal with a variety of issues in SCM and SCRM disciplines. To provide a structural and distinct analysis to capture the investigated SCM issues by the SD method, this research adopts the classification method provided by Tako and Robinson (2012) to separate the SCM issues in the strategic level and the operational level. In the strategic level, SCM seeks to deal with company-wide problems involving long term activities. The studies mainly focus on network optimisation, relationship management and information sharing. Tactical management will produce cost benefits for the supply chain, such as bullwhip effect analysis, reverse logistics management, and cost management. Operational measures are provided to handle the problems related to daily activities based on the given strategic and tactical decision. A list of SCM issues is shown in **Figure 2.18**, which divides the supply chain management issues into Structure optimisation (SO), Processes redesign (PR), Supplier selection (SS), Capacity planning (CPL), Relationship management (RM), Information sharing (ISH), Bullwhip effect (BE), Reverse logistics (RL), Replenishment control policies (RCP), Optimising supply chain operations (OSCO), Cost management (CM), System information (SI), Inventory planning/management (IPM), Planning and demand forecasting (PDF), Production planning (PP), and Distribution planning (DP).

Supply chain management issues

Strategic

Structure optimisation (SO)
Processes redesign (PR)
Supplier selection (SS)
Capacity planning (CPL)
Relationship management (RM)
Information sharing (ISH)
Bullwhip effect (BE)
Reverse logistics (RL)
Replenishment control policies (RCP)
Optimising supply chain operations (OSCO)
Cost management (CM)
System information (SI)
Inventory planning/management (IPM)
Planning and demand forecasting (PDF)
Production planning (PP)
Distribution planning (DP)

Operational

Adapted from: Tako and Robinson (2012)

Figure 2.18. Ordering of SCM issues from strategic to operational level

Following the described literature review method, 162 papers are identified which use the SD method to deal with SCM problems by the end of 2015. The selected papers are categorized based on involved SCM issues. **Figure 2.19** shows the extent to which SCM issues are addressed by the SD approach.

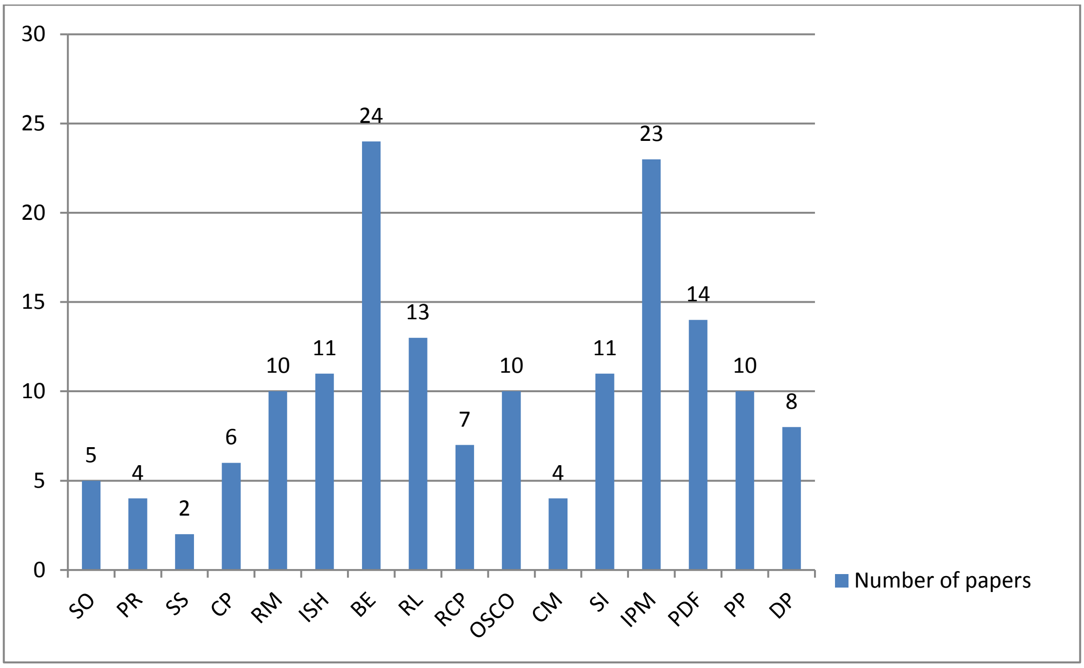


Figure 2.19. The extent to which SCM issues are addressed by SD approach

According to the statistical result, the applications of the SD method are spread out to investigate all kinds of SCM issues, especially in inventory management, bullwhip effect, strategy and policy assessment and information delays (Ge *et al.* 2004; Janamanchi and Burns, 2007; Kumar and Yamaoka, 2007; Manuj and Mentzer, 2008a; Manuj and Mentzer, 2008b; Campuzano, Mula and Peidro, 2010). The built SD models not only take account of the logical interactions in the supply chain system, but also predict dynamic behaviours when time is factored into the sequence (Angerhofer and Angelides, 2000). The visualisation of supply chain operations may lead the modeller to greater understanding of the real system. Moreover, changes can be adapted in developed SD models to explore the dynamic performance in different scenarios, so that the analytical method is provided to support SCM decision making.

It is important to credit the previous publications that have developed conceptual or analytical models to investigate various kinds of risks in the supply chain, as these have provided the dynamic effects that underpin this proposed model and simulated the system structure and behaviours. Choi, Narasimhan and Kim (2012) developed an SD model that integrates multiple considerations germane to global supply chains to analyse the risk of postponement strategy. Kenne, Dejax and Gharbi, (2012) discussed the production panning within a closed-loop supply chain. To manage the risks, an SD-based optimisation method reduces the costs of manufacturing and remanufacturing products. Based on the traditional mathematical model, Lee and Chung (2012) applied SD thinking to develop an inventory model for the supply chain of deteriorating items. Through comparing the supply chain simulation results with statistical calculation results, the developed SD model is validated. It gains the confidence of SD analysis in inventory management. In the supply chain, the awareness of product recycling is increasing not only due to the obligation imposed by legislation but also the financial consideration. Das and Dutta (2013) examined two different methods to reduce the order variation and bullwhip effect in a closed-loop chain. To deal with the carbon emission policy risk, Bai and Mu (2014) proposed a two-echelon supply chain model to explore the system performance under different risk scenarios. Peng, Peng, Chen (2014) analysed the effects of supply disruptions in the post-seismic supply chain using the SD modelling and simulation method. It suggests developing a coordinated system to integrate information in order to recover from the supply failure in risk affected condition. Li *et al.* (2015) offered an integrated SCRM framework to address the dynamic risk effect on system thinking. Guertler and Spinler (2015) and Mehrjoo and Pasek (2016) quantified the risks through exploring the supply chain behaviours using the SD method. The proposed method can be used to help decision makers to predict the outcomes of risk management decisions that might improve supply chain performance. To understand the risk generation mechanism in a food supply chain, Stave and Kopainsky (2015) applied the SD method to conceptualise and represent how a supply chain can be affected by disturbances, so as to assess the risks considering feedback effects in the system.

2.6 CONCLUSION AND RESEARCH GAP

It can be argued that the scholar needs to understand the current research status and find out the gaps in existing knowledge to enhance their understanding (Boote and Beile, 2005). The literature review offers a first attempt at broadly understanding the risk perspectives in the CSC, investigating the current status of CSCRM and exploring the risk management methods implemented. Although the awareness of the vulnerability of the CSC has been given attention by academics and practitioners, the research of CSCRM is a fertile area emerging from growing challenges and the fact that a very limited amount of research actually specifies this issue in literature, as well as in practice. The identified research gaps indicate the valuable points of additional work that are presented below:

- Holistic framework of CSCRM

The literature shows that the majority of research papers concentrate on specific risk management steps instead of providing a comprehensive CSCRM framework in terms of hazard identification, risk analysis and risk reduction. Rao and Goldsby (2009) argue that any myopic research focusing on a specific part of risk management may be suboptimal due to the complex and dynamic characteristics of supply chain system. Therefore, there is a need for a broader view that would facilitate proper risk management from industrial practice (Tang and Musa, 2010). An integrated approach is needed to identify hazards, assess and control the associated risk by following sequential steps in the supply chain level.

- Comprehensive and systematic hazard identification

Hazardous characteristics of chemical substances, uncertainties and disruptions pose significant challenges to CSC operations as well as the surrounding environment, which potentially threaten ecological balance and endanger human health (Bonvicini, Leonelli and Spadoni, 1998). To manage these risks, hazard identification is an essential step to produce a list of risks (Waters, 2011). Even though a substantial amount of literatures can be found dealing with CSCRM problems, the attention that is given to systematic hazard identification is fairly limited. Meanwhile, most of the provided studies are conducted with diversified objectives and concentrated on various risk issues. A further analysis of hazard identification is required to capture a more exhaustive variety of risks under a broader context.

- Novel risk management method

In the previous studies, various methods and different techniques are applied to accommodate the need to analyse and evaluate the risks. Plenty of static models have been developed to assess the cause, probability and consequence of the risks for screening out insignificant hazards (Leveson, 2004). However, little has been done to address the dynamic interactive relations among the variables influencing the system operations (Fernandes, Barbosa-Póvoa and Relvas, 2011). Indeed, the feedback effects emerging from the ignored causal relations govern the system behaviour that can change over time, and hence could significantly affect the risk management results (Leveson, 2004; Bouloiz et al., 2013). It is imperative to develop a methodology that can obtain and represent both linear and nonlinear relationships using multiple sources of data to address the dynamic risk impacts in the complex CSC system.

To fill the gap, this research uses the SD modelling approach to analyse and manage the CSC risks. It is particularly noteworthy that SD offers a methodological approach that describes the major interdependencies and feedback mechanisms between the investigated system and its associated hazardous events in a pre-defined condition. Incorporating the capability of the modification both in the design and the operational phases, the developed SD model can be re-structured and updated to explore the effects of different risks (Yeo, Pak and Yang, 2013). In the developed risk scenarios, the generated hazardous events affect the balanced system and causes unexpected changes in system behaviour. Through evaluating the variation in the system behaviour, the risk effects can be addressed to provide a baseline for comparing the risk effects in different risk scenarios. The using of SD can assist the decision-makers to avoid direct assessment of the risks based on arbitrary decisions

- Optimal CSCRM decision

Ensuring that a particular risk reduction approach does indeed support CSCRM often requires formal modelling of forecasting outcomes of a particular risk reduction decision. It is worth analysing the trade-off between the investment required for reducing action and the risk loss, so as to make better risk management decisions (Schmitt and Singh, 2012). However, the research involved in CSC risk reduction is not specified in academic literature, as well as in practice. To confront the challenges and to gain the benefits, there is a critical need for incorporating structural risk reduction optimisation within the proposed CSCRM framework to manage the risk in a cost-effective way.

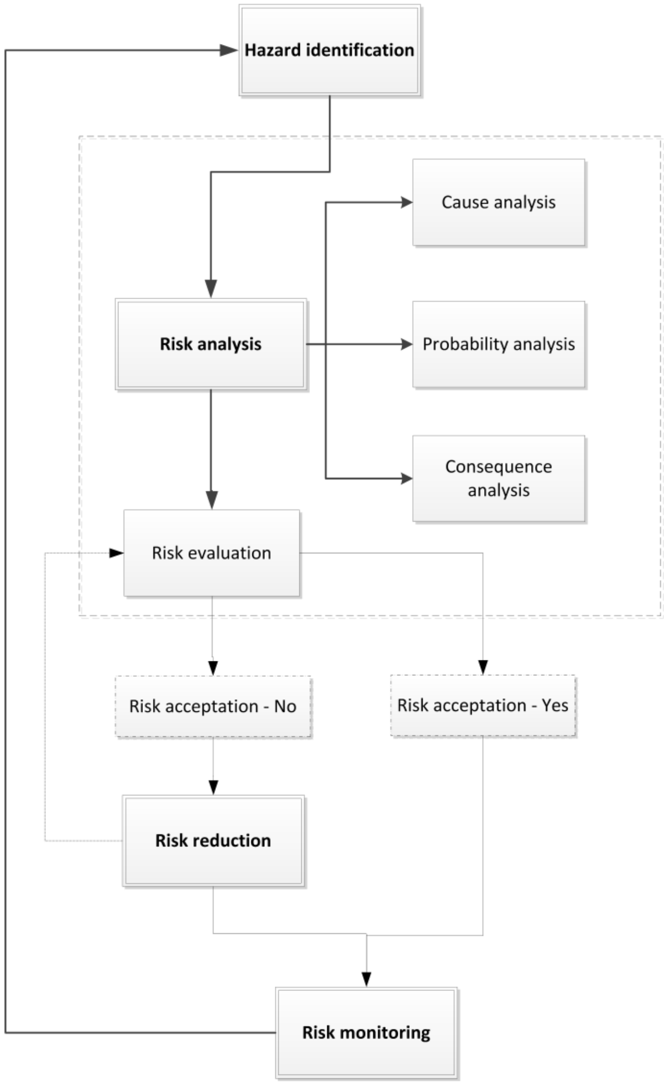
CHAPTER 3 RESEARCH METHODOLOGY

Summary

This chapter discusses the research methodologies, which have been implemented to grasp the defined aims and objectives. This research intends to provide a novel risk management method for capturing, assessing, and managing the risks in a dynamic CSC network. Due to the insufficient industry specific data, literature review and questionnaire survey are conducted to strengthen the knowledge base in hazard identification and risk data collection. SD offers a methodological approach that describes the major interdependencies and feedback mechanisms between the CSC and its associated hazardous events. The application of the proposed modelling and simulation method enhances the practice of risk modelling, which can be used to address dynamic risk effects and potential risk reduction outcomes in the CSC.

3.1 SUPPLY CHAIN RISK MANAGEMENT

Over the past decades, the supply chain has faced various challenges across the worldwide (Ghadge, Dani and Kalawsky, 2012). Driving factors such as customisation habit, competition, globalisation, outsourcing and new technologies have changed the fact of the supply chain and created new requirements to supply chain risk management (SCRM) (Finch, 2004; Ritchie and Brindley, 2007; Choon Oh, and Karimi, 2008; Colicchia and Strozzi, 2012). As well, the risks resulting from interactions between environment and the supply chain network, such as natural disaster, war and political instability, pose significant challenges to supply chain operations, and are difficult to predict and control effectively (Yang *et al*., 2013). Both the academics and practitioners appreciate the efforts in the application of SCRM to protect against the risk and keep the operation smoothly and effectively. Nevertheless, the incorporation and integration of systematic methodologies and analytical tools for improving the resilience and sustainability of the supply chain as a whole, while maintaining its competitiveness in terms of cost effectiveness and operational efficiency, is still largely unexplored. To bridge the gap in SCRM an integrated framework is provided to facilitate the understanding of the source of risks and the need for reducing the undesired risk effects (Marhavilas, Koulouriotis and Gemeni, 2011). **Figure 3.1** graphically represents the established SCRM framework.



(Source: Marhavilas, Koulouriotis and Gemeni, 2011)

Figure 3.1. A general SCRM framework

- Hazard identification

It is widely recognised that hazard identification is a vital phase for conducting an effective risk management (Caridi *et al.*, 2009). A hazard is defined as a physical situation arising from the uncertainties or disruptions that potentially damages the supply chain operations (Holton, 2004). The invisible demand, unknown competitors, and uncertain supply are frequently experienced in the operations that result in undesired losses, while the disruptions arising from operational contingencies, natural disasters, terrorism or political instability pose a threat to a supply chain. To manage these unexpected risks, it is essential to broadly outline the sources of risks across the supply chain network following the structured method.

- Risk analysis

In SCRM research, various methods and different techniques are provided to accommodate the need to analyse and evaluate the risks using multiple sources of data. The cause, probability and consequence of the risks should be assessed for screening out insignificant hazards (Khan and Abbasi, 2001; Pai *et al.*, 2003; Zsidisin and Ritchie, 2008; Tuncel and Alpan, 2010; Tummala and Schoenherr, 2011). In theory, the risk is a potential for undesirable consequence, so that the assessments of the combination of the probability and consequence are conducted in order to suggest appropriate SCRM measures (Mokhtari *et al.*, 2011; Heckmann Comes and Nickel, 2015). In the analysis, the probability refers to the occurrence probability of an accident event with undesired effect, while consequence indicates the magnitude of possible consequence in terms of negative aspect when the hazardous event does occur. To comprehensively estimate the probability and the degree of the possible consequences in a hazardous situation, Ren *et al*. (2009) and Kumar Himes and Kritzer (2014) further consider the likelihood of the hazardous event occurring in a certain period of time and the probability of suffering the given magnitude of the consequence. The interdependency among the hazardous events in different segments of a supply chain is investigated to estimate the risk effects. There are a number of qualitative or quantitative risk analysis methods provided, such as Hazard and Operability Study (HAZOP), FEMA, FMECA, FTA, ETA and Preliminary Risk Analysis (PRA) (Waters, 2009; Beretta and Bozzolan, 2008).

Based on the pre-defined criteria, which are determined according to the experience, supply chain standard, or other regulations, the risk analysis results can be evaluated to screen out significant risks. If the risk is not acceptable, it requires additional reduction actions or safeguards aiming at reducing occurrence likelihood of undesirable events and/or mitigating possible consequences (Ting, 1988).

- Risk reduction

Risk reduction procedure represents the method proposed by researchers to address the research objectives (Zsidisin and Ritchie, 2008). Efforts have, therefore, intended to offer a risk reduction method to reduce the undesired risk effects following the principle outlined in **Figure 3.2**. It will help to verify the advantageous risk reduction methods and suggest better-informed SCRM decisions (Li *et al.*, 2015).

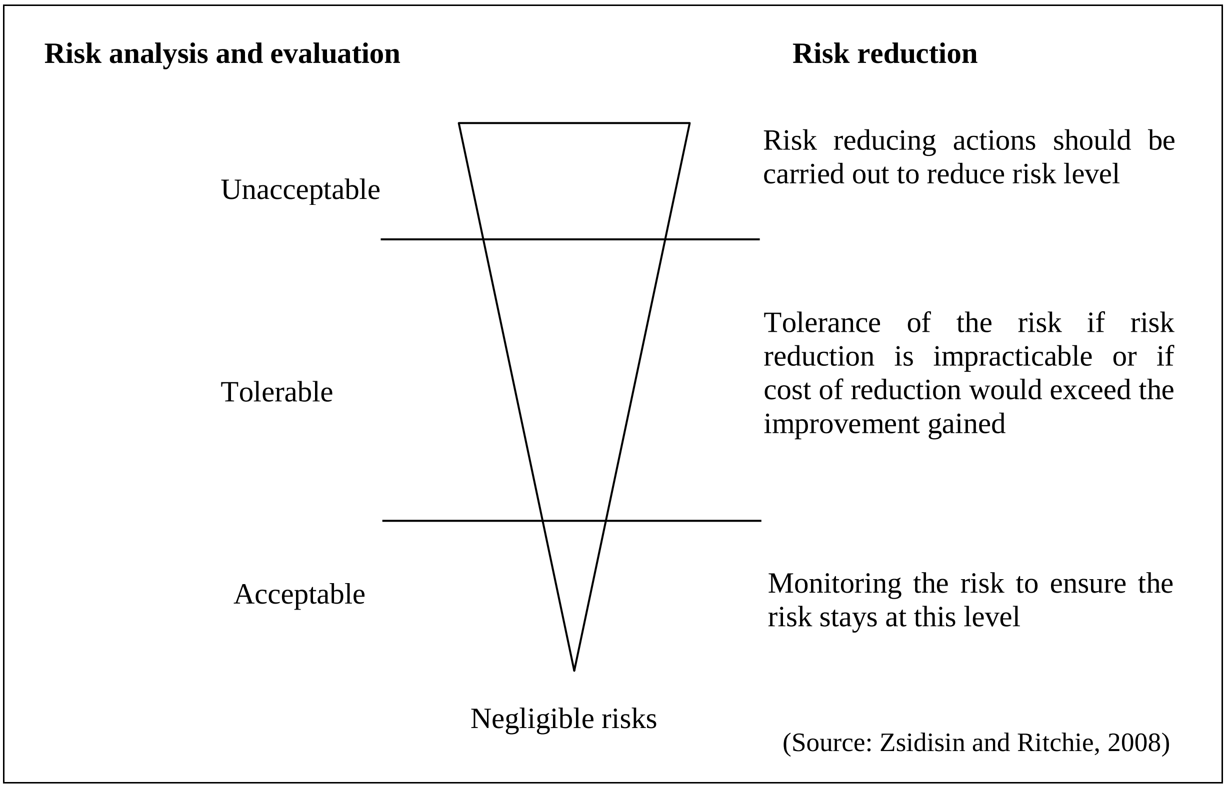


Figure 3.2. The principle of risk reduction

Waring (1996) first proposed the risk reduction principle to instruct the risk reducing actions. Based on the risk evaluation results, there are four levels provided to describe risk effects, which are unacceptable, tolerable, acceptable and negligible. To deal with the unexpected risks, the associated risk reduction principle is suggested: 1) Reducing actions should be carried out to manage the unacceptable risks; 2) Tolerance of the risk if risk reduction is impracticable or if cost of reduction would exceed the improvement gained; 3) Monitoring the acceptable risks to ensure the risks stays in current or lower level; 4) Ignoring the risks with negligible effects.

To assess potential risk reduction measures and continuously improve the CSC system performance, it requires one to forecast the outcomes of implemented risk reduction methods. To carry out risk reduction actions, preventive and responsive risk reduction mechanisms are built to respond to and recover from the risk effects (Merrick *et al.*, 2002). In the preventive mechanism, there is a collaborative relationship among the members of the CSC to identify hazards and take actions to reduce the risks proactively. On the contrary, in reactive mechanism the CSC members deal with the risks only after becoming problems. Based on the various mechanisms, the alternatives risk reduction approaches are proposed, which can be classified as avoidance, prevention and reduction (Merrick *et al.*, 2002). The prevention method is conducted to mitigate the occurrence likelihood of hazardous events, and the avoidance approach is an extreme case in prevention approach which is employed to significantly reduce the possibility of the occurrence of the threatening event. Reduction approach is another kind of solution which is provided to reduce the undesired risk consequence (Ghadge, Dani and Kalawsky, 2011). For instance, insurance is provided to reduce the negative impacts on the financial aspect, a flexible supply strategy supports the firm to be agile, and emergency response procedures are established to support the reduction of the impacts of either a man-made or natural disaster.

- Risk monitoring

The supply chain operation can only proceed when the risk has been reduced to an acceptable level (Ho *et al.*, 2015). However, the structure and operational process should be monitored continuously due to frequent changes. When the new hazard has been identified, the entire risk assessment and risk reduction process are required to be repeated till the risk is acceptable.

3.2 A NOVEL SD BASED CSCRM FRAMEWORK

The empirical and analytical research methods are applied to describe what the supply chain network and individual companies ought to do in regard to SCRM. However, the formulation of risk management from the industrial perspective is a rather difficult task, especially in terms of risk quantification and risk reduction decision making (Nikolopoulou and Ierapetritou, 2012). Managing CSC risks should first understand the sources of risks, and then facilitate risk management in a proper way (Cucchiella and Gastaldi, 2006; Trkman and McCormack, 2009). The framework describes the overall plan and reveals the priorities of the research. It encapsulates observed risks within and surrounding the CSCs in a hierarchical structure. The impacts on system behaviours associated with identified hazards are investigated to capture the critical risks. **Figure 3.3** represents an overview of CSCRM framework for the purpose of this research upon which the research methodology will be directed.

3.2.1 Hazard identification

Hazard identification is a critical step to recognise the uncertainties and disruptions across the supply chain network. There are a number of structured methods provided to identify the hazards. Waters (2009) indicated that the historical data collection, interviews and group meetings can be used to collect necessary data during the research. Yang (2010) provided an alternative viewpoint in hazard identification. The analysis of the corporate financial report and meeting records, constructing operational flow charts and continuous facility examinations were suggested to explore the existing hazardous events in the system. In this thesis, three distinct constructions are developed to establish a conceptual understanding of the CSC risks, which are hazard identification, source of hazards classification, and validation. To facilitate proposed method, literature review and qualitative questionnaire survey comprise the primary methods of research. Specifically, literature review serves as a base and guide to build upon throughout the CSC hazard identification research process. Based on the literature review results, a CSC risk taxonomic diagram is developed that combines the specific risk perspectives in the CSC with widely explored risk issues in the general supply chain. The obtained risks are categorised into nine risk domains: supply risks, operational risks, demand risks, strategy risks, security risks, political risks, natural environment risks and policy risks. Before moving to the next stage, an empirical analysis is conducted to verify the identified hazards and confirm the appropriateness of hazard classification.

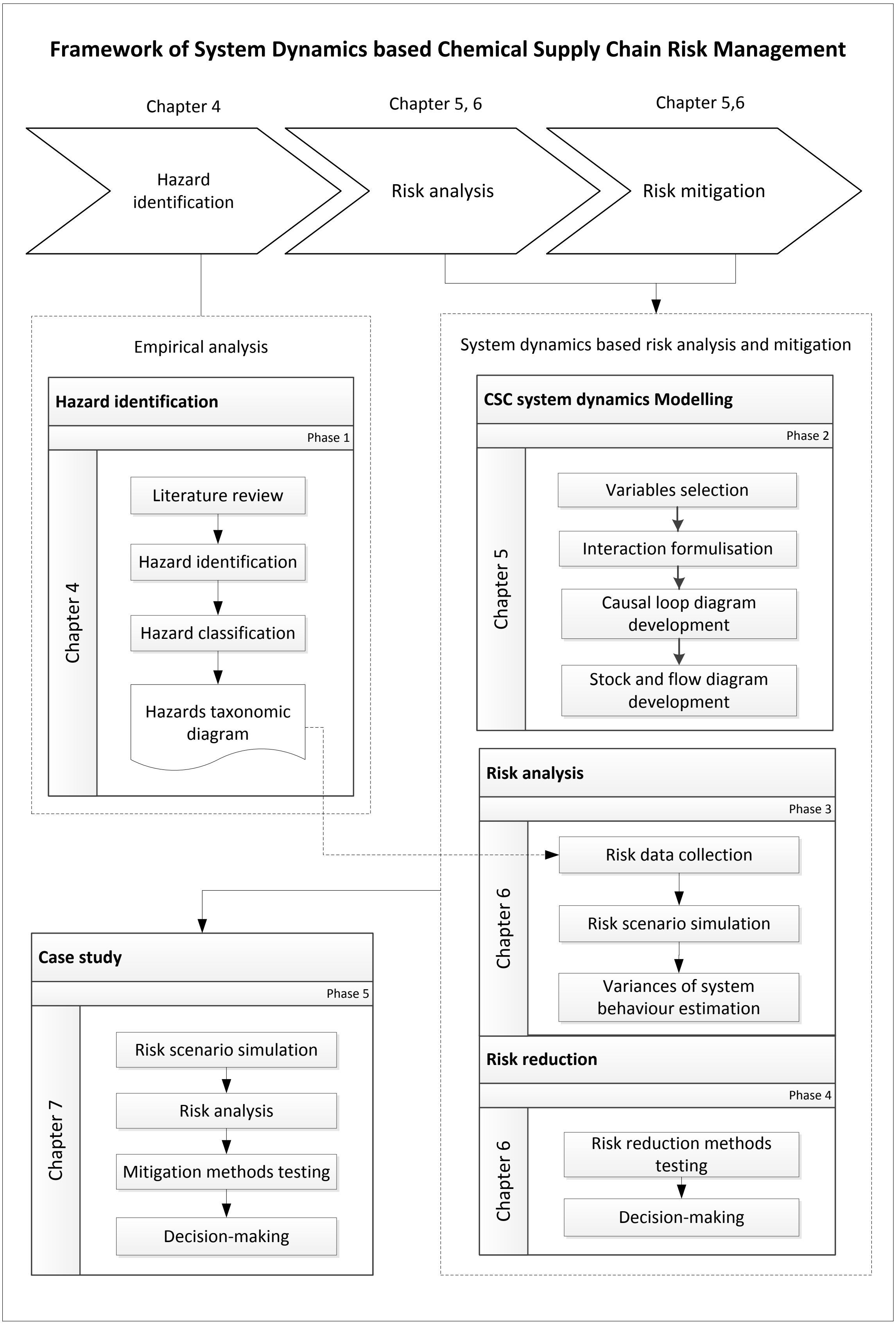


Figure 3.3. Proposed methodology of CSCRM

3.2.2 Risk analysis

Concerning about the complex interactions and the dynamic feedback effects between CSC behaviours and various hazardous events, a SD method is implemented for describing the complex CSC structure and simulating CSC operations under multiple scenarios in *Chapter 5* and *Chapter 6*. In accordance with the SD modelling and simulation procedures, the SD-based risk analysis is carried out following: articulation of problem, causal loop diagram development, stock and flow translation, and model formulation. Specifically, the interactions in the CSC and its contained risk evolution mechanisms drawn from expertise and literature are formalised in the developed causal loop diagram. Then, a stock and flow diagram is correspondingly converted with more detailed quantitative information in terms of the sequential steps: characterise elements, write equations, assign values to parameters, build model, and improve model. The accumulation of the material, information, and cost based on the time step will be addressed to represent the dynamic system operations. In the study, five sub-models will be developed using Vensim© (Commercial software): supplier sub-model, manufacturer sub-model, transporter sub-model, retailer sub-model and customer sub-model. By appropriately connecting the sub-models, it offers a multi-echelon CSC model to describe the complex CSC structure and to simulate the dynamic CSC operations.

The developed SD models simulate CSC operations under a specified state of the system, so that the scenario is established to specify the operational condition. However, the lack of industry-specific risk data challenges the application of the proposed method. To explore the extent of CSC risks, a questionnaire survey is used to inform a set of corresponding risk attributes. Based on the obtained data, the various scenarios are generated with different risk attributes to explore the distinct risk effects on system thinking (Rozman *et al.*, 2012; Featherston and Doolan, 2013). The combination of participatory SD modelling and scenario analysis facilitates the CSC behaviours, as well as mapping the risks through quantifying of the system behaviours.

The quantitative simulation results will be measured in terms of time, cost, and quality aspects, so as to screen out unacceptable risks, which should be further reduced. The criteria are designated according to the experience, standard, or other regulations. In particular, a time-based effect refers to a delay and disruption in material, information or financial flows, which in turn influences the supply chain performance. A cost-based consequence affects the financial flow that may lead to profit decrease. In contrast, a quality-based impact contributes to the damage of quality of product, service or property.

3.2.3 Risk reduction

Risk reduction procedure represents the method of dealing with unexpected hazardous events on system thinking. In *Chapter 6*, two risk reduction methods are provide to reduce occurrence likelihood of undesirable events and/or mitigating possible consequences. Incorporating the capability of SD model modification throughout the modelling life cycle, both in design and operation phases, the risk reduction methods are investigated and the outcomes are estimated through adjusting the input values and modifying the system structure based on the implemented risk reduction methods. Comparing system performance under different scenarios will identify advantageous risk reduction decisions. Therefore, the simulation analysis ensures that the implemented approach does indeed address the research objectives.

3.3 DEFINITIONS AND CONCEPTS RELATED TO RESARCH DESIGN

According to the research philosophical and theoretical foundations, the research methodology, research strategy and research methods are adapted in line with the knowledge (Saunders, Lewis and Thornhill, 2007). The proper approaches used to carry out research are identified, which meet the aim of the study.

3.3.1 Research methodology

Research methodology is a way used to scientifically deal with the research problem (Kothari, 2004). It systematically describes the steps that the researcher can follow to carry out the study, which may differ from problem to problem. In particularly, research methodology explains the consideration of the concepts and theories which underlie the methods. As well, it indicates the reason of why a particular method fits for the research problem in given study. An explanation of the rationale of employed methods is given to answer the research problem in context with identified research gaps and gain the disciplined thinking of scientific study.

3.3.2 Research methods

Research method is regarded as a part of the research methodology, which refers to the technique implemented to conduct the research (Yin, 2013). However, a distinction is made between research method and research technique. Research method is defined as a well organised approach which can be taken towards the selection and construction of the technique, while a research technique refers to a particular step-by-step procedure which describes in detail how to do it (Kothari, 2004).

In this study, both qualitative and quantitative methods are applied to identify, analyse and reduce CSC risks. To identify the hazards existing in the CSC, the literature review is adapted to categorise unstructured risks. The questionnaire is developed to verify the comprehension of hazard identification and examine the appropriateness of the risk classification results. The application of the SD method in CSCRM is an intermediate platform between widely used mathematical programming and empirical study. The causal interdependencies between system behaviours and hazardous events are formalised, so as to address the dynamic risk effects in the supply chain level. Due to the insufficient risk data, another questionnaire is developed to make inferences about the attitudes and opinions from the experts. The obtained risk data are inserted into the developed SD models to explore the CSC operations in various conditions. The simulation analysis comprehends the complex risks in a dynamic CSC system and provides an advantageous CSCRM decision support tool by revealing the gap between the expectation and the real-time performance. Full details about the research methods and research techniques will be explained in the following sections.

3.3.3 Research strategy

Research strategy offers a route to validate the research, which can be considered as the basic research protocol. It employs explanation, description, classification, and analysis to answer the research questions in terms of when, where, how, why, how many and how much. Thus, the selection of an appropriate research strategy is critical to ensure the achievement of the aim and objectives.

In this research, two different kinds of research strategies are applied to carry out studies, which are exploratory, and explanatory. The exploratory research is a flexible and adaptable strategy to define the research hypothesis based on the collected qualitative information. It is widely used in a situation where it is difficult to obtain prior information (Adams and Schvaneveldt, 1991). In this thesis, the exploratory strategy is employed to fill the gap in hazard identification. To investigate the risk generation mechanism, the explanatory strategy is implemented to explain what is going on and conceptualise the risk propagation mechanism (de Weerd-Nederhof, 2001; Saunders, Lewis and Thornhill, 2007). In particular, the major interdependencies and feedback mechanisms are addressed that demonstrate the changes of system behaviours arising from the hazardous events.

3.4 KEY RESEARCH APPROACH: SD

SD is a scenario-based simulation method to predict the behaviours of dynamic systems and analyse the efficacy of decision-making under different scenarios, including the impact of time delays, disruptions and uncertainties in a supply chain system. The adaptation of SD theory not only formalises the dynamic interactions between the investigated system and hazardous events but also considers the feedback effects among the operational processes. Incorporating the capability of the model modification both in the design and the operational phases, the developed SD model can be re-structured and modified to explore the outcomes of potential risk reduction methods.

3.4.1 The theory of SD

Jay Forrester first proposed SD theory to analyse the industrial dynamics by modelling and simulation using a computer-based approach at the Massachusetts Institute of Technology (MIT) in 1958 (Forrester, 1961). It combines theory, methods and philosophy in control engineering and non-liner dynamic system discipline (Garbolino, Chery and Guarnieri, 2009; Oehmen *et al.*, 2010; Garbolino, Chery and Guarnieri, 2010; Bouloiz *et al.*, 2013). The developed system seeks to understand the interactions between structural components and information feedbacks that show as dynamic behaviours in the system perspective (Forrester and Senge, 1980). SD is a broad concept that can be divided into two aspects: 'System' represents the structure of the system and the concept of feedback effect, while 'dynamics' reflects the changes in the behaviours of the various system components over time. The assumed interactions between the variables are formalised to build a *casual loop diagram*, which is used to demonstrate the dynamic hypotheses (Lertpattarapong, 2002). An illustrative example is shown in **Figure 3.4**.

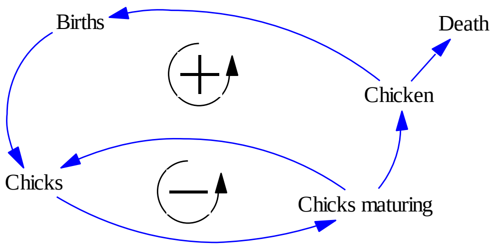


Figure 3.4. An illustrative example of causal loop diagram

Arrows are used to indicate the direction of a cause and effect relationship where the causative variable is represented by the origin of the arrow and the effected variable is on the other side. The "+" or "-" sign on the arrow describes the positive or negative effects between two variables. Based on the developed causal loop diagram, an increase in births results in more chickens in the future, so that the changes of the both sides of the variables toward the same direction. However, more chicks maturing leads to the decrease in the number of chicks, thus the behaviour of the affected variable presents the reduction effect on the influence of the origin variable. A closed chain of causal relations is defined as the feedback loop, which could be positive or negative. In a positive loop, the number of negative relationships is even or zero. This kind of loop is unstable and oscillates so triggering the system to grow, evolve and collapse. In contrast, the negative loop has an odd number of negative relationships that change the loop towards a stable situation.

Stock flow diagram is converted from the developed *Causal loop diagram*, which demonstrates the causal relationships between the stock, flow and control variables with more specific quantitative information. **Figure 3.5** describes an illustrative example of *Stock flow diagram*.

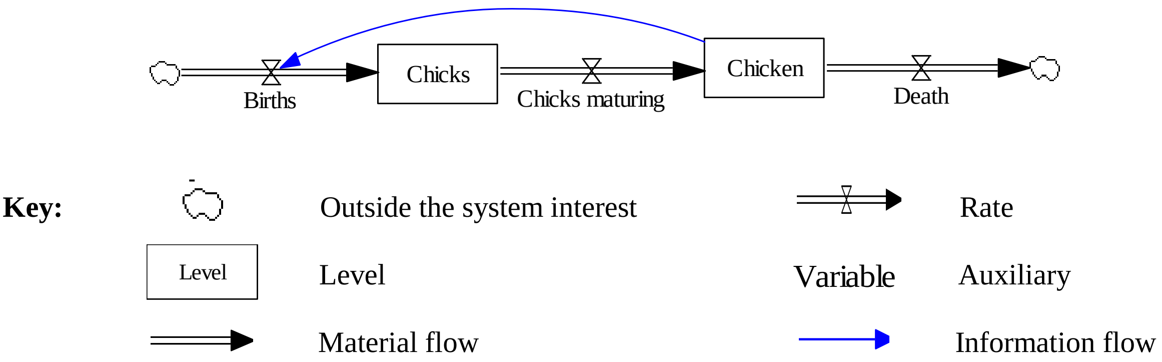


Figure 3.5. An illustrative example of stock and flow diagram

In this diagram, the system components are assigned to the level, auxiliary and rate variables. Specifically, a level variable is a structural element, which is represented in the rectangle box and used to describe an accumulative effect, such as inventory level, amount of labour, and value damaged in a certain period of time. Auxiliary is presented in the box without a border, which arises when the formulation of a level's influence on a rate involves one or more intermediate calculations. In response to changes in levels or exogenous influences, the value of auxiliary changes immediately. A rate only passes the information that governs the change of level variable.

3.4.2 Steps in SD modelling

A SD methodology comprises a set of rigorous procedures to describe a supply chain structure and its behaviours in terms of differing processes, information, decision-making and organisational limits. Yeo, Pak and Yang (2013) suggest that the SD modelling process can be characterised by three phases: logical modelling, model quantification and model application. To model and simulate the CSC risks, an SD-based CSCRM framework is developed based on well-established guidelines for the SD modelling process. The sequential steps are shown in **Figure 3.6**.

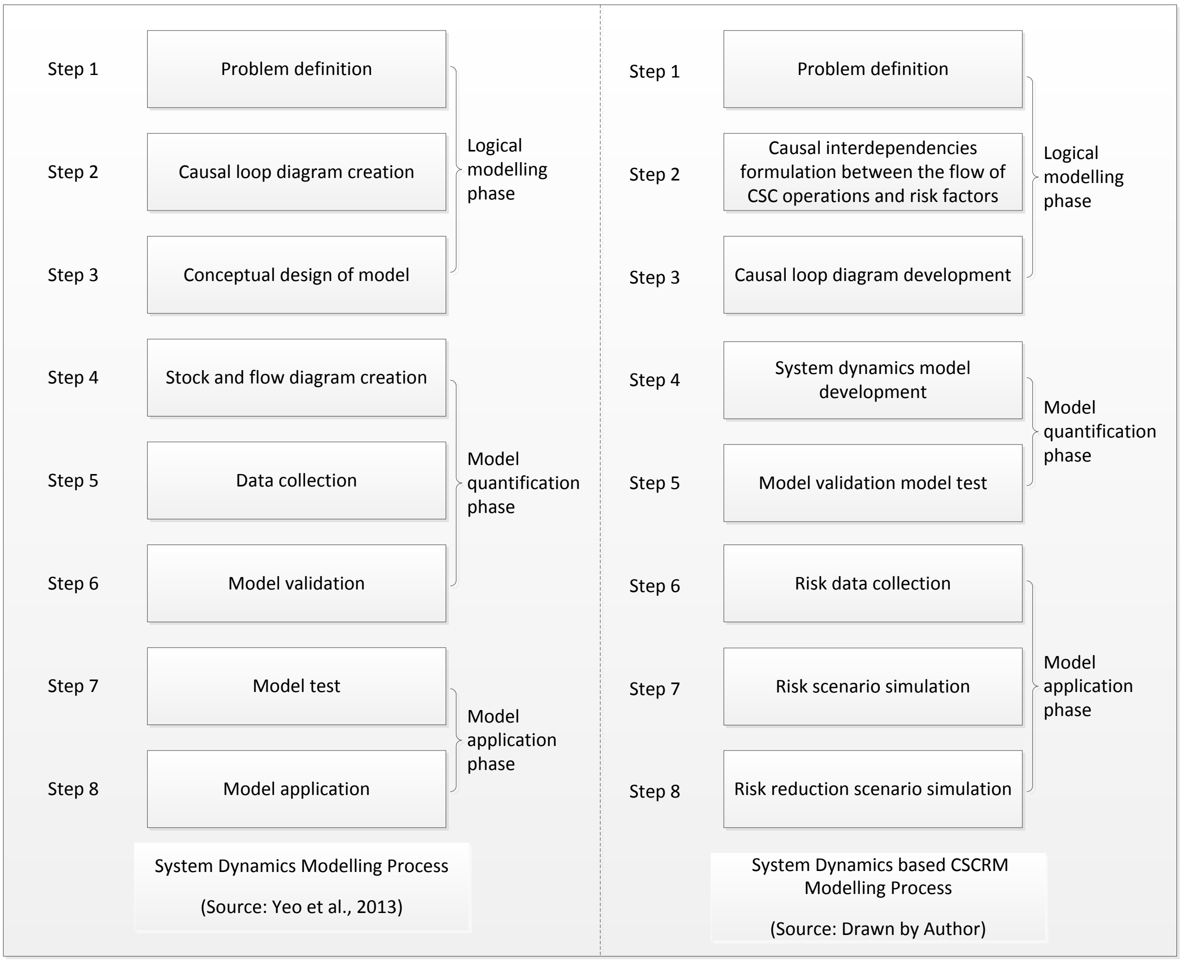


Figure 3.6. Framework of SD-based CSCRM modelling process

In the developed framework, problem definition is the first step, which describes the purpose of the modelling study and specifies the system boundaries. However, very limited research actually provided a formal structure of problem definition in the literature, as well as in practice. Lertpattarapong (2002) suggests defining the research problems following the steps of a list of variables, conceptual models, and problem statement. Yeo, Pak and Yang (2013) provide a verbal statement for defining the goal of system and specifying system boundaries. In this study, the guideline suggested by Sterman (2000) is adapted to facilitate the problem definition in SD modelling. It sequentially defines the system purpose, determines the system boundaries and provides a list of variables. The variables within the system boundaries are identified to clarify research issues. Then, the key variables and their interactions are addressed to represent the interdependencies between the flow of CSC operations and hazardous events. In step 3, the assumed causal relations between the key variables are formalised to build a causal loop diagram, which is used to demonstrate the cause and effect relationships within the system boundaries (Lertpattarapong, 2002). In accordance with addressed causal relations, the stock and flow diagram is developed through translating established causal loop diagrams using computer-based language (Campuzano and Mula, 2011). The created SD model should be verified and tested before model application in Step 5. In Step 6, the risk data is collected, which can be inserted as the input value of further risk scenario simulation. Running the SD model simulates the system operations in different scenarios. Through benchmarking the comparisons of the system performances, the risks are quantitatively assessed to find out the unacceptable risks in Step 7. Incorporating the ability of modifying the developed SD model both in design and operations phases, provides a method to measure the effects of potential risk reduction methods and support CSCRM decisions in step 8.

3.4.3. The advantages of integrating SD in SCRM

Supply chain is characterised by extreme complexity and uncertainty, the hazardous events could affect the balanced system and cause unexpected changes in system performance. SCRM is introduced to manage the undesired risk effects and maintain the system performance (Thun and Hoenig, 2009). Instead of assessing the risks based on expert knowledge or historical data, the application of the SD method to SCRM provides an analytical method for solving multidimensional problems using qualitative as well as quantitative information. It not only simulates the supply chain operations, but also predicts dynamic behaviours as the system changes emerging from the interactive relationships between the SC system and hazardous events (Angerhofer and Angelides, 2000). The logical feedback effects between the hazardous events and system behaviours are obtained to estimate risk effects when time is factored into the sequence. There are five main advantages of implementing the SD approach in SCRM:

- SD is best suited to those problems associated with continuous process where feedback significantly affects the system operations by producing dynamic changes in system behaviours.
- SD has ability to integrate material, people, processes and information in one system.
- SD can use the multiple sources of data.
- SD is a choice for checking the feasibility of different strategic, tactical and operational decisions.
- Ease of building a simulation model and reduced execution time.

3.5 METHODOLOGY FOR DATA COLLECTION AND ANALYSIS

This section gives a detailed explanation of the data collection and analysis methods used in the thesis. To capture and understand the risk factors, it is required to apply an approach involving the use of qualitative methods to gather and examine the risk data along with justification due to the scarcity of the research done in this area. The first sub-section describes the data collection method in the hazard identification phase. A questionnaire survey covering the key concepts of the identified CSC hazards will be conducted to verify the comprehensiveness of hazard identification and the importance of addressed hazards to the CSC. The second sub-section introduces the data collection method used in the risk analysis stage. The risk data will be collected as input values of different risk scenarios to simulate the dynamic risk effects in the supply chain level. **Figure 3.7** describes the methodology for data collection and data analysis, which are applied in line with the research questions and objectives.

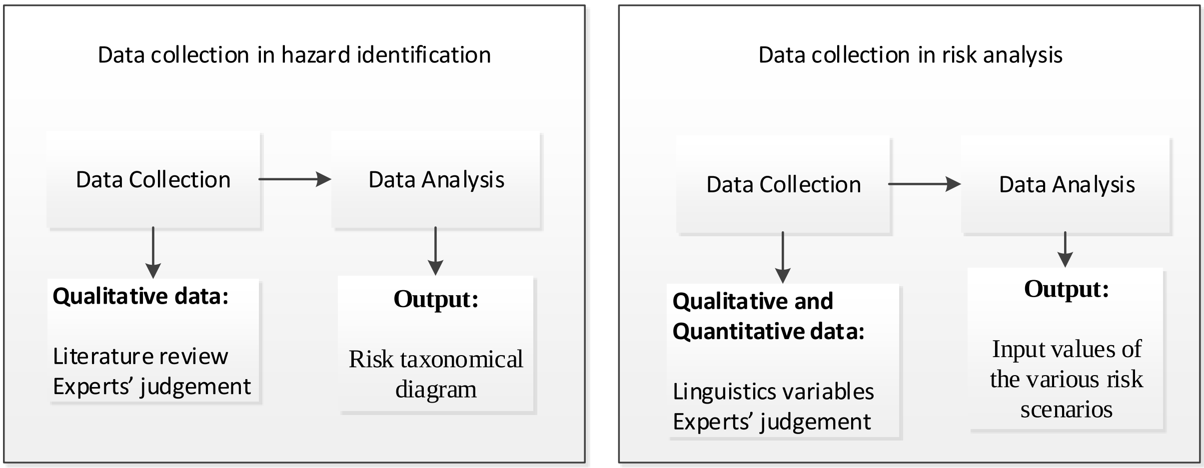


Figure 3.7. The methodology for data collection and data analysis

3.5.1 Data collection method in CSC hazard identification and validation

In spite of the systematic hazard identification and risk decomposition, the research continues with an empirical study covering the key concepts of the sources of CSC risks. *Chapter 4* provides a detailed explanation of data analysis and taxonomic diagram validation in hazard identification. Following the rigorous approaches, the questionnaire is developed in line with research questions, research objectives and related literature to collect the opinions from the experts who are most familiar with conditions to clarify the ambiguity (McCormack and Hill, 1997). In particular, the number of parameters in the construct, the selection of a Likert scale and avoiding negative words are the critical issues, which should be given more attention (Hinkin, 1995). The proposed method makes inferences about the attitudes and opinions to verify the comprehensiveness of addressed hazards and to investigate the importance of captured hazards to a CSC.

In the hazard identification stage, the questionnaire is designed to explore the importance of identified hazards and a Seven-point Likert scale is used to investigate the level of agreement with each question from the respondents. The questionnaire is developed in English in the early stage and translated from English into Chinese since the targeted respondents are academia and experts in the UK and China. To verify the appropriation and accuracy of the questionnaire translation, forward and backward translation methods are employed to examine developed questions. Two forward translators, native speakers of the Chinese and fluent in English, conduct translations independently. Any disagreements are resolved via a reconciliation process, resulting in a single provisional forward translation. Using this translation, backward translation is carried out by independent backward translators (fluent in Chinese and English, and different from the forward-translators) to ensure adequate representation of the forward translation. The forward format is then pilot tested on the target participants before being field-tested on a larger sample. Face-to-face discussions are conducted to help the questionnaire builder obtain a clearer picture of the meaningful advices. Based on the comments, the questionnaire is properly modified to fit in with the requirements (Finalised English and Chinese questionnaires are given in Appendix One). Furthermore, it will be converted to an online questionnaire via e-survey creator. It is expected that after participants had completed the questionnaire, the researcher could sign in onto e-survey creator and view the completed questionnaire.

The questionnaires were sent out to collect the data from risk experts and analysts in May 2014. The participants were selected based on their experience to the research topic using the university membership directories on SCM in Liverpool John Moores University, the University of Liverpool and Wuhan University of Technology in China. As well, recognised CSCM companies in China were contacted. The elected participants were approached by emails with a cover letter. A reminder via phone call was later followed to establish willingness to participate.

The population, sample and response rate in the survey will be described in later sections. As well, a validity test will be conducted to test whether the study measures the necessary items and whether the study receives the reliable responses after receiving the completed questionnaires. Based on the obtained results, a risk taxonomic diagram is developed to illustrate the CSC risks in a hierarchical structure, which provides a comprehensive risk database to CSCRM research.

3.5.2 Data collection method in CSC risk analysis stage

In the risk analysis phase, expert elicitation is a proven methodology that is used to gather information in the CSC domain regarding the lack of accurate industry-specific risk data. The developed CSC system could be affected by hazardous events and bring unexpected consequences during its operations. Indeed, there is a substantial amount of effort that has been devoted to presenting the level of the possible risks. Mokhtari *et al*. (2011), Vilko and Hallikas (2012), and Heckmann, Comes and Nickel (2015) suggested that a risk could be analysed in two attributes: *Occurrence likelihood (LO)* and *Consequence severity (CS)*. *LO* refers to the probability that an accident event occurs by causing an undesired effect, whereas *CS* indicates the magnitude of the possible consequence in terms of the negative aspects. Meantime, Ren *et al*. (2009), and Kumar, Himes and Kritzer (2014) argued that *Consequence probability (CP)* should be considered, which indicates the probability of suffering the given magnitude of the consequence, when the accident happens. In this research, the CSC hazardous events are described by the combination of *LO*, *CS* and *CP*. *LO* estimates whether a CSC risk will materialise. When a hazardous event occurs, the negative effects with a given degree of probability are represented by *CS* and *CP* to describe the experienced consequence in terms of the system's inability to satisfy customer demand, recover from time delay and quality damage, causing financial and life loss (Upton, Zsidisin, and Panelli, 1999). The set of corresponding data of each hazardous event is collected from risk experts and inserted into the developed SD model to explore the risk effects from the whole supply chain perspective. Following the questionnaire development procedures described in *Section 3.5.1*, the questionnaire is constructed to elicit expert opinions on the CSC risks in terms of hazardous event occurrence likelihood, consequence severity and consequence probability.

- LO

The occurrence likelihood of a hazardous event describes the frequency of the hazardous event occurring in a certain time of period, which interrupts CSC operations (Li *et al.*, 2015). It is often used to subjectively estimate whether the risk will materialise. In practice, the accurate numerical value of the occurrence likelihood is difficult to be addressed, therefore, six abstractive categories are provided to describe the likelihood of occurring: 'Rare' (Has never or rarely happened), 'Very low' (Only likely to happen within 2-3 years), 'Low' (May occur within one year), 'Medium' (Likely to happen at some point within a few months), 'High' (Circumstances frequently encountered on a monthly basis), and 'Very high' (Circumstances frequently encountered almost daily). Following this format, the numbers of 0, 1, 3, 5, 7, and 9 are used to represent the corresponding abstractive category. **Table 3.1** illustrates the definition of the occurrence likelihood of a hazardous event.

Table 3.1. Definition of the occurrence likelihood of a hazardous event

LO	Likert scale	Definition
Rare	0	Has never or rarely happened
Very low	1	Only likely to happen within 2-3 years
Low	3	May occur within one year
Medium	5	Likely to happen at some point within a few months
High	7	Circumstances frequently encountered on a monthly basis
Very high	9	Circumstances frequently encountered almost daily

- CS

Consequence severity indicates the magnitude of possible effect when the hazardous event does occur. It is regarded as a negative consequence in the inability to satisfy customer demand, bringing time delay and quality damage, causing financial loss, or even threating human life (Upton, Zsidisin, and Panelli, 1999). In the SCRM discipline, the consequence is frequently measured in three aspects: time, cost, and quality (Vilko and Hallikas, 2012). The time-based consequence refers to delay and disruption in material or information flows, the cost-based consequence exists in the financial flow that may lead to cost increase or profit loss, while the quality-based consequence refers to the damage of quality of product, service or property. To describe the level of consequence severity in various aspects, the words of ‘Negligible’, ‘Minor’, ‘Moderate’, ‘Major’, ‘Critical’ or ‘Catastrophic’ are applied in the proposed research. The definition of consequence severity is shown in **Table 3.2**.

Table 3.2. Definition of consequence severity

CS	Likert scale	Definition
Negligible	0	An insignificant effect on this core activity
Minor	1	Causing some inconvenience with minor impacts
Moderate	3	Causing some disruption with medium impacts
Major	5	Causing major disruptions to CSC operations
Critical	7	Causing failure of CSC operations
Catastrophic	9	Causing complete and irrecoverable failure of CSC operations

- CP

Consequence probability refers to the probability of the consequence given the hazardous event occurred (Li *et al.*, 2015). The level of probability can be described in different words and illustrated in various ways. Hallikas *et al*. (2004) suggested five abstractive categories: very unlikely, improbable, moderate, probable, and very probable, while Chang (2013) used rare, unlikely, possible, likely, and almost certain to describe the consequence probability. In this thesis, a novel Likert nine-point scale is provided to represent the probability of the consequence, which are ‘Impossible’, ‘Rare’, ‘Low’, ‘Medium’, ‘High’ and ‘Definite’. The definition of each Likert scale is described in **Table 3.3**.

Table 3.3. Definition of consequence probability

CP	Likert scale	Definition
Impossible	0	Will never occur
Rare	1	Rarely to occur
Low	3	Unlikely to occur
Medium	5	About an even chance of occurring
High	7	Likely to occur
Definite	9	Definitely will occur

Since the target respondents are academics and experts in the UK and China, the built questionnaire have to be translated from English into Chinese. In order to translate the questionnaire items into the appropriate language, both forward and backward translation process were conducted. Two scholars from Wuhan University of Technology were consulted to ensure that the translated questionnaire had a clear understanding of Chinese respondents. Then, a third party translator subsequently translated the Chinese questionnaire back into English to ensure that the forward translation was an adequate representation of the English original. Hence the translated items were verified that the original meanings were accurately reflected.

After designing the risk analysis questionnaire, the researcher sent a draft of the questionnaires to ten experts with very good knowledge and experience in CSCRM from UK and China in September 2014. It was deemed as a pilot test to assess the readability of representative measurement items. Face-to-face discussions were carried out to help the questionnaire builder to obtain a clearer picture of the meaningful advices. For instance, the experts from China suggested that “risk” was a sensitive word in the Chinese chemical industry. The respondents might not wish to offer any opinions or information related to the “risk” which could reduce the willingness to participate. Based on this comment, the translated questionnaires were properly modified to ensure the use of the words. The finalised English and Chinese questionnaires are attached in Appendix Two.

3.5.3 Data analysis

The analytical data processing method is applied to produce high quality data, which can be used in later hazard identification and risk analysis research. In the study, the questionnaires are designed to facilitate respondents to give a quick and clear answer, so that the numeric numbers are used to represent the corresponding abstractive category. To ensure that the gathered data is reliable and consistent, respondents’ profile analysis and statistical test are conducted prior to carrying out risk analysis and risk reduction research. The analysis of the surveys is described in *Chapter 4* and *Chapter 7*.

3.6 CONCLUSION

In this chapter, the research methodology, research strategy and research methods are presented and discussed, which lie at the core of the aim and objectives for the study. The SCRM framework is explained to lay down the foundations for the study through indicating the main philosophical views behind the research methodologies. Integrating SD modelling and simulation methods in CSCRM offers a methodological approach that deals with the complex interactions and dynamic feedback effects between the CSC system and hazardous events. Meanwhile, risk experts and analysts have contributed potential CSC risks to inform the construction of the SD models and generate various risk input values in different scenarios. The proposed research seeks to understand how a risk affects the CSC operations; how the risk effects can be assessed; and how CSCRM can be brought into an optimised measure to reduce undesired effects. The application of the proposed SD-based CSCRM approach is followed in the next chapters to identify hazards, analyse and reduce the associated risks in the CSC.

CHAPTER 4 CHEMICAL SUPPLY CHAIN HAZARD IDENTIFICATION

Summary

An unforeseen event is a threat that can interrupt the operational process and has a negative impact on the CSC system in terms of time, financial, or reputational losses (Waters, 2011). It is widely recognised that hazard identification is a vital phase of conducting an effective risk management. The chapter gives a description of hazard identification undertaken to capture and verify the risk issues in the CSC. The distinct risks in the CSC and the general supply chain risks are combined to develop a comprehensive risk taxonomic diagram to strengthen the knowledge base in CSCRM. It not only extends the understanding of risks from the industrial perspective, but also decomposes the unstructured risks into different risk categorisations following a rigorous approach. In further risk analysis research, the classified risks can be assessed through applying various risk analysis methods to find out the unacceptable ones.

4.1 A RISK PERSPECTIVE ON CSC OPERATIONS

Complexities and uncertainties are regarded as the sources of risks, which pose significant challenges to CSC operations. In theory, a supply chain risk is a potential for an incident or accident arising from an internal system or external environment in which the effects of the inability to satisfy customer demand (Zsidisin et al., 2004). The industry and the public highly concern the risk issues. The globalisation, complexity, competition, uncertainty, and the hazardous characteristics of chemical substances challenge the CSC operations and result in financial loss, the damage to the environment, or the loss of human life (Mullai, 2009; Bergkamp, 2013; Ehlen et al., 2014).

4.1.1 Globalisation

The CI and CSC have witnessed an expansion into global sourcing and international trade in the few last decades. In the global market, the geographic dispersion of CSC members leads to that huge volume of chemical substances often needing to be purchased and transported all over the world by air, road, railway, pipeline or ship. It helps CSCs achieve the cost benefits in terms of tariff and trade concessions, comparatively lower labour cost, and capital subsidies (Ting, 1988; Meixell and Gargeya, 2005). However, the growth in globalisation and the additional management not only diminish the effectiveness, but also increase the complexity in operations (Atthirawong and MacCarthy, 1980). The conflicts of various local cultures, different languages, inadequate worker skills and other problems are frequently experienced in the global CSCs.

4.1.2 Complexity

CSCs can be enormously long and complex, which can be divided into thousands of sub-systems according to products, geographies and customers. The complex operational processes destroy the efficiency of the CSC operations and bring the risks to the CSC system. Especially, the feedback effects among the logical loops emerging from the interactive relationships amplify or self-correct the disturbances, which cause the dynamic of system operations over time. It is suggested that the drivers of complexity should be mapped across different aspects, for example, cultures, technical standards and introduced policy (Ferrio and Wassick, 2008). As well, the effects arising from the complexity need to be addressed, so as to manage the CSC operations in a global market (Milgate, 2001).

4.1.3 Competition

The globalisation and technology innovation bring great changes in CSCs and thus lead to fiercer competition. More and more external competitors from different countries emerge as a result of the rapid development of the CI, especially in the Middle East and East Asia (Ballhorn *et al.*, 2014). In these areas, the capacity of manufacturers is bigger, the technology used is more advanced and practical, and energy and labour cost is much lower than in developed countries. The local CSCs are able to take advantages of raw material sourcing and manufacturing, which drive the world CSC expansion. To survive, the traditional magnates in European and other counterparts have to alter their traditional viewpoint on the CSC and continuously cut their costs to maintain the market share (Johnson, 2010).

4.1.4 Uncertainty

Dynamic demands, information distortion, and unexpected changes in external environment imposed by globalisation and complexity make it increasingly necessary to manage the uncertainties in the CSC. It is therefore essential that more effect should be put into identifying the uncertainties existing in both internal and external systems (van der Vorst and Beulens, 2002; Tsiakkouri, 2010).

In the supplying process, the operational process can be easily interrupted by environment changes. According to the literature review results, special attention is given to environmental risks to identify, assess and reduce them in the supply chain level (Park, Hong and Roh, 2013). Meanwhile, the other drives towards uncertainty mainly arise from internal systems, which are recognised as dynamic customer demand and demand amplification (Das and Dutta, 2013). In practice, the customer demand is changing over time. The CSCs have to develop an understanding of the nature of customer requirements to improve the effectiveness and efficiency of operations. An important observation of demand distortion, known as the bullwhip effect, amplifies demand variation and increases supply chain operations costs (Mingers and White, 2010). Thus, it requires a robust and flexible CSC to deal with changeable customer demand with information sharing on system thinking. Additionally, chemical materials have their own inherent properties that potentially threaten the environment and human life (Thun and Hoening, 2011). The hazardous characteristics could aggravate the probability and consequence severity of actual or potential risks and lead to undesired effects. To ensure the safety of the CSC, it is important to evaluate the uncertainties associated with material characteristics to provide a guideline for operational activities (van Wyk and Baerwaldt, 2005).

4.2 RISK CLASSIFICATION METHODS

Hazard identification is provided to recognise the causes of accidents across the CSCs (Heckmann, Comes and Nickel, 2015). There is a substantial amount of risk decomposition methods to be found in literature that categorises the supply chain risks in many different ways and from different perspectives. **Table 4.1** gives a brief description of risk classification frameworks provided by different researchers.

Table 4.1. Risk classification methods proposed in literature

Author (Year)	Risk classification method	
Jüttner, Peck and Christopher (2003)	-- Environmental -- Organisational	-- Network-related
Lam (2003)	-- Market -- Operational	-- credit
Chopra and Sodhi (2004)	-- Systems -- Intellectual property -- Receivable -- Capacity	-- Forecast -- Sourcing -- Inventory
Rao and Goldsby (2009)	-- Environmental risk -- Organisational risk -- Decision maker risk	-- Industry risk -- Problem risk
Tang and Musa (2010)	-- Material flow risks -- Financial flow risks	-- Information flow risks
Singhal, Agarwal and Mittal (2011)	-- Operational risks -- Market risks	-- Strategy risks -- External environment risk
Vilko and Hallikas (2012)	-- Operational risk -- Macro risk -- Environment risk	-- Security risk -- Policy risk
Rangel, de Oliveira and Leite (2014)	-- Plan -- Make -- Return	-- Source -- Delivery -- Others

Jüttner, Peck and Christopher (2003) defined supply chain risks based on three factors: environmental, network-related and organisational. Specifically, the environment risks refer to the interaction between the environment and the supply chain network, such as natural disaster, war and political instability. The risks arising from internal factors of the supply chain network and lying within the interaction of entities are attributed to network-related risks, e.g., supply problem, information distortion, outsourcing risk. The organisational risks belong to the inbound risks of various supply chain entities, which refer to labour shortage, IT failure, *etc*. Based upon a framework originally proposed by Lam (2003), it mainly focused on the risks in the operational level and broadly classified the risks into three categories, which include market, credit, and operational risks. Similarly, Chopra and Sodhi (2004) offered an operational level risk classification method. It suggested that the supply chain risks cause unanticipated changes in the flow, which are attributed to disruptions and delays. Therefore, the systems risk, forecast risk, intellectual property risk, sourcing risk, receivable risk, inventory risk and capacity risk should be managed at the appropriate level across the entire supply chain network. Tang and Musa (2010) explored material, information and financial flow in the supply chain to address potential risks. The risks in material flow arise from physical movement in sourcing, manufacturing and delivering. In financial flow, the risks of exchange rate, price and cost, financial strength of supply chain partners, and financial handling and practice are the common risks. The information distortion, information system security and information disruption contribute to information flow risks. To facilitate proper risk classification from industrial practice, Rao and Goldsby (2009) expanded the risk decomposition method through investigating the industry characteristics. The supply chain risks were divided into five categorises, which are environmental risk, industry risk, organisational risk, problem risk and decision maker risk. In line with the supply chain functional aspects, Singhal, Agarwal and Mittal (2011) defined risk criteria and classified the risks associated with the identified hazards into four categories: operational, strategy, market and external environment. Vilko and Hallikas (2012) analysed both internal and external risks though investigating the risks related to supply, operational, security, macro, policy, and environment dimensions. Rangel, de Oliveira and Leite (2014) offered a novel risk decomposition method to categorise the risks based on their related process. It grouped the risks into plan, source, make, deliver, return, and other aspects.

It is important to notice that the risks are about to become more complicated in the complex and global CSC, so that hazard identification and risk classifications are becoming increasing difficult.

Both academics and operators appreciate the need to follow a structural method to decompose, and validate CSC risks. Adapting the conceptualised risk classification principle proposed by Manuj and Mentzer (2008b), a unique classification framework for the CSC risk decomposition is developed, shown in **Figure 4.1**.

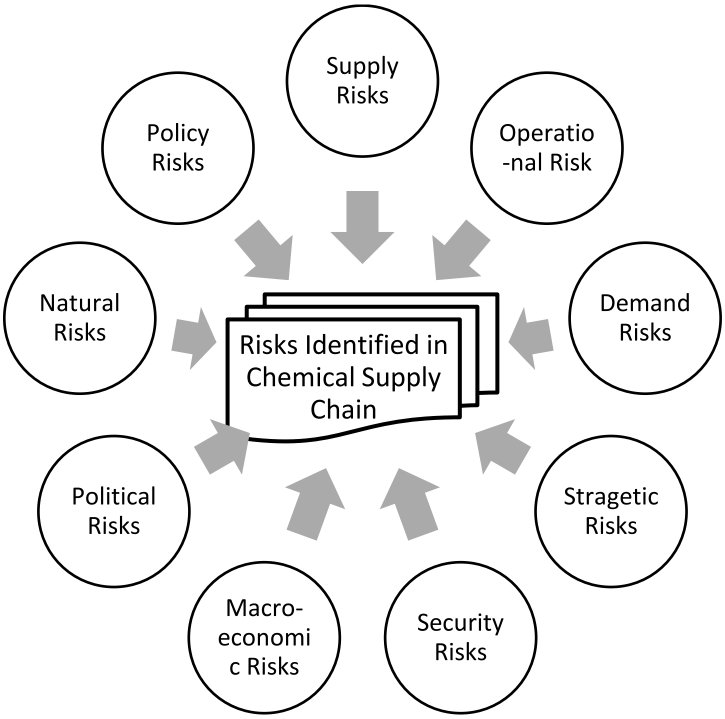


Figure 4.1. Sources of risks in the CSC

Based on the source of risks, it categorises the CSC risks into nine groups: supply risks, operational risks, demand risks, strategic risks, security risks, Macro-economic risks, political risks, natural environment risks and policy risks. Specifically, the operational risks arise from the specialised operational features of the internal organisation that may cause production, transportation or services disruptions. Strategic risks refer to the problems in strategic decisions within the organisations. Supply and demand risks are the undesired events resulting from the interactions between the members in the CSC, which happen external to the organisation, but within the supply chain. On the contrary, the security, macroeconomic, policy, political and natural environment risks occur from the interactions between the CSCs and the external environment (Mason-Jones, Naylor and Towill, 2000). **Table 4.2** presents the definition criterion and features of each source of risks.

Table 4.2. Definition criterion and features of each source of risks

Risk definition criterion	Definition (Description and characteristics)
Related to supply characteristics	Supply risks stem from potential or actual disturbances surrounding the supply procedure in CSC operations.
Related to operational characteristics	Operational risks refer to the undesired events arising from operational activities in the focal firm that may cause product damage or service disruption.
Related to demand characteristics	Demand risks arise from downstream activities, which are specific to the changes of market or downstream members.
Related to strategic characteristics	Strategy risks relate to the characteristics of strategies that influence the whole supply chain context.
Related to macroeconomic characteristics	The source of macroeconomic risks is a broad term referring to economic fluctuations in economic activities and price changes.
Related to security characteristics	Security risks refer to third parties who surround the internal or external environment intend to steal proprietary, data, and knowledge or interrupt the CSC operations.
Related to political characteristics	Political risks stem from the uncertainty and instability when the major change happens in political regimes.
Related to environment characteristics	Natural environment risks refer to the natural disasters that bring the varitions of the CSC behaviour in the affected region.
Related to policy characteristics	Policy risks indicate the changes of legislation, regulations, and policies that may affect the CSC organisations and operations.

4.3 CSC HAZARD IDENTIFICATION AND CLASSIFICATION

The study seeks to facilitate proper and comprehensive hazard identification from industrial practice. The systematic literature review provides critical insights into CSCs to identify the addressed hazards in previous studies. Meanwhile, integrating the distinct risk perspectives of CSC strengthens the knowledge base in hazard identification that comprises a risk portfolio for the material, information and financial flows from original-supplier to end-customer. Furthermore, a classification and analysis is conducted to categorise captured risks to special named categories based on shared characteristics, which contain supply risks, operational risks, demand risks, strategic risks, security risks, macroeconomic risks, political risks, natural environment risks and policy risks. **Figure 4.2** presents an organised CSC risk decomposition framework to describe where these risks are focused.

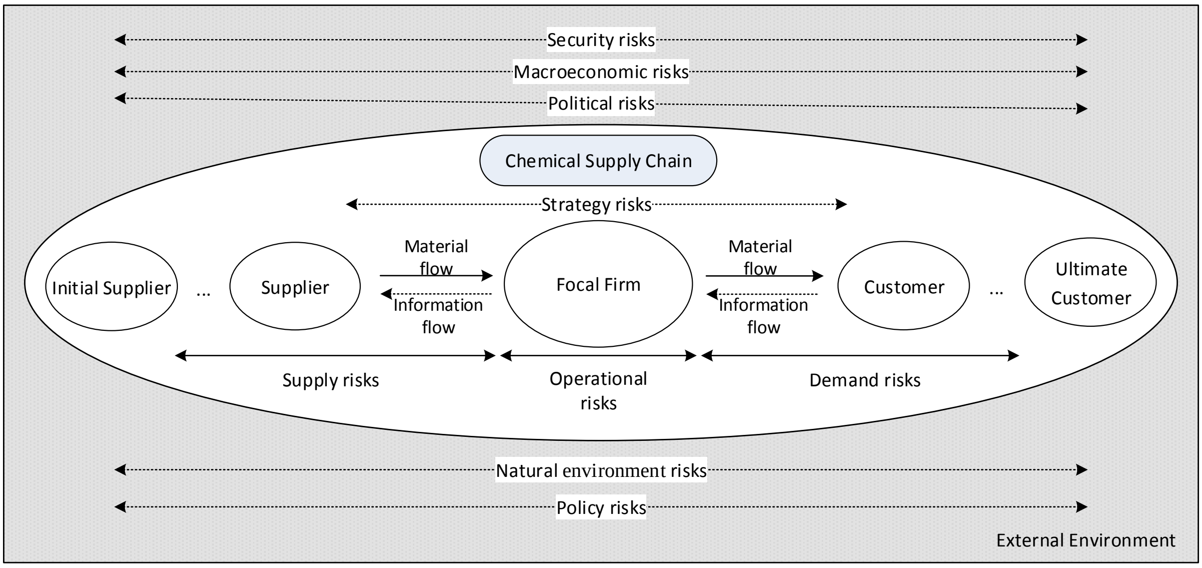


Figure 4.2. A schematic of where the risks are focused along the CSC

4.3.1 Supply risks

The physical extension of the CSCs originating from a global sourcing strategy leads to huge volumes of chemical substances purchased and transported around the world (Harland, Brenchley and Walker, 2003; Colicchia and Strozzi, 2012). Supply risks appear and reside within the movement of material associated with inbound supply activity being unable to deliver the materials or provide the service to meet the downstream requirements. According to the survey conducted by Accenture, approximately 50% of the respondents who involve 151 supply chain executives suggest that the leading risk to the CSC is supply disruptions (Waters, 2011). Conducting a critical interpretive synthesis of the literature, the hazards associated with the supply process are identified, including supply market uncertainty, high sourcing cost, supply activities disruptions, low supplier reliability, low supplier flexibility, complexity of materials' types, materials unavailable, low material quality, and lack of supply process monitoring. **Figure 4.3** provides a schematic presentation of the supply risks discussed.

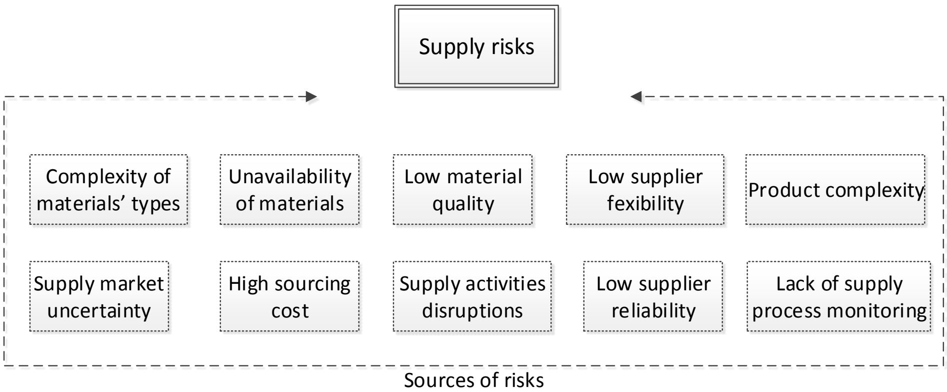


Figure 4.3. A schematic presentation of the supply risks discussed

In the CI, there are more than 70,000 kinds of chemical products. The *types of chemical materials are extremely complex*, so that the sufficient understanding should be obtained by suppliers to distinguish and provide the required materials to the downstream members (Brown *et al*., 2014). Meanwhile, the exchanges of chemicals are extensive and the trades take place worldwide at any time. The prices of chemical substances fluctuate all the time, especially the fossil fuel, which leads to the necessity of opportunistic buying. In order to making more profit, chemical companies have to exploit every cost saving opportunity to avoid *high sourcing cost*.

In the operations, the reliability and flexibility are two critical indicators used to measure the supply service. *A reliable supplier* is necessary to provide adequate quantities and qualities of inputs to the production process, while *the flexibility of the supplier* is regarded as one of the antecedents of supply chain flexibility to respond to the dynamic changes and complex requirements (Swafford, Ghosh and Murthy, 2006; Avittathur and Swamidass, 2007; Gosling, Pruvis and Naim, 2010). The majority of raw materials are sourced from remote and unstable areas of the world. In these areas, the *supply activity disruptions*, *unavailable materials*, and *the damage of material quality* are frequently experienced, which lead to supply process disruption or even breakdown, as well as contributing to the *uncertainties of the supply market* (The white paper of Advisen insurance intelligence, 2013). Due to frequent changes, the structure and operational process should be monitored continuously to reduce the risks. However, *the low visibility of the sourcing phase* obstructs the hazard identification. It is imperative that the CSC members collaborate to improve the transparency of operations in the material, financial, and information aspects (Jüttner, 2005).

4.3.2 Operational risks

Operational risks refer to the uncertainties and disruptions arising from problems from internal controls, systems, or people that may cause products damage or services disruption (Manuj and Mentzer, 2008a). As described in the previous section, this kind of risk is the possibility of inherent uncertainties associated with focal company. Integrating risk perspectives of the CSCs with investigated hazards in the literature, **Figure 4.4** describes the addressed operational risks in the CSC.

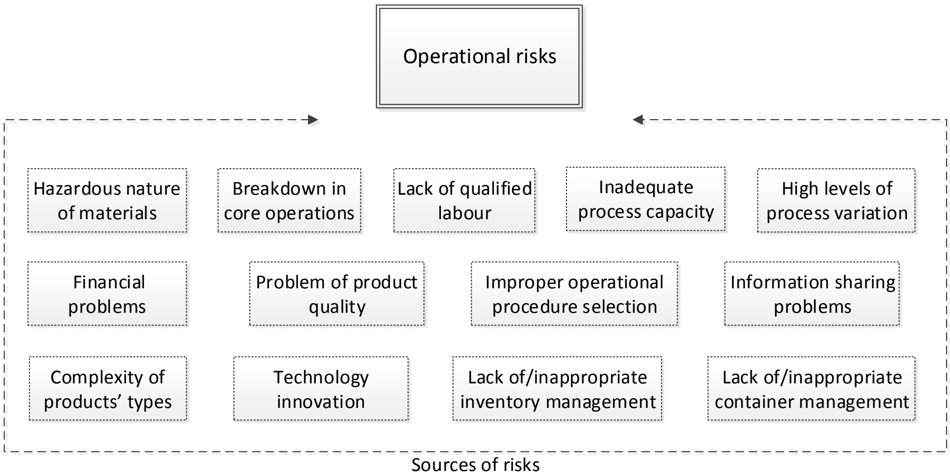


Figure 4.4. A schematic presentation of the operational risks discussed

The operational risks are comprised of fourteen risk factors, which are hazardous nature of materials, breakdown in core operations, improper operational procedure selection, inadequate process capacity, high level of process variation, complexity of product types, lack of/inappropriate inventory management, lack of/inappropriate container management, problem of product quality, lack of qualified labours, technology innovation, information sharing delay, information sharing inaccuracy and financial problems.

Specifically, chemical materials have their own inherent properties that determine the distinct features of the CSC operations. Especially, *the hazardous characteristics*, such as extreme low storage temperature, high storage pressure, flammable and explosive, endanger the whole operational activities (Bruinen de Bruin *et al*., 2007). It is significant for the CSCs to ensure the safety of the operational process with the least negative impact (Van Wyk and Baerwaldt, 2005). The effort has been devoted to identify the operational process related hazards. The risks of *improper procedure selection*, *inadequate process capacity*, and *breakdown in core operational process* have been widely analysed and a number of risk management approaches provided to minimise the risk effects (Kenne, Dejax and Gharbi, 2012). In particular, 35% of 151 supply chain executives in U.S. pointed out the labour issues, including lack of skilled workers, strike of workers, carelessness and a lack of motivation among the workforce, generate the significant uncertainties and disruptions to supply chain operations (Waters, 2011). It is indicated that these captured risks may be short term, but with serious consequences in operational process (Jiang and Huo, 2008). To provide qualified products and required services, *quality management* has been widely applied to improve the service level (Tang, 2006). As well, CSCs employ advanced technical, expensive and sophisticated equipment to support the movement and production of a wide variety of chemicals. *The developing of information systems* can be harnessed to help members reduce the deficiencies associated with information sharing, such as *information sharing delay*, *information sharing inaccuracy* and *etc*. (Yu, Yan and Cheng, 2001).

In the operations, most chemical manufacturers implement a make-to-stock strategy to catch the huge demand and the reactions are always carried out in batch mode. These features compel the members to maintain a *higher inventory level* (Ryan and Silvanto, 2013). Inventory management is necessary to control the material flow through establishing collaboration to increase the communication. Meanwhile, containers are widely used to store raw materials, work-in-process (WIP), by-products and finished products during the operations. The characteristics of immiscibility and incompatibility of chemical substances determine that the containers cannot be mixed, therefore, *the lack of container management* is a distinct risk compared with other issues in the CSCs (Karimi, Sharafali and Mahalingam, 2005). However, very limited studies actually specify this risk issue in academic literature, as well as in practice. A coordinated approach is required to manage the inventory and improve the utilisation of containers through improving information visibility. In terms of financial aspects, the risks arise from the inherent money transactions and appear as poor returns on financial performance (Waters, 2011). As described in *Chapter* 2, many studies have been carried out to optimise the investment planning in the CSC. The provided investigations estimated the financial problems in the planning stage, but additional work is necessary to provide a comprehensive framework to assess and manage the financial risks in the operations.

4.3.3 Demand risks

Demand risks specify to the possibility of unexpected changes arising from market or downstream members (Samvedi, Jain and Chan, 2012). Based on the literature review, it is found that the attention given to demand risks is much more than other sources of risks. The components of demand risks contain demand invisibility, customer requirement changes, forecasting errors, products substitution, and competitive uncertainty. A schematic presentation of the demand risk sources discussed is presented in **Figure 4.5**.

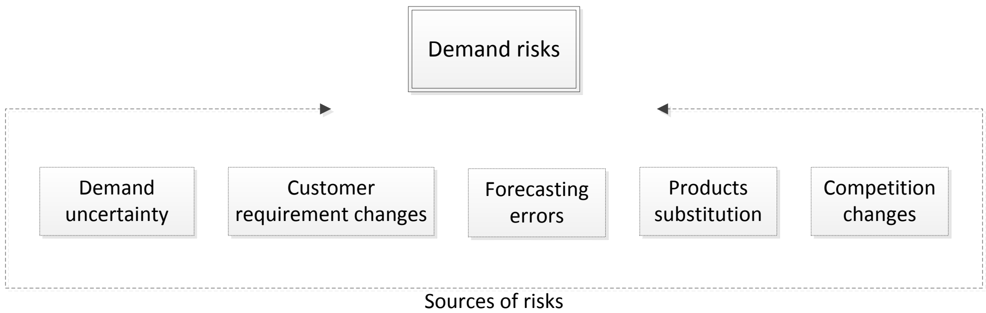


Figure 4.5. A schematic presentation of the demand risks discussed

Compared with the general products, which can be distinguished according to the certain set of attributes, the majority of chemical products are hardly identified by this method as the attribute can only be defined in a certain range rather than a specific value (Bartels, Augat and Budde, 2006). Meanwhile, the multiple recipes can be used to produce the required chemical products. The CSC should understand the availability of alternative options, so as to reap the benefits in terms of cost saving (Mele, 2011; Brown *et al*., 2014). The CSCs have the incentive of adjusting its raw materials and manufacturing process to make the advantage position through evaluating financial performance and social obligation (in environment protection aspect). It requires supply chain members to develop an understanding of the nature of *customers' tastes* and *chemical substitution policy* to ensure that the CSC outputs shift to expectation.

Moreover, the CSC members make the plan of purchasing, manufacturing and other operational activities based on the forecasting. Chaos in system due to the distorted information from the downstream increases the possibility of overreactions (Udenio, Fransoo and Peels, 2015). The *inaccurate forecasting* will result in the loss of market opportunities, as well as damage the competiveness of CSCs. Miller (1991) indicates that the *competitive risk* covers the uncertainties associated with competition between the existing products and services and potential entrants. Based on the report of CEFIC (2012b), there is more external competition as a result of rapid expansion of the CI in some developing countries. The traditional chemical producers in developed countries have to take alternative strategies and continue to cut their costs to remain competitive. Otherwise, the original market share will shrink sharply under the increasing competition.

4.3.4 Strategic risks

According to the definition described in *Chapter 2*, the strategic risks appear and reside in the strategy level. The academics and operators have devoted great effort to extend current knowledge in strategic risks analysis and management, especially in supply policy management, network design, and supply chain relationship management (Schmidt and Wilbert, 2000; Leppelt et al., 2013). Taking into consideration the distinct CSC features, the strategic risks are captured and represented as improper network design, lack of information sharing, lack of partner relationship management, improper selection of facilities location, and improper supply chain strategy selection. **Figure 4.6** presents a schematic presentation of the strategic risks discussed.

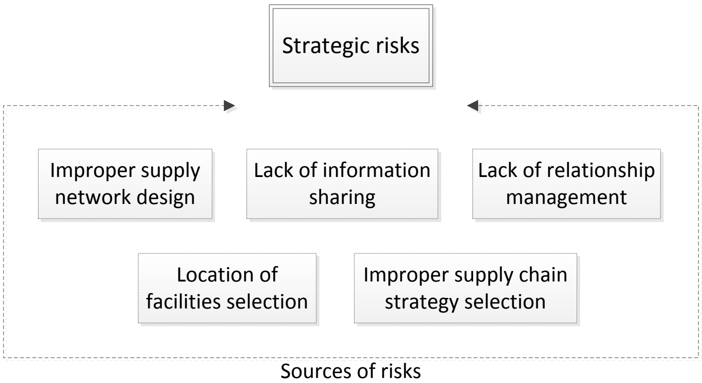


Figure 4.6. A schematic presentation of the strategic risks discussed

It is interesting to observe that all the listed strategic risk factors have been identified and analysed in the previous study (shown in *Section 2.4.1*), except for the risk of improper supply chain strategy selection. In the SCM discipline, a strategy is defined as a plan establishing upon the system and surrounding environments to manage the supply chain operations in high hierarchy (Manuj and Mentzer, 2008b). Different strategies are determined to achieve the objectives, but the adverse impacts of a specific strategy may bring new risks at the same time. For instance, there are three kinds of supply strategies widely used, which include single, dual/multiple sourcing, and outsourcing strategy (Tang and Musa, 2011). The single sourcing strategy is implemented to reduce the sourcing price based on the stable schedule. The advantage of single sourcing is price reduction, while the supply disruption risk will increase accordingly. In contrast, dual/multiple sourcing strategies refer to purchasing materials from more than one supplier. This kind of strategy brings competition among the suppliers, which results in technological development, quality benefit and cost saving, while it is usually difficult to reduce the cost (Yu, Zeng, and Zhao, 2009). Outsourcing is another strategy that the firm outsources its non-core business to some other professional companies to obtain competitive advantages (Kroes and Ghosh, 2010). Even though there are many benefits to be yielded, outsourcing may exacerbate vulnerabilities because the relative processes are difficult to be controlled and monitored and that may cause catastrophic fracture (Van Wyk and Baerwaldt, 2005). Therefore, the proper CSC strategy selection is a challenging topic in CSCRM, which should be addressed in further research.

4.3.5 Security risks

Security risks plague the supply chain managers, as well as bringing more worries to the public. The hazardous characteristics of chemical materials, complex interactions and globalisation increase the occurrence likelihood of security hazardous events and lead to more serious consequence in the CSCs. Combining the major risk perspectives of CSC with the identified hazards in the literature, the list of security risks is produced, which include information system security problems, infrastructure security problems, transportation security problems, labour strikes, criminal activities and terrorism. **Figure 4.7** shows a schematic presentation of the strategic risks.

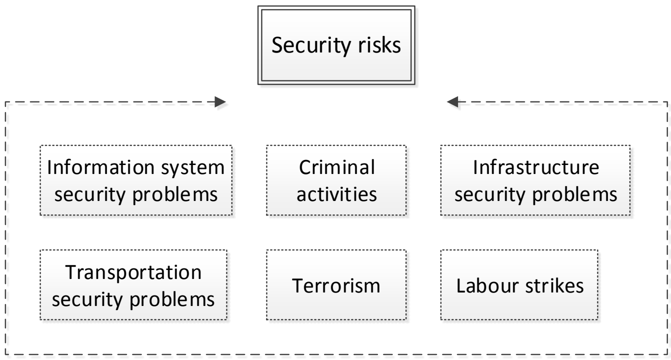


Figure 4.7. A schematic presentation of the security risks discussed

In the CSC, the operational flows could be interrupted by illegal activities, which are gaining more and more attention by the CSC. The security risks related to *information system security problems*, *criminal* and *terrorism* threaten the CSC operations and bring undesired consequence, especially in financial and reputation aspects (Manuj and Mentzer, 2008a; Adhitya and Srinivasan, 2010). Obviously, the consequences of such activities could be catastrophic, not only because of the hazardous characteristics of chemical substances, but also the vulnerability of the world CSC. The majority of fossil fuels are sourced from dangerous areas of the world where they can be easily attacked, therefore, the *infrastructure security* and *transportation security* problems are the major risks for CSCs, which should be given much more attention (Ehlen *et al*., 2014). Additionally, *labour issues* are of high concern to the CSC. Rao and Goldsby (2009) suggested providing a comfortable working atmosphere for employees and, in turn, improving low productivity and reducing the probability of labour strikes.

4.3.6 Macroeconomic risks

It is described that "the stability of the macroeconomic environment is important for business and, therefore, is important for the overall competitiveness of a country" (World Economic Forum, 2014). The source of macroeconomic risks is a broad term referring to economic fluctuations in the economic activity and price changes (Oxelheim and Wihlborg, 1987; Rao and Goldsby, 2009). Apart from the addressed hazardous events in the literature, the captured macroeconomic risks contain economic fluctuation, financial crisis, price fluctuation, inflation, and exchange rate arbitrages, shown in **Figure 4.8**.

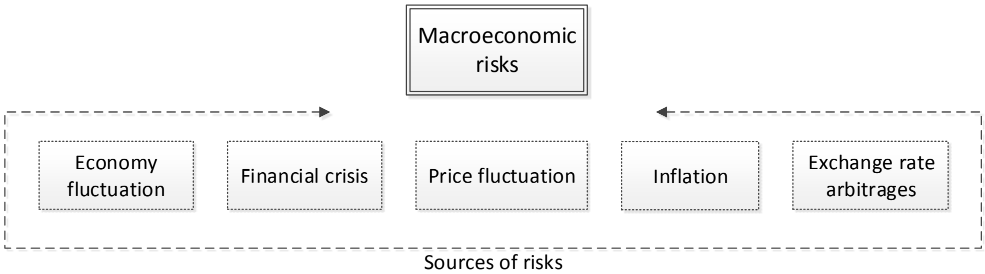


Figure 4.8. A schematic presentation of the macroeconomic risks discussed

In the CSCs, the macroeconomic risks show distinct characteristics, but few studies actually deal with them in a developed SCRM framework. Basically, the market economic environment is characterised by a high degree of fluctuations and uncertainties. The chemical products are sensitive to the material and operating cost, so that the *economic changes* will trigger the variation of system preformation (Adhitya, Srinivasan and Karimi, 2009). Meanwhile, the *inflation of goods* and *financial crisis* will lead to movement of chemical price, which brings uncertainties to the market (Rao and Goldsby, 2009). The CSCs have to adjust their networks to the global market, so as to exploit benefits in terms of *exchange rate arbitrage*, *optimal interest rates* and *low raw material or labour price* (Gurnani and Tang, 1999).

4.3.7 Political risks

Due to the globalisation, huge volumes of chemicals are purchased and shipped from unstable regions of the world. It leads to the CSCs experience a higher probability of political risks (Shubik, 1983).

The academics and practitioners are increasing concerned about the risks of government instability, revolution, war and government attitude, shown in **Figure 4.9**.

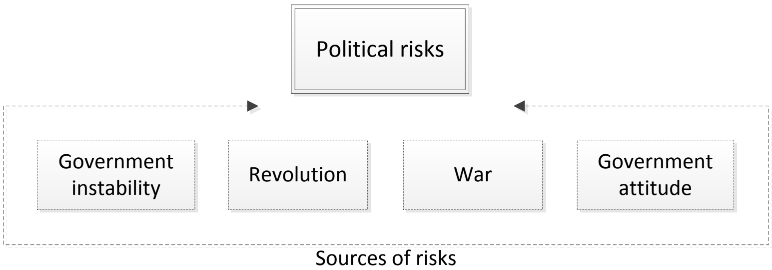


Figure 4.9. A schematic presentation of the political risks discussed

The wars in Afghanistan (2001), Iraq (2003) and *political instability* in Libya from 2011 disrupt the CSC operations and cause the feedstock prices to soar. The CSCs have to suffer the higher sourcing costs and operating costs in response to the threats (Robb and Bailey, 2003). After 2012, the on-going Syrian Civil War not only affects the local CSCs, but also brings a series of chain reactions to the world economy. The governments and chemical companies deliver interesting insights into the investigation of the connection between political problems and supply chain management research.

In other aspects, *the government attitudes* can influence local firms and determine their trading partners in some cases. Thus, the government has the ability to hold one of the particular chemical materials as hostage that brings price fluctuation in world market. For instance, the Arab OPEC members decided to no longer sell oil to some countries that supported Egypt in 1973, which caused the oil crisis (Miller, 1993). The CSC managers are recognising the importance of evaluating political risks in respective regions to reduce the risks and make beneficial decisions.

4.3.8 Natural environment risks

In order to provide a detailed partition, the scope of general environment risks addressed in the literature review is narrowed down to be defined as the natural phenomena that could impair CSC operations in the affected region, which include natural disaster, infectious disease and weather risk

(Cruz and Krausmann, 2013). A schematic presentation of the various natural environment risks discussed is shown in **Figure 4.10**.

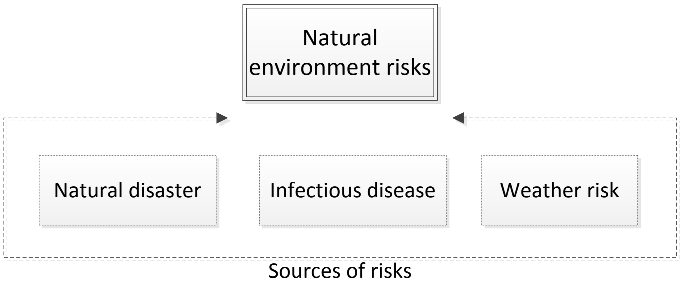


Figure 4.10. A schematic presentation of the nature environment risks discussed

In recent years, the United Nations reports that the earth is becoming more active and that frequent natural disasters, such as bad weather, climate changes, and earthquake, happened in various parts of the world (Bahinipati and Patnaik, 2015). Also, the infectious diseases seriously affect CSC operations and cause tremendous loss. According to the World Health Organization (WHO) report, an outbreak of severe acute respiratory syndrome in Southern China has caused 775 deaths between November 2002 and July 2003 and spread to 37 countries within weeks (Wong *et al*., 2003). The lack of labour and government travel ban in the affected area resulted in 75% of the plants shutdown, which had serious economic losses to the CSCs. Increasingly, CSCs are aware of the importance of preparing for and responding to the natural environment risks. The risk relief procedure and emergency responding plan is developed to deal with the undesired effects in the supply chain level (Zsidsin *et al.*, 2004)

4.3.9 Policy risks

Policy risks arise from the changes of legislation, regulations, and policies, such as new policy being introduced, quota restrictions and sanctions. Schildhouse (2006) indicates that it is significant to fully understand policy risks and all the available policy materials before getting down to business. In the CSCs, the most of attention on policy risk is given to the hazardous chemicals substitution, while there is very little literature addressing the problems in the requirement of environmental protection.

In this study, the sources of policy risks are described as changes in legislation/regulation/policy, the requirement of environmental protection and stakeholder/social attitudes, shown in **Figure 4.11**.

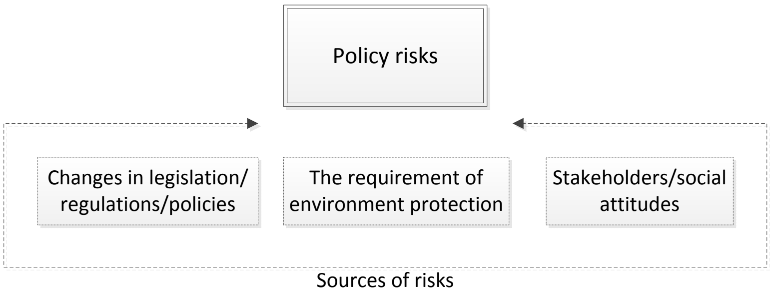


Figure 4.11. A schematic presentation of the policy risks discussed

Hazardous characteristics of chemical substances pose significant challenges to CSC operations as well as to the surrounding environment, which potentially threaten ecological balance and endanger human health (Papageorgiou, 2009). Government and authorities play an important role in CSCRM, not only by preparing legislation but also by sending to industry informal regulatory guidance and recommendations (Scruggs *et al.*, 2014). However, the changes in policy could affect the business community and bring challenges to CSC operations. For instance, CO_2 emission is of such concern to government that CSCs are forced to reduce the carbon intensity. Under this circumstance, the CSC transportation cost per tonne-km increases (CEFIC, 2012b).

Meanwhile, the stakeholder/social attitudes play a significant role in execution and implementation of that policy, which reflect how difficult the government policy is to implement. Recently, CSC participants have been aware of the significant liability risks, which associate with harmful effects of production and consumption of chemicals. CSC members seek to substitute the hazardous manufacturing materials and pollution intensive production process to achieve environmentally friendly. Therefore, stakeholder and social attitudes should be considered from the industrial perspective when conducting CSCRM. It should make great efforts to reduce risk and improve service level through a coordinated approach to making the environment diverse, sustainable and economical.

4.4 HAZARD IDENTIFICATION DATA ANALYSIS AND TAXONOMIC DIAGRAM VALIDATION

The visibility of the risks is one of the most challenging points in CSCRM, it is therefore essential to comprehensively identify and validate hazards existing in the CSC. The study started with identifying the hazards that have been addressed in the relevant literatures (shown in *Chapter 2*), and then extended to the general supply chain risks. A decomposition method was applied to classify unstructured hazards into different risk domains. The questionnaire was built to explore the appropriateness of the developed risk taxonomic diagram in order to ensure the comprehensiveness of identified hazards and the feasibility of the proposed risk classification method.

The participants were selected based on their experience to the research topic using the university membership directories on SCM in Liverpool John Moores University, the University of Liverpool and Wuhan University of Technology in China. As well, more than 100 recognised CSCM companies in China were contacted to establish willingness to participate. The sample is a proportion of the population. To generalise the findings, the sample size calculations should fit in with statistical measures (McColl et al., 2001). In total, 118 questionnaires were sent out to collect the data from risk experts and analysts in May 2014 and 47 replies were received in three months. There were 29 valid questionnaires and 18 invalid ones, as the respondents did not reply or did not answer all the questions in the questionnaire, therefore the valid return rate was 24.58%.

Then, a validity test was conducted to test whether the study measures the required items and whether the study receives the reliable responses (Davis, 2000). The reliability of the obtained results was examined through employing Cronbach's alpha method, based on the functions shown below (Sijtsma, 2009; Cohen and Swerdlik, 2010):

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum_{i=1}^{K} \sigma_{Y_i}^2}{\sigma_X^2}\right) \qquad \text{Eq. 4.1}$$

$$\alpha_{standardised} = \frac{K\bar{\gamma}}{(1+(K-1)\bar{\gamma})} \qquad \text{Eq. 4.2}$$

where K is defined as the number of the questions in the investigation, X is the number of total sample, σ_X^2 is the variance of the total sample, Y_i indicates the question i, $\sigma_{Y_i}^2$ is the variance of the current question, and *i* is the question number. The Cronbach's Alpha is obtained in Eq. 4.1. In order to inspect extracted Cronbach's Alpha, Eq. 4.2 is provided to examine Cronbach's Alpha Based on Standardised Items, where K is defined as the number of the questions in the survey and $\bar{\gamma}$ indicates the mean of the non-redundant correlation coefficients.

In this study, a total of 55 questions were tested. The Cronbach's alpha of the whole survey is 0.893 and Cronbach's Alpha Based on Standardised Items is 0.889. In principle, the collected data is reliable when it is over 0.8, the result is acceptable when it is between 0.7 and 0.8, and the internal consistency is poor if the obtained answer is less than 0.7 (Cohen and Swerdlik, 2010). Therefore, the proposed survey achieves a high level of reliability. The Cronbach's Alpha of the reliability test is illustrated in **Table 4.3.**

Table 4.3. The reliability test for the questionnaire survey

	Cronbach's Alpha	Cronbach's Alpha Based on Standardised Items	Number of questions
Whole survey	0.871	0.869	221

Furthermore, decision makers and operators investigated the importance of the identified hazards to the CSCs, so as to suggest the concerned hazardous events. **Table 4.4** illustrates the mean, the standard deviation (S.D.) and the ranking of the importance of the identified hazards based on the results from expert judgements.

Table 4.4. Results of the importance of hazards to the CSC operations

Identified Hazards		**How important is this hazard to CSC operations?**		
		Mean	**S.D.**	**Rank**
Supply risks	Supply market uncertainty	4.85	0.76	8
	High sourcing cost	3.38	2.44	38
	Supply activities disruptions	6.12	0.66	1
	Low supplier reliability	4.50	1.00	17

	Low supplier flexibility	2.11	1.67	53
	Complexity of material types	2.31	2.11	52
	Unavailability of materials	2.35	1.44	51
	Low material quality	2.55	0.78	47
	Lack of supply process monitoring	4.01	1.11	20
Operational risks	Hazardous nature of materials	4.69	1.33	12
	Breakdown in core operations	6.01	0.69	2
	Improper operational procedure selection	5.77	1.56	4
	Inadequate process capacity	4.69	2.19	12
	High level of process variation	3.11	2.11	42
	Complexity of product types	2.72	1.20	45
	Lack of/inappropriate inventory management	4.56	1.00	14
	Lack of/inappropriate container management	4.99	1.45	7
	Problem of product quality	3.57	0.05	31
	Lack of qualified staffs	3.89	0.88	25
	Technology innovation	2.11	1.33	53
	Information sharing delay	4.71	1.20	11
	Information sharing inaccuracy	3.96	1.56	24
	Financial problems	3.24	1.41	39
Demand risks	Demand invisibility	5.89	0.33	3
	Customer requirement changes	3.58	0.88	30
	Forecasting errors	5.22	1.20	5
	Product substitution	3.61	1.45	30
	Competition changes	3.87	1.67	27
Strategic risks	Improper supply chain network design	3.99	1.78	22
	Lack of information sharing	3.45	1.33	36
	Lack of partner relationship management	4.52	0.88	15
	Improper selection of facilities location	3.47	1.20	35
	Improper supply chain strategy selection	4.75	0.82	10
Security risks	Information system security problems	3.18	2.19	41
	Infrastructure security problems	3.98	1.33	23
	Transportation security problems	4.12	1.05	18
	Labour strikes	3.22	1.56	40
	Criminal acts	3.54	1.41	34
	Terrorism	3.56	0.88	32
Macroeconomic risks	Economy fluctuation	3.56	1.45	32
	Financial crisis	2.98	2.11	44
	Price fluctuation	4.01	1.00	20
	Inflation	2.51	1.67	49
	Exchange rate arbitrages	3.06	1.41	43
Political risks	Government instability	2.57	1.41	46
	Revolution	2.36	1.56	50
	War	3.79	1.05	27
	Government attitude	2.54	1.41	48
Natural environment	Natural environment disaster	4.78	0.76	9
	Infectious disease	4.52	1.20	15

risks	Weather risk	5.10	0.77	6
Policy risks	Changes in legislation/ regulations/ policies	4.03	0.71	19
	The requirement of environment protection	3.42	1.41	37
	Stakeholders'/society's attitudes	3.65	1.45	28

*S.D. = Standard Deviation

The results show that the classified nine risk categories have close levels of overall importance (Average of supply risks: 3.61; Average of operational risks: 4.14; Average of demand risks: 4.43; Average of strategic risks: 4.04; Average of security risks: 3.60; Average of macroeconomic risks: 3.22; Average of political risks: 2.82; Average of natural environment risks: 4.80; Average of policy risks: 3.70). The importance of each hazard is ranked to suggest the significant influential factors to CSC. According to the analysis, supply activities disruptions, breakdown in core operations, and demand uncertainty are of high concern to the participants, which could be frequently experienced in the CSC operations. S.D. represents the amount of variation or dispersion of an obtained set of data. In the survey, the obtained S.D. is between 0.70 and 2.44. A high standard deviation indicates the experts regard the value of measurement factor to spreading out over a wider range of values, while a low standard deviation suggests the participants share similar sentiments.

After analysing the importance of each identified hazards in the previous questionnaire survey, the priority of the identified hazards is obtained over the population of respondents that illustrates the concerned hazardous events according to their overall importance. Based on the survey results, the top 10 risks are supply activities disruptions, breakdown in core operations, demand invisibility, improper operational procedure selection, forecasting errors, weather risk, lack of/inappropriate container management, supply market uncertainty, natural environment disaster, improper supply chain strategy selection. The highly ranked CSC risks are regarded as the risks with serious risk effects from industrial perspectives, which are required to be given much more attention in the operations. As well, a CSC risk database can be developed with respect to the outcomes of risk ranking to support the further CSCRM research. It provides a foundation for applying various risk management methods to assess and mitigate risks and to improve both safety and reliability of the CSC systems. To graphically illustrate the ranked CSC risks, a typological model was developed through the preceding discussion of risk factors in the CSCs and integrating summarised questionnaire results. The identified CSC hazards are ranked in each categorisation and outlined in a hierarchical structure, shown in **Fig 4.12**.

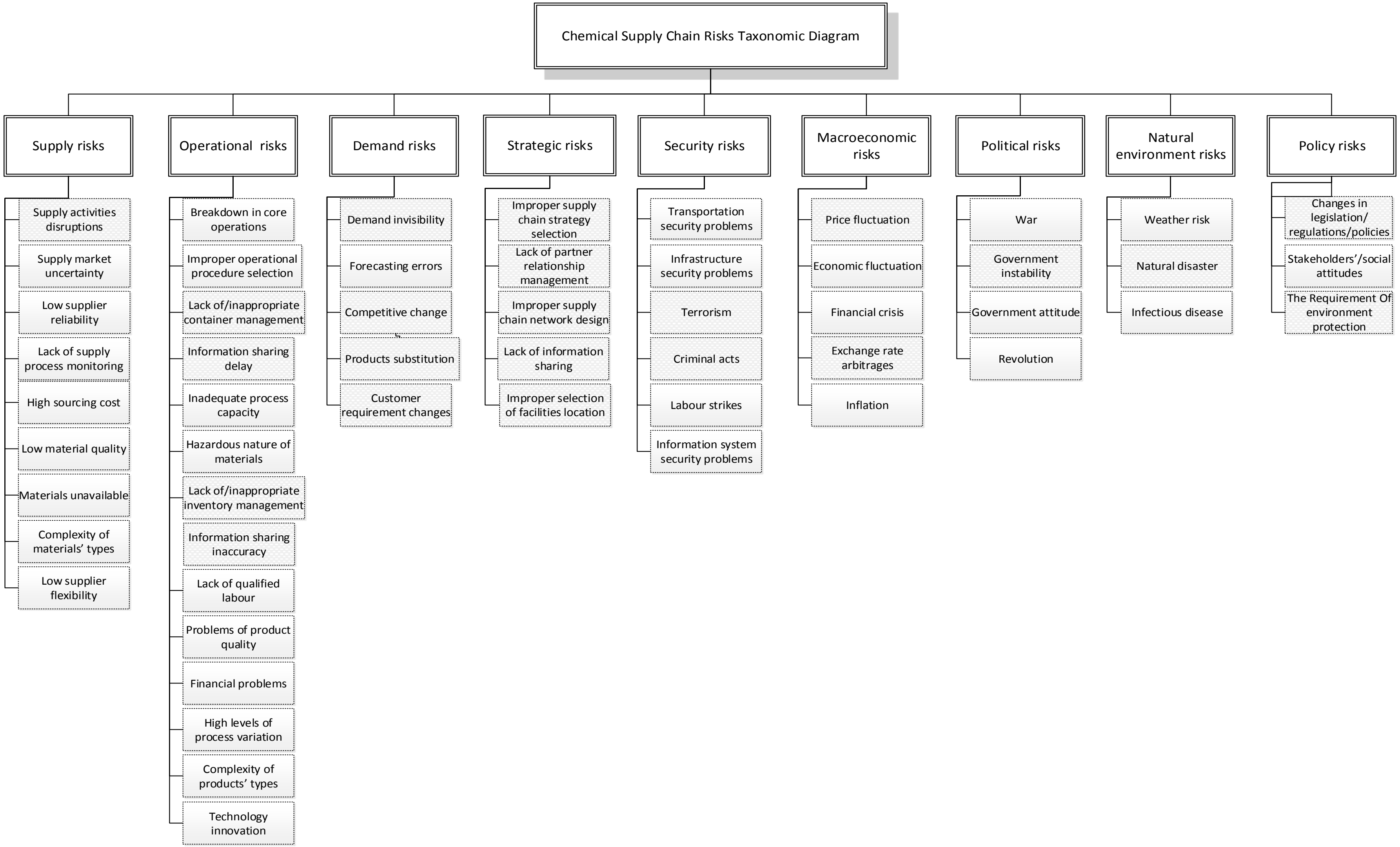


Figure 4.12. A taxonomic diagram for CSC risks

4.5 CONCLUSION

It is widely recognised that hazard identification is a vital phase for conducting an effective CSCRM. The literature review serves as a base and guide to strengthen the knowledge base in hazard identification. The CSC risks addressed in the previous research and the general supply chain risks frame were integrated to develop a structured risks taxonomic diagram. In the developed diagram, the unstructured hazards were decomposed into different risk categorisations: supply, operational, demand, security, political, policy, macroeconomic and natural environment aspects. Furthermore, the questionnaire survey was carried out to make the inference about the attitudes and opinions from experts following a rigorous approach. The importance of the identified hazards to the CSC system was addressed, which provided a portfolio of risks and suggested the concerned hazardous events from industrial perspectives. In further research, the captured risks can be assessed through applying different risk analysis methods, so as to find out the risks that should be reduced.

CHAPTER 5 CONCEPTUAL MODELLING OF CHEMICAL SUPPLY CHAIN RISKS USING SYSTEM DYNAMICS APPROACH

Summary

This chapter discusses the development of a conceptual CSC model and its associated risks following a SD approach. In theory, the SD modelling process can be achieved by a description of several separate conceptual sub-models that contain the major interdependencies and feedback mechanisms in the system. The integration of developed models can be applied to analyse the changes of system behaviours arising from the disturbances in different scenarios, so as to investigate the various risk effects in different risk scenarios. A validation is carried out to test and verify the correspondence of the model structure and the robustness of the model's behaviours that establishes sufficient confidence in the developed model.

5.1 PROBLEM DEFINITION

In CSCRM, it is challenging to provide a novel risk analysis method employing both qualitative and quantitative data/information to manage changeable CSC risks taking into consideration the complex interactions between the hazardous events and their associated changes of system behaviour. In order to facilitate this problem, a SD modelling approach is implemented to address the time risk effects that bring about the variation in the system behaviours. The system thinking is adapted that considers the CSC as a system made up of interacting parts, rather than investigating the risk as an isolated event. Following the rigorous approaches described in *Chapter 3*, the first step is problem definition. The purpose of the modelling research is identified and the system boundaries are specified, so that the researchers can turn to planning and developing a problem solution. In particular, it provides the questions of what are the major concerns in modelling activities and which parameters or variables would contribute to those concerns (Sterman, 2000). According to the guideline suggested by Sterman (2000), a formal structure of problem definition in the SD method has been suggested to facilitate the problem definition in SD model developing, which consists of 1) Define purpose of system, 2)

Determine system boundaries, 3) List of variables. The section will follow this formal structure to specify the problem that should be defined in the research.

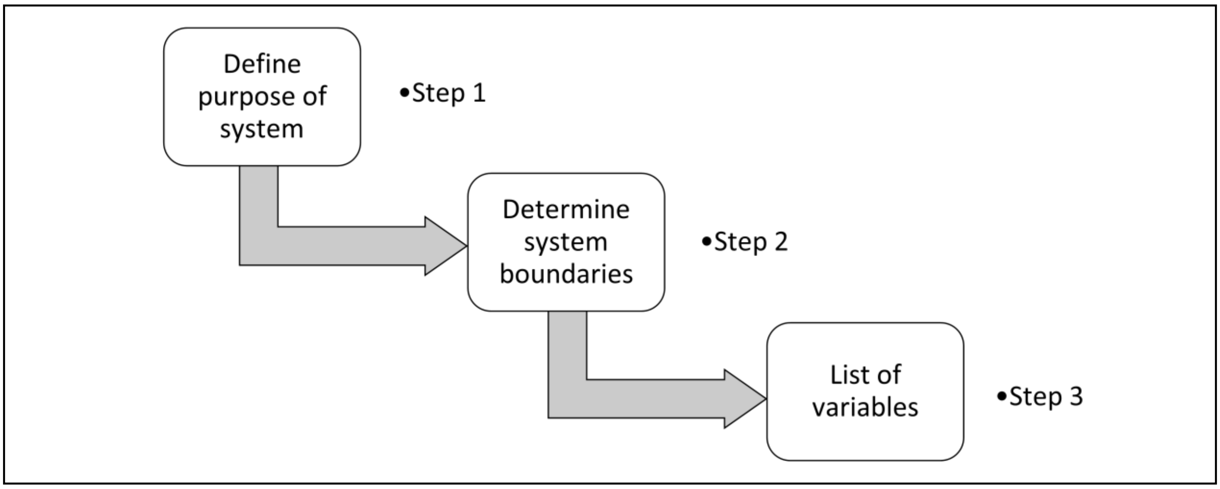


Figure 5.1. Research approach for the problem definition

In the problem definition stage, it starts with purpose identification and system boundary classification (Mashayekhi and Ghili, 2012). The aim of CSC risk modelling is to understand the structural causes that trigger the changes of system performance arising from risks. The SD modelling seeks to provide a novel risk management method that is capable of exploring a wider variety of hazardous events in the CSCs, and which accounts for the causal relationships and feedback effects existing in CSC operations. Therefore, it accommodates the need to describe the connections between hazardous events and their associated changes of system behaviours. In the proposed study, two sub-systems are considered in the system boundaries, which are CSC system and hazardous event system, respectively. The CSC system comprises all the entities participating in a production chain in which raw materials are converted into final chemical products, and then delivered to customers. As described in previous research (shown in **Figure 3.8)**, a CSC is made up of the central company, which is always the manufacturer, and its linked upstream suppliers and downstream customers. The structure resembles tree branches, which integrate suppliers, manufacturers, distributors, retailers and customers in one system. In another aspect, it is significant to investigate the risk itself. As described in Section 3.5, a risk can be analysed in three dimensions, which are *LO*, *CS* and *CP*. According to these defined scope, the variables contained in the system are specified that include risk, product/inventory, information, financial, human resources, and physical assets (Narasimhan and Talluri, 2009). From the perspective of the SD methodology, a list of basic variables is identified to help to clarify CSCRM issues, shown in **Table 5.1**.

Table 5.1. The list of major variables related to CSC risk modelling

Risk	Product/inventory	Information
• Occurrence likelihood (LO) • Consequence severity (CS) • Consequence probability (CP)	• On order product • Product inventory on-hand • Work in progress (WIP) • Backlogged orders • On order raw material • Availability of raw material • Safety stock • Customer order	• Lead time • Recovery time • Transparency of information • Time for information sharing
Financial	**Human resources**	**Physical assets**
• Price • Cost	• Number of workers • Productivity	• Amount of equipment • Equipment capacity • Public infrastructure

5.2 CAUSAL LOOP DIAGRAM DEVELOPMENT

Due to the potential for disruptions in the CSC, any or all of the materials, information and monetary flows can be affected by the occurrence of a hazardous event, so that there is a discrepancy between the actual operations and the planning. The analysis of CSC risk modelling that falls into the category mainly is carried out for the purpose of improving the understanding of dynamic system behaviours caused by risks through theory building. The conceptual causal-loop diagrams are created to formalise logical interactions within the CSC and to represent the risk evolution mechanism in previous research within the system boundaries (Lertpattarapong, 2002). In the research, the CSC risk model is expressed in two separate models: the CSC sub-model and hazard event sub-model.

5.2.1 Chemical supply chain sub-model

In the CSC, the sourcing, conversion, logistics, storage and other activities generate required outputs to fulfil the downstream demand within the CSC network. To develop the SD-based CSC model, it is essential to identify the significant activities and formalise their associated cause and effect relationships in the system boundary. Adapted from the representative functions, the collection of separate models is developed to represent the CSC operations, which include the sourcing and forecasting sub-model, manufacturing sub-model, warehousing sub-model, and transportation sub-model. Through properly connecting the developed sub-models, the whole picture of causal relations in the CSC system is obtained, which is capable of presenting the CSC operations.

5.2.1.1 Source and forecast function sub-model

In the global market, tremendous volumes of chemical substances have been purchased around the world. The sourcing process involves the movement of materials associated with inbound supply activity that delivers the materials to meet the downstream requirements. In practice, the customer demand is usually uncertain and difficult to be accurately forecasted. The CSCs have to develop an understanding of the nature of customer requirements, so as to minimise the gap in actual demand and the planning (Barlas and Gunduz, 2011).The traditional CI has reached maturity in the1990s, so that the development of the traditional CSCs can be predicted to some extent (Bartels, Augat, and Budde, 2006). In contrast, there is usually very little historical data for speciality supply chains that in turn makes the job of demand forecasting difficult. Therefore, CSCs use both historical data and current downstream order as input data to forecast next term customer demand. An important observation in demand forecasting error represents the oscillation in the material flow that challenges the sourcing activities in the network, as well as in the CSCs (Udenio, Fransoo and Peels, 2015). To make the efficient plan of operational activities on systems' thinking, it requires identifying the causal relationships among the demand forecasting process. **Figure 5.2** presents a conceptual causal loop diagram of demand forecasting process, which is established upon the implemented forecasting method.

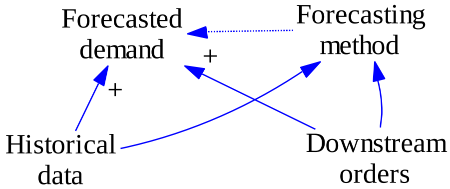


Figure 5.2. Causal loop diagram of demand forecasting

The dash line describes that the implemented forecasting method could determine the accuracy of the demand forecasting result, which is based upon the historical value or current downstream order. Meanwhile, the changes for the causative and effective variables share the same tendency under all circumstances that the increase of historical value or current downstream order will lead to a higher forecasted demand.

Based on the forecasted demand and designed strategies, the raw materials are sourced from suppliers to provide required materials or services to the CSCs. Furthermore, the qualified suppliers are selected to ensure the efficiency and effectiveness of CSC operations. The preference for supplier selection is established upon the long-term relationship, short-term performance, as well as the other criteria, such as reliability, cost, and reputation (Akkermans, 2001; Sarkar and Mohapatra, 2006). Accordingly, a causal loop diagram is developed to illustrate the supplier selecting mechanism, shown in **Figure 5.3**.

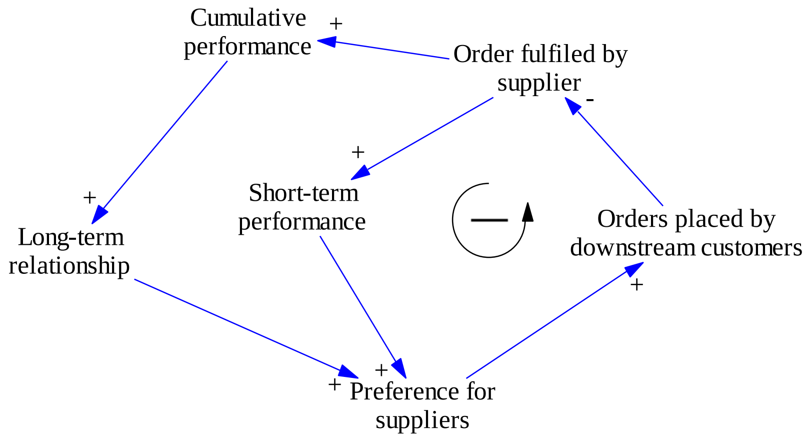


Figure 5.3. Causal loop diagram of supplier selection

As shown in the figure, two distinct loops can be observed to represent the cause and effect relationships between the criteria and preference for suppliers. By multiplying the individual effect of each relationship, the polarity of the loop is addressed. In the developed diagram, the number of negative relationships in the loops is odd, therefore the changes of loops move toward a stable situation. It appears to reinforce the effect between the supplier performance and preference for supplier selection, and the increase of short-term performance and long-term relationship will contribute to the effected variable - "*Preference for suppliers*". Under this circumstance, the downstream customers are more likely to place more orders to the suppliers with better performance. However, the increase of orders placed puts pressure for the supplier to maintain the pace, which leads to the decrease of the short-term performance.

5.2.1.2 Manufacture function sub-model

In the CSC, the complexity and vulnerability are frequently experienced in the manufacturing process where the chemical products are formulated though blending, reaction and other activities with different recipes. Restrictions, such as the amount of reaction materials, reaction time, and sequence of material adding can be observed which are intended to ensure the safety of production activities. Growing interest in SCM has highlighted the necessity of developing a modelling framework that can be used to address this kind of complexity and uncertainty from the industrial perspective (Özbayrak, Papadopoulou and Akgun, 2007). Based on applied strategies, the manufacturing process is carried out in line with the schedule or the orders from downstream customers. Basically, the raw material inventory, labour productivity and equipment capacity determine the volume of chemical substance can be produced by the system (Georgiadis, 2013). **Figure 5.4** describes the formalised interactions between the various components that determine the production capability.

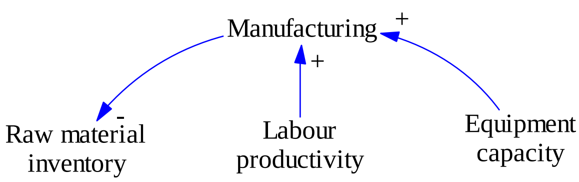


Figure 5.4. Cause and effect relationships of production capability

In the developed conceptual model, the manufacturing capacity depends on the combination of the capacity of the available equipment and the size of the labour force to handle the equipment within the system. Specifically, equipment capacity is determined by the capacity of reactors and other instruments, which is difficult to be changed in a short period of time, while the size of the labour force can be controlled and managed by operators (Lertpattarapong, 2002). From industrial perspectives, lack of qualified labour or employing ineligible labours brings risks to the transportation operations, which are of high concern to academics and participants. It is interesting to observe that a number of models are established to allocate the manufacturing capacity taking into consideration the causal relations and feedback effects between mentioned factors (Coyle, 2001; Cagliano, De Marco and Rafele, 2010; Weiler *et al*., 2011). The positive relationships indicate the improvement of equipment capacity and labour productivity could bring the simultaneous increase in manufacturing capacity. Meanwhile, the availability of raw materials is another critical element in the manufacturing system. The semi-continuous and continuous modes are frequently applied in production, so that the lack of raw materials could significantly delay the manufacturing operations and cause serious consequences. There is a negative effect between the raw material inventories and the ability to start the manufacturing process. To address the complex interactions in the manufacturing system, the causal loop diagram of the manufacturing sub-system is provided in **Figure 5.5**.

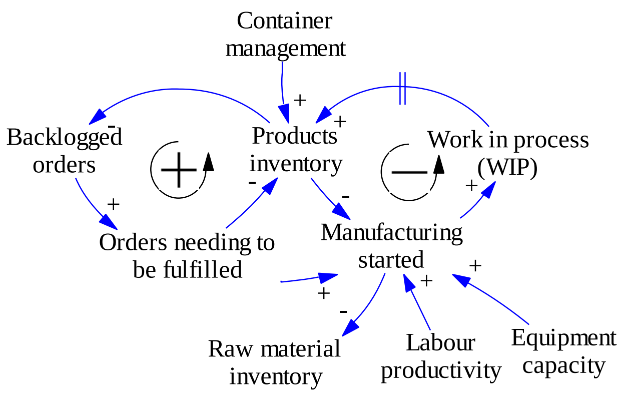


Figure 5.5. Causal loop diagram of manufacturing sub-system

5.2.1.3 Warehouse function sub-model

Even though a basic distinction can be found among supply, trans-shipping and distribution warehouses, the major function appears the same, that the warehouse is a hub in the CSC network where goods are temporarily stored or rerouted to a different channel in the network. In the CSC, the immiscible and incompatible characteristics determine that the chemical substances have to be stored in the specific containers or tanks based on their identities (Pasman and Rogers, 2012). Basically, the increase of containers/tanks could offer extra warehouse capacity to some extent. Incorporating the containers/tanks issue, the warehouse's endogenous operation is explained in **Figure 5.6**. The operations performed within manufacturing and handling is the functions of plenty of key variables, which often seem to have strong causal relations. The arrows are used to represent the directions and tendencies of relationships. In particular, the arrow with the symbol "||" not only describes the original and affected variables, but also indicates there is a time lag between the interactive variables. The delay between products in the early stage of manufacture and finished goods received can be observed in the developed diagram. Furthermore, it is observed that there are two distinct loops, one controlling products inventory and the other controlling manufacturing activities. In the inventory loop, an increase in customer service could lead to higher inventory levels and lowering the inventory levels could consequently cause the reduction of order fulfilment ability due to the generation of backlogged orders (Özbayrak, Papadopoulou and Akgun, 2007). Hence, there is a negative effect between the products inventory and the backlogged orders in the system. Any actions that attempt to reduce backlogged orders could cause an increase in the products inventory, while the changes in the products inventory could affect the ability of order fulfilment. Along the material flow, the containers or tanks are set up within each operation unit to store the non-discrete raw materials, work-in-progress (WIP), by-products and finished products based on their identities. Container management should be conducted to improve the utilisation and efficiency of the containers in the manufacturing process, as well as in the whole CSC system.

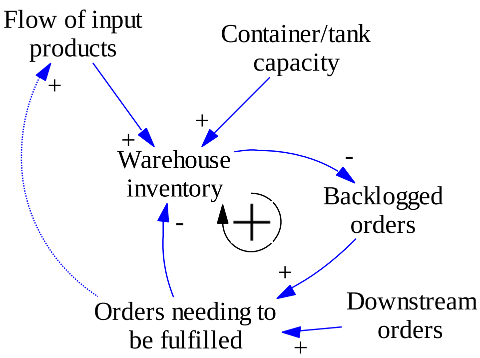


Figure 5.6. Causal loop diagram of a warehouse and container sub-system

The developed system as a whole is unstable in that it is dominated by a positive feedback loop (two of negative relationships contained). Any actions that attempt to improve the order fulfilment rate could lead to the oscillation of the system. To be specific, the flow of input products leads to the warehouse inventory increase, while the increase of inventory has a negative effect on the generation of backlogged orders. The combination of downstream orders and backlogs is the orders needing to be fulfilled in the next simulation step. The containers are used to store chemical substances in the warehouse, therefore, it is necessary to address the interaction between the container system and warehouse capacity. Generally, the increase of the containers' capacity brings a positive effect to the warehouse inventory, so that the changes of both sides towards the same direction.

5.2.1.4 Transport function sub-model

CSCs require highly coordinated material, information and finance flows with the conveyance of hazardous substances between its members (Reiskin, White and Johnson, 1999). In order to support the movement of variety of materials, multiple transportation modes are employed and highly technical, expensive and sophisticated transportation equipment is used during the transportation. Hence, it is significant to observer the cause and effect relationships among the materials inventory, of transportation capacity and transportation time. **Figure 5.7** incorporates transportation time as a variable to address the causal relations within the material movement.

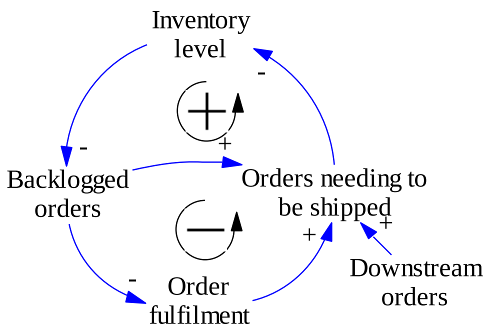


Figure 5.7. Causal loop diagram of transportation inventory

It is worth observing that two distinct loops can be found in the diagram. The large loop describes the relationship between inventory level and order fulfilment, which contains the variable of "I*nventory level*", "*Backlogged orders*", "*Order fulfilment*", and "*Orders needing to be shipped*". The developed system is stable that it is dominated by a negative loop (three of negative relationships contained). Any actions that attempt to change the elements result in the self-correcting of the system. Transporter inventory level is influenced by the calculation of the inflow of products from suppliers and shipped products to customers within a given period of time. Backlogged orders will happen if the outflow of shipped orders fails to keep pace with customer demand. In the next delivery, the backlogs should be first fulfilled, therefore, the negative effect is observed that the increase of backlogged orders will reduce the order fulfilment rate. In contrast, the other logic feedback loop is positive that there is self-reinforcing effect existing. The increase of "*Orders needing to be shipped*" will cause the amplification of the "*Backlogged orders*".

Pet-Armacost *et al.* (1999) indicate that the transportation decisions could directly affect a transportation system's capability. The capacity of a transportation system is established upon the evaluation of infrastructure capacity and transporter capacity according to the choices of transport features, such as mode of transport, type of container and route of transport (Chen and Kasikitwiwat, 2011). Infrastructure capacity is determined by the selected route, which cannot be changed by a transporter (Chen *et al.*, 2002). In contrast, the capacity of a transporter could be controlled and managed by the transporter itself. Equipment capacity is determined by the capacity of instruments and a specified number of operators are required to handle the transportation equipment. Transporter capacity depends on the capacity of the available equipment and the size of the labour force within the system. The factors that affect transportation capacity are graphically described in a causal loop diagram, shown in **Figure 5.8**.

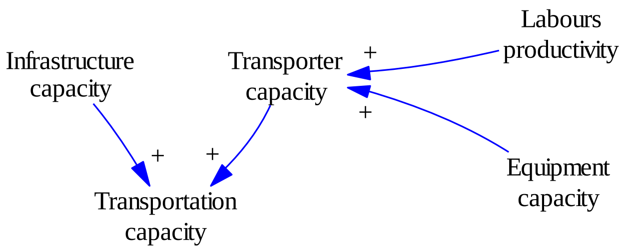


Figure 5.8. Causal loop diagram of transportation capacity

Transportation time is one of the key indicators in transportation activities. In transportation science, Bureau of Public Road (USA) indicates that transportation time can be calculated by:

$$T = T_0\left[1 + \alpha(\frac{V}{C})^{\beta}\right] \quad \text{Eq. 5.1}$$

where T_0 represents the transportation time when there is zero traffic flow on the transportation channel, C is set as the capacity of the transportation channel, V is the current volume of the products being transported, and α and β are two variable parameters (Schreckenberg *et al.*, 2005).

To address the dynamic transportation time, **Figure 5.9** describes the interaction between the suggested factors based on the mathematical equation. The more transportation channel capacity leads to the shorter transportation time, while the increase of transported products on the road means that it requires longer transportation time.

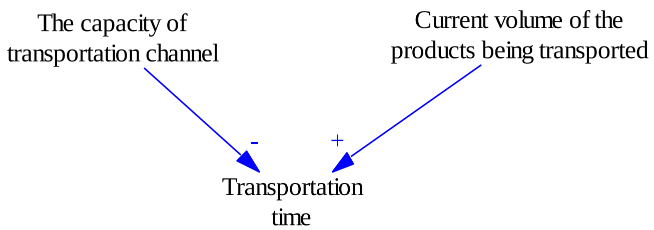


Figure 5.9. Causal loop diagram of transportation time

5.2.2 Risk sub-model

The developed CSC system could be affected by hazardous events and bring unexpected consequences during its operations.

Indeed, there is a substantial amount of effort that has been devoted to presenting the level of the possible risks. Mokhtari *et al*. (2011), Vilko and Hallikas (2012), and Heckmann, Comes and Nickel (2015) suggested that a risk could be analysed in two attributes: *Occurrence likelihood (LO)* and *Consequence severity (CS)*. Meantime, Ren *et al*. (2009), and Kumar, Himes and Kritzer (2014) argued that *Consequence probability (CP)* should be considered, which indicates the probability of suffering the given magnitude of the consequence, when the accident happens.

In this research, the CSC hazardous events are described by the combination of *LO*, *CS* and *CP*. *LO* estimates whether a CSC risk will materialise. *LO* refers to the probability that an accident event occurs by causing an undesired effect, *CS* indicates the magnitude of the possible consequence in terms of the negative aspects, and *CP* shows the probability of suffering the given magnitude of the consequence, when the accident happens. When a hazardous event occurs, the negative effects with a given degree of probability are represented by *CS* and *CP* to describe the experienced consequence. The set of corresponding data of each hazardous event is collected from risk experts and inserted into the developed SD model to explore the risk effects from the whole supply chain perspective. In order to capture the overall effect, it is essential to develop a risk model for comprehensively representing the generating mechanism of risk. **Figure 5.10** illustrates the cause and effect relationship between identified risk attributes and the influenced variable.

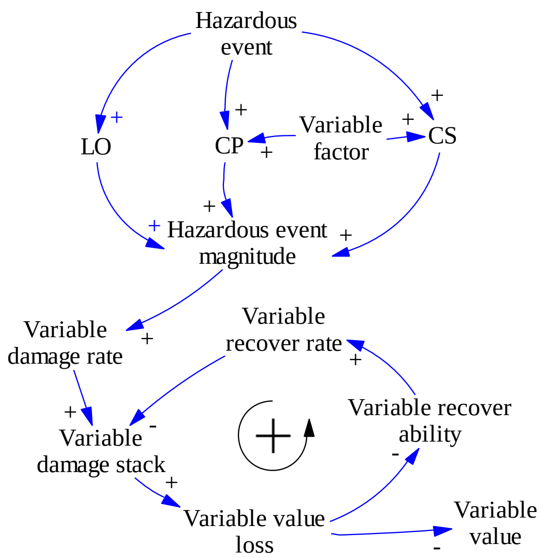


Figure 5.10. Causal loop diagram of a hazard and affected variable

In the model, specific variables are created to represent the involved risk attributes. It is significant to note that the variables of *CS* and *CP* are determined by the combination of the hazardous event and the affected variable, whereas *LO* is decided by the hazardous event itself. The co-determination of *LO*, *CS* and *CP* represents the risk magnitude of a hazardous event, which is stored in the variable of *"Variable damage rate"*. It appears to be a reinforce effect between the "*Hazardous event magnitude*" and "*Variable damage rate*" that the increase of causative variable will amplify the changes in the affected variables. Through evaluating the associated changes of the system behaviour caused by the variation of risk inputs, the risk effects can be quantitatively assessed in order to explore possible risk reduction solutions. To deal with the concerned risks, the implementation of the established risk management procedures contributes to the recovery of the damages over time. The undesired risk effects are reduced step by step, which is represented in the variable of “*Variable recovery rate*”. A distinct loop is observed to illustrate the feedback effect between “*variable recover rate*” and “*variable value loss*”, which are determined by “*variable recover ability*” and “*variable damage stack*”. The polarity of a loop can be addressed by multiplying the individual effect of each relationship: (-)×(+)×(+) ×(-) = (+), therefore, it has a positive effect in whole loop.

5.3 STOCK AND FLOW DIAGRAM DEVELOPMENT

In accordance with the provided SD modelling method (shown in **Figure 3.6**), the next step of the SD modelling is developing stock and flow diagrams through correspondingly translating established causal loop diagrams. It is carried out following the sequential steps: characterise elements, write equations, assign values to parameters, build model, and validate model. The reasons for using this software are that: 1) It combines the SD theory and simulation concept with discrete events, which can be applied to represent the uncertainties of individual CSC events in detail; 2) It demonstrates the causal relations between the stocks, flows and control variables with more specific quantitative information; 3) It offers a method to subsequently explore the time-dependent system performance; 4) It addresses the variation in system behaviours affected by the risks through modifying the system structure and variable setting.

In order to ease and accelerate the modelling process, the collections of conceptual stock and flow diagrams are developed instead of capturing all the details in the developed system. The commonly used components of materials, information, money, demand, personnel and equipment are identified and used to create the collections of templates or libraries of the CSC. In the diagram, the system components are assigned to the level, auxiliary and flow variables. The individual relationship between the components is represented as a relatively simple algebraic equation to capture both the linear and nonlinear relationships. Furthermore, changes and new situations can be adapted by modifying the developed model to explore the dynamic CSC system performance under various scenarios.

5.3.1 Chemical supply chain sub-model

The SD model is capable of simulating system operations and generating dynamic behaviours of system components under a specified state of the condition. It addresses sourcing, conversion, logistics, storage and some other activities and integrates suppliers, manufacturers, distributors, retailers and customers in one system. Based on the developed causal loop diagrams, five representative stock and flow diagrams are created: supplier sub-model, manufacturer sub-model, transporter sub-model, retailer sub-model and customer sub-model. The developed models are regarded as the conceptual models that can be customised to fit the real environment in further research. By connecting developed models, a multi-echelon CSC model is built to address the dynamic behaviours of the CSC system.

5.3.1.1 Supplier sub-model

In the CSC, the supplier provides products or services with required quality and quantity to downstream members within a period of time. From the addressed causal relations in the developed causal loop diagrams of sourcing (shown in **Figure 5.2**), warehousing (shown in **Figure 5.6**) and transportation (shown in **Figure 5.7**), it can be seen that the sourcing process is driven by the customer demand and supply process builds up the products for distribution. The developed conceptual supplier sub-model is required to capture these two causal links, which is represented in **Figure 5.11**.

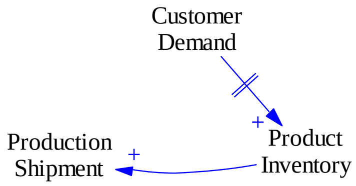


Figure 5.11. The causal links in the conceptual supplier sub-model

Based upon the addressed causal links, the stock and flow diagram of conceptual supplier sub-model is developed, shown in **Figure 5.12**. The developed model plays the role of sourcing products from upstream suppliers, storing the products on-hand and delivering sourced products to downstream customers. It is noteworthy that the necessary variables have been suitably created to represent the identified functions in the supply phase.

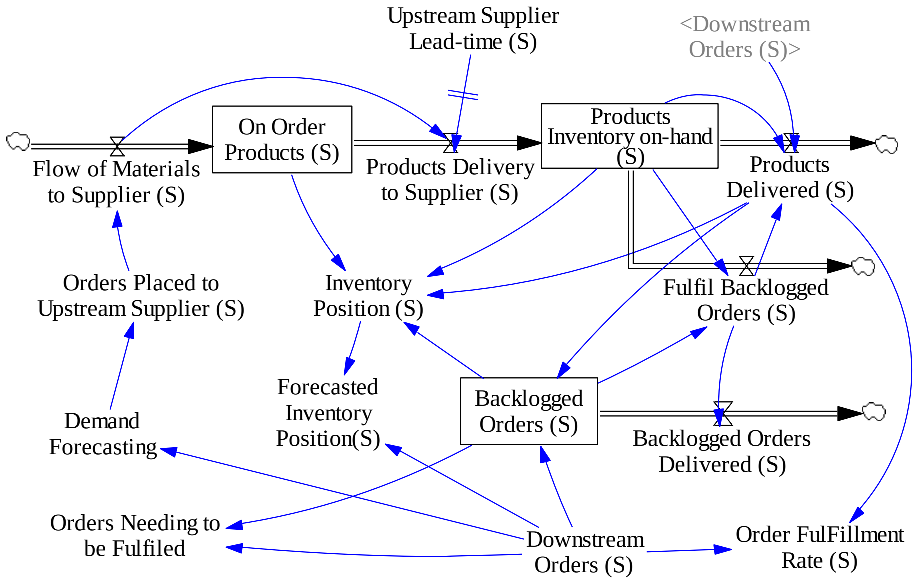


Figure 5.12. Stock and flow diagram of conceptual supplier sub-model

To provide a detailed description, the key variables in the model are shown below:

1) Downstream Orders (S)

The variable represents the dynamic downstream requirements, which is considered as an auxiliary variable. During the simulation, the orders can be generated randomly based on a kind of uncertainty or the input of historic data.

2) On Order Products (S)

It is defined as a level variable used to describe the accumulation of materials. The inputs are determined by the orders placed to upstream suppliers, while the outputs are conditioned by the lead-time of upstream suppliers.

3) Upstream Supplier Lead-time (S)

Lead-time is regarded as an auxiliary variable that represents a phenomenon of the delay in the material flow. The disruptions would increase the lead-time and cause the undesired effects: the failure to fully satisfy downstream demands, stock out, and the delay in downstream operations. To respond, the time gap between the products ordered and received from upstream supplier can be controlled and managed by the CSC through carrying out planning, improving information exchanging and quick response (De Treville, Shapiro and Hameri, 2004).

4) Product Inventory on-hand (S)

It is considered as a level variable as it reflects the inventory that is available for shipping. The inflow of products received, outflow of products delivered and initial value determine the inventory level of products. In order to manage products handling risk, the efforts are spent on reducing the inventory level in the whole CSC network instead of minimising the amount of inventory in the entity level (La ńez, Puigjaner and Reklaitis, 2009). Hence, system thinking should be employed to analyse the inventory system taking into consideration the feedbacks between the material movements in the CSC.

5) Backlogged Orders (S)

This variable is used to store the un-served orders, so that it is regarded as a level variable. If the inventory could not meet the downstream demand, the backlogged orders appear and lead to the decrease of order fulfilment rate. Normally, the backlogged orders are priority that should be first fulfilled in the next operation.

6) Products Delivered (S)

The variable of products delivered represents a flow of materials used to satisfy the downstream demand. It is a flow variable conditioned by the lead-time, which modifies the products inventory position based on the time step.

7) Inventory Position (S)

Inventory position is a vital auxiliary variable updated over time. According to the formalised causal loop diagram, the value of inventory position is obtained through evaluating the combination of "*On-order Products (S)*", "*Products Inventory on-hand (S)*", "*Products Delivered (S)*", and "*Backlogged Orders (S)*".

8) Demand Forecasting (S)

In the diagram, it is an auxiliary variable that describes forecasted demand. Established upon the implemented forecasting method, the purchasing, manufacturing, inventory management, transportation and other activities are scheduled and executed based on the value of this variable.

9) Order Fulfilment Rate (S)

Order fulfilment rate indicates the reliability of a supplier to supply required products on time (Chae, 2009). Basically, it is calculated by the comparison of products shipped and products needing to be shipped, therefore, it is a percentage of delivered orders in relation to the orders placed by downstream customer. In the CSC, the majority of fossil fuel is sourced from dangerous and unstable areas of the world, the activities of sabotage, war, terrorism and vandalism increase the uncertainty of supplying activities, which could significantly affect order fulfilment rate of a supplier.

5.3.1.2 Manufacturer sub-model

In the CSC, the manufacturing phase is a complex system where the chemical products are formulated through blending, separation, reaction and packaging processes. Diverse manufacturing recipes can be applied for converting raw materials to finished products, thus, the uncertainties existing in manufacturing processes simultaneously challenge the manufacturing operations (Ritchie and Brindley, 2007). However, the production activities are regarded as the internal activities carried out by the firm, which can be measured and controlled in terms of operational processes and system outputs (Mapes, New and Szwejczewski, 1997; Gunasekaran and Kobu, 2007).

In the modelling stage, a conceptual model of the manufacturer sector is developed instead of capturing all the details. The sourcing, manufacturing, storage, and shipment functions are established and properly connected based on the addressed relationships. Apart from the described causal links among the sourcing, storage, and distribution part (shown in *Section 5.3.1*), the logic interactions in the manufacturing process should be addressed before developing the SD model to simulate the manufacturing process. It can be described as the downstream demand drives the manufacturing activities and the inventory on-hand determines the products can be shipped. The production department owns a certain number of capacities that can produce a certain volume of final products for a set amount of time. At the same time, the logistics and warehouse department work together to ship the final products in the given time when the manufacturer receives the orders. To simplify the modelling process, there is only one step production in the developed conceptual manufacturer sub-model. In further research, the model can be customised to simulate the multiple steps' production process. Following the described causal relations, the identified components have been created and linked to represent a conceptual manufacturing operation in **Figure 5.13**.

In the developed conceptual manufacturer sub-model, the key variables and their functions are presented as follows:

1) Downstream Demand (M)

As described in the supplier sub-model, the downstream demand is considered as an auxiliary variable that drives the operations of the developed system. In this variable, the dynamic behaviour of downstream demand is represented using mathematic equations, so that the downstream orders are generated over time based on the defined principle or the information passed from the downstream members.

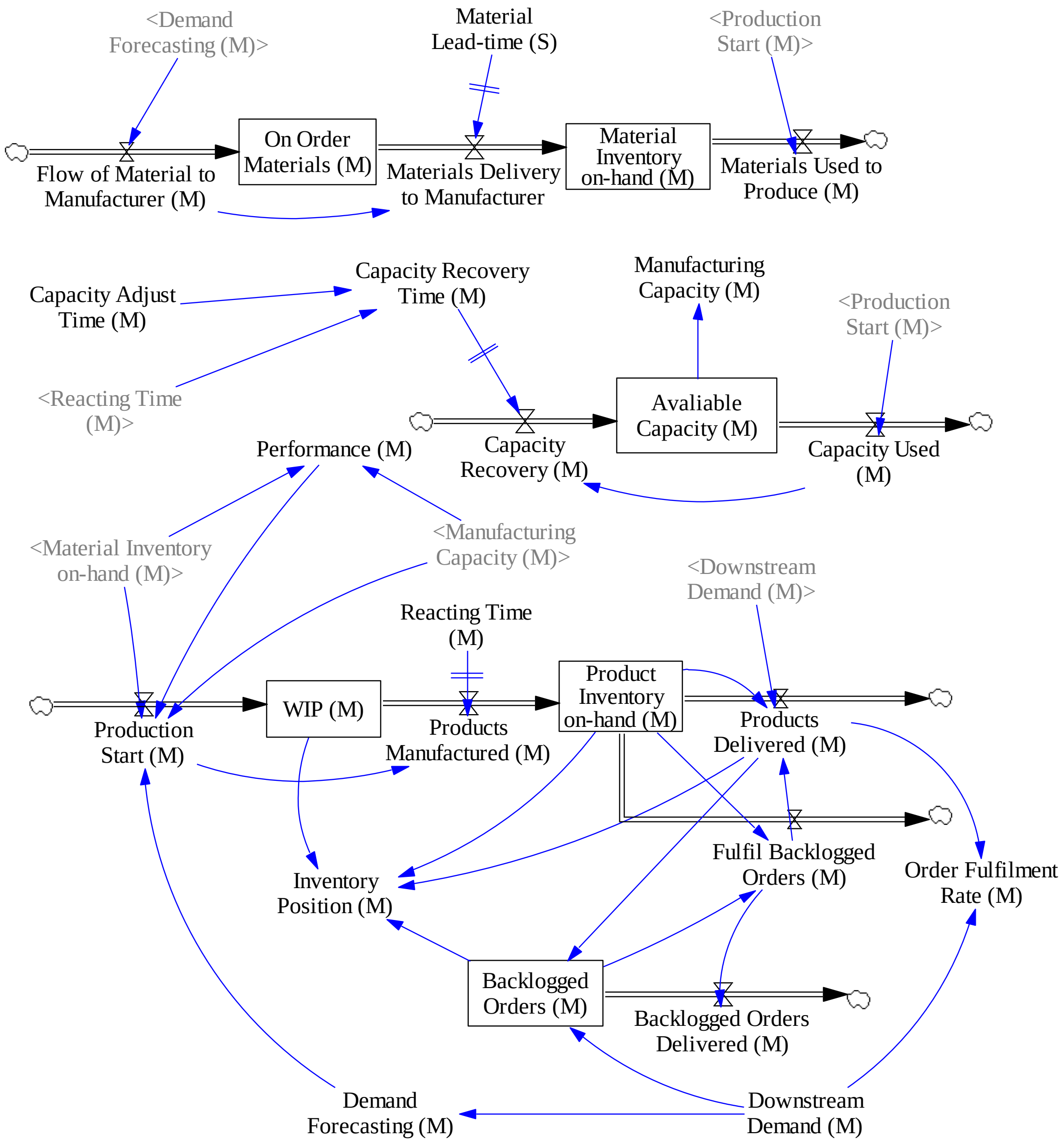


Figure 5.13. Stock and flow diagram of conceptual manufacturer sub-model

2) Demand Forecasting (M)

Based on the implemented forecasting method, the orders are predicted relying on the historical data or current orders. It is regarded as a vital auxiliary variable that supplies the information to CSC members. In general, there are two forecasting methods widely used in the CSC: the extant forecasting method and the consensus forecasting method (Goodwin and Wright, 2010). The extant forecasting method relies on the historical data and implements mathematical models to evaluate the customer demand, while the consensus forecasting method is a coordinated approach to forecast the customer demand and the forecasted demand is acknowledged by the members to achieve higher forecast accuracy

(Chae, 2009). According to the implemented method, appropriate mathematical equations are inserted in the variable to generate predicted values.

3) On-Order Materials (M)

As with the created variable of "*On-order products*" in the supplier sub-model, this variable is designed as a level variable to represent the accumulation of outstanding orders.

4) Material Inventory on-hand (M)

It is another level variable as it reflects the volumes of raw materials in storage, which are available for manufacturing. As decribed in a previous analysis of relationship formalisation, the lack of materials could disrupt the downstream conversion and bring undesired consequences in terms of low service level, unqualified products, *etc*.

5) Materials used to Produce (M)

It supplies information of changed material inventory over time. Based on the interactive relationship, the volume of material used to produce can be observed which depands on the materials inventory and forecasted demands.

6) Avaliable Capacity (M)

Manufacturing capacity refers to the ability to respond to the dynamic requirements from downstream sectors. In practice, the manufacturer capacity is conditioned by the equipment capacity and labour capacity (Gunasekaran, Patel and McGaughey, 2004). In the developed model, available capacity is designed to accumulate the free capacity in a certain period of time. Therefore, it is set as a level variable modified by the input variable of capacity recovery and output variable of capacity used based on the time step. During the operations, the excess capacity represents that the system fails to receive sufficient orders to warrant the current productivity, which leads to resource wasting and profit lost (Baldwin, Gu and Yan, 2013).

7) WIP (M)

Work in progress (WIP) represents the partialy finished products that are at various stages of the converting process. In the model, it is created as a level variable as it reflects the volume of materials under processing whose outputs are conditioned by the reaction time or the processing time corresponding to the input flow of products.

8) Reacting Time (M)

Reacting time describes the time required in the converting phase. It is an auxiliary variable representing a phenomenon of delay in material flow. In the CSCRM, it is necessary to measure the on time production and compare it with the initial plan, so as to evaluate the manufacturing operations in the time aspect (Thakkar, Kanda and Deshmukh, 2009).

9) Product Inventory on-hand (M)

As described in the supplier sub-model, it is considered as a level variable that presents the accumulation of products within a given period of time. This variable is amended by the variation between the products manufactured and products delivered along the time axis. During the CSC operations, the chemical reactions are carried out in batch, so that the inventory of finished products will sharply increase in a specific time. To provide sufficient capacity, an effective and efficient planning is required to manage products inventory as well as the container system.

10) Inventory Position (M)

In developed model, the inventory position is addressed through logically calculating the variables of "*WIP (M)*", "*Products Inventory on-hand (M)*", "*Products Delivered (M)*", and "*Backlogged Orders (M)*". It is a vital auxiliary variable updated over time.

11) Prodocts Delivered (M)

It offers the information of the products delivered to downstream entities, which is determined by the minimal values of products inventory on-hand and customer demand. In a CSC, it could be the input of the materials flow to the downstream.

12) Backlogged Orders (M)

A backlog describes the outflow of shipped orders failing to maintian the pace with demand. As in the supplier sub-model, it is another level variable used to store the unserved orders.

13) Order Fulfilment Rate (M)

Order fulfilment rate is a flow variable that offers the information on manufacturing system performance, which suggests the capability of a manufacturer to provide the right products within the required time. The disruptions in manufacturing activities will result in the decrease of the order fulfilment rate and damage the relationship with downstream members.

5.1.3.3 Transporter sub-model

In the traditional CSCs, transportation process is regarded as a functional part of supply chain members or an intendant operating company that is used to connect the flow of materials between the supply chain members. Compared with other well organised processes in the CSC, the transporting of chemical substances is vulnerable in that the environmental factors and surrounding risks could easily disrupt the material movements and cause catastrophic effects. To practically analyse the transportation process, a representative stock and flow model is established based on the observed cause and effect relationships among the transportation that takes into consideration the inventory of materials, capacity of transportation system and transportation time, shown in **Figure 5.14**.

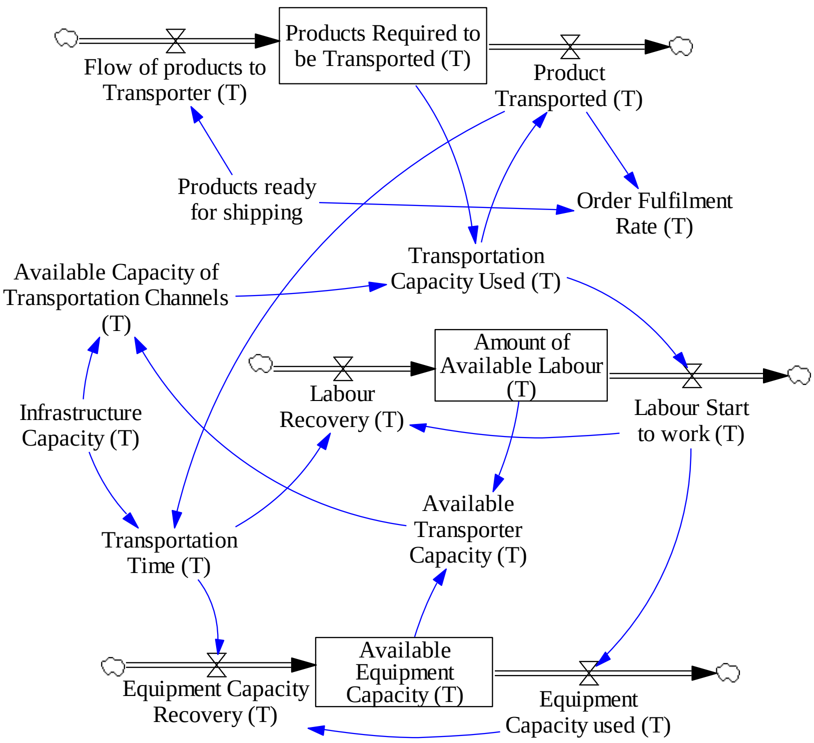


Figure 5.14. Stock and flow diagram of conceptual transporter sub-model

As described in **Figure 5.7**, the transporter inventory level is determined by the arrival flow of products from the upstream members and the outflow of shipped products to the customers. The level variable of products required to be transported is developed to represent the accumulation of transporter inventory. Based upon **Figure 5.8**, the capacity of a transporter depends on the capacity of the available equipment and the size of the transporter's labour force within the CSCT system. Therefore, the equipment capacity is created to describe the capacity of instruments, while the labour capacity is developed to represent the number of operators handling the available equipment. When the products waiting for shipping exceed the maximum capacity, the materials cannot be shipped until the capacity is released. The increase of equipment capacity and labour productivity could offer an extra capacity to the transportation system, which can be used to fill the transportation capacity gap in the operations. In order to capture involved functions in the transportation phase, the key variables are explained as follows:

1) Products Required to be Transported (T)

The focal company responds to downstream orders by shipping the requisite products for which the transportation system has sufficient available capacity, otherwise the unprocessed products will accumulate in this variable based on the time step. To realise this particular function, it is built as a level variable and the change of it is governed by the products ready for shipping and outflow of shipped products to customers within a given period of time.

2) Products Transported (T)

This variable is set as a flow variable that represents the movement of materials over time. The value of this variable changes immediately that establishes upon the transportation capacity and the inventory of the products waiting for transportation.

3) Amount of Available Labours (T)

The amount of available labour is regarded as a level variable that indicates the labour capacity can be used. The value of this variable is amended by the arrival flow of labour recovery and labour hired and the outflow of labour starting to work.

4) Available Equipment Capacity (T)

As is the consideration with the amount of available labour, this is another level variable as it shows the available capacity of equipment in a certain period of time. The value is modified by the input variable of capacity recovery and output variable of capacity used based on the simulation time step. In the transportation system, it refers to the ability of the transporter to respond to the dynamic demand. The lack of capacity leads to the failure of fully fulfilling the downstream requirements within the given period, while the excess of capacity causes resource wasting and profit losses.

5) Infrastructure Capacity (T)

Chen at al. (2002) indicate that infrastructure capacity is determined by the selected route and surrounding environment, which cannot be controlled or changed by the transportation service providers. To supply this kind of information, it is created as an auxiliary variable in the developed model.

6) Available Transporter Capacity (T)

It offers the information of transporter capacity that can be used in the current situation. Based on the developed causal loop diagram, a specified number of operators are required to handle the transportation equipment, so that the transporter capacity depends on the capacity of the available equipment capacity and the size of the labour force within the transportation system.

7) Available Capacity of Transportation System (T)

The capacity and capability of a transportation system is determined by the transport features, such as route condition, transportation mode and transportation strategy (Peng *et al.*, 2014). It is an auxiliary variable to supply information of the capacity of the transportation system.

8) Transportation time (T)

In transportation science, transport time is determined by the volume of products in transportation and the capacity of the available infrastructure, which is one of the key performance indicators to evaluate the delivery activity in terms of the time aspect (Massey and Jacobs, 2012). In the developed model, it is developed as an auxiliary variable that represents a phenomenon of the delay in material flow.

9) Order Fulfilment Rate (T)

As described in previous sub-models, order fulfilment rate is designed as an auxiliary variable that reflects the system performance. This variable supplies the percentages of order fulfilled in every simulation step to describe the reliability of transportation service providers.

5.1.3.4 Retailer sub-model

In the CSC, the retailer is an intermediate platform of evaluating and integrating the resrouces from suppliers and requirements of downstream members to provide sourced products to customers, which is similar to the function of suppliers. **Figure 5.15** shows a conceptual retailer sub-model, which illustrates purchasing, storage, delivery and demand forecasting activities in the system.

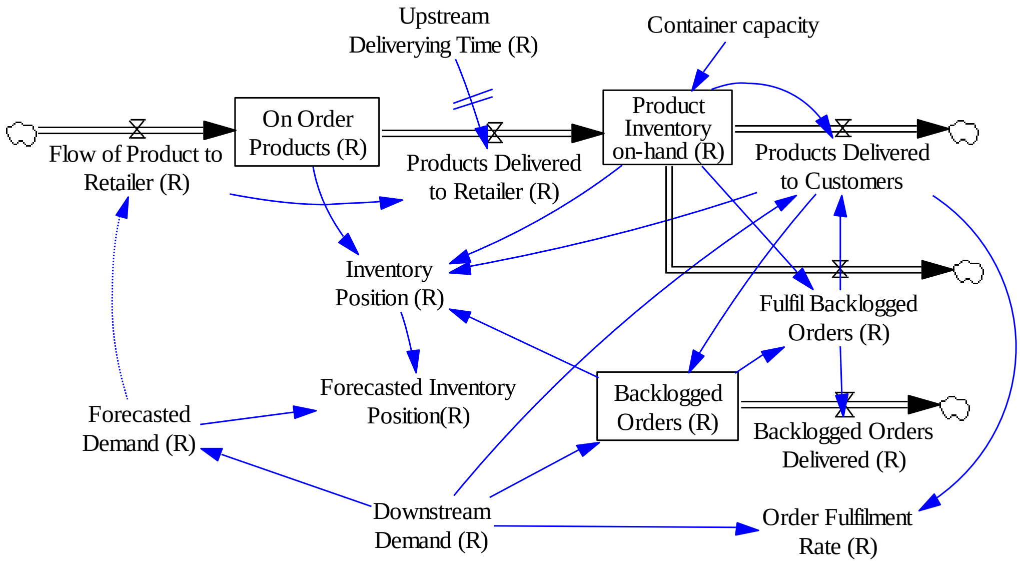


Figure 5.15. Stock and flow diagram of conceptual retailer sub-model

In the developed model, there are three functional departments, including the sourcing, logistics and warehouse departments. The retailer sources the required materials from upstream suppliers based on a pre-defined order policy and stores the purchased products in the warehouse. Cooperating with the logistics department, the required materials are shipped to the downstream members. Basically, the basic function of retailers is to provide sourced products to customers, so that the majority of created variables have the same definitions and functions as the variables described in the supplier sub-model (shown in **Figure 5.13**). In addition to the same place, the variables having specific features are explained as follows:

1) On-Order Products (R)

The retailer sources products from various upstream suppliers. To creat superior value and bring competitive advanages, the evaluation of the resrouces from potential suppliers is carried out to make beneficial sourcing decisions. A specific variable is developed to represents the accumulative effect of the products on ordered, which is conditioned by the lead-time of upstream suppliers. It is regarded as the input of the material flow in the retailer sub-model.

2) Product Inventory on-hand (R)

This is another level variable as it describes the products which can be used to fulfil customer demands. It is obtained through accumulating the difference between the arrival flow of products received and the out flow of products delivered in each simulation step. In the operations, a specific control algorithm can be inserted in the developed variable to control and manage inventory on-hand, so as to reduce products handling cost and optimise system performance.

3) Products Delivered to Customers (R)

According to the order fulfilment strategy, a certain number of products are forwarded to the customers over time. A flow variable is created to describe the phenomenon of material movement in the developed model.

4) Order Fulfilment Rate (R)

It is an auxiliary variable that measures the performance of a retailer. A failed order completion results in the decrease of the order fulfilment rate and brings undesired losses in terms of money, reputation and market share.

5.1.3.5 Customer sub-model

In the CSC, the customers place orders to purchase goods or services from upstream members. However, competition and the changes of customer taste bring uncertainties to CSC operations. CSCs have to develop an understanding of the nature of the market and provide a robust and agile supply chain network to deal with dynamics. **Figure 5.16** provides a conceptual model to present the interaction between the orders placed to upstream partner and the relationship with upstream partners.

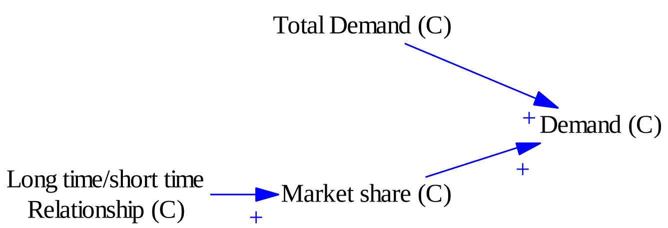


Figure 5.16. Stock and flow diagram of conceptual customer sub-model

In the created CSC model, the simulation is started from the customer placing an order in accordance with defined order policy or historical data. Total demand is an auxiliary variable i.e. it generates initial order information to developed system. To deal with the increased domestic and global competition, novel techniques and strategies are implemented to achieve the desired the market share. Instead of focusing on price competition, there is more and more attention paid to the criteria in terms of quality, reliability and lead-time aspects (Gulledge and Chavusholu, 2008). All the CSC members cooperate to shift the outputs to fit the various demands on the systems' thinking. Therefore, the variable of market share supplies the information that it is not conserved but updated over time. According to total demand and market share, the number of orders placed to the system is obtained, which is regarded as the driver of the built system operation.

5.3.2 Risk sub-model

A hazardous event is a threat in the sense that some undesired things can interrupt the operational process and have a negative impact on the CSC performance (Waters, 2011). As described in the causal loop diagram development phase, the particular features of a hazardous event are demonstrated in three aspects in order to address the time-dependent effects on system thinking. The created causal and effect relationships are correpondingly translated into a stock and flow diagram and the necessary variables have been suitably added, shown in **Figure 5.17**.

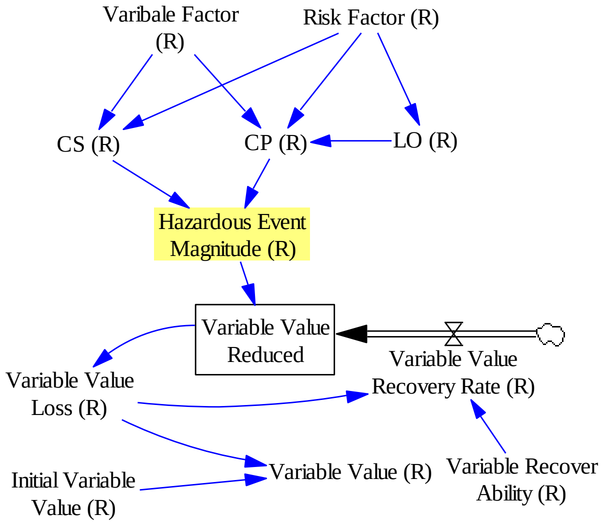


Figure 5.17. Stock and flow diagram of risk sub-model

The risk sub-model is created based on the causal relations addressed in **Figure. 5.10**. The values of *CS* and *CP* for a given variable are determined by the combination between hazardous event and affected variable, while it is not to be expected that *LO* can be evaluated or managed in the variable level. The co-determination of *L*O, CS and CP represents the risk magnitude of a hazardous event. A reinforce effect can be addressed between the hazardous event magnitude and the damage of a particular hazardous event. The existing cause and effect relations in the system influencing the performance of CSCs escalate the risk effects and damage the effectiveness and efficiency of their operations. Therefore, the risk effects can be quantitatively assessed through evaluating the associated changes of the system behaviour caused by the variation of risk inputs. However, the existed risk management procedures contribute to the recovery of the damages over time. The damage is reduced in accordance with the variable recovery rate on a step by step basis. Based upon the mapped causal relations, the proper connections of risk variables following the identified interactive relationships reveal a representative risk generation mechanism. The descriptions of key variables are presented below:

1) LO (R)

It is considered as an auxiliary variable that indicates the possibility of a hazardous event occurring. The information is obtained from expert knowledge, historical data or other methods and set as input value of a risk scenario.

2) CS (R)

This variable presents the magnitude of the possible undesired consequence when the hazardous event does occur and affect the target variable. It is built as an auxiliary variable that supplies the information of the identified hazard, which is conserved during the simulation period.

3) CP (R)

As is the description with LO, this variable is considered as an auxiliary variable that supplies the information about the probability of suffering the given magnitude of the consequence when the hazardous event brought an unexpected consequence.

4) Hazardous Event Magnitude (R)

Based on the inserted three attributes of risk, the magnitude of hazardous event is addressed, which contains two kinds of information: probability and severity. It is built as an auxiliary variable to govern the change of the affected variable.

5) Variable Value Reduced (R)

The information of a risk is passed to the level variable as it reflects the accumulation of the damage of the affected variable in a certain period of time. According to the addressed relations, it is modified by the arrival flow of value recovery rate.

6) Variable Recover ability (R)

It describes the ability to respond to undesired effects, which is built as an auxiliary variable that supplies the information of variable recovery rate.

7) Variable Value (R)

It is defined as an auxiliary variable that receives and passes the information in each simulation step. During the operations, the damage to variables' value are obtained and inserted into the developed CSC system to assess the risk effects.

5.4 MODEL VALIDATION AND ANALYSIS

A conceptual SD-based CSC risk model is designed and developed to support risk analysis and risk reduction against the backdrop of the scenarios. Before carrying out experiments to simulate system operations, the developed SD model should be validated in terms of the correspondence of the model structure and the robustness of the model's behaviours (Forrester and Senge, 1980; Qudrat-Ullah and Seong, 2010). Once validation and confidence in the behaviour of the built SD model had been established, a base case and a series of risk scenarios are generated to examine the variations in system behaviours produced by the changes.

5.4.1 Model validation

The validation process is employed to ensure the assumption meets the research purposes and the CSC operations are technically presented in the built models, which is therefore an importation step in SD methodology (Forrester and Senge, 1979; Qudrat-Ullah and Seong, 2010). To verify the developed SD models, three rigorous tests involving both formal-quantitative and informal/qualitative methods are suggested: structure and parameters verification; testing under extreme conditions; and dimensional consistency examination (Barlas, 1994).

Specifically, the principle behind SD is that the structure generates the observed behaviours (Viana et al., 2014). It is claimed that an SD model is developed based on the causal relationship from real systems (Barlas, 1996). Therefore, the structure of the proposed model is tested through comparing variables and equations against the observation from literature, available knowledge from the experts and referenced models. In particular, the model validation in this step means verification of the internal structure of the model, instead of concentrating on the system behaviours.

The “statistical significance” testing is another critical part in the SD model validation process. It intends to find out whether the value of the parameter is estimated with sufficient accuracy (Moizer, 1999). Especially, the parameter values under extreme conditions can be set by the model developers to assess whether the time-dependent performance coincided with the anticipated behaviour of the system in reality. The principle is applied: “if input A has affected the system, then behaviour B should be resulted” (Peterson and Eberlein 1994). The implementation of extreme-condition testing is provided by the “Reality Check” feature in Vensim© software. Based on the assumption of an independent input value of a variable, it exploits a better performance of the system to anticipate the dynamic and complex behaviours compared with human beings (Owen, Love and Albores 2008). However, it is crucial to note that a number of behaviour reproductions in the simulation should be analysed in trends, frequencies and fluctuations of system behaviour rather than to give a detailed mathematical account of a specific value (Das and Dutta, 2013).

Finally, the dimensional consistency tests are carried out to logically examine the dimensions of created variables. The well-established software provides a powerful dimensional calculation function that automatically checks the dimensional consistency of the developed model based on defined causal relations.

SD is a scenario based modelling and simulation method to predict the system behaviours. Therefore, the model validation only can be conducted under certain conditions. The detailed descriptions of proposed analysis are given in later chapters (see in *Chapter* 6 and *Chapter* 7). Following the described SD model verification method, the developed SD models can be validated and all the concerned variables are tested to verify whether the system behaviour matches the expected results to ensure the reliability and applicability.

5.4.2 Scenario-based SD simulation

Scenario analysis represents an approach for developing a set of stories that encourages considering a broad ranges of issues (van den Heijden, 1997). Applying SD to the scenario provides an integration interface between the system model and scenario models that allow the simulation of system behaviour sensibility to scenarios, assess system operations through developed model simulation, and find out the impact upon expected system behaviours (Lane, Monefeldt and Rosenhead, 2000). In the proposed research, the combination of participatory SD modelling and scenario analysis facilitates the CSC behaviours as far as the processes, information, and decision-making are concerned. As well, it maps the risks through quantifying of the system behaviours with a consideration of the interactive hazardous events on system thinking (Rozman *et al.*, 2012). The scenario can be consulted and translated to variables in developed SD models by amending the model structure, modifying defined equations, and changing the inserted value of the created variable. It takes the advantage of transforming the risk input into the various system behaviours, so that the risk effects are quantified to address the signification risks. Furthermore, the associated risk reduction scenarios are provided to manage and control the undesirable risk impacts. Through iterating the provided SD modelling approaches, the developed SD models can be properly amended under controlled conditions to estimate risk reduction outcomes in various scenarios, so as to suggest competitive CSCRM decisions.

5.4.3 Sensitivity analysis

In practice, the behaviour of the SD model is insensitive to plausible changes in most of the variables, while the variables significantly affecting the system operations need to be identified during model developing and validating phases (Forrester, 1969). The behaviour sensitivity test can help to confirm whether a small perturbation to a designed variable causes a significant change in the system's behaviour (Forrester, 1969; Moffatt, 1991). According to the historical or a hypothetical pattern, all the concerned variables can be tested regardless of the size of model and the sensitivity analysis outputs will allow a more representative picture of model behaviours, so that it can be used to calibrate the developed model to fit in with the scenario description or real world (Christopher and Patil, 2002).

Meanwhile, sensitivity analysis can be implemented in risk reduction and investigation through varying the input of a system to assess the output on system operations. It takes the advantages of observing the risk effects lying in the system behaviours instead of setting the risk input as a static value. Specifically, the values of CSC risk attributes can be shifted to explore the variation in system behaviour that is produced by risks in the developed CSC system. Through comparing the range of simulation outcomes in each risk scenario, the significant risks are estimated and mitigated. Following the same procedure, the simulation of changing the variable value helps the modeller to observe where the sensitive variable locates in the specific risk scenario. The results provide a hint for the potential risk reduction solutions in further research.

5.6 CONCLUSION

This chapter develops conceptual models along the CSCs and captures the risk generation mechanism following SD approaches. The elements of materials, information, money, demand, personnel and equipment are identified and analysed to support modelling and simulation of the dynamic CSC operations based on qualitative and quantitative information. In the developed models, the assumed interactions are formalised to demonstrate the causal relations within the system boundaries and the collections of conceptual stock and flow models are developed to map the risks through simulating the system behaviour with a consideration of the interactive hazardous events on system thinking. To investigate various risk effects, an integration of system model and scenarios is provided that allows the simulation of system sensibility to scenarios, assesses system operations through the developed model simulation, and finds out the risk impacts upon expected system behaviours.

CHAPTER 6 CHEMICAL SUPPLY CHAIN RISK ANALYSIS AND REDUCTION USING SYSTEM DYNAMICS METHOD

Summary

This chapter discusses the application of SD-based CSCRM method for constructing a CSC model to assess diverse risks and to explore possible risk reduction measures. It combines the theory, method and scenario to investigate dynamic risk impacts in a CSC not only in operations, but also in the broad fields, such as planning, management and decision making aspects. As introduced in *Chapter 5*, SD is a scenario-based modelling and simulation method, so that all the concerned risks can be analysed regardless of the size of risk factors. The developed SD models can be customised and connected to generate the dynamic behaviour under a specified state of the condition. Through evaluating the difference between the expectation and real-time performance of the developed system, the simulation results represent more precise system behaviours, so as to address more accurate risk effects in the CSCRM research.

6.1 APPLICATION OF DEVELOPED SD MODELS TO SIMULATE THE CSC OPERATIONS

SD is applied to assess the variation of the system behaviours in various risk scenarios and explore possible risk reduction measures on system thinking. Findings from the formalised causal relationships and developed conceptual SD models in previous research are adapted in this chapter, which not only shortens the execution time of modelling process but also reduces the complexity of model development. The obtained numerical results can offer supportive information for assessing potential risk reduction measures and continuously improving the CSC system performance.

6.1.1 Problem description

To carry out scenario-based simulation, the problem and system boundaries should be specified in the first step. The developed CSC system consists of three representative echelons: a raw material supplier, a manufacturer, and a customer that specialises in supplying, manufacturing, storing and delivering a certain type of chemical substances for industrial use. The customer places the orders following the requirements. Based on the forecasted demand, the supplier and manufacturer plan the sourcing and manufacturing activates. In the supplying phase, the raw materials are sourced from the upstream entity and supplied to the manufacturer in accordance with the transportation capacity. In the manufacturing phase, it consists of a complex structure, involving blending, separations, reaction, and storage. The complexity of the above manufacturing processes affects the effectiveness of performances of the company and may cause undesirable losses. The transportation by waterway and road using specialised vehicle connects the material flows and final products between raw material suppliers, manufacturers, and customers involved in the supply chain. The hazardous characteristics, such as extreme low storage temperature, high storage pressure, flammable and explosive, endanger the whole transportation activities from the origin to destination. Meanwhile, the weather conditions, newly introduced policies and other undesired events result in uncertainties and disruptions to the transportation operations where there is a major pressure for the CSC members to satisfy customer demand within a narrow time-window under the challenge of risks. CSCRM is required to assess and manage the inherent and surrounding risks to maintain the safety and efficiency of the supply chain operations.

Having taken into account the above case, the following sections are developed to demonstrate the application how the developed SD-based CSCRM method can dynamically analyse the risks in CSCs. To simplify the SD modelling process, three conceptual sub-models are developed and sequentially connected, namely a raw material supplier, a manufacturer, and a customer. **Figure 6.1** presents the movements from the raw materials to the final products, as well as the information shared between the supply chain members in the developed sub-models.

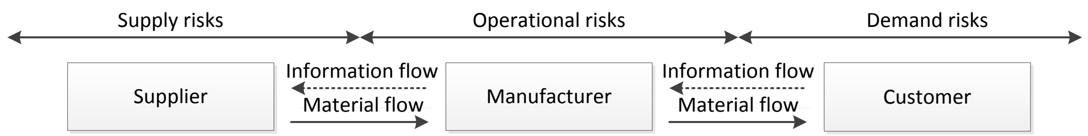


Figure 6.1. Flows of materials and information in the scenario

(1) Customer

The simulation process begins with the customer ordering the final products in accordance with his requirements. The order is made every 7 days and the ordering pattern follows a normal distribution, with a minimum 100 tons, a maximum of 200 tons, a mean of 150 tons, and a standard deviation of 30 tons.

(2) Manufacturer

To produce the final products in the given time, the sourcing, manufacturing, logistics and warehouse departments work together in the manufacturing sector. The manufacturer applies a make-to-stock strategy, so that the operational activities are executed based on the manufacturing schedule. In this study, 800 tons of raw materials can be converted into 800 tons of final chemical products per week without much loss in the manufacturing process. When the manufacturer receives the order, the logistics department cooperates with the warehouse operators to check the product inventory and to deliver the required quantity of products to the customer. The logistics department owns a certain number of specialised carriers that can ship 500 tons of final products per delivery. The forward transportation time is 4 days, and the capacity recovery duration is 3 days. To specify the state of the case study, there are several assumptions: (1) The operational activities are scheduled and executed based on the forecasted demand; (2) The next term customer demand is estimated based on the historical data (3) If the product inventory could not meet the customer demand, the backlogged orders appear. In the next delivery, the backlogged orders should be fulfilled first.

(3) Supplier

The supplier has three functional departments, including the sourcing, logistics and warehouse departments. The sourced raw materials are stored in a specific warehouse. Cooperating with the logistics department, the required materials are shipped to the downstream manufacturer within the maximum capacity of 200 tons per delivery and the lead-time of 2 week. Meanwhile, the supplier sources the required materials from upstream suppliers to fill the gap between the forecasted inventory level and the safety stock level according to a pre-defined order policy. In this study, the raw materials' safety inventory level is 500 tons and the raw material lead-time is 3 weeks. It is assumed that the upstream supplier could provide the required quantity and quality of the raw materials immediately.

6.1.2 Scenario-based SD model development

According to the SD modelling procedures described in *Chapter 5*, the scenario-based CSC models were developed in accordance with the sequential steps: defining the problem boundaries, finding the causal relations in a CSC system, developing a stock and flow diagram, and validating the developed model. In particular, the causal relationships can be adapted from formalised cause loop diagrams. As well, the stock and flow diagram can be referenced from developed reference models of generalised CSC and hazardous event sub-model, which reduced the complexity of the model developing activities. A multi-echelon CSC model was developed to facilitate the risk management in a complex and vulnerable CSC.

6.1.2.1 Finding causal relations in CSC system

The causal loop diagram was developed to represent the cause and effect relations in the system. The variables were created to represent the system structure and the arrows were used to describe the direction of the causal relationships. It formed a macro-structure for the causal relations of the proposed CSC system through connecting interacted variables, illustrated in **Figure 6.2**.

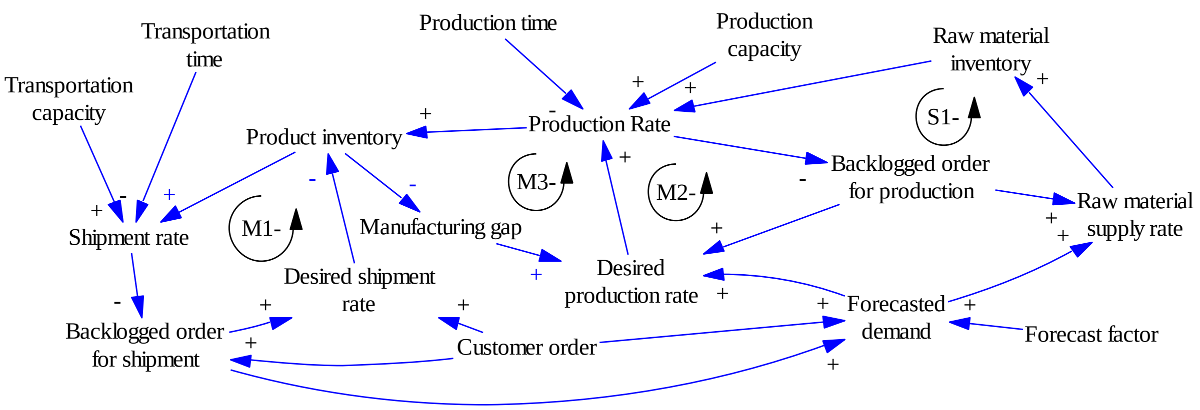


Figure 6.2. Causal loop diagram of proposed CSC

In the developed causal loop diagram, four distinct loops are observed, which control the raw material supplying (S1), the manufacturing (M2), the warehousing (M3) and the shipping activities (M1) in the investigated CSC. Loop S1 contains a closed chain of causal relations to represent the interaction between the raw material inventory and production rate, indicating that the more raw materials supplied, the higher production rate can be achieved. Loop M1 shows that the produced products and shipped products govern the changes in the product inventory. The increase of the inventory has a negative effect on the generation of backlogged orders and will result in the improvement of the order fulfilment rate. Loop M2 describes a balancing effect in which the increase in the production rate results in the decrease in production backlogged orders. The production rate represents the number of products that can be manufactured during a given period of time. It is determined by the combination of the production capacity, the raw material inventory and the desired production rate. Furthermore, the variable of backlogged orders for manufacturing affects the desired production rate in the same direction, which is shown as a reinforcing effect (+). Accordingly, the improvement of the desired production rate increases the related production rate (+). The polarity of the whole loop is addressed by multiplying the individual effect of each relation: $(-)\times(+)\times(+) = (-)$, which is negative. In Loop M3, a negative relationship is observed among the connected variables: production rate, product inventory, manufacturing gap and desired production rate. It describes the negative feedback effects between the production rate and the manufacturing gap.

In the risk sub-model, the developed causal loop diagram (shown in **Figure 5.12**) was adapted to simulate the generation of the risk impact on the variable level. A risk was explored in three aspects (*LO*, *CS*, and *CP*) to address the time-dependent effects on system thinking. These obtained risk attributes represented the magnitude of a hazardous event, which were set as the input of the risk scenario simulation. Inserting consequence severity with given probability into the built SD model, the existing cause and effect relations in the system influencing the performance of CSCs escalate the risk effects and damage the effectiveness and efficiency of their operations.

6.1.2.2 Developing stock and flow diagram of CSC system

The developed causal loop diagram represents the system structure and formalises the existing logical interactions between the related components within the defined system boundaries. Next, a stock and flow diagram of CSC is developed through translating the established causal loop diagram using VENSIM© software, as shown in **Figure 6.3**.

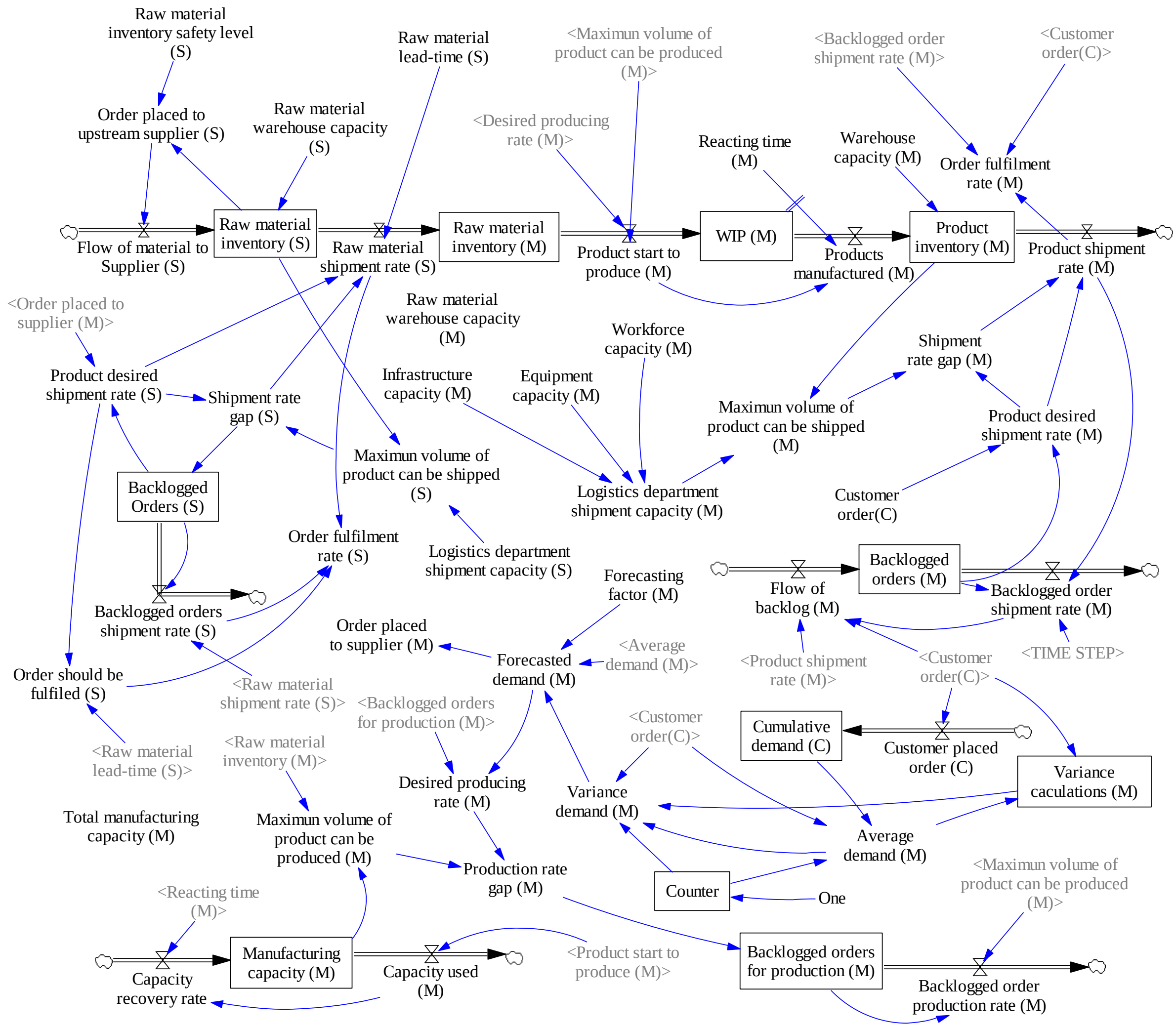


Figure 6.3. Scenario-based CSC sub-model development

In this model, three types of variables are used to describe the structure of the system, which are named as stock, flow and auxiliary, respectively. Stock is a structural element, which is represented in the rectangle box and used to describe the accumulation of a variable's value in forms of material, information, finance, or energy. Flow only passes the information to change the value of the stock. Auxiliary is presented in the box without border, which arises when the formulation of a variable's influence on a rate involves one or more intermediate calculations. The arrows connect the interrelated variables and indicate the directions of the cause and effect relations formed.

To fit into the described environment, the developed sub-models (shown in *Section 5.3*) are customised and connected to simulate system operations and generate the dynamic behaviour of system components under a specified state of the condition. As described in problem definition, the supplier responds to downstream requirements by providing the requisite materials to the manufacturer. The manufacturer then produces final products and ships them to the customer in the anticipation that the transporter has sufficient available capacity. Referencing the developed models (shown in **Figure 5.13**, **Figure 5.14**, **Figure 5.15**, and **Figure 5.17**), the necessary variables are developed and the involved functional parts are appropriately connected in line with the observed causal relations.

Table 6.1 lists the definition of the key variables used to develop the CSC sub-model in this study.

Table 6.1. Definition and role of major variables in built SD model

Variable	Equation	Function
Customer order (C)	A probabilistic input	Variable representing the uncertainty of placed orders
Products desired shipment rate (M)	Equal: Customer order (C)+Backlogged orders (M)	Variable describing the volume of the products needed to be shipped
Shipment rate gap (M)	IF THEN ELSE (Condition, 0, Products desired shipment rate-Products shipped)	Variable returning the first value if condition is true; the second value if condition is false
Product inventory (M)	INTEG (input data of Products manufactured (M) – exit data of Product shipment rate (M)	Variable representing an accumulation of the products
Backlogged orders (M)	INTEG (input data of Shipment rate gap (M)-exit data of Backlogged orders shipment rate (M))	Variable representing the volume of the backlogged orders in current situation
Logistics department shipment capacity (M)	Min (Min (Infrastructure capacity, Equipment capacity), Workforce capacity)	Variable describing the maximum capacity of transportation system
Products manufactured (M)	DELAY FIXED (input WIP, delay time-Reacting time (M), 0)	Returns the value of the input delayed by the delay time
Forecasted demand (M)	SMOOTH((Average demand(M)+ Variance demand (M)), Forecasting factor (M))	Variable depending on the forecasting method and forecasting factor
Raw material inventory (M)	INTEG (input data of Raw material shipment rate (S) – exit data of Raw material used to produce (M)	Variable representing the raw material inventory of the manufacturer
Raw material inventory (S)	INTEG (input data of Flow of material to	Variable representing the

	supplier (S) – exit data of Raw material shipment rate (S)	accumulation of raw material in the supply sector
Backlogged orders (S)	INTEG (input data of Shipment rate gap (S)-exit data of Backlogged orders shipment rate (S))	Variable representing the volume of the backlogged orders in the current situation
Logistics department shipment capacity (S)	A flow variable defined based on the description of the case	Variable describing the capacity of transportation system in the supplier sector
Time step	1 week	Variable indicating the simulation step
Simulation period	50 weeks	Variable representing the total simulation steps

Note: C - Customer; M - Manufacturer; S – Supplier.

The applied SD technique is a scenario-based simulation method, that the initial value of the system should be defined in the baseline scenario (Bouloiz *et al*., 2013). In this research, the simulation time step is set as 1 week, and the simulation period is defined as 50 weeks. The simulation process begins when the customer places an order, which follows a specific distribution. The system operations are simulated and system behaviour is addressed to provide a baseline for comparing the risk effects in different risk scenarios. However, the historical data of CSC risks is often unknown, and therefore the risk input data is obtained from expert judgements in estimating the dynamic risk effects. To rationalise the judgements, the Delphi technique is employed to quantitatively investigate the risk attributes in terms of *LO*, *CS* and *CP*. Nine-point Likert scale is adapted to investigate the level of agreement of each question from the respondents. And then, the obtained numerical number should be normalized into an accurate numerical percentage. The *LO* and *CP* indicate whether the risk or the risk consequence will materialise. Therefore, the normalized number should be scaled into [0, 1], in which 0 means never happen and 1 means always happen. A set of functions is developed to generate the risk magnitude of a hazardous event:

$$Random\ number\ 1 = RANDOM\ UNIFORM(0, 1, 50) \quad \text{Eq. 6.1}$$

$$Random\ number\ 2 = RANDOM\ UNIFORM(0, 1, 50) \quad \text{Eq. 6.2}$$

$$\text{Hazardous event occured} \quad \text{Eq. 6.3}$$

$$= \begin{Bmatrix} \text{False, Hazardous event occurrence likelihood } (LO) \leq \text{Random number 1} \\ \text{Ture, Hazardous event occurrence likelihood } (LO) > \text{Random number 1} \end{Bmatrix}$$

$$\text{Consequence occured} = \begin{Bmatrix} \text{Ture, Consequence probability } (CP) \leq \text{Random number 2} \\ \text{False, Consequence probability } (CP) > \text{Random number 2} \end{Bmatrix} \quad \text{Eq. 6.4}$$

$$Hazardous\ event\ magnitude = \text{Hazard event occured} \times \text{Consequence occured} \times \text{Consequence severity } (CS) \quad \text{Eq. 6.5}$$

where Eq. 6.1 and Eq. 6.2 produce two random numbers, which are between 0 and 1. The simulation period is set as 50 weeks, so that there are 50 different number generated over time. When the generated number is larger than the value of *LO*, the output of Eq. 6.3 is true that indicates that the hazardous event happens. Conversely, the output of false represents that the hazardous event does not occur. Similarly, Eq. 6.4 represents whether the affected variable suffers the given magnitude of the *CS*. Eq. 6.5 shows that the hazardous event magnitude is established upon the particular risk features in terms of probability and consequence severity ($LO \times CS \times$CP). It incorporates time as a variable that assists the generation of hazardous events and estimates the risk consequence affecting the CSC system in practice.

6.1.3 Model validation

As suggested, the correspondence of the model structure and the robustness of the model behaviour need to be verified in both the normal and abnormal conditions. Comparing the simulated system behaviours against the anticipated behaviours, the confidence of the built model is obtained. Then, it can be employed to investigate the dynamic system behaviours in a series of risk scenarios and risk reduction scenarios. In the SD model validation study, three rigorous tests involving both quantitative and qualitative methods are suggested: Structure and parameters verification; Dimensional consistency examination; and System testing under extreme conditions (Barlas, 1994).

(1) Structure and parameter verification

In the first step, the model validation focused on the examination of the internal structure of the model, instead of verification of the system behaviour. It is claimed that an SD model is developed based on the causal relations, thus the represented cause and effect variables should coincide with the practice (Peterson and Eberlein, 1994). Following this principle, the model was tested through comparing the variables and equations against the existing literature and the available knowledge of the experts.

(2) Dimensional consistency examination

The dimension consistency verification was carried out to check whether the dimension of each variable was properly set. The applied software providing a powerful dimensional calculation function helped verify the dimensional consistency of the model by tracking their fundamental dimensions as performed calculations. The screenshot depicts the operational interface of the Vensim© as seen in **Figure 6.4**.

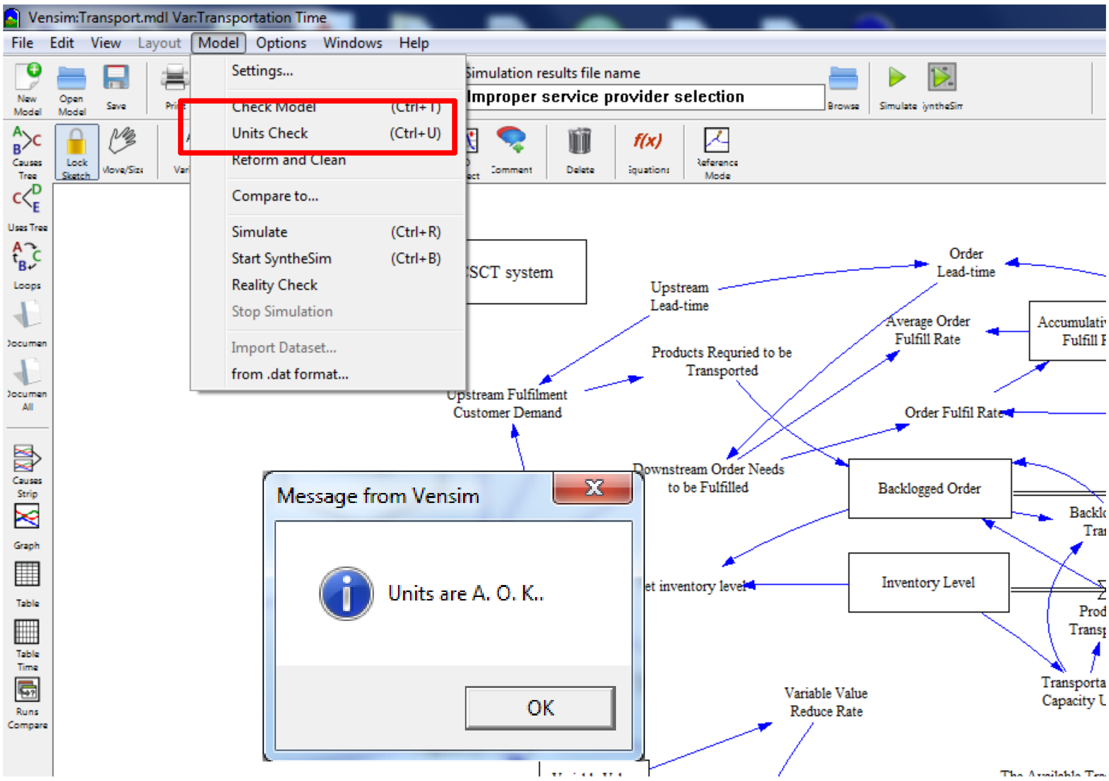
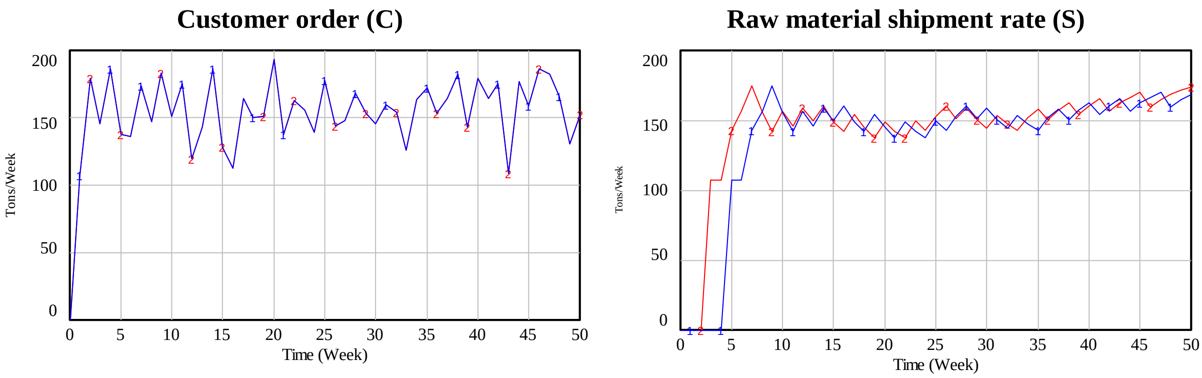


Figure 6.4. Dimensional calculation in Vensim© software

The SD model was developed based on the logic interactions. Therefore, the dimensions could also be calculated according to the defined mathematical equations. The principle of dimensional homogeneity determined that only commensurable variables might be compared or calculated. For instance, the "*Transporter inventory level*" was calculated from the arrival flow of products from the suppliers (tons/week) and outflow of shipped products to the customers (tons/week) within a given period of time. Hence the dimensional unit of the "*Transporter inventory level*" should be defined as "Tons". In some contexts, there were dimensionless variables expressed as "dmnl", such as the percentages, risk input and risk effect. For instance, the order fulfilment rate was created to represent the reliability of a supply chain member to supply required products on time, thus, it was a percentage of shipped orders (tons) in relation to the order placed by downstream customer (tons). Based on the equation, it was calculated by tons/tons = "dmnl". In addition, the dimensionless variables did not affect the calculation of dimensional units in the equation.

(3) Extreme condition testing

The reliability of the developed SD model was verified through comparing the system performance under an extreme condition against the anticipated behaviour of the real system (Qudrat-Ullah and Seong, 2010). However, it is noteworthy that the test should focus on the logical results on the trend, frequency and fluctuation of the system performance, rather than to present a detailed mathematical outcome. Despite the size of model, all the concerned variables can be tested to verify whether the system behaviour matches the expected results. For instance, the "*Raw material lead-time (S)*" in the supplier sector is tested under an extreme condition. Poor transportation system, bad weather condition and other risk issues may cause disruption in delivery of raw material from the supplier's storage to manufacturer's one. The delay in raw material delivery postpones the arrival flow of raw material inventory and results in the gap of the raw material inventory in the manufacturer sector. To address the system performance under such an extreme condition, the delay of a raw material shipment from the supplier to manufacturer was set as 2 weeks, which equals to the initial raw material lead-time. Running the model, the system behaviour is observed as to how the developed system responds to the unexpected disturbance. **Figure 6.5** presents the obtained system behaviour under the testing scenario.



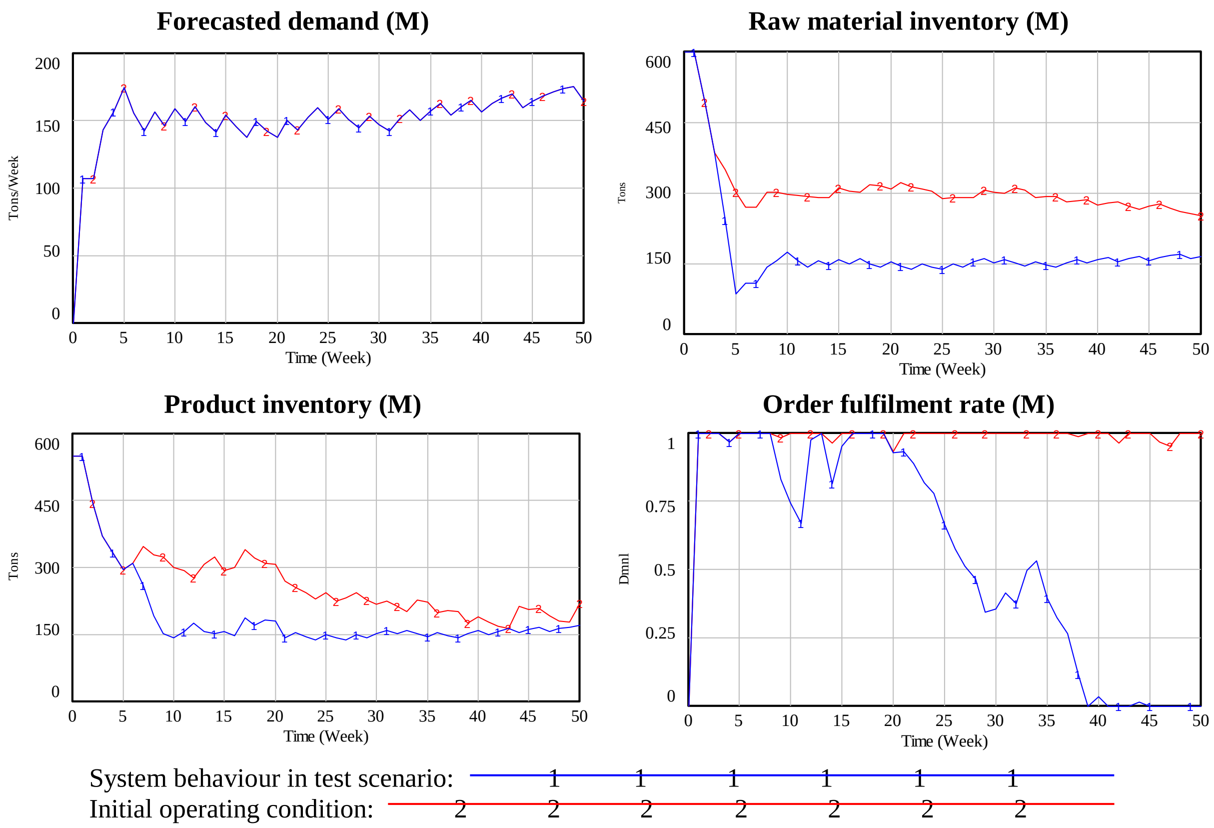
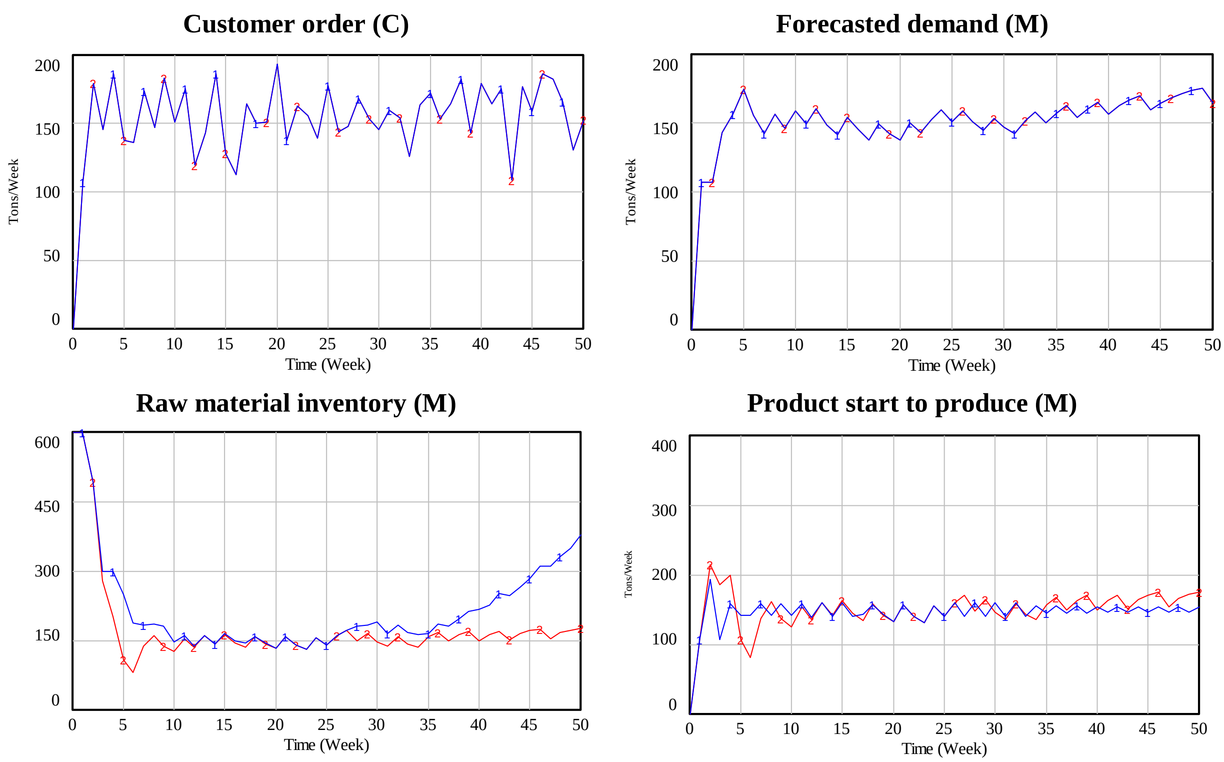


Figure 6.5. System behaviour under the testing scenario of supplying delay

In agreement with the setting, the raw material lead-time was extended to 4 weeks, which was twice that in the initial design. The delay of the raw material supply caused that the raw material inventory to drop to a low level until the shipped materials were received in week 5. The insufficient raw materials interrupted the production process, thus the products on-hand decreased. These were used to bridge the gap of the manufacturing delay. Compared with the initial simulation result, the inventory dropped following the simulation steps till week 7. Afterwards, the shipped products and arrival flow of products manufactured remained in a state of equilibrium. The product inventory maintained approximately 150 tons along the time axis. The time lag of raw material supplement affected the manufacturing activities which resulted in the failure to keeping pace with downstream requirements. According to the simulation results, the reduction of the average order fulfilment was forecasted to be 44.76% during the simulation period.

In the created model, “*Manufacturing capacity (M)*” is another significant variable, which reflects the ability of the manufacturer to produce the required number of orders within a certain period of time. If the number of placed orders exceeds the available manufacturing capacity in the system, the backlogs will appear and accumulate to a high level following the simulation steps. In order to verify this phenomenon, a reduction of total manufacturing capacity was set to exam how the built system responds to the unexpected change of the manufacturing capacity. In theory, the manufacturing capacity could reduce to 0 tons/week in the extreme condition. In this circumstance, the system operation was completely interrupted in that there were no products provided to the customer during the simulation period.

In order to extract a more meaningful explanation of the extreme condition verification, **Figure 6.6** presents the system behaviours under decreasing the initial manufacturing capacity by 25%. The No1# line presents the system performance under the testing of the reduction of manufacturers’ capacity to 75%, and the No2# line indicates the initial system performance.



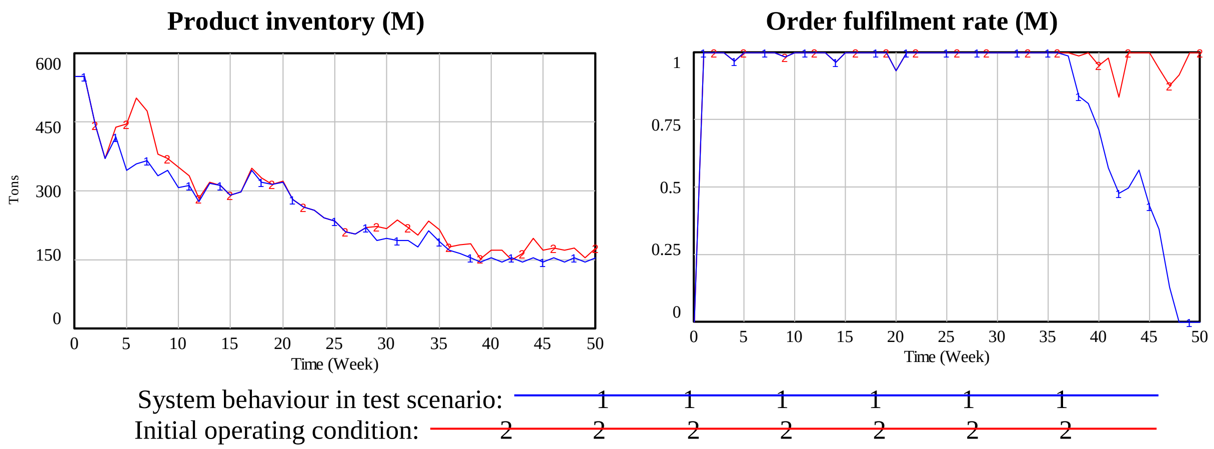


Figure 6.6. System behaviour under the testing scenario of manufacturing capacity shrinking

In the proposed condition, the placed orders and forecasted demands maintain the same level, because there do not have any cause and effect relations with the variable of *"Manufacturing capacity"* in the developed system. The manufacturing capacity shrinking put huge pressure on the CSC manufacturer to fulfil the customer demand. The materials waiting for production accumulated to a high level following the simulation step. It was designed that the manufacturing capacity was 300 tons in total and the products required to be manufactured were 150 tons/week on average. Coinciding with the expectation, the oscillation of the manufactured products in each week was smooth and reached a stable level over time. In addition, the stocked products in the early stage were exhausted, so that the backlogs appeared during the latter simulation period. According to the model description, the backlogs were prioritised, so that the shipped products were used to first meet the backlogs in the following shipments. The order fulfilment rate was produced as an expected result - decreasing to 0%.

6.1.4 Sensitivity analysis

In the model developing phase, the variable or parameter was set to a constant, which turned out the loss of variation. However, the dynamics played a significant role in risk modelling and analysing. To calibrate the developed model to fit in with the model developers' expectation, a number of behaviour representations were intended to confirm whether the small disturbances of designed variables lead to a significant variation in the system behaviours (Forrester, 1969; Moffatt, 1991).

Sensitivity analysis is provided to practically experiment with different parameter values. The shifting of the parameter value represents the sensitivity of the variable to the model behaviours, which can help the developer to find out where the sensitive variable is located and suggests where more effort that should be devoted. A Monte Carlo technique is combined with the SD modelling and simulation to investigate the uncertainty and randomness that yields new insights in risk simulation. It tends to follow a particular pattern: (1) Defining the inputs domain; (2) Generating the random inputs from a probability distribution; (3) Imposing a deterministic computation on the inputs; (4) Outputting the result (Robert and Casella, 2013). The repeated random samples will be generated based on a probability distribution and the simulation output will allow a more representative picture of model behaviours that contributes to the understanding of built system.

Vensim© software provides an integrated Monte Carlo technique to produce hundreds or thousands of possible outcomes, so as to investigate the sensitivity of the created system's variables/parameters. The interface to set up the required values is shown in **Figure 6.7**.

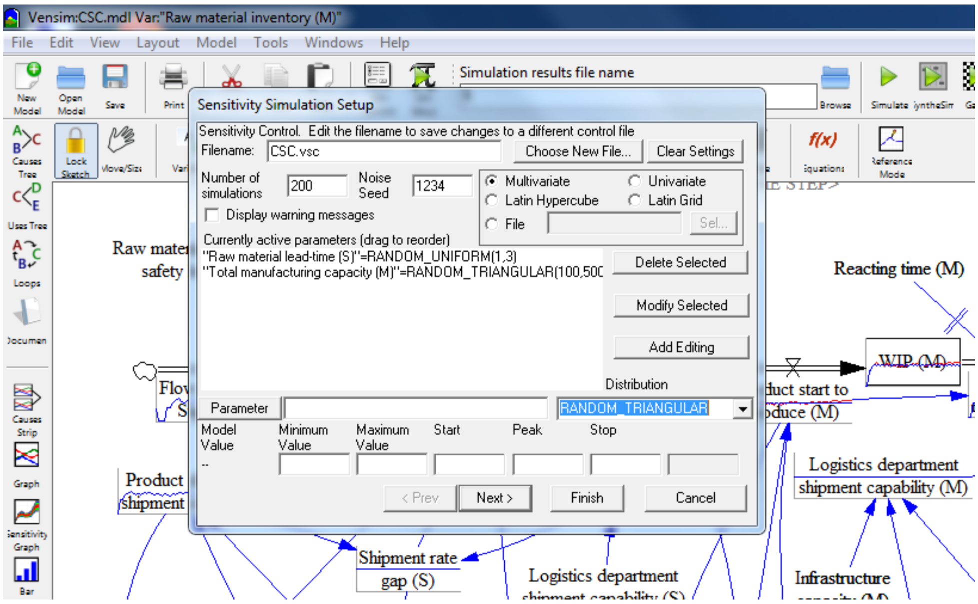


Figure 6.7. The interface of sensitivity simulation setup in Vensim©

A CSC system contains complex cause and effect interactions and dynamic feedback loops, so that oscillation is one of the frequently experienced behaviour modes (Hekimoğlu and Barlas, 2010). It is difficult to address the non-linear and cyclic behaviour patterns using statistical methods, but an SD-based sensitivity analysis offers a meaningful interpretation of the output behaviours. It is represented as a sensitivity graph that derives the tolerance interval of the outputs establishing upon all simulation runs. The assumption about the pattern of variability was analysed to exam the sensitivity of the interested objects. An example of sensitivity analysis was considered for the impact of the "*Manufacturing capacity*" variation. It was intended to address the oscillation of the system behaviour for a given probability distribution. The input of sensitivity analysis was set as a random triangular distribution:

$$Value = Random\,Triangular\ (a, b, c, d, e), \qquad \text{Eq. 6.6}$$

where *a* refers to the minimum value, *b* suggests the maximum value, *c* indicates the lower limit , *d* represents the peak value, and *e* shows the upper limit. The system generated numbers of noise seeds which are located in the triangle between the *c* and *e* with the peak at *d*. In this simulation, the "*Total manufacturing capacity*" was set as a *Random Triangular* (0, 600, 200, 400, 500) with the associated dimension of tons. This function represented that the total manufacturing capacity is a continuous probability distribution with lower limit 200 tons, upper limit 500 tons in a triangular distribution with the minimum value 0 tons, the maximum value 600 tons, and the peak value 400 tons. The potential system behaviours under different conditional probabilities were highlighted in **Figure 6.8**.

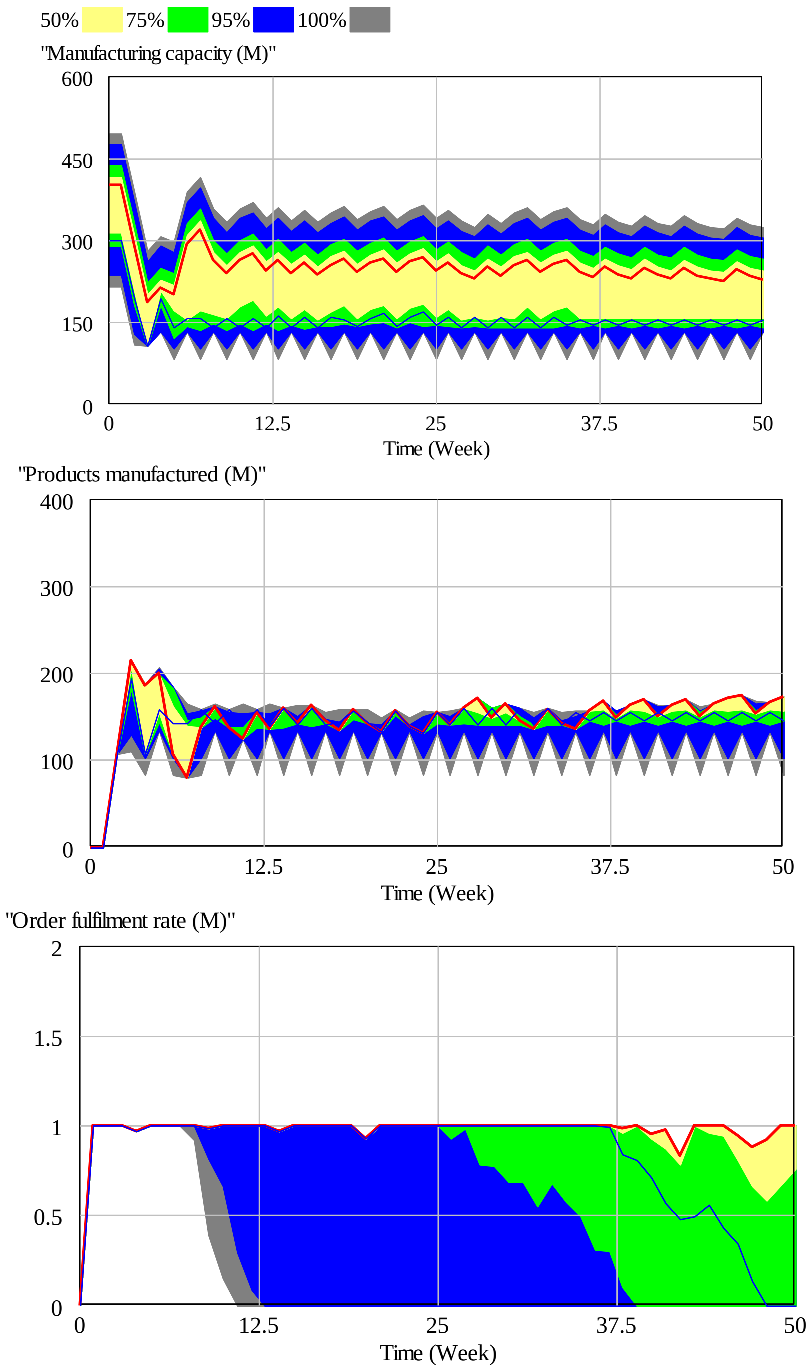


Figure 6.8. Sensitivity graph for "*Total manufacturing capacity*" variation

The developed SD model was believed to be capable of representing the changes in the behavioural pattern of a CSC system. Based on the simulation, it observes that a small disturbance of manufacturing capacity could lead to the significant variations in the system behaviours. In order to gain more knowledge on the developed model, more sensitivity analyses were conducted with different parameter distributions. In the built model, there were 9 exogenous parameters, which governed the changes of interrelated variables. In order to explore the sensitive elements, these variables were set as the input parameters in different sensitivity simulation scenarios. The analysis was performed with the assumption that the parameter values were uniformly distributed within $\pm 50\%$ range of base values. Parameter distributions setting of sensitivity analyses are given in **Table 6.2**.

Table 6.2. Parameter distribution setting of sensitivity analysis

Parameter Name	Model Value	Range	Distribution
Raw material lead-time (S)	2	[1-3]	Random uniform
Raw material inventory safety level (S)	500	[250-750]	Random uniform
Logistics department shipment capability (S)	800	[400-1200]	Random uniform
Total manufacturing capacity (M)	400	[200-600]	Random uniform
Reacting time (M)	1	[0.5-2]	Random uniform
Equipment capacity (M)	180	[90-270]	Random uniform
Infrastructure capacity (M)	800	[400-1200]	Random uniform
Workforce capacity (M)	180	[90-270]	Random uniform
Forecasting factor (M)	0.2	[0.1-0.3]	Random uniform

Iterating the described SD modelling procedures and conducting sensitivity analysis, the simulation outcomes are given in **Table 6.3**.

Table 6.3. Results table of sensitivity analysis of the built CSC model

Parameter Name	Range of Order Fulfilment Rate (S)	Range of Order Fulfilment Rate (M)
Raw material lead-time (S)	[92.16%-96.08%]	[56.26%-97.55%]
Raw material inventory safety level (S)	[12.15%-94.12%]	[37.88%-96.72%]
Logistics department shipment capability (S)	[94.12%]	[96.72%]
Total manufacturing capacity (M)	[94.12%]	[14.92%-96.72%]
Reacting time (M)	[94.12%]	[17.15%-96.72%]
Infrastructure capacity (M)	[94.12%]	[96.72%]
Equipment capacity (M)	[94.12%]	[2.45%-96.72%]
Workforce capacity (M)	[94.12%]	[2.45%-96.72%]
Forecasting factor (M)	[94.12%]	[62.48%-97.55%]

Interestingly, the variation of the parameters in the manufacturer sector rarely affected the supplier's performance, while the changes of the upstream parameters could bring significant impacts to the downstream members. The reason was that there were no reverse loops between the manufacturer and the supplier in the developed model. The sensitivity analysis results table suggests that 2 of the 9 parameters had very limited effect on the system performance, while the others - "*Raw material lead-*

time (S)", "*Raw material inventory safety level (S)*", "*Total manufacturing capacity (M)", "Reacting time (M)",* "*Equipment capacity (M)*", "*Workforce capacity (M)*", and "*Forecasted factor (M)*" were sensitive to the developed CSC system. In these variables, the changes of the input value to an extent can lead to the variations of the system behaviour. Hence, more attention should be paid to these variables during the model developing and validation phase.

6.2 RISK SCENARIOS SIMULATION AND ANALYSIS

SD modelling is employed to describe the connections between the risks and their associated changes of the system behaviours. It is a scenario-based analytical method in which the risk with a set of risk attributes is defined as an input to the model. Through establishing different risk scenarios and setting specific risk input, the SD model is capable of representing the generating mechanism of all the concerned risks.

6.2.1 The results of the base case behaviour

The CSC system behaviour was obtained as the baseline through simulating the system operations under the initial operating condition. It was then used for benchmarking the comparison of the risk impacts under different risk scenarios. The key behaviours of the developed system are shown in **Figure 6.9.** In the developed system, a series of random numbers are generated between 100 and 200 based on the defined distribution that represents the dynamic of the customer demand. Using the previous order data, the demand forecasting is carried out to predict the next term downstream orders. In this arrangement, it makes the fluctuation smooth and narrows the gaps between forecasted demand and placed orders over time. Based on the forecasted demand, the members involved in the supply chain arrange the sourcing, producing and other operational activities.

The manufacturer places orders to its upstream supplier when the raw material inventory drops below a pre-defined safety level. It is assumed that the upstream members are capable of supplying the required the raw materials immediately when the orders are placed. Therefore, the "*Flow of raw* *material to supplier (S)"* is equal to "*Order placed to upstream supplier (S)"*. The order fulfilment rate indicates the reliability of a supplier to supply the required products on time (Chae, 2009). In the initial condition, the supplier offers sufficient materials to the downstream manufacturer, so that the "*Order fulfilment rate (S)"* is estimated to be 100% during the simulation period.

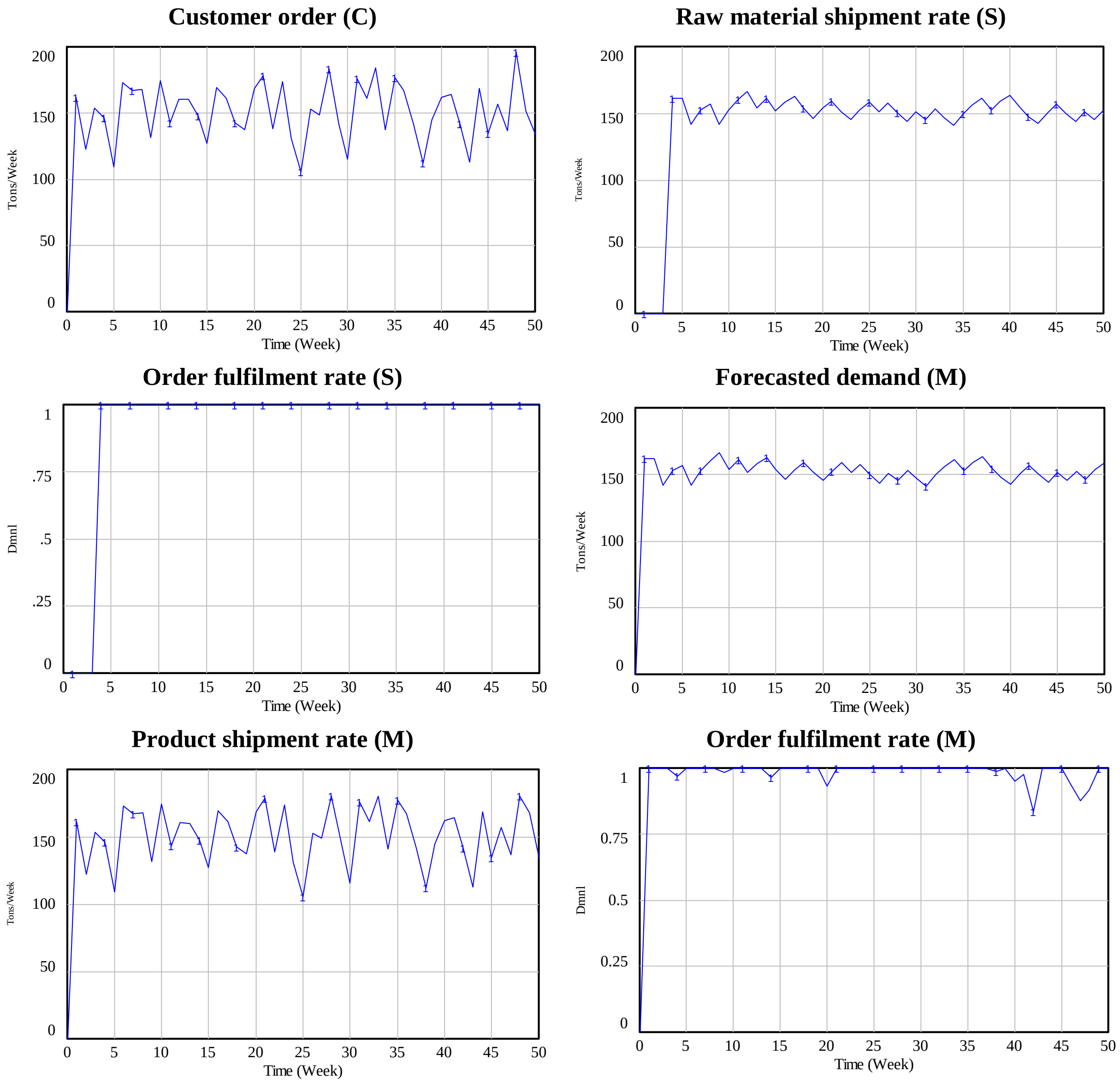


Figure 6.9. The behaviours of developed system in the base scenario

6.2.2 Risk scenario definitions and simulation results

One of the key contributions of the thesis is adapting the system thinking in CSC risk modelling and simulation to sequentially identify the CSC hazards, assess and reduce their associated risks within a changeable system. Based on the outcomes of Questionnaire One - the importance of hazards to the

CSC operations, the priority of the identified hazards are ranked over a population of respondents to illustrate the concerned hazardous events from industrial perspectives. Three typical risks are frequently experienced and mostly concerned by the risk managers or researchers, which are supply disruption, breakdown in the core manufacturing process, and unexpected changes in the customer demand. And then, Questionnaire Two are send out to collect a set of risk data (*LO*, *CS* and *CP*) that contributes to the generation of the input value of each risk scenario. Inserting the obtained risk attributes, the risk effects are quantified and the unacceptable risks are screened out through investigating the associated changes of the system behaviour on system thinking.

6.2.2.1 Scenario 1 - Supply disruption

Due to the geographic diversity of the involved members, a huge volume of chemical substances needs to be purchased and transported globally. The security problems, labour issues, political risk and others disturbances can be the triggers of the interruptions in the supply process (Achzet and Helbig, 2013). To investigate the risk impacts, the developed SD models can be properly amended to explore the associated changes of the system behaviour in a certain risk scenario. In this scenario, *LO* was set as 4.76, *CS* was assigned to 3.22, and *CP* was 2.78. Normalizing the obtained numerical risk data offer percentages of each risk attributes. The *LO* was evaluated as 16% in every supply activity, *CS* was assigned to delay the raw material shipment by 22%, and the forecasted *CP* was 57%. In particular, the *LO* and *CP* are the degrees of probability that indicate whether the risk or the risk consequence will materialise. Therefore, the obtained value should be normalized to the scale of [0, 1], in which 0 means never happen and 1 means always happen. To describe how the system performs under the developed risk scenario, an illustrative example is shown in **Figure 6.10**, which demonstrates the risk generation mechanism in the scenario of “Breakdown in core operations”.

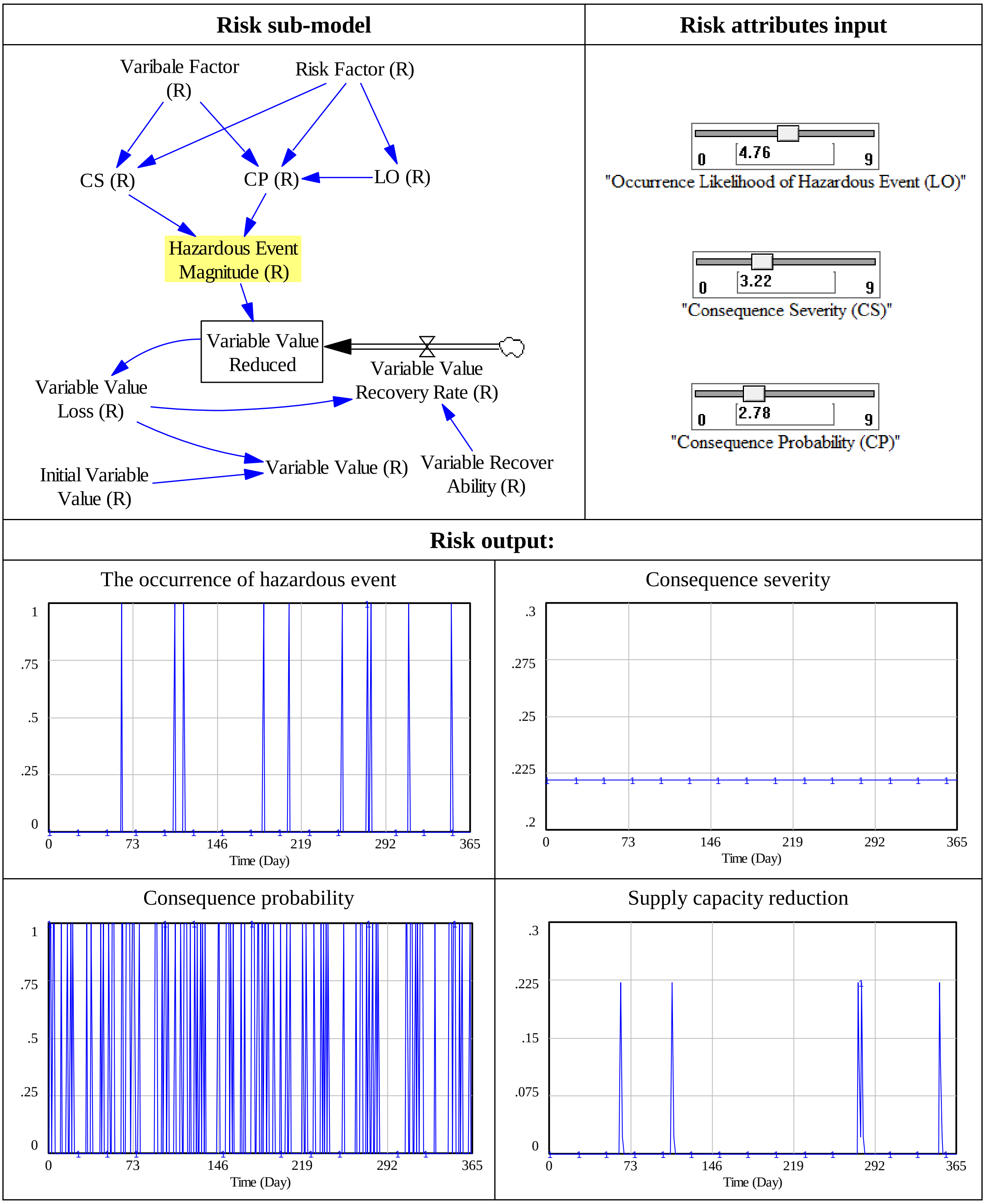


Figure 6.10. The risk generation in "Supply disruption" scenario

Linking the risk sub-model with the developed CSC model, the risk effects on system performance were addressed, as shown in **Figure 6.11**.

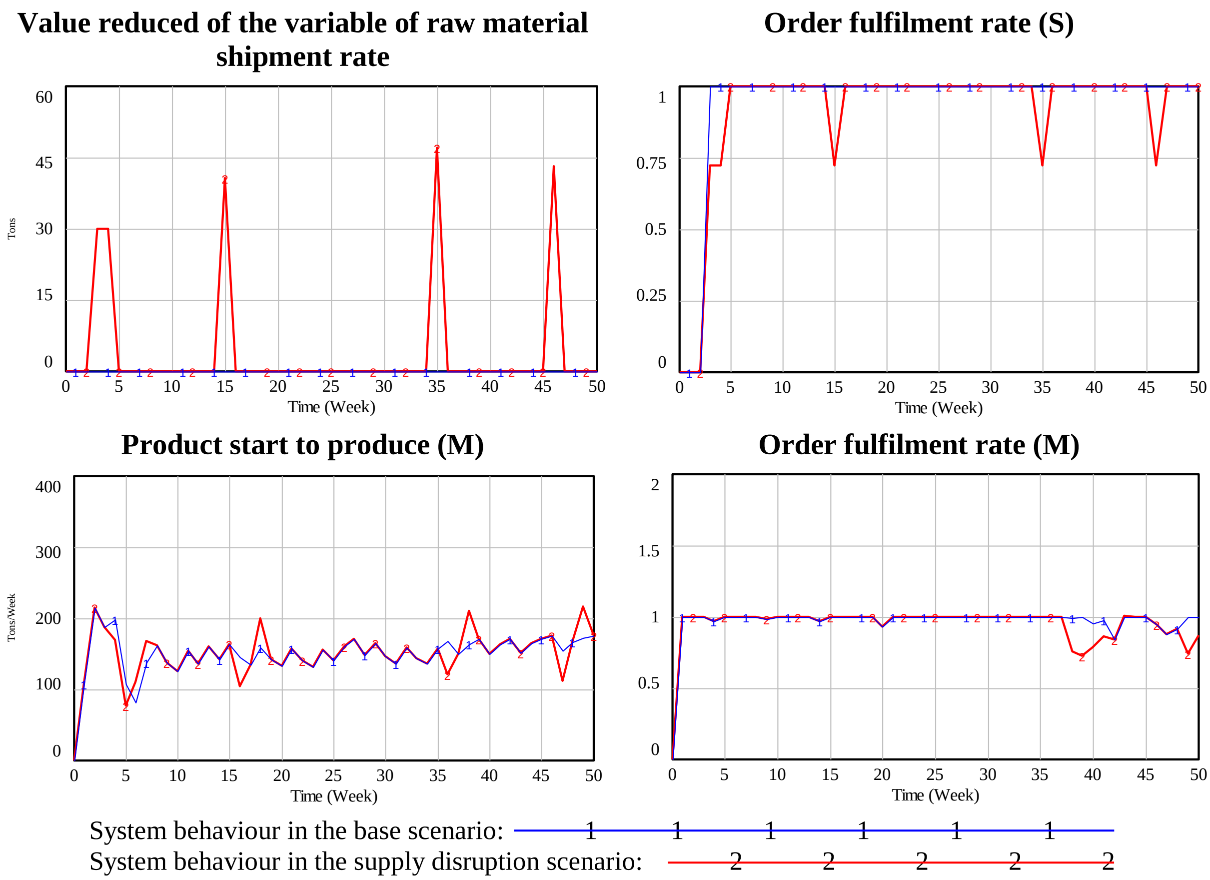


Figure 6.11. System performance in supply disruption scenario

The No#1 line illustrates the system behaviour under the initial operating condition, and the No#2 line shows the system performance in the supply disruption scenario. During the simulation period, the flow of supply operations is interrupted by the unexpected events five times, so that the supplier fails to fully fulfil the downstream demand. The "*Order fulfil rate (S)*" is forecasted to drop approximate 30% compared with the initial behaviour in the baseline scenario. It is interesting to observe that two consecutive hazardous events occur in week 3 and week 4, which postpone 60 tons of the raw material supplements. However, the manufacturing operation is not significantly affected by the supplement gaps. There are sufficient raw materials stored by the manufacturer, which can be used to maintain the production based on the schedule. In other periods affected by hazardous events, the amount of the "*Product start to produce (M)*" is reduced due to the insufficient raw material on hand. After receiving the delayed raw materials, a significant increase is observed in the following days that the manufacturing process is carried out to clear the backlogs. The late delivery of the raw materials further leads to the outflow of the system failing to maintain pace to the customer demand. The average "*Order fulfilment rate (M)*" is forecasted to decrease to 94.39%, which is 3% less than the initial value.

6.2.2.2 Scenario 2 - Breakdown in the core manufacturing process

In the CSCs, the manufacturing is always a complex system and the devices are often vulnerable. To ensure the safety, many CSCs stakeholders are keen on insights into novel technologies and competitive strategies to reduce the vulnerability and maintain the competitiveness (Markmann, Darkow and von der Gracht, 2013). However, a slight change in the CSC system may interrupt the production activity and cause huge losses in terms of time, cost and reputation. Breakdown in the core manufacturing process is regarded as a risk with a low probability but serious consequence, which poses significant challenge to the CSC operations. In this study, a scenario was developed to simulate the effects of this particular risk. The input value of the scenario was inserted into built SD model to investigate the risk affected system performance. It was an undeniable fact that huge efforts have been devoted to the manufacturing domain, thus *LO* was much lower than other risks. It was forecasted to be 4% per manufacturing process. However, the *CS* of the hazardous event was catastrophic. It was estimated to reduce the volume of manufactured products by 38% because of the batch formulation characteristic. *CP* was assigned as 51% when the hazardous event occurred.

Figure 6.12 shows the system performance in the proposed scenario. The No#1 line illustrates the system behaviour under the initial operating condition, and the No#2 line shows the system performance in the investigated scenario. Established upon the inserted risk attributes, the developed CSC system was affected by the hazardous events twice in this scenario, which were in week 7 and week 46. Furthermore, the severity of the consequence was critical, which directly caused a 49.79 tons and 106.04 tons decrease of the manufactured products in these period. The significant decreases caused the oscillations of the inventory system along the downstream of the supply chain. To recover from the disruptions, more products were manufactured in the following weeks, therefore the system performed back to the normal. "*Order fulfilment rate (M)*" was established to indicate the performance of the manufacturer satisfying the fluctuated requirements. In week 7, the manufacturer had sufficient inventories to fill the gap in manufacturing disruption, so that the "*Order fulfilment rate (M)*" maintained the same level as the base value. However, the hazardous event that occurred in week 47 caused serious consequences such that 22.5% of the orders were produced on time in the risk period. Under this circumstance, the average "*Order fulfilment rate (M)*" decreased to 90.97%.

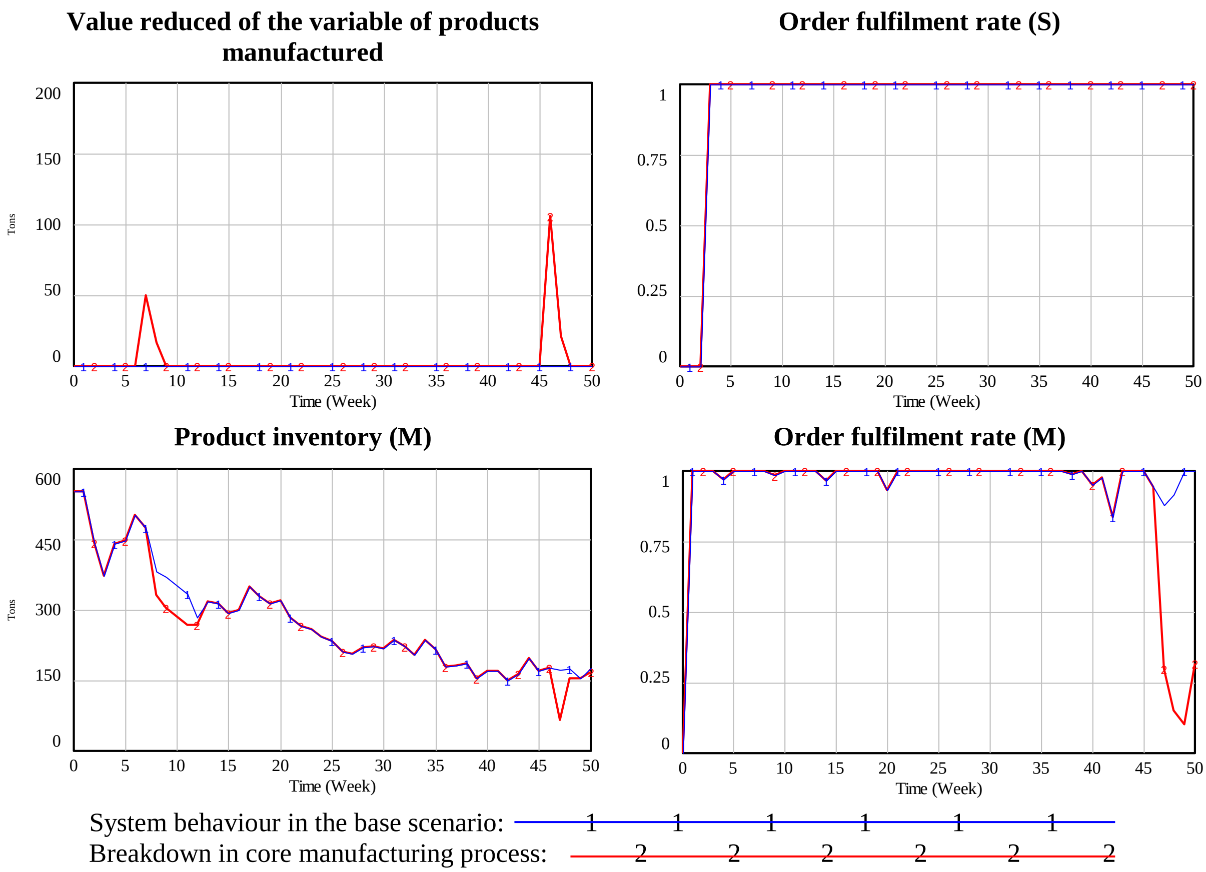


Figure 6.12. System performance in breakdown in core manufacturing process risk scenario

6.2.2.3 Scenario 3 - Unexpected changes in customer demand

The demand risk arises from downstream activities, which is specific to the possibility of an unexpected change of the orders. In practice, demand forecasting plays a significant role in the operations such that the supply chain members schedule the purchasing, manufacturing, transporting and other activities according to the forecasted demand. However, the mismatch between forecasted demand and actual demand obstructs the CSC from keeping pace with the customer requirements or increases the CSC inventory level. Risk modelling and simulation is required to address the impact of demand fluctuation and to continuously improve the system performance in this case.

In this study, the analysis focused on the risk in terms of increase of customer demand. Based on the expert judgement, the input values of this risk scenario were obtained: *LO* was inserted as 29%; *CS* was estimated to increase the initial value by 28%, whereas *CP* was set as 43% when the hazardous event occurred. Through running the developed SD model, the CSC system performance was obtained, as illustrated in **Figure 6.13**. The No#1 line illustrates the system behaviour under the initial operating condition, and the No#2 line shows the system performance in the scenario of customer demand increase.

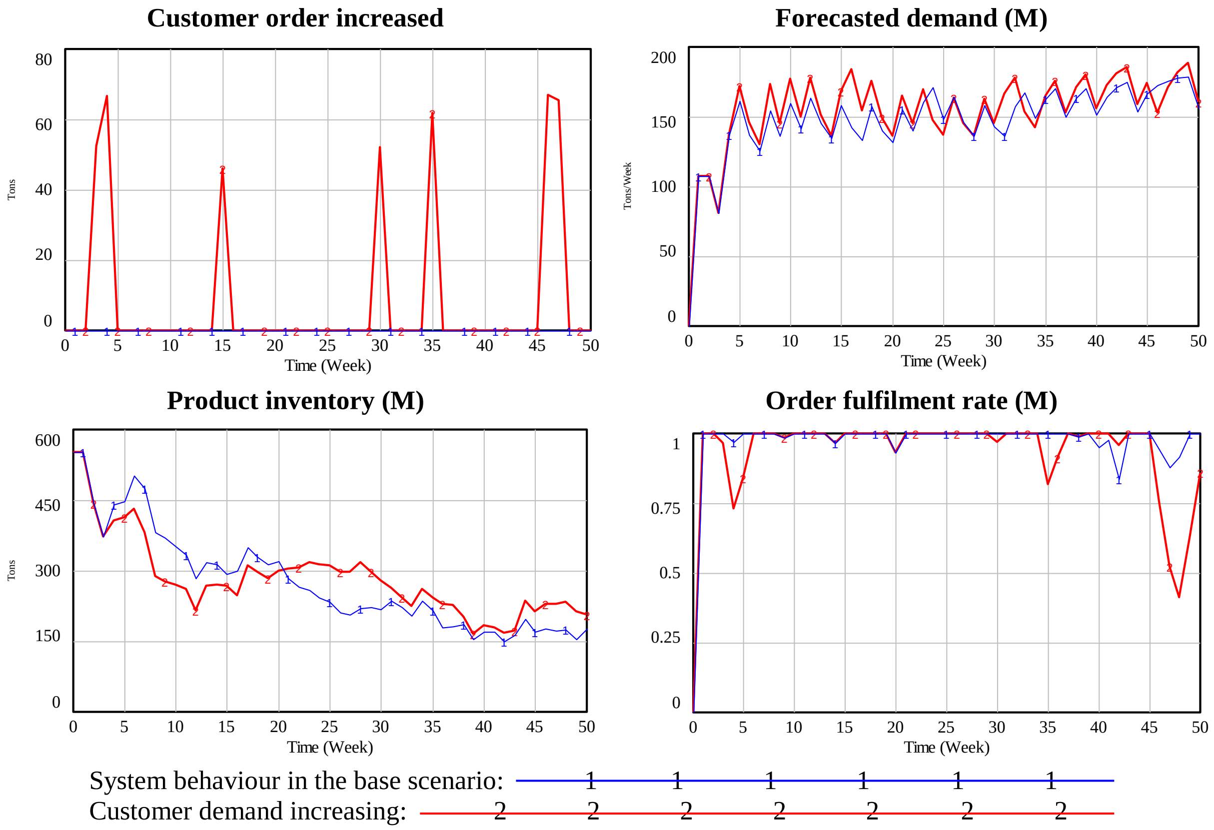


Figure 6.13. System performance in customer demand increasing scenario

It can be observed that the developed CSC system was affected by the unexpected accidents six times during the simulation period. The increased demand fluctuated between 45.9 tons and 66.8 tons depending on the placed order. In particularly, two consecutive hazardous events occurred in week 45 and week 46, so that "*Order fulfilment rate (M)*" decreased to 41.01% in these periods. The CSC system could not meet the suddenly increased demand due to the limited system capability. Therefore, "*Product inventory (M)"* consistently decreased in the first 21 weeks compared with the initial performance. However, the implemented forecasting method not only smoothened the oscillations of placed orders but also improved the mean of forecasted demand. The increase of manufactured products was accumulated following with the time step. Thus, the product inventory was estimated to hold up well against the base scenario.

6.3.2.4 Analysis of risk scenario simulation results

It was suggested that managing the CSC risks should first understand the source of risks, and then find a way of reducing the risk in probability and severity by having the proper action (Trkman and McCormack, 2009). The risk scenarios and associated risk attributes were proposed to investigate the risk effects from a whole supply chain perspective along the time axis. It is interesting to note that the obtained risk data show different characteristics. For instance, the risk of breakdown in the core operating process is rarely experienced. The reason is that the industry has devoted a lot of efforts to deal with it, so that the *LO* of these specific hazardous events is much lower than others. *CP* and *CS* are determined by the combination between the hazardous event and affected variable. There are different fitting results when selecting different variables, thus the simulation results are diversified.

The risk attributes illustrate the risk consequence on the affected variable along the time axis. It is regarded as a disturbance that can pass along the feedback chains, which are made up of the contained causal relations. The developed SD model incorporates risk attributes to the CSC system and accommodates the need to describe the connections between risks and their associated changes of system behaviour. In order to provide more meaningful insights, the system behaviours in different risk scenarios were addressed with the maximum, minimum and average values during the simulation period, listed in **Table 6.4**. In particular, the variation of the system performance between the risk scenario and the initial behaviours were highlighted to suggest the significant risk, shown as "Var.".

Table 6.4. The description of SD simulation results of proposed risk scenarios

	Order fulfilment rate (S) (dmnl)		**Raw material inventory level (M) (tons)**		**Products Inventory level (M) (tons)**		**Order fulfilment rate (M) (dmnl)**	
Scenario 1 - Supply disruption	Max	1	Max	600	Max	550	Max	1
	Min	0	Min	77.09	Min	110.72	Min	0
	Ave	0.9137	Ave	178.15	Ave	271.27	Ave	0.9439
	Var	**-0.0275**	**Var**	**0**	**Var**	**-4.23**	**Var**	**-0.0233**
Scenario 2 - Breakdown in the core manufacturing process	Max	1	Max	600	Max	550	Max	1
	Min	0	Min	80.13	Min	64.99	Min	0
	Ave	0.9412	Ave	181.93	Ave	267.64	Ave	0.9097
	Var	**0**	**Var**	**3.78**	**Var**	**-7.86**	**Var**	**-0.0575**
Scenario 3 - Unexpected changes in the customer demand	Max	1	Max	600	Max	550	Max	1
	Min	0	Min	80.13	Min	163.72	Min	0
	Ave	0.9412	Ave	183.65	Ave	282.98	Ave	0.9259
	Var	**0**	**Var**	**5.5**	**Var**	**-7.48**	**Var**	**-0.0313**

In CSC risk simulation, different risk impacts were addressed to indicate the variation in the system performance produced by varying the risk inputs. According to the simulation result, the hazardous event of breakdown in the core manufacturing process could significantly affect the CSC operations and result in more serious impact. The developed system failed to meet customer requirements in some simulation steps and the average order completion rate decreased to 90.97% during the simulation period. To respond to and recover from this challenging risk scenario, more effort should be spent to provide a cost-effective risk reduction package.

6.3 RISK REDUCTION SCENARIOS SIMULATION AND ANALYSIS

Risk reduction procedure represents the method to address the research objectives of dealing with the risks in CSCRM. The flexibility of the SD model modification provides a powerful tool to explore the effects of potential risk reduction methods. Two potential methods are provided to screen out advantageous risk reduction approaches, which are iterating the general SD modelling procedures and conducting sensitivity analysis, respectively. Applying the proposed methods, the created SD model is modified to fit in with the implemented risk reduction measure. Then, the system performances under different scenarios are estimated, thereby helping make the advantageous risk reduction decisions.

6.3.1 General risk reduction method

It is indicated that SD-based CSCRM decision-making does not require a decision-maker directly assessing different risks and providing arbitrary decisions based on past experience or historical data (Yeo, Pak and Yang, 2013). Instead, the expert just proposes potential reduction measures, and then the whole SD approach should be iterated to investigate the potential risk reduction outcomes. The flexibility of the SD model provides a powerful tool to investigate the dynamic system performance by appropriately amending the input of variables, re-defining the cause and effect relationships, and modifying the model structure under different scenarios. The variance of system performance is transparently presented, which suggests whether a particular risk reduction approach does indeed achieve the desirable objectives.

In this section, three scenarios suggested by the experts were demonstrated to illustrate the SD-based risk reduction method: improving manufacturing reliability, increasing resilience to risks, and outsourcing orders in risk affected situation. The conditions of each scenario are presented in **Table 6.5**.

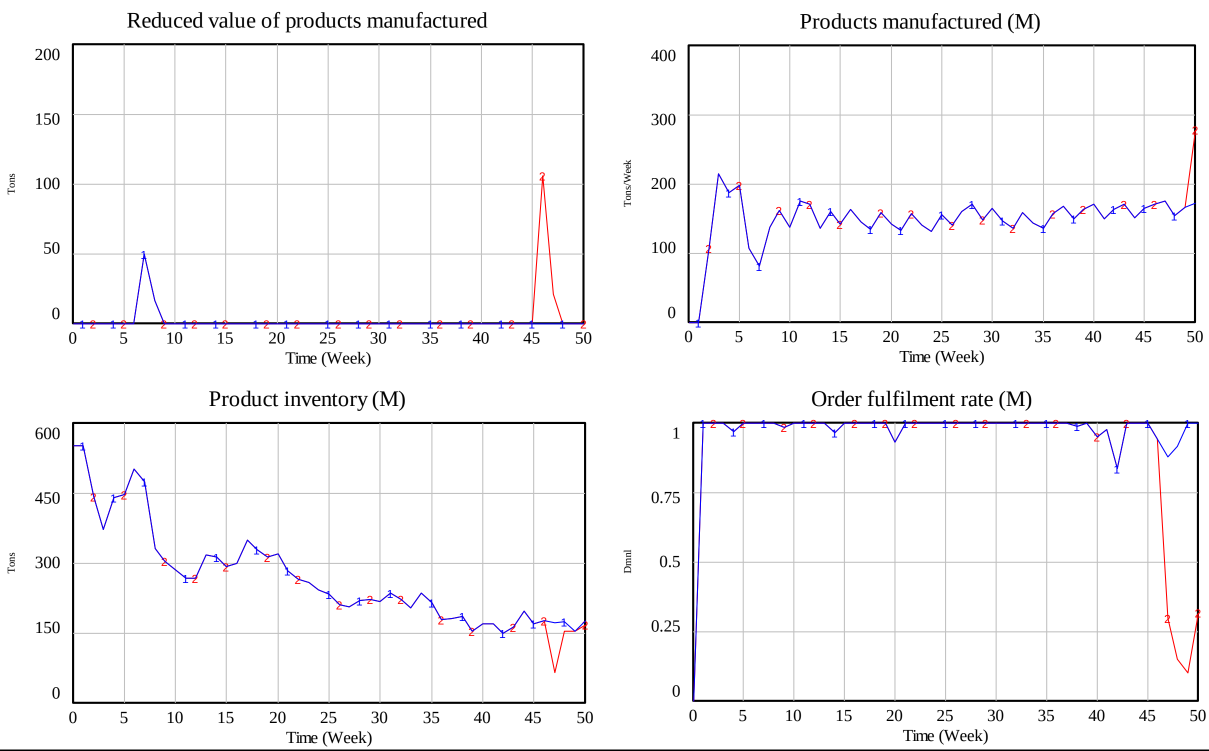
Table 6.5. Scenario conditions of suggested risk reduction methods

Case study	Related variable	Variable value set	Description
Scenario 1: Improving manufacturing reliability	Hazardous event occurrence likelihood	Occurrence likelihood (*LO*) decrease	Current situation: 8% Degree of decrease: 20% of current situation
Scenario 2: Increasing resilience to risks	Consequence severity	Consequence severity (*CS*) mitigate	Current situation: 62% Degree of decrease: 20% of current situation
Scenario 3: Outsourcing orders in risk affected situation	Adding new structure and associated variables	Outsourcing orders	Outsourcing maximum 20% of current ordering period

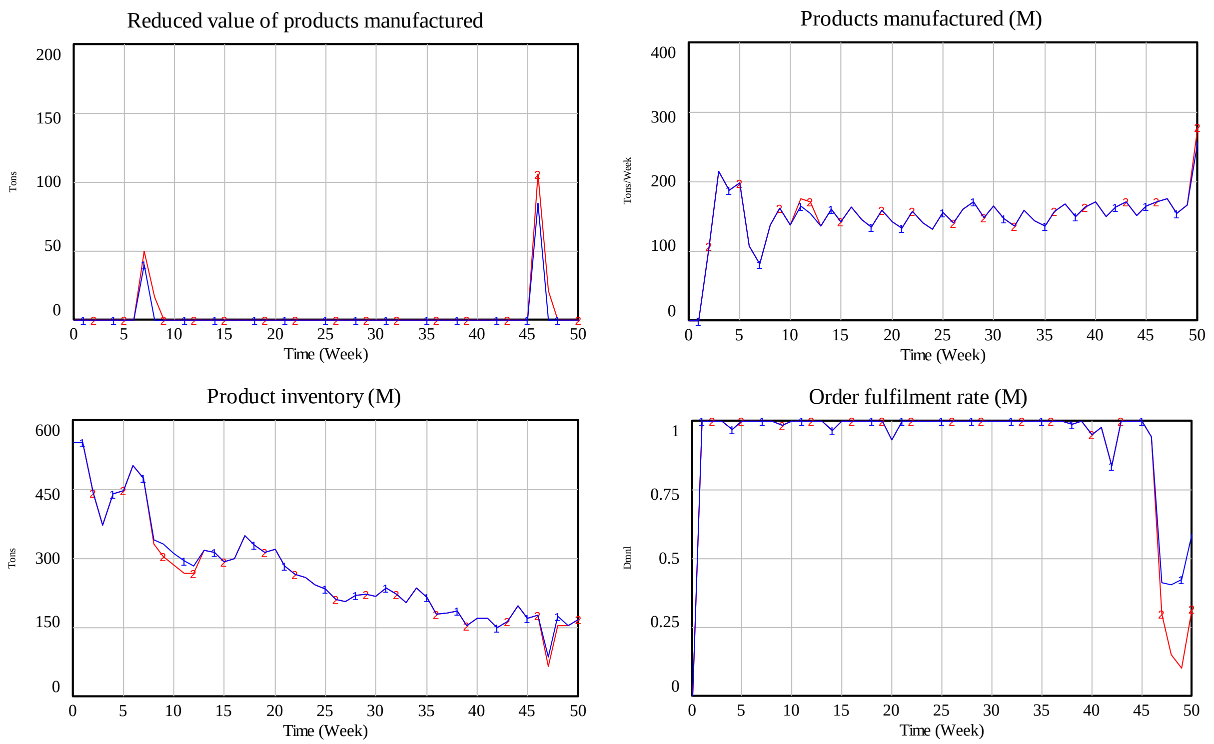
In each of the scenarios, the effects of implemented reduction methods were simulated by 20% variation of the base value, which was widely used to test the performance of implemented risk reduction approaches in the real world (Bouloiz *et al.*, 2013). In particular, the method of improving manufacturing reliability sought to experience a lower occurrence likelihood of the hazardous event. The measure of introducing the risk response method was intended to reduce the consequence severity of a hazardous event. The application of these two risk reduction measures could be achieved through modifying the inputs of the created variables without amending the model structure. On the contrary, the risk reduction method of outsourcing offered a scenario that required the model developers to modify the developed model and add new structural units. All the SD modelling approaches were iterated to explore the system performance in the proposed scenario.

Making revisions in accordance with the design ensured that the potential outcomes of implemented risk migration methods could be correctly observed. The simulation period was set as 50 weeks and the time step was set as 1 week. The simulation result of each risk reduction scenario is given in **Figure 6.14**.

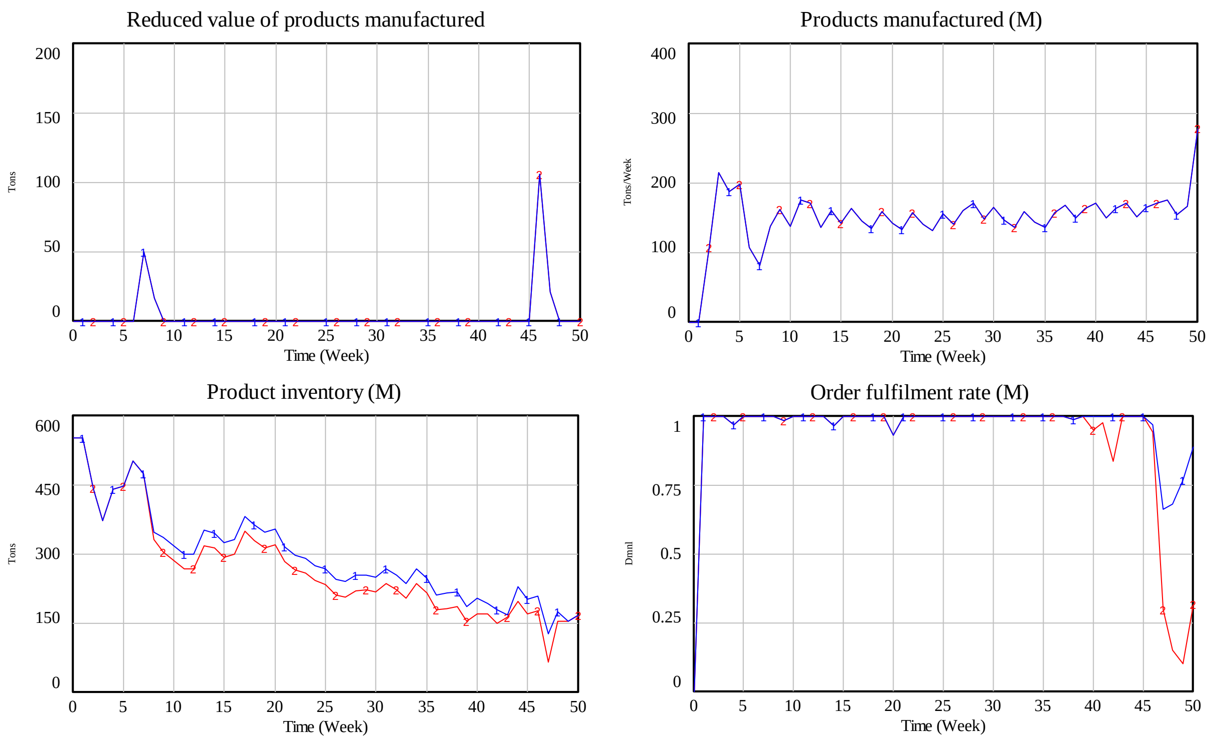
Case 1: Improving manufacturing reliability



Case 2: Increasing resilience to risks



Case 3: Outsourcing orders in risk affected condition



Risk reduction scenarios: 1 1 1 1 1 1 1 1
Breakdown in core manufacturing process: 2 2 2 2 2 2

Figure 6.14. System performances of suggested risk reduction scenarios

In improving the manufacturing reliability scenario, the implemented measure reduced the occurrence likelihood of the hazardous event, so that the hazardous event did not bring any disturbance to the CSC operations in week 46. In this circumstance, the system only needed to deal with the undesired disturbance in week 7. According to the simulation result, the system absorbs the negative risk impacts and the average “*Order fulfilment rate (M)”* improves to 96.72% in 50 weeks. In contrast, the reduction method of introducing the risk response method reduced the consequence severity instead of avoiding the generation of negative consequence. The simulation result suggested that the CSC system operations coincide with the scenario assumption. The system is interrupted by the hazardous events in week 7 and week 45 with the lower risk damaging values of 39.83 tons and 84.83 tons, respectively. In the circumstances, the average “*Order fulfilment rate (M”)* is forecasted to increase to 92.86% during the simulation period.

In order to respond to the two hazardous events, the outsourcing decision was applied to fill the gap in the manufacturing disruptions. Even though the produced products maintained the same quantity in the risk affected situation, the extra products sourced from outside could be used to meet the shortage because of damage. In this scenario, the average “*product inventory (M)”* is higher than other implemented risk reduction methods, which is estimated to increase to 292.97 tons in average. Accordingly, the increase of product inventory leads to the improvement of average “*Order fulfilment rate (M)”* to 95.68% over time.

The SD technique provides a systematic and flexible approach to evaluate the risk reduction decisions that may improve the CSC system performance. The addressed system behaviours in different scenarios could be benchmarked to reveal the gap between the expectation and the real-time performance, so as to suggest the beneficial reduction decisions. In order to provide the meaningful insights, **Table 6.6** extracts the numerical results from the SD simulation that depicts the system performance of each risk reduction scenario. The system behaviours in different scenarios were observed from the simulation results.

Table 6.6. Simulation results of suggested risk reduction methods

	The volume of damaged products (tons)	**The average manufactured products (M) (tons)**	**Outsourced orders in total (tons)**	**The average product inventory (M) (tons)**	**The average order fulfilment rate (M) (dmnl)**
Risk scenario	126.98	149.40	0	267.64	0.9097
Risk reduction scenario 1	**66.23**	**147.32**	**0**	**270.31**	**0.9672**
Risk reduction scenario 2	101.58	148.46	0	270.53	0.9286
Risk reduction scenario 3	126.98	149.40	87.62	292.97	0.9568

Comparing the indicators of the system performance, the risk reduction measure of improving manufacturing reliability achieved a better result. In this scenario, it not only provided a more reliable CSC system to deal with the hazardous events but also cut the production rate. As well, both the service level and the manufacturing cost had been led to a better record.

The proposed risk reduction method quantitatively analyses the system performance in different scenarios, instead of directly assessing the risks and providing the arbitrary decisions by experts. Establishing upon the flexibility of SD model modification, the model developers can insert different input values and amend the developed model structure throughout the life cycle specifically in design and operations phases. The obtained numerical results serve as supportive information for assessing potential risk reduction measures and continuously improving the CSC system performance. In further cost and benefit analysis, the developed SD model and obtained results can also be employed to estimate the equilibrium point between the investment and the benefit of CSCRM decisions.

6.3.2 Sensitivity analysis-based risk reduction method

As described in the model validation section (*Section 6.1.3*), combining the sensitivity analysis with SD simulation can be used to investigate whether a small disturbance of a designed variable brings a significant variation in the system behaviours. Using this method, all the concerned variables in the developed model can be tested regardless of the size of model, so that it offers a method to help the model developers to practically explore the possible risk reduction outcomes by testing the sensitive variables in the risky condition. The simulation results derive the tolerance interval of the outputs based upon all simulation runs, which is regarded as the range of the possible risk reduction outcomes. Comparing with the general SD-based risk reduction method describing in the previous section, it takes the advantage of observing the variations lying in the system behaviours instead of setting the variables or parameters as a static value.

In the sensitivity analysis, the first step is the input parameters identification and their distribution functions definition. The variations of different variables were performed with the assumption that the parameter values were uniformly distributed within ± 50% range of the base values. Using the identified parameters and their distributions given in **Table 6.2**, the sensitivity analysis was conducted to explore the sensitive variables in different risk scenarios. The simulation outcome of each parameter is given in **Table 6.7**.

Table 6.7. Results table of the sensitivity analysis in the risk reduction research

	Parameter Name	**Range of Order Fulfilment Rate (S)**	**Range of Order Fulfilment Rate (M)**
Scenario 1 - Supply disruption	Raw material lead-time (S)	[0.8996-0.9333]	[0.5468-0.9755]
	Raw material inventory safety level (S)	[0.0933-0.9137]	[0.3562-0.9439]
	Logistics department shipment capability (S)	[0.9137]	[0.9439]
	Total manufacturing capacity (M)	[0.9137]	[0.9439]
	Reacting time (M)	[0.9137]	[0.9439]
	Infrastructure capacity (M)	[0.9137]	[0.9439]
	Equipment capacity (M)	[0.9137]	[0.0245-0.9439]
	Workforce capacity (M)	[0.9137]	[0.0245-0.9439]
	Forecasting factor (M)	[0.9137]	[0.6094-0.9755]
Scenario 2 - Breakdown in the core manufacturing process	Raw material lead-time (S)	[0.9216-0.9608]	[0.5414-0.9755]
	Raw material inventory safety level (S)	[0.1088-0.9412]	[0.3398-0.9097]
	Logistics department shipment capability (S)	[0.9412]	[0.9097]
	Total manufacturing capacity (M)	[0.9412]	[0.9097]
	Reacting time (M)	[0.9412]	[0.9097-0.9697]
	Infrastructure capacity (M)	[0.9412]	[0.9097]
	Equipment capacity (M)	[0.9412]	[0.9097]
	Workforce capacity (M)	[0.9412]	[0.9097]
	Forecasting factor (M)	[0.9412]	[0.9097]
Scenario 3 - Unexpected	Raw material lead-time (S)	[0.9216-0.9608]	[0.5942-0.9268]
	Raw material inventory safety level (S)	[0.1156-0.9412]	[0.2994-0.9259]

changes in the customer demand	Logistics department shipment capability (S)	[0.9412]	[0.9259]
	Total manufacturing capacity (M)	[0.9412]	[0.9259]
	Reacting time (M)	[0.9412]	[0.5950-0.9259]
	Infrastructure capacity (M)	[0.9412]	[0.9259]
	Equipment capacity (M)	[0.9412]	[0.0245-0.9259]
	Workforce capacity (M)	[0.9412]	[0.0245-0.9259]
	Forecasting factor (M)	[0.9412]	[0.6925-0.9268]

In the different scenarios, the sensitive variables appeared to be various in the developed model. For instance, reducing raw material lead-time could bring a positive impact on order fulfilment rate when the manufacturing process was interrupted. The average "*Order fulfilment rate (S)*" was observed a significant improvement by 1.86% and the average "*Order fulfilment rate (M)*" increased to 97.55% over times. Similarly, the method of reducing reacting time could improve the flexibility of the manufacturing system and obtain a preferable system performance based on the results of sensitivity analyses. The proposed reduction method raised the average "*Order fulfilment rate (M)*" from 90.97% to 96.97% in the simulation period. However, the parameter of "*Reaction time (M)*" was insensitive to the developed system in the scenarios of supply disruption and customer demand increase. In this case, there is no need to consider the possible risk reduction method of amending this variable in further analysis.

6.4 CONCLUSION

This chapter describes the implementation of the SD modelling and simulation to analyse, evaluate and reduce the risks in CSCs. The proposed method is capable of representing the CSC operations and predicting the dynamic behaviours as the system changes under different risk circumstances. As well, it enhances the studying of the complex interactions between the CSC and the hazardous events, the dynamic feedback loops among the developed system, and the uncertain nature of the risks. It is particularly innovative, when being used to support risk management in a dynamic environment, compared to the traditional static risk analysis methods largely based on the experts' knowledge or the limited historical data. The expert intervention is applied to generate risk scenarios and corresponding risk reduction scenarios in the methodology. Through benchmarking the system behaviour in different scenarios, the risk generation mechanism is simulated and the risk effects are addressed. Furthermore, two potential risk reduction methods are suggested, which are established upon the general SD modelling procedures and sensitivity analysis method. In accordance with requirements, the developed SD model can be re-structured and updated to explore the outcomes of potential risk reduction solutions, which can assist the decision-makers to avoid direct management of the risks based on arbitrary decisions.

CHAPTER 7 CASE STUDY OF CHINA'S CHEMICAL SUPPLY CHAIN TRANSPORTATION RISK MANAGEMENT

Summary

This chapter presents the implication of the proposed SD-based CSCRM on a CSCT system. The case study helps to understand and improve the formalised causal relations and conceptual models developed in previous research. The applied SD model not only simulates the CSCT operations, but also predicts the dynamic behaviours as the system inputs change under different risk circumstances. Furthermore, the results of implementing the procedure of risk reduction will be discussed by taking the advantage of flexible model modification. The outcomes of different risk reduction approaches are compared to offer the decision makers an alternative CSCRM package.

7.1 CASE OVERVIEW

The case study used in this chapter is mainly from the annual report of a focal company - Guoqiang Logistics Company located in the Wuhan Chemical Industry Park in Wuhan City, China. The investigated specific CSC specialises in supplying, manufacturing, storing and delivering a certain kind of chemical substance for industrial use, which is essential to produce chemical products, such as polyethylene, ethylene propylene rubber and detergents (Li, 2014). Guoqiang Logistics Company has made its mark in Wuhan, China for over 15 years. It started up in providing energy in fuel and later on specialty chemical transportation service to the CSCs. To support the movement of the materials, multiple transportation modes are employed and highly technical, expensive and sophisticated transportation equipment is used during the transportation (Guoqiang Logistics Company official website, 2015). According to the report, it owns 20 special vehicles, each with a capacity of 20 units. These vehicles are used to deliver a certain kind of chemical substance to the downstream partner for industrial use, which forms the essential inputs to produce the chemical products, such as polyethylene, ethylene propylene rubber and detergents. The normal transportation time is 2 days and has a cost of $100 per unit (Li, 2014). It is interesting to note that the choice of transport feature could directly affect the capacity of a transportation system, whereby the infrastructure capacity and available transporter capacity are two important elements. In particular, the infrastructure capacity is determined by the selected route and external environment, while the capacity of a transporter can be controlled and managed by the transporter itself (Lahmar, Assavapokee and Ardekani, 2006). In order to manage the inventory and monitor the chemical transportation process, the company launched a new IT system to collect and share the information (Li, 2013). The inventory system is a significant part that manages the material flow in the supply chain. After receiving the orders from the customer, the chemical substances will be temporarily stored in a specified warehouse owned by the company. The gross storage capacity is 300 units and the storage cost is $10 per unit-day. The failure of the shipped products keeping the pace with the requirements leads to the backlogged orders. The delays in the transportation service flows add to the cost of transportation with an extra cost of $50 per unit-day (Li, 2014).

Due to the complexities and uncertainties, there is a huge pressure on the company to satisfy the customer within the requirements of shorter lead-times. The hazardous characteristics, such as extreme low storage temperature, high storage pressure, flammable and explosive, challenge the transportation activity. Furthermore, the competition, bad weather conditions, policy introduced, and other associated risks bring unexpected disruptions and result in the undesired effects on the CSCT system in terms of time, financial, and reputation aspects. The stakeholders and operators realise the importance of improving the safety and reliability in the CSCT system, to prepare for, respond to and recover from the risks.

7.2 SD MODELLING AND VALIDATION

SD modelling is employed to accommodate the need to describe the connections between the risks and their associated changes of the system behaviour (Hirsch, Levine and Miller, 2007). It enhances the studying of a complex CSCT operations, and then expands to a diversity of disciplines, which not only provides a valid description of the real system, but also reflects the interactions of hazardous event and managerial activities in this system (Sterman, 2000). Moreover, it offers a flexible model modification function to amend the built system in the design and operations phases, which is capable of helping decision makers to estimate the system performance under different scenarios and reveal the gap between the expectation and the real outcomes.

In the previous chapter, the development of conceptual CSC models and its associated risks are discussed following the provided SD modelling approach (shown in *Chapter* 5). The major interdependencies and feedback mechanisms in the investigated system are addressed, which provides a conceptual structure and understanding of the general CSC system. Referencing the developed conceptual models, the structure of the referenced models can be customised and the necessary variables can be added in line with the real situation. The proposed modelling and simulation research tests the experimental modelling set up for its viability and for bridging the gap between the theory and the practice. The risks inherent in the CSCT are quantitatively analysed, and the outcomes of alternative risk reduction decisions are systematically predicted. Four interlocking steps are described to develop an SD model including novel risk modelling, risk analysis and risk reduction approaches. These four aspects are: (1) developing an SD based CSCT model based on the cause and effect relationships within the system; (2) running the created SD model to investigate the risk effects of a variety of risk scenarios; (3) benchmarking the series of system performances that resulted from the initial situation and the risk scenarios to identify the critical hazards; and (4) providing flexible methods to explore the potential risk reduction methods and measure the outcomes of alternative risk reduction decisions.

7.2.1 Defining the causal relations between variables in risk affected CSCT systems

Following the application of the SD modelling approach, the assumed interactions between the system components are formalised and the temporal basis functions are set to represent the interdependences with more quantified information. Therefore, an SD model is developed to represent the structure of the system and reflect the dynamics of system behaviours due to contained feedback effects.

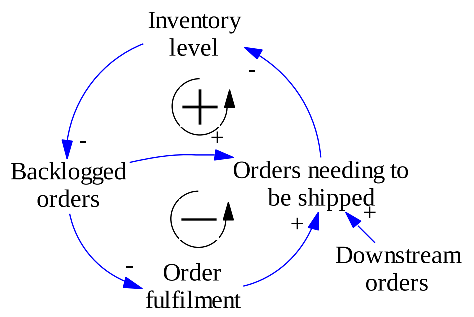
7.2.1.1 The impact of hazardous events

The study intended to address the dynamic impacts caused by the risks in a developed CSCT system. The risk experts and analysts helped identify the potential CSCT hazards to inform the construction of the model. Their experience was collated by questionnaire and set as the input values of the different risk scenarios. The formalised causal loop diagram of a hazardous event (shown in **Figure 5.12**) was adapted to address time-dependent risk impact, which took into consideration the observed probability and represented the risk consequence on the variable level. The existing causal relations and feedback effects amplified or corrected the change of variable that resulted in the variation of system performance. The applied SD modelling and simulation method accommodated the need to describe the connections between the diverse risks and the CSCT system and address the variation in the system behaviours and the changes under different risk circumstances.

7.2.1.2 The dynamic inventory system

In the CSC, large volumes of chemical substances are transported across the regional boundaries in response to periodic ordering (Reiskin, White and Johnson, 1999). Warehouse and special containers were used to store the chemical materials, but the features of immiscibility and incompatibility dictated that the containers could not be mixed during transportation and storage (Erera, Morales and Savelsbergh, 2005). The disruptions from the internal system or external environment could interrupt the transportation process and result in the decrease of service level. In particular, the inventory system could be significantly affected due to the existing feedback effects among the logical loops emerging from the interactive relations. A coordinated approach was necessary to manage the inventory level and improve the utilisation of the storage capacity (Manuj and Mentzer, 2008a). In order to address the generation mechanism of this phenomenon, the conceptual model of the inventory system (shown in **Figure 5.6**) was adapted to formalise the causal relations among the proposed CSCT system. To present the described causal relations using the SD modelling software, the causal loop diagram of the CSCT inventory system is shown in **Figure 7.1**.

The conceptual causal loop diagram of CSCT inventory system (As shown in Figure 5.7)	Customized causal loop diagram of CSCT inventory system



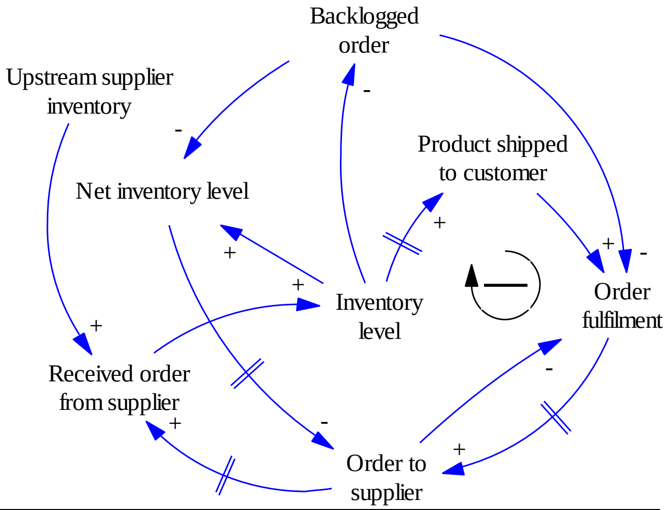


Figure 7.1. Causal loop diagram of the CSCT inventory system

From the completed goods inventory, the required products are shipped to the customers with a certain number of capacities. However, the failure of the shipped products keeping the pace with the requirements leads to backlogs. The delays in the transportation service flows could reduce the order fulfilment rate and damage the relationship with its suppliers. In the customized causal loop diagram, there is a feedback loop found in the diagram, which governs the changes in the inventory system. The developed model appears to be stable, and dominated by a negative loop (containing three of the negative relationships). Any actions that attempt to change the variables result in a self-correction of the system. As soon as the products leave the supplier's plant, they are on the company's inventory. When the products waiting for shipping exceed the maximum capacity, the materials cannot be taken over from the supplier until the capacity is released. The transporter inventory level is calculated by the arrival flow of products from the suppliers and the outflow of shipped products to the customers within a given period of time. If the shipped orders fail to keep pace with the customer demand, the backlog of orders will appear and a reduction in the order fulfilment rate can be observed during the simulation. The arrow with the symbol "||" is used to represent the delay in order processing, and a time lag between the interactive variables.

7.2.1.3 The dynamic transportation capacity

The capacity of a transportation system is particularly vulnerable in the event of a natural disaster, terrorism or other significant disturbances (Peng *et al.*, 2014). The infrastructure capacity is determined by the selected route and environmental factors, while the capacity of a transporter depends on the capacity of the available equipment and the size of the transporter's labour force within the CSCT system. The equipment capacity is created to describe the capacity of instruments, which refers to the ability of a transporter to respond to the dynamic orders. Meanwhile, a specified number of operators are required to handle the available equipment, so that the size of the labour force also needs to be managed. To represent these relationships, the CSCT capacity causal loop diagram is developed based on the conceptual transportation capacity sub-model (shown in **Figure 5.8)**. The structure of the referenced model was customised and the detailed information was addressed, as shown in **Figure 7.2**.

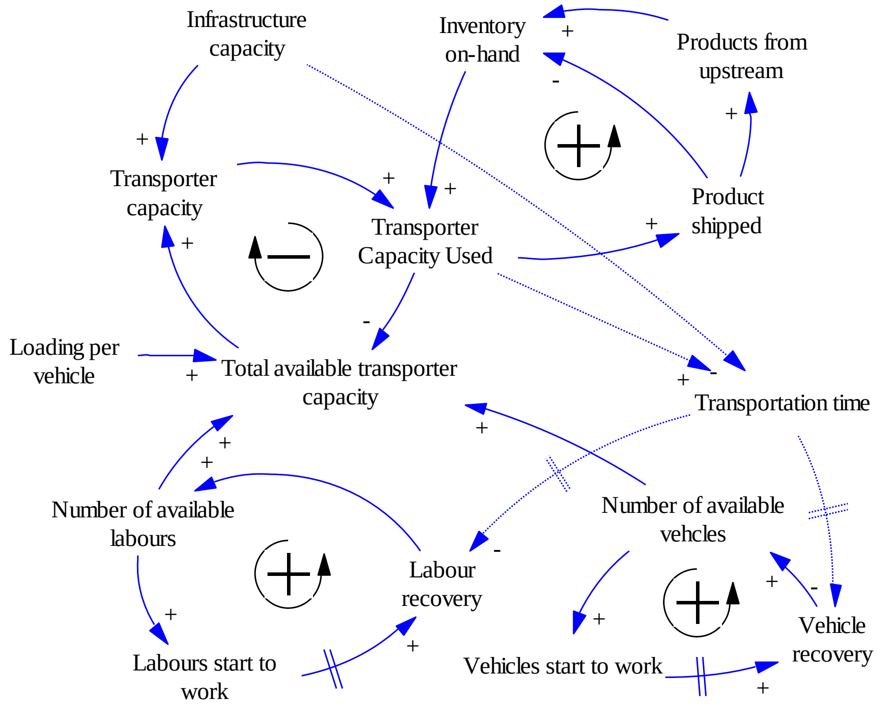


Figure 7.2. Causal loop diagram of the dynamic transportation capacity

In the developed causal loop diagram, two distinct loops were observed that represented the feedback effects related to the labour issue and transportation equipment capacity, respectively. The increase of equipment capacity and labour productivity could offer an extra capacity to the transportation system, which can be used to fill the transportation capacity gap in the risk scenarios.

7.2.1.4. Dynamic transportation time

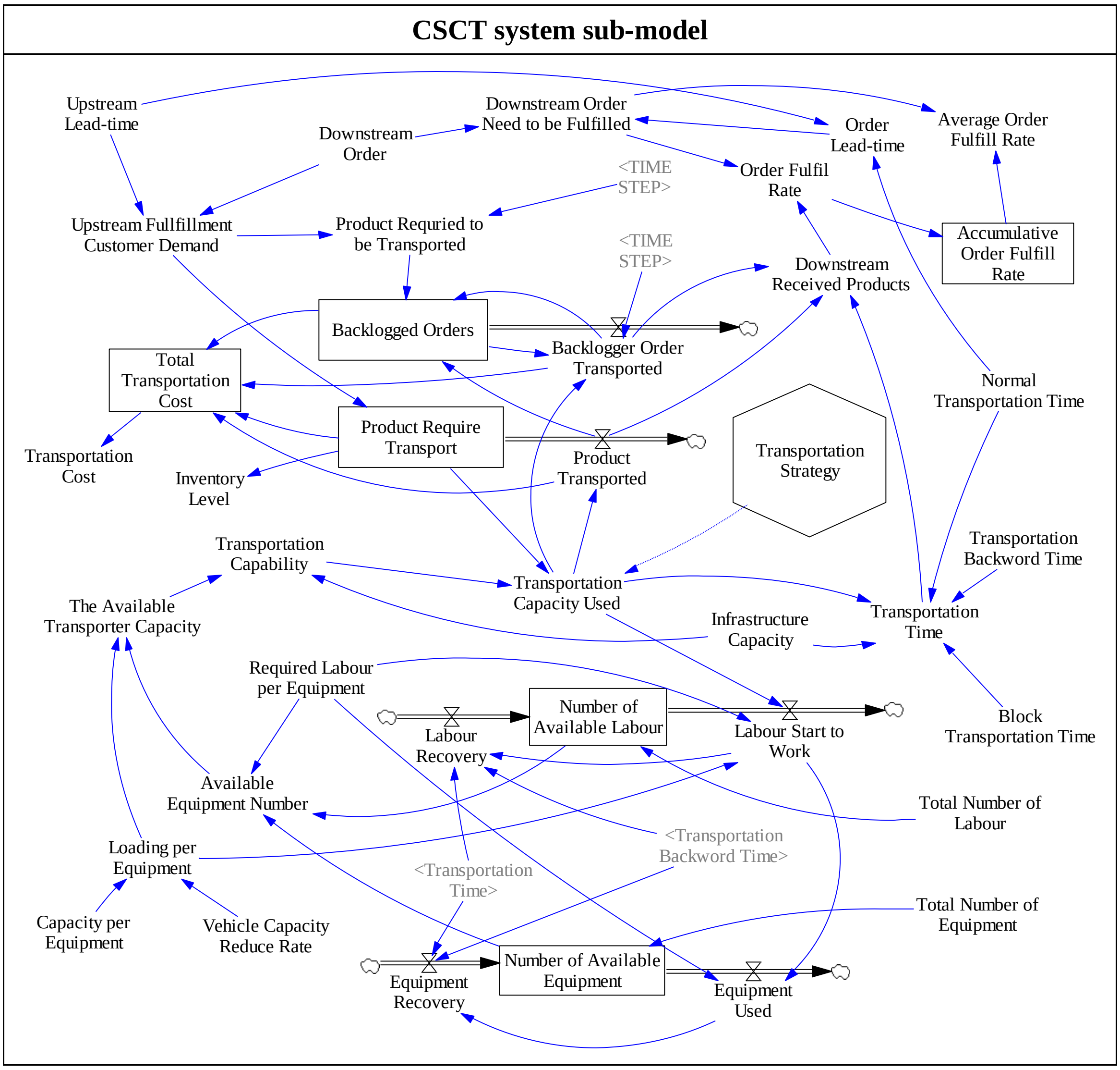
A hazardous event can interrupt the flow of CSCT operations and result in significant disturbance to the CSCT system. It is crucial to understand how the dynamic variables within the model evolve in response to time delays. The transport time can be calculated by Eq. 5.1 in transportation science. However, it is suggested that there will be an over- exaggeration when the ratio of *V*/*C* is larger than 1.2, so that the function utilisation is obstructed in conditions when infrastructure capacity sharply decreases. To fill this gap, a segment function is provided to estimate transportation time in the post-seismic supply chain (Peng *et al.*, 2014). The authors have tailored this segment function to ensure that it can account for the transportation time in a risk affected CSCT system, which is represented as:

$$T = \left\{ \begin{array}{c} T_{block,}\, C_t = 0 \\ (1+\partial)T_0, \dfrac{V_t}{C_t} \leq 1 \\ (1+\partial)T_0 \dfrac{V_t}{C_t}, \dfrac{V_t}{C_t} > 1 \end{array} \right\} \qquad \text{Eq. 7.1}$$

where T represents an operator-estimated transportation time. T_0 is described as the initial transportation time. V_t is the current volume of products in transit and C_t is the current infrastructure capacity. $C_t = 0$ represents that the transportation route is blocked, while T_{block} is the length of blockage time. ∂ is a factor describing the change of the initial transportation time when a hazardous event happens. Transportation time under different conditions can be estimated.

7.2.2 Developing stock and flow diagram of risk affected CSCT system

The causal-loop diagram is developed to represent both the interdependencies within the CSCT and the risk evolution mechanism. Referencing the developed conceptual SD models, the formalised causal loop diagram is converted to a stock and flow diagram. As described in the case, the supplier responds to downstream requirements by providing the requisite materials to the transporter, in the anticipation that the transporter has sufficient available capacity. The transportation capacity is determinate by the combination of equipment capacity, labour capacity and infrastructure capacity. The delays in the transportation service flows could damage the order fulfilment rate and add to the cost of transportation. To illustrate the inventory of materials, capacity of transportation system and transportation time, the developed conceptual transportation sub-model (shown in **Figure 5.15)** was customised and more detailed information was added in **Figure 7.3**. Meanwhile, the risk sub-model (shown in **Figure 5.18**) could be linked with the developed CSCT system sub-model that assisted the generation of hazardous events and estimated the risk consequence affecting the CSCT system in practice.



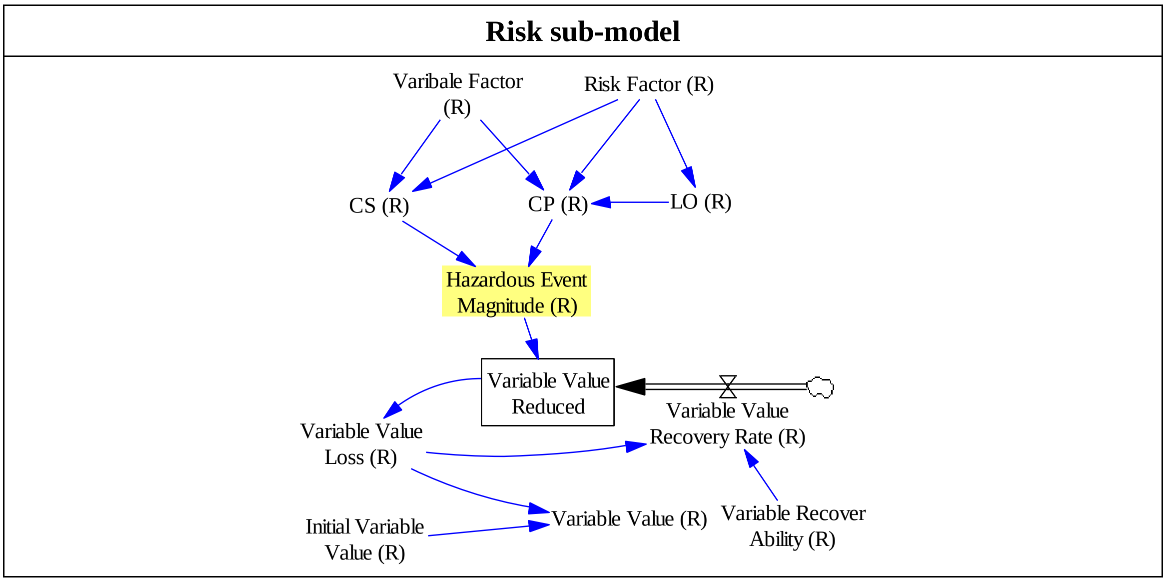


Figure 7.3. Stock and flow diagram of risk affected CSCT system

The variable in the rectangle is a stock, which is regarded as the structural element in the built model. In the diagram, the variables of inventory level, the quantity of labour and equipment, backlogged orders and variable values reduced are created as stocks to describe the accumulation of a material, information, or financial behaviour over time. A flow only passes the information that governs the change of stock. The developed CSCT model is a system that allows for the occurrence of a major incident, which disrupts the supply chain operations and impairs system performance. Control is used to describe the hazardous events that govern the changes of the CSCT model. **Table 7.1** defines the major variables used to build the SD model.

Table 7.1. Definition and role of major variables used to model the risk affected CSCT system

Variable Name	Definition	Function
Downstream Order	A probabilistic input	Variable assuming a kind of uncertainty
Upstream Fulfil Customer Demand	DELAY FIXED (input-Downstream Order, delay time-Upstream Lead-time, 0)	Returns the value of the input delayed by the delay time
Inventory Level	INTEG (input data of Upstream Fulfil Demand –exit data of Products Transported)	Variable representing the volume of the products needing to be transported
Backlogged Orders	INTEG (input data of Products Required to be Transported –exit data of Products Transported	Variable representing an accumulation of the backlogged products
Net Inventory Level	Equal: Inventory level – Backlogged Orders	Variable representing the volume of products
Products received	DELAY FIXED (input-Products transported, delay time-Transportation time, 0)	Returns the value of the input delayed by the delay time
Transportation Capacity Used	Min (Transportation Capacity can be used, Products Required to be Transport)	Variable representing the products transported with the

		maximum capability
Infrastructure Capacity	Depends on the selected route and environment condition	Variable affecting the value of transportation capacity
The Available Transporter Capacity	Depends on the operational capacity of transporter	Variable partly determining the value of transportation system capacity
Order Fulfil Rate	Equal: Products Received / Order needs to be fulfilled	Variable representing the rate of order completion
Random Number	RANDOM UNIFORM (0, 1, 365)	Generating uniformly distributed random varieties on the closed interval [0, 1]
LO	IF THEN ELSE (Random Number > Occurrence Likelihood of Hazardous Event Occurrence, 0, 1)	Variable active when the value of it exceeds Random Number
CS	Depends on the effects of hazardous event	Variable representing the impact of hazardous event
CP	IF THEN ELSE (Random Number > Probability of Consequence, 0, 1)	Variable active when the value of it exceeds Random Number
Variable Value Reduce	INTEG (input data of Variable affected by the hazardous event – exit data of Variable value recover rate)	Variable representing the level of variable affected by the hazardous event

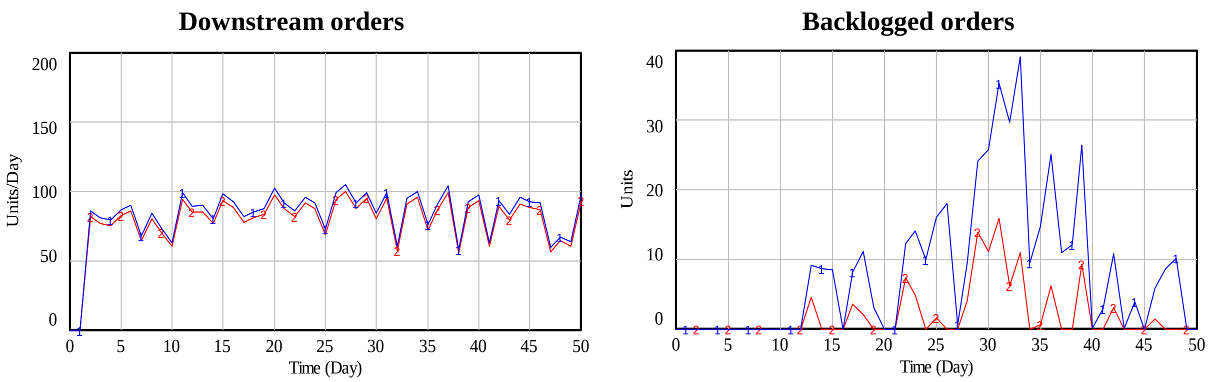
7.2.3 Model validation

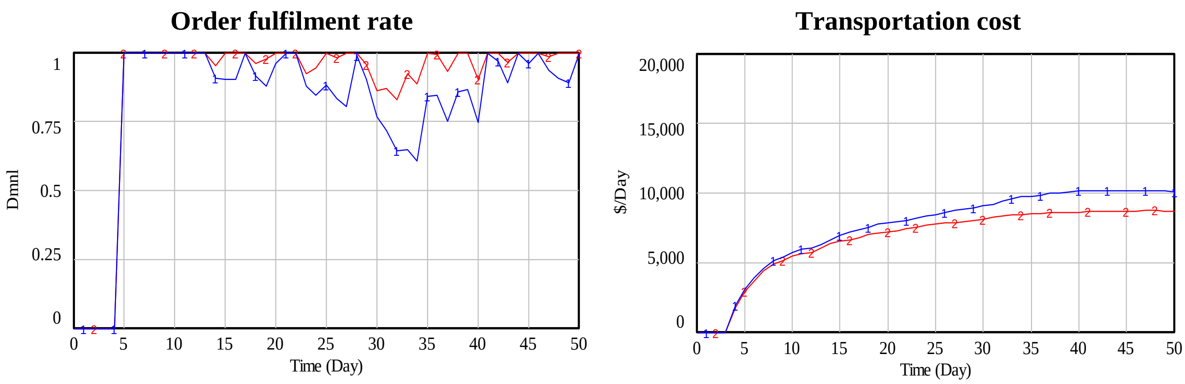
The developed SD model should be tested before carrying out experiments to simulate system operations (Qudrat-Ullah and Seong, 2010). The validation is focused on the verification of the correspondence of the model structure and the robustness of the model behaviours. Forrester and Senge (1980) suggest three validation tests - of the structure and parameters; under extreme conditions; and of the dimensional consistency of SD models.

In addition to the tests, the structure of the proposed model was tested by comparing the variables and the equations against existing literature and available expert knowledge. It was claimed that the model was developed based on the causal relations; thus, the model structure and the contained interactions should be examined against the real system (Barlas, 1996).

“Statistical significance” testing is another critical part in the SD model validation process. Regardless of the size of the model, all the variables of concern to the system developers could be tested to address whether the model adequately represented the real system at the operational level. The parameter values under extreme conditions were set by the authors in order to assess whether the performance of the model coincided with the anticipated behaviour of the system in reality. Based on the assumption of an independent input value of a variable, it elicited a better performance of the system compared with human beings. However, it was significant to note that the emphasis was on the trend, frequencies and fluctuation prediction, rather than the value of system behaviour prediction (Das and Dutta, 2013). In the examination, a logical result was obtained to verify the developed system.

To demonstrate the proposed method, an illustration is provided to describe the SD model validation under extreme conditions. In the CSCT system, the transportation capacity is a significant variable, which reflects the ability of the transportation system to ship the orders to the customers. The value of transportation capacity depends on the combination of the current transporter capacity and infrastructure capacity. If the average number of placed orders is larger than the available transportation capacity, the backlogged orders are expected to accumulate to a high level following each simulation step; otherwise the backlogs do not appear. In order to verify this phenomenon, an increase of average downstream orders was set to explore how the built system responded to the unexpected changes. The increase of *"Downstream order"* by 5% is shown in **Figure 7.4.** The No1# line presents the testing of increasing downstream orders by 5% and the No2# line indicates the base system performance.





CSCT performance under 5% increase of "Downstream order": 1 1 1 1

Base CSCT performance: 2 2 2 2 2 2 2 2 2

Figure 7.4. CSCT system performance under 5% increase of "Downstream order"

According to the simulation results, the downstream orders were forecasted to fluctuate between 58.13 units and 104.73 units during the simulation period. The unexpected customer demand increase puts huge pressure on the transportation system to fulfil the increased requirements. The backlogs frequently appear when the shipped orders fail to maintain the pace with customer demand. The order fulfilment rate represents the performance of the CSCT system, which drops from 82.09% to 75.92%. According to the simulation results, the developed model presents a representation that coincides with logical behaviour in the scenario. In accordance with the system design, the developed CSCT model has spare capacity to gradually adapt to the negative effects of demand increase. Though it is regarded as a kind of waste in normal situation, it provides the backup capacity to deal with the unexpected requirements in risk scenarios. During the "statistical significance" testing, it is significant to identify the extreme value at which the developed system could absorb the negative effects and perform as initially expressed. Through changing the input value of downstream demands, the threshold value was experimentally addressed that if a 2.54% increase of downstream orders was imposed on the valid model, more backlogs would appear during the simulation period.

Finally, the dimensional consistency tests were carried out to examine the dimensions of the provided equations. The SD model was developed based on the existing causal relations and feedback effects, thus the dimensions of variables also can be calculated according to the provided mathematical equations. It is significant to verify whether the dimensional units on both sides of the equation are presented the same. In the research, the software used provides a powerful function of dimension calculation that automatically verifies the dimensional consistency of this model. It verifies the relationships between interacted variables by tracking their fundamental dimension as performed calculations. Once validation and confidence in the behaviour of built SD model had been established, it could be used to address the system performance in a series of risk scenarios and risk reduction scenarios.

7.3 RISK DATA COLLECTION, ANALYSIS AND VALIDATION

Due to the lack of accurate industry-specific data, expert intervention is applied for generating risk scenario input value to estimate risk effects in the methodology. Based on the identified hazards, the questionnaire is built to collect risk data from respondents. To ensure the reliability and consistency of obtained data, the results of the questionnaire are measured using Cronbach's alpha method. Then, the validated risk data are inserted as the input values of established risk scenarios to simulate the distinct risk effects on CSC operations.

7.3.1 Risk data collection

In the study, the transportation service provider is determined as the focal company in the CSC and the primary data are collected on described risk attributes regarding the operational aspects. Operational risks refer to the specialised internal features of CSCT that may cause transportation delay or damage. Adapting the identified hazards in the developed risk taxonomic diagram (shown in **Figure 4.12**), fourteen major risks inherent in the CSCT operations were empirically analysed, which are *hazardous nature of materials; breakdown in core operations; inappropriate choice of service provider; inappropriate choice of transportation route; inadequate transportation capacity; high levels of process variation; the complexity of the products to be transported; lack of/inappropriate inventory management; lack of/inappropriate container management; lack of qualified labour; the challenge of technological innovation; information sharing delay; information sharing inaccuracies; and financial problems.*

Although both academics and practitioners have raised the awareness of CSCRM, the insight from risk issues linked to the transportation process is limited, emerging from increasing challenges in today's already volatile environment. In literature, the CSCT risk consequence is frequently evaluated in terms of time, cost, and quality aspects (Vilko and Hallikas, 2012). The time-based consequence refers to delay and disruption in material or information flows, the cost-based consequence exists in the financial flow that may lead to cost increase or profit loss, while the quality-based consequence refers to the damage of quality of product, service or property. Transportation activities can be disrupted by physical damage, which not only affects service levels, but also results in cost increases within the CSCT system (Wilson, 2007; Liu *et al.*, 2011). Tatano and Tsuchiya (2008) provide a framework to estimate the economic losses accruing from transportation interruption. Leonelli *et al*. (2000) and Fabiano *et al*. (2005) have investigated the CSCT risks relating to available infrastructure capacity, available vehicle capacity, amount (quantity) and type (quality) of damage and transportation time. To demonstrate the interaction between the investigated system and risk factor, the core elements of the CSCT system are determined, which are available infrastructure capacity, available transporter capacity, transported object damage (quality), transported object damage (quantity), transportation time, timeliness of information sharing, accuracy of information sharing, transportation cost. Based on the identified hazards and selected core elements of CSCT system, the questionnaire was designed to comprise the input values of risk scenarios. Nine-point Likert scale was adapted to investigate the level of agreement of each question from the respondents. The experts as the executives in the CSCT process were selected as the target participants. In particular, the experience of respondents should be in line with the research objectives and requirements. The gathered risk data was analysed and validated prior to being inserted into the developed SD model to conduct risk analysis and risk reduction research.

7.3.2 Risk data analysis and validation

Empirical studies are designed for the collection of risk data forming the target population for this study, so as to deal with the lack of accurate industry-specific data. The questionnaire responses informed a set of corresponding data – *LO*; *CS* and *CP*. In the following section, the obtained risk data is analysed and validated to ensure the reliability and consistency of results.

7.3.2.1 Respondents' profile analysis

The survey has to narrow down the target population to the research institutes or companies involving in CSCT process in China. The sample size should fit in with statistical measures, so that it is able to generalise the findings (McColl *et al.*, 2001). The author had randomly contacted about 200 domain experts using the university membership directories on SCM or chemical engineering in Wuhan University of Technology. Also, the same amount of recognised practitioners had been randomly chosen from CSCT services providers to elicit their opinions as an executive with expert knowledge on CSCT risk management.

In total, 181 questionnaires were sent out between 27th April 2015 and 31th July 2015 and 59 replies were received in three months. There were 42 valid questionnaires and 17 invalid ones, as the respondents did not reply or did not answer all the questions in the questionnaire, therefore the valid return rate was 23.20%. The questionnaire was also converted to an online questionnaire via e-survey creator to ensure that more validated participants can take part in the survey. It was expected that after participants completed the questionnaire, the researcher was able to sign in onto e-survey creator and view the given answers. Till the end of July 2015, there were 37 valid questionnaires and 11 invalid ones, as the respondents did not answer all the questions of this survey. Hence, 79 valid responses were received in total. The summary of questionnaires reply detail is shown in **Table 7.2**.

Table 7.2. The summary of questionnaires reply detail

	Questionnaire distributed	Questionnaire returned	Valid replies	Invalid replies	Valid reply rate
In person and by email	181	59	42	17	23.20%
Online	-	48	37	11	-

The balanced sample obtained the opinions from academic researchers and industrial experts with equal weights. It is interesting to note that the majority of respondents are the researchers in academia

(51.90%), while the others work in the industry, which account for 48.10% of the total respondents (working in service provider: 21.52%; goods provider: 16.64%; infrastructure provider: 7.59%; and other: 2.53%).

In terms of involved transportation modes, almost all respondents select road transport. It indicates that the road transportation mode dominates the chemical transportation process. Even though the chemical substances can be conveyed by other methods, it also requires vehicles to deliver the products from port/dock to the final destination. Due to numbers of participants coming from Wuhan, which is the one of the most developed inland shipping districts and the central node of the railway network in China, approximately 35.44% and 29.11% of respondents have been involved in railway and waterway transportation modes.

From an organisation's gross revenue aspect, many participants are working in research institutes, so that more than 50% of the respondents work for a non-profit or low profit organisation (56.96%). In Chinese CIs, there are a lot of Small and Medium-size Enterprises (SMEs) (Gross revenue < $50M) providing chemical transportation services, which account for 85.83% of the respondents. In the analysis, there are only 4 respondents working for state owned super-giant enterprises involving in the chemical manufacturing and transportation.
It indicates that approximately 82.28% of the respondents have been engaged in the CI and the CSC for more than 5 years. The long professional working experiences of the participants contribute to this questionnaire achieving a high reliability. The 79 respondents' profile in the survey is presented in **Table 7.3**.

Table 7.3. The summary of questionnaires respondent profile

Respondent Profile		**Number**	**%**
What is the type of your organisation?	Goods Provider (e.g. Manufacturing)	13	16.46
	Service Provider (e.g. Distribution, Warehousing)	17	21.52
	Infrastructure Provider (e.g. Port)	6	7.59
	Researchers in the academia	41	51.90
	Other	2	2.53

What types of transportation modes are you involved in? (Please tick all that apply):	Road Transport	78	98.73
	Rail Transport	28	35.44
	Air Transport	6	7.59
	Waterway Transport	23	29.11
What is your organisation's gross revenue?	\$0-\$1M	45	56.96
	\$1M-\$5M	20	25.32
	\$5M-\$10M	12	15.19
	\$10M-\$50M	8	10.13
	>\$50M	4	5.06
For how many years have you worked in the chemical industry or chemical supply chain?	1-5 years	14	17.72
	6-10 years	17	21.52
	11-15 years	19	24.05
	16-20 years	16	20.25
	>20 years	13	16.46

7.3.2.2 Risk data analysis and validation

The questionnaire survey with academic experts and company managers generated insights into the CSC system and its associated risks that contributed to bridging the gap in risk data visibility. In particular, the reliability of the obtained results are of high concern to the questionnaire builders, so that a validity test is conducted to test whether the study measures the required items and whether the study receives the reliable responses (Davis, 2000). As described in *Chapter 4*, Eq. 4.1 and Eq. 4.2 are applied to measure the reliability of the questionnaire survey through employing Cronbach's alpha method.

A total of 221 questions are tested, which contain the occurrence likelihood of hazardous events (13 questions), consequence severity and associated consequence probability (208 questions). In this study, the Cronbach's alpha of the whole survey is 0.871 and Cronbach's Alpha Based on Standardised Items is 0.869. It is important to note that the proposed survey achieves a high level of reliability according to the evaluation criteria provided by Cohen and Swerdlik (2010). Additionally, the reliability of occurrence likelihood of the investigated hazardous events, consequence severity and consequence probability of hazardous events are examined separately to verify the consistency and stability of the scores from the measurement scales. The Cronbach's Alpha of each reliability test is illustrated in **Table 7.4.**

Table 7.4. The reliability test for the questionnaire survey

	Cronbach's Alpha	Cronbach's Alpha Based on Standardised Items	Number of questions
Whole survey	0.871	0.869	221
Occurrence likelihood of hazardous events	0.854	0.853	13
Consequence severity of hazardous events	0.866	0.864	104
Consequence probability of hazardous events	0.859	0.860	104

According to the outcomes of the questionnaire survey, the risk attributes are obtained which represent the hazardous events in terms of probability and severity aspects. The results will be categorised and analysed in order to establish deeper understanding of obtained risk data. The occurrence likelihood of hazardous events is measured to subjectively estimate whether the risk will materialise using a nine point Likert scale. *LO* is defined as a subjective view of whether the risk will materialise, which are evaluated using nine-point scale in the questionnaire. **Table 7.5** summarises the acquired data on occurrence likelihood of identified hazardous events (*LO*). And then, the obtained numerical number will be normalized into an accurate numerical percentage, which is supposed to be calibrated into [0, 1], in which 0 means never happen and 1 means always happen.

Table 7.5. The summary of data on occurrence likelihood of hazardous event (*LO*) acquired

	Occurrence likelihood of hazardous event (*LO*)	
	Mean	S.D.
Hazardous nature of materials	5.98	0.88
Breakdown in the core operations	3.22	1.20
Improper service provider selection	2.33	1.00
Improper transportation route selection	4.78	1.86
Inadequate transportation capacity	5.44	0.88
High level of process variation	4.78	1.20
Complexity of product types	5.00	1.41
Lack of/inappropriate inventory management	4.11	1.45
Lack of/inappropriate container management	4.33	1.41
Lack of qualified Labour	3.89	1.05
The challenge of technology innovation	2.33	1.00
Information sharing delay	4.78	1.56
Information sharing inaccuracy	5.22	1.20
Financial problems	1.44	0.88

As shown in the survey, the hazardous events of inadequate transportation capacity, complexity of product types and information sharing inaccuracy are the frequently experienced problems in the operational process. The risks of improper service provider selection, the challenge of technology and financial problems rarely disrupt the CSCT operations. No risk falls into the scale of circumstances frequently encountered on a monthly or daily basis. Therefore, the obtained data can be classified into three levels: (1) high likelihood: the hazardous event is likely to happen at some point within a few months (red colour, the mean value of a risk attribute is greater than 5); (2) moderate likelihood: the circumstance may occur within one year (yellow colour, the mean value of a risk attribute is between 3 and 5); and (3) low likelihood: the hazard is only likely to happen within a few years (green colour, the mean value of a risk attribute is less than 3).

Although some of the circumstance may occur within one year or several years, the consequence severity could be catastrophic and cause significant loss. The magnitudes of possible consequences in terms of negative aspect depend on the combination of hazardous event and affected variables. **Table 7.6** lists the summary of data on consequence severity and consequence probability acquired, which can be inserted into the developed SD model to estimate the risk impacts in later risk scenario simulation research.

Table 7.6. The summary of data on consequence severity and consequence probability acquired

Hazardous nature of materials				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	3.44	1.05	2.78	1.20
Available Transporter Capacity	4.78	1.67	4.78	1.76
Transported Object Damage (Quality)	4.11	1.67	4.11	1.67
Transported Object Damage (Quantity)	4.78	1.41	3.45	1.05
Transportation Time	6.12	1.06	5.44	1.33
Timeliness of Information sharing	3.16	1.56	4.56	0.88
Accuracy of Information sharing	3.21	1.86	3.49	1.20
Transportation Cost	5.78	1.05	4.33	1.06
Breakdown in the core activities				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.

Available Infrastructure Capacity	3.89	1.05	2.11	1.05
Available Transporter Capacity	6.78	1.56	5.44	1.33
Transported Object Damage (Quality)	3.44	0.88	4.11	1.05
Transported Object Damage (Quantity)	4.78	1.56	4.78	1.20
Transportation Time	7.67	1.00	6.11	1.76
Timeliness of Information sharing	3.67	1.00	4.11	1.05
Accuracy of Information sharing	4.11	1.05	4.78	1.20
Transportation Cost	6.33	1.41	5.89	1.05
Improper service provider selection				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	3.22	1.86	2.78	1.86
Available Transporter Capacity	4.11	1.45	4.11	1.45
Transported Object Damage (Quality)	4.56	1.05	5.44	1.33
Transported Object Damage (Quantity)	4.56	0.88	5.00	1.00
Transportation Time	5.00	1.00	6.27	1.33
Timeliness of Information sharing	4.11	1.05	4.11	1.05
Accuracy of Information sharing	5.22	1.86	4.65	0.77
Transportation Cost	4.99	1.20	5.89	1.76
Improper transportation route selection				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	3.22	2.11	3.89	1.45
Available Transporter Capacity	3.89	1.05	3.44	0.97
Transported Object Damage (Quality)	1.44	0.88	3.67	1.00
Transported Object Damage (Quantity)	1.67	1.00	4.11	1.45
Transportation Time	5.67	1.06	6.33	1.00
Timeliness of Information sharing	2.56	1.67	4.56	1.41
Accuracy of Information sharing	3.44	1.67	4.56	2.11
Transportation Cost	5.22	1.20	5.67	0.88
Inadequate transportation capacity				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	1.67	1.41	0.89	0.33
Available Transporter Capacity	4.78	2.11	5.44	1.04
Transported Object Damage (Quality)	3.44	1.33	3.44	1.67
Transported Object Damage (Quantity)	3.67	2.00	3.22	1.56
Transportation Time	6.56	1.33	6.78	1.20
Timeliness of Information sharing	2.87	2.07	4.11	1.57
Accuracy of Information sharing	4.11	1.05	4.62	1.05
Transportation Cost	5.89	1.44	6.11	1.45
High level of process variation				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	1.89	1.05	3.22	1.20
Available Transporter Capacity	2.99	1.81	3.89	1.05
Transported Object Damage (Quality)	2.78	1.20	3.70	1.21
Transported Object Damage (Quantity)	3.22	1.56	3.45	1.46
Transportation Time	4.78	1.20	5.00	0.87

Timeliness of Information sharing	3.44	0.88	4.33	1.00
Accuracy of Information sharing	3.89	1.45	4.78	0.67
Transportation Cost	4.78	1.56	4.36	1.22
Complexity of product types				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	1.89	1.45	2.11	1.15
Available Transporter Capacity	3.44	1.67	3.67	1.09
Transported Object Damage (Quality)	2.78	1.02	2.78	1.22
Transported Object Damage (Quantity)	2.56	1.33	3.44	0.88
Transportation Time	4.78	1.20	5.22	1.20
Timeliness of Information sharing	3.67	1.73	3.67	1.41
Accuracy of Information sharing	4.33	1.00	4.78	1.29
Transportation Cost	4.50	1.66	3.49	1.21
Lack of/inappropriate inventory management				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	2.56	1.67	3.00	2.24
Available Transporter Capacity	3.00	1.41	3.44	2.19
Transported Object Damage (Quality)	5.89	1.05	5.44	0.88
Transported Object Damage (Quantity)	6.33	1.00	5.67	1.41
Transportation Time	5.00	1.41	5.22	1.20
Timeliness of Information sharing	3.22	1.20	5.00	1.41
Accuracy of Information sharing	4.11	1.45	5.67	0.84
Transportation Cost	5.89	1.36	5.67	0.91
Lack of/inappropriate container management				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	2.56	1.33	2.56	2.19
Available Transporter Capacity	3.22	2.11	3.22	2.11
Transported Object Damage (Quality)	6.78	1.20	6.78	1.56
Transported Object Damage (Quantity)	6.33	1.73	6.33	1.41
Transportation Time	4.33	1.41	5.44	0.88
Timeliness of Information sharing	2.56	1.88	5.22	1.28
Accuracy of Information sharing	4.56	0.69	5.67	1.06
Transportation Cost	6.11	1.45	5.89	1.09
Lack of qualified Labour				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	1.67	1.10	3.44	1.67
Available Transporter Capacity	3.89	1.04	4.56	1.33
Transported Object Damage (Quality)	3.91	0.99	5.44	1.33
Transported Object Damage (Quantity)	4.11	1.01	5.22	1.28
Transportation Time	4.78	1.23	5.44	1.45
Timeliness of Information sharing	3.89	1.10	3.89	1.29
Accuracy of Information sharing	4.57	1.68	4.33	1.10
Transportation Cost	4.30	1.31	4.78	1.26
The challenge of technology innovation				

Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	1.67	1.01	2.78	1.56
Available Transporter Capacity	2.78	1.22	3.89	1.95
Transported Object Damage (Quality)	2.33	1.41	2.33	1.42
Transported Object Damage (Quantity)	1.89	1.45	3.44	1.38
Transportation Time	3.22	1.18	3.67	1.41
Timeliness of Information sharing	3.56	0.93	3.89	0.98
Accuracy of Information sharing	2.89	1.54	3.22	1.66
Transportation Cost	3.89	1.05	3.89	1.45
Information sharing delay				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	0.89	0.33	1.00	1.03
Available Transporter Capacity	1.44	0.85	1.78	1.27
Transported Object Damage (Quality)	1.89	1.59	1.89	1.49
Transported Object Damage (Quantity)	2.02	1.11	1.21	0.96
Transportation Time	3.89	1.36	4.38	1.67
Timeliness of Information sharing	4.78	1.23	5.00	1.73
Accuracy of Information sharing	4.56	0.67	5.54	1.37
Transportation Cost	4.33	1.41	5.21	1.42
Information sharing inaccuracy				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	1.11	0.79	1.67	1.15
Available Transporter Capacity	2.33	1.73	1.89	1.01
Transported Object Damage (Quality)	1.67	1.00	2.33	1.41
Transported Object Damage (Quantity)	2.78	1.86	2.78	1.56
Transportation Time	4.56	1.33	5.44	1.33
Timeliness of Information sharing	5.23	1.41	5.67	1.41
Accuracy of Information sharing	5.67	1.10	5.89	1.05
Transportation Cost	5.41	1.14	6.11	2.11
Financial problems				
Core elements of CSCT system	Consequence severity (*CS*)		Consequence probability (*CP*)	
	Mean	S.D.	Mean	S.D.
Available Infrastructure Capacity	0.84	0.64	1.58	0.95
Available Transporter Capacity	5.04	1.73	4.67	1.41
Transported Object Damage (Quality)	3.23	1.41	3.44	1.67
Transported Object Damage (Quantity)	3.47	1.36	3.44	1.99
Transportation Time	4.78	1.22	4.33	1.73
Timeliness of Information sharing	3.89	0.98	3.76	1.31
Accuracy of Information sharing	3.66	1.47	4.11	1.45
Transportation Cost	5.59	1.59	5.44	1.34

In the empirical analysis, the consequence severity of hazardous event was explored in the variable level in terms of system capacity, product damage rate, transportation time, information sharing and transportation cost. For instance, the financial problems of a transportation service provider could cause some inconvenience with minor impacts to the infrastructure capacity (mean value: 0.84) and result in major disruptions to the flow of material movement due to the reduction of available transporter capacity (mean value: 5.04) as shown in **Table 5.6**. Meanwhile, the consequence probability (*CP*) was investigated to explore the probability of the consequence given the hazardous event occurring. The obtained results indicate that the CSCT system rarely suffers the available infrastructure capacity damage (mean value: 1.58), whilst the available transporter capacity damage is about an even chance of occurring with the mean value of 4.67.

7.4 RISK SCENARIO SIMULATION AND RESULTS

A hazardous event can either trigger a low or high impact on the system performance for different probabilities. It is regarded as a condition for the hazardous event occurring at the indicated consequence severity. Due to the lack of accurate industry-specific data, the expert elicitation is a proven methodology to source the data in risk management domain. The questionnaire was designed to facilitate the respondents to give the numeric number to represent the corresponding abstractive category. The analyses of gathered data were carried out prior to being inserted into the developed SD model to simulate the CSCT operations. The collected data from the risk experts and analysts was described in a previous section (shown in **Table 7.5** and **Table 7.6**), which comprised the input values in the proposed CSCT model to simulate the system performance under different risk scenarios.

7.4.1 Base case behaviour

An SD simulation begins with running the developed model under a specified scenario, so that the initial value of each variable (such as: simulation period; downstream order; transporter capacity; and infrastructure capacity) must be defined at the outset. In this research, the **simulation period** was set as 365 days, and the **time-step** for simulation was set as 1 day. A number of assumptions were made in the definition of the established scenario. In reality, customer demand is uncertain and difficult to forecast accurately (Barilas and Gunduz, 2011). Therefore, the **downstream order** was assumed to be placed every day and follow a normal distribution with a minimum of 50 units, and a maximum of

100 units, with a mean of 85 units, and a standard deviation of 20 units. The volume of products in transit was determined by the capacity of the transporter and infrastructure. In view of the regulations and policies governing the transportation operations, it was assumed that the volume of products in shipment should not exceed infrastructure capacity in the proposed model. The **transporter capacity** was set at 400 units in total, and the **infrastructure capacity** was set at 150 units per day. The CSCT system performance under these base operating conditions is shown in **Figure 7.5**.

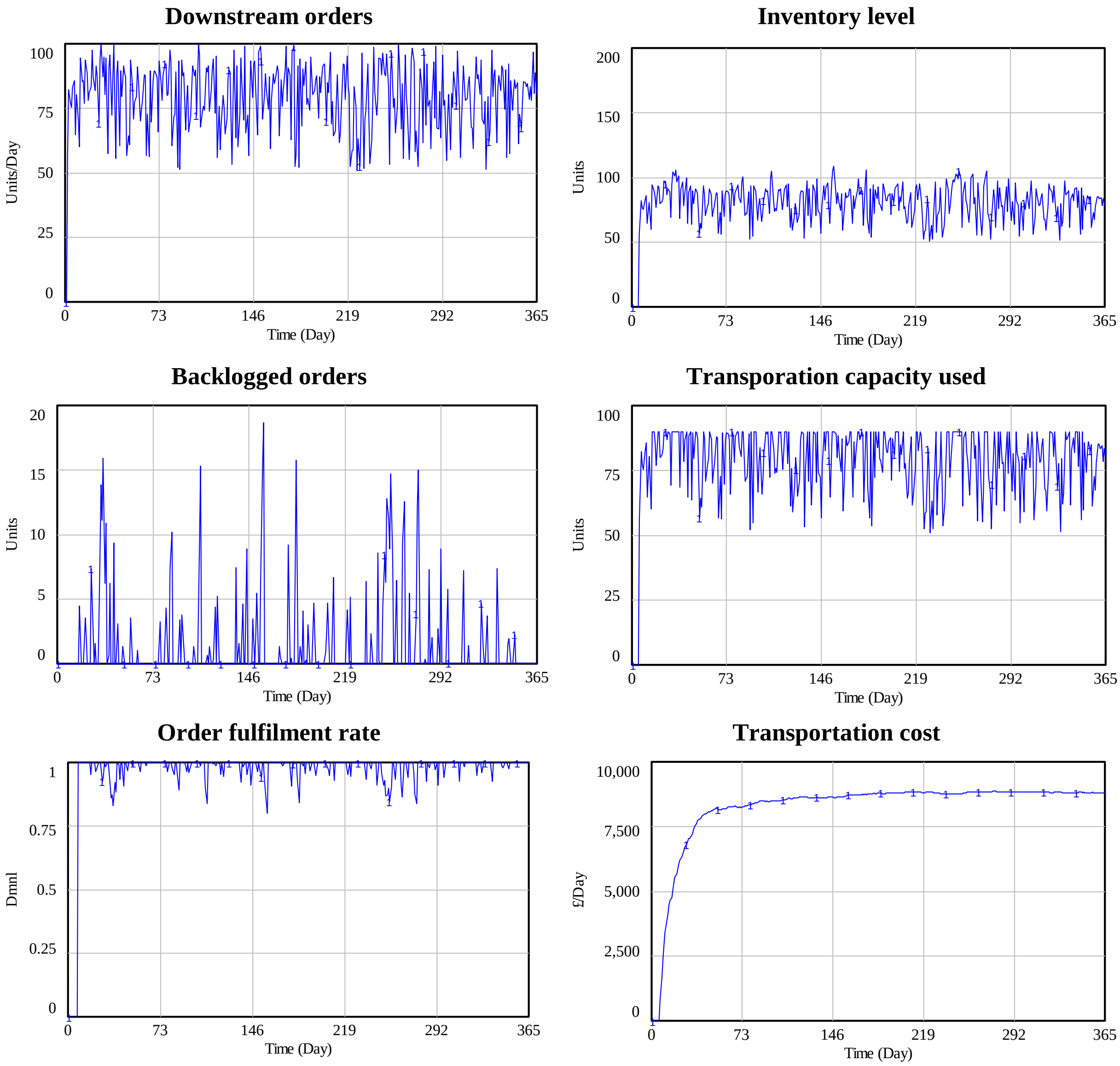


Figure 7.5. Base system performance of developed CSCT

In accordance with the system design, the downstream order was generated as a probabilistic input based on the set policy, which fluctuated between 50 units per day and 100 units per day. Following the receipt of customer orders, the upstream supplier provided the required volume of products to the transporter on time. The inventory comprised the balance of the volume received and volume shipped by the transporter, which fluctuated between 50 units and 110 units. The simulation produced some late deliveries due to a lag in transportation capacity. In this circumstance, the order fulfilment rate was estimated to rise and fall between 0.78 and 1.00 during the simulation period. This initial system performance was set as the baseline for benchmarking a series of system performance involving a variety of risk scenarios.

7.4.2 Risk scenarios simulation and analysis

It has been indicated that SD is a scenario-based method and can be used to investigate the impact of parameter changes on system behaviour over time (Yeo, Pak and Yang, 2013). The disturbance is amplified or self-corrected along the existing information feedback loops in the developed system, thus the system behaviour appears to be dynamic. Through comparison with a direct expert judgement, it provides a method of quantitatively estimating the problematic performance as the consequence of the system changes in response to different risk scenarios. Thus, it helps analysts to understand how the CSCT system will perform in different risk scenarios, and estimate the possible risk effects associated with these scenarios on system thinking.

Following the application of the SD modelling and simulation, the independent risks were investigated to evaluate the distinct risk effects in the system level. The experts were asked to give the input values to each risk scenario regarding the probability and consequence severity. Using the developed risk sub-model (shown in Figure 5.18) generated the hazardous events and their consequence severity following the specific distributions, according to the particular features of the risk. Fourteen risk scenarios were established and experts were asked to assign input values to each risk scenario regarding the probability and consequence severity. Inserting the obtained LO, CS and CP (shown in Table 7.5 and Table 7.6) into the developed model simulates time-dependent CSCT system performance. **Table 7.7** presents the system performance with the maximum, the minimum and the average values in the risk scenarios during the simulation period.

Table 7.7. The descriptions of SD simulation results of created risk scenarios

	Transportation capacity (units)		Transportation time (Day)		Inventory level (units)		Order fulfilment rate (%) (dmnl)		Transportation cost ($)	
Based value	Max	90.00	Max	2.00	Max	108.67	Max	100.00	Max	8746
	Min	90.00	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	90.00	Ave	2.00	Ave	79.62	Ave	96.20	Ave	8235
Hazardous nature of materials	Max	90.00	Max	4.18	Max	132.81	Max	100.00	Max	8874
	Min	63.88	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.34	Ave	2.07	Ave	87.43	Ave	94.78	Ave	8356
Breakdown in the core operations	Max	90.00	Max	4.60	Max	320.74	Max	100.00	Max	9340
	Min	7.92	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	88.29	Ave	2.14	Ave	96.03	Ave	82.10	Ave	8487
Improper service provider selection	Max	90.00	Max	3.00	Max	139.63	Max	100.00	Max	9029
	Min	70.02	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.59	Ave	2.03	Ave	80.76	Ave	94.60	Ave	8320
Improper transportation route selection	Max	90.00	Max	3.40	Max	139.63	Max	100.00	Max	9076
	Min	70.02	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.64	Ave	2.04	Ave	80.71	Ave	94.90	Ave	8307
Inadequate transportation capacity	Max	90.00	Max	3.94	Max	123.70	Max	100.00	Max	8905
	Min	62.20	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.63	Ave	2.16	Ave	80.34	Ave	95.00	Ave	8291
High level of process variation	Max	90.00	Max	2.91	Max	125.68	Max	100.00	Max	8980
	Min	76.99	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.79	Ave	2.03	Ave	80.09	Ave	95.40	Ave	8281
Complexity of product types	Max	90.00	Max	3.00	Max	125.68	Max	100.00	Max	8897
	Min	75.60	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.81	Ave	2.04	Ave	80.07	Ave	95.30	Ave	8254
Lack of/inappropriate inventory management	Max	90.00	Max	3.00	Max	131.71	Max	100.00	Max	9039
	Min	73.98	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.72	Ave	2.03	Ave	80.33	Ave	94.90	Ave	8306
Lack of/inappropriate container management	Max	90.00	Max	2.73	Max	131.71	Max	100.00	Max	8927
	Min	73.98	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.71	Ave	2.02	Ave	80.35	Ave	94.80	Ave	8384
Lack of qualified Labour	Max	90.00	Max	2.91	Max	123.70	Max	100.00	Max	8963
	Min	71.10	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.75	Ave	2.03	Ave	80.12	Ave	95.40	Ave	8273
The challenge of technology innovation	Max	90.00	Max	2.44	Max	123.70	Max	100.00	Max	8880
	Min	77.98	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.84	Ave	2.01	Ave	79.96	Ave	95.70	Ave	8244
Information sharing delay	Max	90.00	Max	2.58	Max	116.68	Max	100.00	Max	8860
	Min	81.99	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.93	Ave	2.02	Ave	79.75	Ave	95.89	Ave	8325
Information sharing inaccuracy	Max	90.00	Max	2.82	Max	118.66	Max	100.00	Max	8877
	Min	80.51	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.92	Ave	2.04	Ave	79.79	Ave	95.70	Ave	8344
Financial problems	Max	90.00	Max	2.91	Max	121.63	Max	100.00	Max	8877
	Min	72.00	Min	2.00	Min	0.00	Min	0.00	Min	0.00
	Ave	89.86	Ave	2.02	Ave	79.86	Ave	95.79	Ave	8342

In order to provide meaningful insights, **Table 7.8** extracts the results from **Table 7.7** that depicts the comparison of the system performance of each risk scenario with the base value. It can be calculated by the equation:

Result = (Risk scenarios simulation result-Base value)/Base value Eq. 7.2

For instance, the average of transportation capacity is 89.34 tons in the risk scenario of "Hazardous natural of materials", while the initial value is 90.00 tons. Therefore, the comparison of the transportation capacity in this risk scenario with the base value is -0.73%. Through evaluating the variations in system behaviour, it provides quantitative results to find out the significant risks in the complex CSCT system.

Table 7.8. The comparisons of the risk scenarios simulation results with the base system performance

	Transportation capacity	Transportation time	Inventory level	Order fulfilment rate	Transportation cost
Hazardous nature of materials	-0.73%	3.5%	9.8%	-1.47%	1.47%
Breakdown in the core operations	-1.90%	7.00%	20.61%	-14.65%	3.06%
Improper service provider selection	-0.46%	1.5%	1.43%	-1.66%	1.03%
Improper transportation route selection	-0.40%	1.9%	1.37%	-1.35%	0.87%
Inadequate transportation capacity	-0.41%	8.05%	0.90%	-1.25%	0.68%
High level of process variation	-0.23%	1.55%	0.59%	-0.83%	0.56%
Complexity of product types	-0.21%	2.00%	0.57%	-0.94%	0.23%
Lack of/inappropriate inventory management	-0.31%	1.50%	0.89%	-1.35%	0.86%
Lack of/inappropriate container management	-0.32%	1.05%	0.92%	-1.45%	1.81%
Lack of qualified Labour	-0.28%	1.35%	0.63%	-0.83%	0.46%
The challenge of technology innovation	-0.18%	0.40%	0.43%	-0.52%	0.11%
Information sharing delay	-0.08%	0.95%	0.16%	-0.32%	1.09%
Information sharing inaccuracy	-0.09%	1.85%	0.21%	-0.52%	1.32%
Financial problems	-0.16%	1.10%	0.30%	-0.43%	1.30%

In the risk scenario of breakdown in core operations, there was an estimated a 1.90% decrease in the average transportation capacity and a sharp increase of transportation time due to the occurrence of hazardous event. Barlas and Gunduz (2011) and Liu and Papageorgiou (2013) suggested that the changes of the capacity and an increase of lead-time will cause the oscillations in inventory level along the supply chain. The SD simulation results confirmed these effects, with the average inventory level increasing approximately 1.2 times compared with the initial value. The transporter is unable to fully satisfy the customer requirements, so that the developed CSCT system presents a lower order fulfilment rate. The average order fulfilment rate fell, by 14.65% during the simulation period. Similarly, the effects of the other risks are listed in **Table 7.8**, which provides quantitative results to evaluate the risks in the complex CSCT system. It indicates that the major risk drivers in the developed CSCT model are the risks of *hazardous nature of materials*, *breakdown in the core operations*, *improper service provider selection*, *improper transportation route selection*, *lack of/inappropriate inventory management*, *lack of/inappropriate container management* and *information sharing inaccuracy*.

7.5 RISK REDUCTION SCENARIOS SIMULATION AND ANALYSIS

Ensuring that a particular risk reduction approach does indeed support CSCRM often requires a formal modelling of forecasting the outcomes of a particular risk reduction decision. It is worthwhile simulating the system operations to explore the potential effects of risk reduction methods on the changes of system behaviours (Li *et al.*, 2015). The SD model can be modified both in the design and operations phases based on the proposed reduction measures, which is able to help the decision makers to estimate risk reduction outcomes under different scenarios.

7.5.1 Applying general risk reduction method to manage the risks

It is indicated that SD based risk management decision-making processes do not require a decision-maker directly assessing different risks and providing the arbitrary decisions based on the past experience or limited historical data (Yeo, Pak and Yang, 2013). Instead, the expert just proposes a reduction measure, and then the whole SD approach (shown in **Figure 3.6**) should be iterated to investigate the possibility of the risk reduction outcomes. In this case, the application of SD addresses the complex interactions and the dynamic feedback effects between the CSC system performance and implemented risk reduction methods.

The results of risk analysis outlined in **Table 7.8** shows that the risk of *"Breakdown in the core operations"* is the most serious risk in the CSCT system. Insufficient transportation capacity obstructed the performance of the transportation system under the challenge of the hazardous events. The inventory accumulated to a high level and the average order fulfilment rate decreased by 15%. The obtained system performance was set as a baseline for benchmarking the outcomes of risk reduction measures. In this section, two potential risk reduction approaches were suggested by the experts in response to the undesired risk effects: increasing transportation equipment capacity and increasing transportation equipment number. The conditions of the proposed cases are presented in **Table 7.9**.

Table 7.9. Case study conditions of suggested risk reduction methods

Case study	Variable value set	Description
Case 1: Effect of transportation	Current situation	20 Units/device
equipment capacity increase	Capacity increase	Degree of increase: 5%, 10%, 15% and 20% of current situation
Case 2: Effect of transportation	Current situation	20 devices
equipment number increase	Number increase	Degree of increase: 5%, 10%, 15% and 20% of current situation

It is particularly innovative that not only the model structure but also the variables' value of the developed SD model can be modified based on the suggested risk reduction measures. The effects of the implemented risk reduction methods are obtained through comparing the system behaviours under different scenarios. In each case, the effects were simulated in four different scenarios - 5%, 10%, 15% and 20% increase of the exogenous parameter values were inserted to assess the performance of the built CSC system. It should be noted that a range of variations is widely used to test the performance of the implemented risk reduction approach in the real world (Bouloiz *et al*., 2013).

The results of risk reduction scenarios can be used to understand the effects of implemented risk reduction methods on system performance. Advantageous risk reduction decisions can be obtained by comparing system performance under different scenarios. In order to provide meaningful insights, **Table 7.10** extracts the simulation results of 5%, 10%, 15% and 20% increases in the parameter values that depict the comparisons of the system performances of each risk reduction scenario.

Table 7.10. Effects of implemented risk reduction methods

Transportation equipment capacity increase	**Degree of increase**				
	Base value	5%	10%	15%	20%
Average inventory level (units)	85.62	83.95	82.99	82.35	82.02
Average order fulfilment rate (dmnl)	81.22%	82.78%	83.67%	84.32%	84.64%
Average transportation cost ($)	9020	8823	8714	8636	8596
Transportation equipment number increase	**Degree of increase**				
	Base value	5%	10%	15%	20%
Average inventory level (units)	85.62	84.15	83.39	82.32	82.14
Average order fulfilment rate (dmnl)	81.22%	82.61%	83.49%	84.35%	84.47%
Average transportation cost ($)	9020	8864	8738	8632	8616

The improvement of transportation capacity built the robustness of CSCT system, whereas the increase of transportation equipment number improved the flexibility of the transportation system. It was found that both of the implemented methods could significantly improve the system performance in terms of the inventory level, order fulfilment ability and transportation cost. The highlighted system behaviour indicated the preferable risk reduction approaches in the designed scenarios that can lead to a better system performance. The method of increasing transportation capacity performed better in the scenario of 5%, 10% and 20%. For instance, it could decrease 1.99% of the average inventory level, improve the average order fulfilment rate from 81.22% to 82.78%, and cut the transportation cost by $197 per shipment during the simulation period in the scenario of a 5% increase. However, the approach of increasing transportation equipment numbers offered a better performance in the scenario of a 15% increase. It showed that the average inventory level decreased to 82.32 units, which had 0.03

units lower than the first risk reduction method. Meanwhile, the average order fulfilment rate increased to 84.35% and the average transportation cost decreased to $8632 per shipment in 365 days. The multiple scenario simulations allow quantifying the CSCT performance for diverse risk reduction actions. It takes into account the complex interactions and dynamic feedback effects among the built system, which will significantly affect the outcomes of the risk reduction methods. The SD method serves as a decision supportive tool for continuously improving the system performance and optimising risk reduction in CSCRM.

7.5.2 Applying sensitivity analysis to manage the risks

The developed SD model was believed to be capable of representing the changes in the behavioural pattern of the CSCT system. It observes that a small change caused by a risk reduction measure could lead to a significant variation in the system behaviours. A set of sensitivity analyses with different parameter distributions was conducted to explore the sensitive variables in the developed model, so as to suggest the beneficial risk reduction methods. In the developed system, there were six exogenous parameters, which governed the changes of interrelated variables. These identified variables were set as the input parameters performing with the assumption that the parameter values were uniformly distributed within $\pm 50\%$ range of the base value, as shown in **Table 7.11**.

Table 7.11. Parameter distribution setting in risk reduction

Parameter Name	Model Value	Range	Distribution
Normal Infrastructure Capacity	200	[100-300]	Random uniform
Normal Transportation Time	2	[1-3]	Random uniform
Required Labour per Equipment	2	[1-3]	Random uniform
Total Number of Labour	40	[20-60]	Random uniform
Total Number of Equipment	20	[10-30]	Random uniform
Capacity per Equipment	20	[10-30]	Random uniform

As described, integrating sensitivity analysis with SD simulation offers a method to explore whether a small disturbance of a designed variable brings significant variation in the system behaviours. The simulation results delivery a tolerance interval of the system outputs based upon all simulation runs. Through evaluating the range of obtained outcomes, the sensitive variables are practically addressed which suggest the potential targets of the risk reduction approach. In the developed model, the sensitivity of six exogenous parameters was investigated following the uniform distribution within ± 50% range of the base values. The simulation outcomes are given in **Table 7.12**.

Table 7.12. The sensitivity analysis outcomes of concerned variables

Parameter Name	Inventory Level	Order Fulfilment rate	Transportation cost
Normal Infrastructure Capacity	[85.62]	[81.22%]	[9020]
Normal Transportation Time	[81.97-2900]	[3.42%-85.72%]	[8588-94349]
Required Labour per Equipment	[85.62-5376]	[3.24%-81.22%]	[9020-163121]
Total Number of Labour	[85.62-7980]	[2.53%-81.22%]	[9020-235627]
Total Number of Equipment	[85.62-7980]	[2.53%-81.22%]	[9020-235627]
Capacity per Equipment	[81.76-6743]	[2.66%-84.98%]	[8553-201016]

It is interesting to observe that the variables of "*Normal transportation time*", "*Required labour per equipment*", "*Total number of labour*", "*Total number of equipment*", and "*Capacity per equipment*" are sensitive to the developed system. In order to respond to and recover from the undesired risk impacts, the risk reduction methods can be implemented to modify the identified sensitive variables, so as to achieve the research objectives. In particular, the highlighted methods of reduction of the transportation time and the improvement of equipment capacity were more sensitive than others. For instance, the reduction of the transportation time can improve the order fulfilment rate from 81.22% to 85.72% and reduce the transportation cost from 9020

Therefore, the amending of these variables could lead to the better results. Meanwhile, it was found that the outcomes of the sensitivity analysis coincided with the described simulation results of using general risk reduction methods to manage the risks in CSCT system (shown in **Table 7.5**). The variations of "*Capacity per equipment*" lead to larger changes of the system behaviours, which indicate that the system is more sensitive to the method of the "*Capacity per equipment*" optimisation.

The combining of the sensitivity analysis with the developed SD system helps to explore how the uncertainty in the output of the developed system can be apportioned to different sources of inputs. It offers the system developers a convenient method to investigate the potential risk reduction solution without relying on the expert knowledge or limited historical data. However, the model structure cannot be changed or modified in the proposed approach, so that the suggested variables whose value can be modified belong to the developed system. In this circumstance, the observed system behaviours establishes upon the developed model structure and causal relations to indicate the optimal risk reduction decisions.

7.6 CONCLUSION

Generally, the occurrence of the hazardous event will interrupt the flow of the CSCT operations and result in various negative effects. To address the risk management issue, both researchers and practitioners have adopted a wide range of methods to identify, analyse and manage the risks inherent in or surrounding a CSCT network. However, there remains a lack of the practical methodology that takes into consideration the complex interactions and the dynamic feedback effects among the developed models or systems. Instead of assessing the risks based on the expert knowledge or historical data, this study introduces a systematic methodology for the quantitatively analysing the risks in a CSCT system. It maps the risks through addressing the dynamic effects caused by the hazardous events, which combines the modelling approach for the quantification of the system performance with an interactive procedure. An in-depth investigation into the connections between the risk exposures and the CSCT system performances helps the analysts to assess different risk scenarios to find out the significant risks that should be further reduced. An SD based CSCRM method provides a transparent decision support tool to reveal the gap between the expectation and the real-time performance. In particular, not only the structure of the developed model but also the inserted values of the variables can be modified based on the risk reduction design, so that the improvement in the system behaviours can be addressed to indicate the best risk management solution.

CHAPTER 8 CONCLUSION AND FUTURE RESEARCH

Summary

This chapter summarises the research findings on the hazard identification, risk analysis and risk reduction in all previous chapters. It shows that the proposed SD-based CSCRM offers the decision makers and the operators an insight into the risk affected CSC operations and suggests the advantageous CSCRM packages. The limitations of the proposed research are outlined and the opportunities arising from the developed methods are suggested for the future improvements and applications.

8.1 Conclusion and Contribution of the Research

Complexities and globalisation pose significant challenges for the safety and efficiency of CSC operations. The risks arising from the uncertainties and disruptions among the internal system and the surrounding environment appear in a huge variety of forms, which are not only specific to the hazardous characteristics of chemical substances, but also the part of global CSC risk landscape in the economy, geopolitics, culture, regulations, technology and environment aspects. Both academics and industrial participants appreciate the need to improve the safety and reliability of the CSC, to prepare for, respond to and recover from risks. However, little has been done to address the dynamic interactive relations among the variables influencing the system operations (Fernandes, Barbosa-Póvoa and Relvas, 2011). Indeed, the feedback effects emerging from the ignored causal relations governing the system behaviour change over time, which could significantly affect the risk management results (Leveson, 2004).

Following the generated research questions, the studies are carried out to provide an integrated method by using both qualitative and quantitative techniques to identify the hazards, analyse their associated the risks and reduce the concerned risks in the supply chain level. Specifically, a novel framework is developed for systematically identifying the CSC hazards, analysing and reducing the associated risks on system thinking. A combination of the qualitative and quantitative methods has been employed to enhance the practice of risk modelling and simulation. It offers a methodological approach to deal with the existing causal relations and feedback effects between the CSC system and its associated risk scenarios. Instead of assessing the risks based on arbitrary decisions, the SD method addresses the risk effects in a dynamic system and screens out the significant hazards. Furthermore, the risk reduction methods are explored through combining the modelling approaches for the quantification of the system performance with an interactive risk reduction procedure. It enables the estimation of the risk reduction outcomes, which supports the CSCRM decisions.

To achieve the set objectives, the applied methods and research outcomes can be concluded as follows:

1) Providing a novel risk management framework to sequentially capture, assess and manage the risks within a changeable system (***Chapter 3***).
2) Conducting literature review and questionnaire survey to systematically identify the hazards and decompose their associated risks in the CSCs (***Chapter 4***).
3) Developing conceptual SD models to formalise the causal relations among the system boundaries, so as to address how the CSC operations could be affected by the risks (***Chapter 5***).
4) Developing a set of stories to deal with the distinct CSC risks within the support of the combination of participatory SD modelling and scenario analysis. Inserting the obtained risk data into the developed models simulates the time-dependent risk effects in various scenarios and explores the possible risk reduction measures (***Chapter 6***).
5) Conducting a case study to test the provided CSCRM method and to bridge the gap between the theory and the practice (***Chapter 7***).

In CSCRM research, any myopic decisions may be suboptimal due to the complex and dynamic interactions in the CSC. One of the key contributions of the thesis is adapting the system thinking in CSC risk modelling and simulation to sequentially identify the CSC hazards, assess and reduce their associated risks within a changeable system.

In the CSC, the risks are the threats in terms of some unpleasant things which appear in a huge variety of forms and impact on diverse parts of the CSC. The invisibility of the risks is one of the most challenging issues in CSCRM, it is therefore essential to comprehensively identify hazards existing in CSC network. Even though there is a substantial amount of literature dealing with CSCRM, the attention on systematic hazard identification and classification from an industrious perspective is fairly limited. To bridge this gap, the study starts with the literature review to address the CSC risks (*Chapter 2*), and then extends to the general SC risks to enrich the captured hazards (*Chapter 4*). To substantiate and describe the risks within the CSC, it is desirable to provide a distinct decomposition method to classify unstructured hazards into nine categorises: supply risks, operational risks, demand risks, security risks, political risks, policy risks, macroeconomic risks and natural environment risks. Based on the addressed risks, a questionnaire is developed to ensure the feasibility of the provided risk classification method and to address the importance of identified hazards to the CSC. An interesting insight is that the internal vulnerability and those risks arising from the internal supply chain network attract more attention than the risks existing in the surrounding environment from a practical viewpoint. The questionnaire respondents regard the supply risks, operational risks, demand risks, strategic risks and natural environment risks as the most important ones. Furthermore, the preceding discussion validates the identified hazards and their associated risk classification method. To broadly outline the sources CSC risks, a model is developed in a hierarchical structure.

In risk analysis stage, various methods and different techniques were applied to accommodate the need to analyse and evaluate the risks in the previous research. However, little has been done to address the dynamic interactive relations among the variables using the all kinds of data, which could influence the system operations and risk management outcomes. It is challenging to provide a novel CSC risk analysis method employing both qualitative and quantitative data/information to manage changeable CSC risks taking into consideration the complex interactions between the hazardous events and their associated changes of system behaviour. It is particularly noteworthy that this study introduces a systematic methodology for the assessment of risk scenarios in the CSCs instead of analysing and reducing the risks based on the expert knowledge or limited historical data. The integration of the SD method in the CSCRM is an intermediate platform between widely used mathematical programming and empirical study, so that both qualitative and quantitative data can be applied in the proposed research. In the developed SD model, it not only represents the structure of CSC but also describes the causal relations between the CSC system and hazardous events. In risk scenarios, each hazardous event affects the balanced system and causes unexpected changes in system behaviours. The proposed method addresses the risks through evaluating the variation in the system performance produced by varying the risk inputs.

Risk reduction measures aim at dealing with the certain risks to improve the effectiveness and efficiency of the system in different operating environment. It is significant to highlight that the provided SD based CSCRM method can be used to suggest the rational risk reduction decisions. Because of the flexibility and modification capability of the developed SD models, it is believed that the provided reduction method of iterating SD modelling procedures and conducting sensitivity analysis methods compensate the absence of the literature of risk reduction method in the context of CSCRM. The whole SD modelling and simulation approaches can be iterated to analyse the system performance in different scenarios by amending the model structure, modifying the defined equations, and changing the inserted value of created variables. Therefore, the outcomes of risk reduction approaches are explored to ensure that the implemented measures indeed support CSCRM.

Additionally, the application of the SD-based CSCRM method is demonstrated to test the experimental modelling set up for its viability and for bridging the gap between the theory and the practice. Instead of directly assessing the risks and providing the arbitrary decisions, the incorporation of SD into CSCRM gives an insight into the risk affected CSCT operations, especially with the consideration of time-dependent CSCT system behaviours in different operational conditions. Therefore, it is beneficial to transform the risk input into the variation of system behaviours in the developed CSCT system in order to find out the signification risks in the proposed case. The risk reduction activities are carried out on the basis of the flexibility of the model modification to enhance the practice in risk reduction. In the study, the proposed models and method are examined in a detailed practical analysis. It adds detail to previously presented methods and gives a reference to investigate new development directions for the application of the developed SD-based CSCRM.

8.2 Limitations of Research and Future Research

The research has achieved its aim of providing an integrated framework and an analytical method to manage the risks in the dynamic CSC network. However, the complexity of the SD model that the researcher seeks to develop, and the application of the provided method are limited in some circumstances, which may need in further investigation. The limitations of this research are identified as:

1) In order to restrict the scope of the peer-reviewed journals, the literature review only focuses on the development in the past fifteen years. There are many articles related to CI or CSC published during 1985 – 2000, so that the restriction on the year of publication may lead to the deficiency of some of the quality journals. It would be useful if more literature could be reviewed, especially in the hazard identification stage.

2) In this study, the developed CSC risk taxonomic diagram incorporates the general risk issues due to insufficient research in the CSC hazard identification aspect. It would be useful if more specific hazards from the industrial perspective could be identified and validated so as to strengthen the knowledge base in hazard identification and direct further risk assessment and risk reduction studies.

3) The questionnaire survey is used to address the hazardous events in three risk attributes due to incomplete data, but it is acknowledged that both the size of the sampling population and the subjective nature of the responses could be a source of bias. There is a requirement for a future comparative study to demonstrate the proposed method and verify the obtained risk data.

4) The degree of the complexity of the SD model that the researcher seeks to investigate influences the outcomes of risk analysis and risk reduction, because there is an interrelationship between the level of specification of the created model and the level of accuracy of the risk management outcomes. It would be useful if the complexity of the developed model could be improved to represent more precise system behaviours and address more accurate risk effects in the CSCRM research.

5) Scenario simulation is conducted to assess and reduce the concerned risks in the research. However, the current study does not address all the identified hazards due to the time constraints. It would be useful if more scenarios could be generated to deal with distinct CSC risks on system thinking.

6) A reputable specialty chemical transportation service provider is used to demonstrate the proposed CSCRM method. It adapted the conceptual CSCT sub-model to simulate the CSCT operations, as well predict the dynamic behaviours as the parameters change in different risk scenarios. It would be useful if the developed SD models and proposed SD-based CSCRM method could be tested in more case studies to demonstrate the applicability in various risk aspects and different industries.

While this study has made significant contributions to academic and industrial areas, additional research seems to be needed to deal with the limitations described above. The current research can be extended on the following aspects:

- Due to the lack of accurate industry-specific data, expert intervention is applied for generating risk input to estimate the risk effects in the methodology. In the research, the target respondents are selected from the academia and industry in the UK and China. A future comparative study needs to be conducted using a more extensive data source to verify the generated risks attributes and examine the CSCRM results.

- The SD method is employed to conceptualise and analyse the CSC risks on system thinking. The generalised causal relations describe the changes of system behaviours arising from the risks. Future work may be needed to develop specific SD modules with particular designs for investigating certain kinds of risks, so as to achieve a higher reliability of the CSCRM decisions.

- Before taking actions to reduce a certain risk, the benefits and investments associated with the CSCRM decisions should be forecasted, so that the substantive investigation is required to practically analyse the risk reduction outcomes, especially in the financial aspect. In future, the cost and benefit analysis can be integrated into the provided SD-based CSCRM method to explore the benefits of the implemented risk reduction methods in different operational conditions. The new model can be used to more faithfully suggest an optimised CSCRM decision.

- The implemented risk reduction solution could be the source of other risks due to the interactions among the developed system, so that any research focusing on a specific risk may be suboptimal. Another possible area for future research is to provide a structural method to monitor the time-dependent system behaviours using the developed SD models. It ensures that the generation of the new risks with the risk reduction measures can be observed via simulation in a dynamic CSC system.

- The provided method can be applied to investigate the various risks in terms of policy, human, and other aspects and suggest the advantageous CSCRM decisions. Furthermore, the application of an SD-based CSCRM method and developed SD models needs to be generalised to the supply chain context, so as to provide a flexible and rigorous risk management tool in various industries.

Alan Kay indicates that *"The best way to predict your future is to invent it"* (1971). Future research in SCRM from an industrial perspective is a broad domain. In the competitive and uncertain environment, novel frameworks, approaches, techniques and strategies are expected to build the robustness of the CSC network and improve the resilience in times of challenges.

REFERENCES

Acar, Y. and Gardner Jr, E.S. (2012) Forecasting method selection in a global supply chain. *International Journal of Forecasting*, 28(4), pp. 842-848.

Achzet, B. and Helbig, C. (2013) How to evaluate raw material supply risks-an overview. *Resources Policy*, 38(4), pp.435-447.

Adams, G.R. and Schvaneveldt, J.D. (1991) *Understanding research methods*. 2nd, New York: Longman.

Adhitya, A., Srinivasan, R. and Karimi, I.A. (2007) Heuristic rescheduling of crude oil operations to manage abnormal supply chain event. *American Institute of Chemical Engineers Journal*, 53(2), pp. 397-422.

Adhitya, A., Srinivasan, R. and Karimi, I.A. (2009) Supply chain risk identification using a HAZOP-based approach. *American Institute of Chemical Engineers Journal*, 55(6), pp. 1447-1463.

Adhitya, A. and Srinivasan, R. (2010) Dynamic simulation and decision support for multisite specialty chemicals supply chain. *Industrial & Engineering Chemistry Research*, 49(20), pp. 9917-9931.

Akkermans, H. (2001). Emergent supply networks: system dynamics simulation of adaptive supply agents. P*roceedings of the 34th Annual Hawaii International Conference on System Sciences*, Hawaii, USA, 6 January. pp. 3006-3007.

An, H., Wilhelm, W.E. and Searcy, S.W. (2011) Biofuel and petroleum-based fuel supply chain research: A literature review. *Biomass and Bioenergy*, 35(9), pp. 3763-3774.

Angerhofer, B.J. and Angelides, M.C. (2000) System dynamics modelling in supply chain management: research review. *Proceedings of* the *2000 Winter Simulation Conference*, Orlando, USA, 10-13 December. pp. 342-351.

Applequist, G.E., Pekny, J.F. and Reklaitis, G.V. (2000) Risk and uncertainty in managing chemical manufacturing supply chains. *Computers & Chemical Engineering*, 24(9), pp. 2211-2222.

Aqlan, F. and Ali, E.M. (2014) Integration lead principle and fuzzy bow-tie analysis for risk assessment in chemical industry. *Journal of Loss Prevention in the Process Industry*, 29, pp. 39-48.

Asamoah, D., Annan, J. and Nyarko, S. (2012) AHP approach for supplier evaluation and selection in a pharmaceutical manufacturing firm in Ghana. *International Journal of Business & Management*, 7(10), pp. 49-62.

Atthirawong, W. and MacCarthy, B.L. (1980) Factors affecting location decisions in international operations-a Delphi study. *International Journal of Operations & Production Management*, 23(7), pp. 794–818.

Avittathur, B. and Swamidass, P. (2007) Matching plant flexibility and supplier flexibility: lessons from small suppliers of US manufacturing plants in India. *Journal of Operations Management*, 25(3), pp.717-735.

Awudu, I. and Zhang, J. (2012) Uncertainties and sustainability concepts in biofuel supply chain management: A review. *Renewable and Sustainable Energy Reviews*, 16(2), pp. 1359-1368.

Bai, J., and Mu, D. (2014) Impacts of carbon emission policies on the supply chain based on system dynamics. *International Conference on Service Systems and Service Management (ICSSSM)*, 11th, Beijing, China, 25-27 June. pp. 1-7.

Bahinipati, C.S. and Patnaik, U. (2015) The damages from climatic extremes in India: do disaster specific and generic adaptation measures matter. *Environmental Economics & Policy Studies*, 17(1), pp. 157-177.

Baldwin, J.R., Gu, W. and Yan, B. (2013) Export growth, capacity utilization, and productivity growth: evidence from the Canadian manufacturing plants. *Review of Income and Wealth*, 59(4), pp. 665-688.

Ballhorn, D.J., Godschalx, A.L., Smart, S.M., Kautz, S. and Schädler, M. (2014) Chemical defense lowers plant competitiveness. *Oecologia*, 176(3), pp. 811-824.

Bandaly, D., Satir, A., Kahyaoglu, Y. and Shanker, L. (2012) Supply chain risk management-I: Conceptualization, framework and planning process. *Risk Management*, 14(4), pp. 249-271.

Barbosa-PÓvoa, A.P. (2012) Progresses and challenges in process industry supply chain optimization. *Current Opinion in Chemical Engineering*, 1(4), pp. 446-452.

Barlas, Y. (1994) Model validation in system dynamics. I*nternational Conference of System Dynamics Society*, 12th, Stirling, UK. System Dynamics: Methodological and Technical Issue. Proceedings, ed. by Monaghan, C. and Wolstenholme, E. pp. 1-10.

Barlas, Y. (1996) Formal aspects of model validity and validation in system dynamics. *System Dynamics Review*, 12(3), pp. 183-210.

Barlas, Y. and Gunduz, B. (2011) Demand forecasting and sharing strategies to reduce fluctuations and the bullwhip effect in supply chains. *Journal of the Operational Research Society*, 62(3), pp. 458-473.

Barry, J (2004) Supply chain risk in an uncertain global supply chain environment. *International Journal of Physical Distribution & Logistics Management*, 34(9), pp. 695 – 697.

Bartels, E., Augat, T. and Budde, F. (2006) Structural drivers of value creation in the chemical industry. In: Budde, F., Felcht, U. and Frankemolle, H. (eds.) *Value creation: strategies for the chemical industry*. Weinheim: Wiley-VCH Verlag GmbH & Co., pp. 27-39.

Bassett, M. and Gardner, L. (2010) Optimizing the design of global supply chains at Dow AgroSciences. *Computers & Chemical Engineering*, 34(2), pp. 254-265.

Beretta, S. and Bozzolan, S. (2008) Quality versus quantity: the case of forward-looking disclosure. *Journal of Accounting, Auditing & Finance*, 23(3), pp. 333-376.

Bilsel, R.U. and Ravindran, A.R. (2012) Modeling disruption risk in supply chain risk management. *International Journal of Operations Research and Information System*, 3(3), pp. 15-39.

Bonvicini, S, Leonelli P, Spadoni, G. (1988) Risk analysis of hazardous materials transportation: evaluating uncertainty by means of fuzzy logic. *Journal of Hazardous Material*, 62(1), pp. 59-74.

Boote, D.N. and Beile, P. (2005) Scholars before researchers: On the centrality of the dissertation literature review research preparation. *Educational Research*, 34(6), pp. 3-15.

Bouloiz, H., Garbolino, E., Tkiouat, M. and Guarnieri, F. (2013) A system dynamics model for behavioural analysis of safety conditions in a chemical storage unit. *Safety Science*, 58, pp. 32-40.

Brown, P.N., Yu, R., Kuan, C.H., Finley, J., Mudge, E.M. and Dentali, S. (2014) Determination of Aloin A and Aloin A in Aloe vera raw materials and finished products by high-performance liquid chromatography: single-laboratory validation. *Journal of Aoac International*, 97(5), pp. 1323-1328.

Bruinen de Bruin, Y., Hakkinen, P.B., Lahaniatis, M., Papameletiou, D., Del Pozo, C., Reina, V., Van Engelen, J., Heinemeyer, G., Viso, A.C., Rodriguez, C. and Jantunen, M. (2007) Risk management measures for chemicals in consumer products: documentation, assessment, and communication across the supply chain. *Journal of Exposure Science and Environmental Epidemiology*, 17(4), pp. 55-66.

Burgess, T., Hwarng, B., Shaw, N. and De Mattos, C. (2002) Enhancing value stream agility: The UK speciality chemical industry. *European Management Journal*, 20(2), pp. 199-212.

Cagliano, A.C., De Marco, A. and Rafele, C. (2010) Using system dynamics in warehouse management: a fast-fashion case study. *Journal of Manufacturing Technology Management*, 22(2), pp. 171-188.

Cai T. (2014) Robust optimization for smart manufacturing planning and supply chain design in chemical industry. In: Luo, Z. (eds.) *Smart Manufacturing Innovation and Transformation: Interconnection and Intelligence*. Hershey: Business Science Reference, pp. 21-27.

Campuzano, F., Mula, J. and Peidro, D. (2010) Fuzzy estimations and system dynamics for improving supply chains. *Fuzzy Sets and System*, 161(11), pp. 1530-1542.

Campuzano, F. and Mula, J. (2011) *Supply chain simulation: a system dynamics approach for improving performance*. London: Springer.

Caridi, M., Crippa, L., Perego, A., Sianesi, A. and Tumino, A. (2009) Do virtuality and complexity affect supply chain visibility? *International Journal of Production Economics*, 127(2), pp. 372-383.

Carneiro, M.C., Ribas, G.P., and Hamacher, S. (2010) Risk management in the oil supply chain: A CVaR approach. *Industrial & Engineering Chemistry Research*, 49(7), pp. 3286-3294.

Carsano, G., Vecchietti, A.R. and Montagna, J.M. (2011) Optimal design for sustainable bioethanol supply chain considering detailed plant performance model. *Computer & Chemical Engineering*, 35(8), pp. 1384-1398.

Chae, B. (2009) Developing key performance indicators for supply chain: an industry perspective. *Supply Chain Management: An International Journal*, 14(6), pp.422-428.

Chang, C. (2013) *Container Shipping Risk Management: A Case Study of Taiwan Container Shipping Industry*, 2009-2013. Ph.D. thesis, University of Plymouth.

Chen, A., Yang, H., Lo, H.K and Tang, W. (2002) Capacity reliability of a road network: an assessment methodology and numerical result. *Transportation Research Part B-Methodological*, 36(3), pp. 225–252.

Chen, A. and Kasikitwiwat, P. (2011) Modelling capacity flexibility of transportation networks. *Transportation Research Part A-Policy and Practice*, 45(2), pp. 105-117.

Choi, K., Narasimhan, R. and Kim, S.W. (2012) Postponement strategy for international transfer of products in a global supply chain: A system dynamics examination. *Journal of Operations Management*, 30(3), pp.167-179.

Choon Oh, H., Karimi, I.A. and Srinivasan, R. (2008) Supply chain management in the chemical industry: trends, issues, and research interests. In Tang, C., Teo, C., and Wei, K.K. (eds.) *Supply chain analysis-A handbook on the interaction of information, system and optimization*. New York; London: Springer, pp. 45-67.

Chopra, S. and Sodhi, M.S. (2004) Managing risk to avoid supply-chain breakdown. *MIT Sloan Management Review*, 46(1), pp. 53-61.

Christopher, F.H. and Patil, S.R. (2002) Identification and review of sensitivity analysis methods. *Risk Analysis*, 22(3), pp. 553-578.

Christopher, M. and Lee, H. (2004) Mitigating supply chain risk through improved confidence. *International Journal of Physical Distribution & Logistics Management*, 34(5), pp. 388-396.

Christopher, M. and Peck, H. (2004) Building the resilience supply chain. *International Journal of Logistics Management*, 15(2), pp. 1-13.

Cohen, M.A. and Kunreuther, H. (2007) Operations risk management: Overview of Paul Kleindorfer's contributions. *Production and Operations Management*, 16(5), pp. 525-541.

Cohen, R. and Swerdlik, M. (2010) *Psychological testing and assessment*. Boston: McGraw-Hill Higher Education.

Colicchia, C. and Strozzi, F. (2012) Supply chain risk management: a new methodology for a systematic literature review. *Supply Chain Management: An International Journal*, 17(4), pp. 403-418.

Coyle, R.G. (2001) *System dynamics modelling: A practical approach*. Boca Raton: CRC Press LLC.

Craighead, C.W., Blackhurst, J., Rungtusanatham, M.J. and Handfield, R.B. (2007) The severity of supply chain disruptions: design characteristics and mitigation capabilities. *Decision Sciences*, 38(1), pp. 131-156.

Cruz, A.M. and Krausmann, E. (2013) Vulnerability of the oil and gas sector to climate change and extreme weather events. *Climatic Change*, 121(1), pp. 41-53.

Cucchiella, F. and Gastaldi, M. (2006) Risk management in supply chain: a real option approach. *Journal of Manufacturing Technology Management*, 17(6), pp.700-720.

Daniel, S.E., Tsoulfas, G.T., Pappis, C.P. and Rachaniotis, N.P. (2004) Aggregating and evaluating the results of different environmental impact assessment methods. *Ecological Indicators*, 4(2), pp. 125-138.

Das, D., and Dutta, P. (2013) A system dynamics framework for integrated reverse supply chain with three way recovery and product exchange policy. *Computers & Industrial Engineering*, 66(4), pp. 720-733.

Davis, D. (2000) *Business research for decision making*. Duxbury: Thomson Learning.

De Treville, S., Shapiro, R.D., and Hameri, A. (2004) From supply chain to demand chain: the role of lead time reduction in improving demand chain performance. *Journal of Operations Management*, 21(6), pp. 613-627.

de Weerd-Nederhof, P.C. (2001) Qualitative case study research. The case of a PhD research project on organising and managing new product development systems. *Management Decision*, 39(7), pp. 513-538.

Ehlen, M.A., Sun, A.C., Pepple, M.A., Edison, E.D. and Jones, B.S. (2014) Chemical supply chain modelling for analysis of homeland security events. *Computer & Chemical Engineering*, 60(2), pp. 102-111.

Erera, A.L., Morales, J.C. and Savelsbergh, M. (2005) Global intermodal tank container management for the chemical industry. *Transportation Research Part E: Logistics and Transportation Review*, 41(6), pp. 551-566.

Fabiano, B., Currò, F., Reverberi, A.P., and Pastorino, R. (2005) Dangerous good transportation by road: from risk analysis to emergency planning. *Journal of Loss Prevention in the Process Industry*, 18(4-6), pp. 403-413.

Ferrio, J. and Wassick, J. (2008) Chemical supply chain network optimization. *Computers & Chemical Engineering*, 32(11), pp. 2481-2504.

Featherston, C.R. and Doolan, M. (2013) Using system dynamics to inform scenario planning: a case study. *The 31st International Conference of the System Dynamics Society* [online] Cambridge, USA, 21-25 July.

Available at: http://www.systemdynamics.org/conferences/2013/proceed/papers/P1193.pdf

[Accessed: 15th January 2016]

Fernandes, L.J., Barbosa-Póvoa, A.P., and Relvas, S. (2011) *Supply chain risk management review and a new framework for petroleum supply chains*. Berlin: Springer.

Finch, P (2004) Supply chain risk management. *Supply Chain Management: An International Journal*, 9(2), pp. 183-196.

Fisk, P. (2014) *Chemical risk assessment: a manual for REACH*. Chichester: John Wiley and Sons Ltd.

Foerstl, K., Reuter, C., Hartmann, E. and Blome, C. (2010) Managing supplier sustainability risks in a dynamically changing environment-Sustainable supplier management in the chemical industry. *Journal of Purchasing and Supply Management*, 16(2), pp. 118-130.

Ford, D.N. and Bhargav, S. (2006) Project management quality and the value of flexible strategies. *Engineering, Construction and Architectural Management*, 13(3), pp. 275-289.

Forrester, J.W. (1961) *Industrial dynamics*. Cambridge: The MIT Press.

Forrester, J.W (1969) *Urban dynamics*. Cambridge: The MIT Press.

Forrester, J.W. and Senge, P. (1980) Tests for building confidence in system dynamic models. *TIMS Studies in the Management Science*, 14, pp. 209-228.

Frier, P. (2003) Hazard and exposure considerations related to chemical risk assessment. *Greener Management International*, 41, pp. 47-55.

Furuhama, A., Hasunuma, K., Aoki, Y., Yoshioka, Y. and Shiraishi, H. (2011) Application of chemical reaction mechanistic domains to an ecotoxicity QSAR model, the KAshinhou Tool for ecotoxicity (KATE). *SAR and QSAR in Environment Research*, 22(5-6), pp. 505-523.

Gao, Y., Shang, Z. and Kokossis, A. (2009) Agent-based intelligent system development for decision support in chemical process industry. *Expert Systems with Applications*, 36(8), pp. 11099-11107.

Garbolino, R., Chery, J.P., and Guarnieri, F. (2009) Dynamic system modelling to improve risk analysis in the context of Seveso industries. *Chemical Engineering Transactions*, 17, pp. 373-378.

Garbolino, R., Chery, J.P., and Guarnieri, F. (2010) Dynamic risk assessment in the process industries: Proposal of a methodology based on the system dynamics approach. *Proceedings of the Supporting the European Safety and Reliability Conference (ESREL)* [online] Rhodes, Greece, 5-9 September.

Available at: https://halshs.archives-ouvertes.fr/hal-00661004

[Accessed: 15th January 2016]

García-Flores, R. and Wang, X. (2002) A multi-agent system for chemical supply chain simulation and management support. *OR Spectrum*, 24(3), pp. 343-370.

Ge, Y, Yang, J.B., Proudlove, N, and Spring, M. (2004) System dynamics modelling for supply-chain management: A case study on a supermarket chain in the UK. *International Transaction in Operational Research*, 11(5), pp. 495-509.

Gebreslassie, B.H., Yao, Y. and You, F. (2012) Design under uncertainty of hydrocarbon biorefinery supply chains: Multi-objective stochastic programming models, decomposition algorithm, and a comparison between CVaR and downside risk. *American Institute of Chemical Engineers Journal*, 58(7), pp. 2155-2179.

Georgiadis, P. (2013) An integrated system dynamics model for strategic capacity planning in closed-loop recycling networks: A dynamic analysis for the paper industry. *Simulation Modelling Practice and Theory*, 32(2), pp. 116-137.

Ghadge, A., Dani, S. and Kalawsky, R. (2012) Supply chain risk management: present and future scope. *International Journal of Logistics Management*, 23(3), pp. 313-339.

Ghadge, A. (2013) *A Systems Thinking Approach for Modelling Supply Chain Risk Propagation*, 2009-2013. Ph.D. thesis, University of Loughborough.

Goodwin, P. and Wright, G. (2010) The limits of forecasting methods in anticipating rare event. *Technological Forecasting and Social Change*, 77(3), pp. 355-368.

Gosling, J., Purvis, L. and Naim, M.M. (2010) Supply chain flexibility as a determinant of supplier selection. *International Journal of Production Economics*, 128(1), pp. 11-21.

Guertler, B. and Spinler, S. (2015). When does operational risk cause supply chain enterprises to tip? A simulation of intra-organizational dynamics. *Omega*, 57(Part A), pp. 54-69.

Gulledge, T. and Chavusholu, T. (2008) Automating the construction of supply chain key performance indicators. *Industrial Management & Data Systems*, 108(6), pp. 750-774.

Guillén-Gosálbeza, G. and Grossmann, I. (2010) A global optimization strategy for the environmentally conscious design of chemical supply chains under uncertainty in the damage assessment model. *Computers & Chemical Engineering*, 34(11), pp. 42-58.

Gunasekaran, A., Patel, C. and McGaughey, R.E. (2004) A framework for supply chain performance measurement. *International journal of production economics*, 87(3), pp. 333-347.

Gunasekaran, A. and Kobu, B. (2007) Performance measures and metrics in logistics and supply chain management: a review of recent literature (1995–2004) for research and applications. *International Journal of Production Research*, *45*(12), pp. 2819-2840.

Guoqiang Logistics Company official website (2015) [Online]

Available from: http://www.gqyuns.com/

[Accessed: 15th January 2016].

Gurnani, H. and Tang, C.S. (1999) Note: Optimal ordering decisions with uncertain cost and demand forecast updating. *Management science*, 45(10), pp. 1456-1462.

Hallikas, J., Karvonen, I., Pulkkinen, U., Virolainen, V.M. and Tuominen, M. (2004) Risk management processes in supplier networks. *International Journal of Production Economics*, *90*(1), pp. 47-58.

Harland, C., Brenchley, R. and Walker, H. (2003) Risk in supply network. *Journal in Purchasing and Supply Management*, 9(2), pp. 51-62.

Heckmann, I., Comes, T. and Nickel, S. (2015) A critical review on supply chain risk-definition, measure and modeling. *Omega*, 52, pp. 119-132.

Hekimoğlu, M., and Barlas, Y. (2010) Sensitivity analysis of system dynamics models by behaviour pattern measures. *Proceedings of the 28th International Conference of the System Dynamics Society* [online] Seoul, Korean, 25-29 July.

Available at: http://www.systemdynamics.org/conferences/2010/proceed/papers/P1260.pdf

[Accessed: 15th January 2016]

Hinkin, T.R. (1995) A review of scale development practices in the study of organizations. *Journal of Management*, 21(5), pp. 967-988.

Hirsch, B.G, Levine, R. and Miller, L.R. (2007) Using system dynamics modelling to understand the impact of social change initiatives. *American Journal of Community Psychology*, 39(3-4), pp. 239-253.

Ho, W., Zheng, T., Yildiz, H. and Talluri, S. (2015) Supply chain risk management: a literature review. *International Journal of Production Research*, 53(16), pp. 5031-5069.

Holton, G.A. (2004) Defining risk. *Financial Analysts Journal*, 60(6), pp. 19-25.

Hung, K. and Ryu, S. (2008) Changing risk preferences in supply chain inventory decisions. *Production Planning and Control: The Management of Operations*, 19(8), pp. 770-780.

Iles, A. and Martin, A.N. (2013) Expanding bioplastics production: sustainable business innovation in the chemical industry. *Journal of Cleaner Production*, 45(45), pp. 38-49.

McColl, E., Jacoby, A., Thomas, L., Soutter, J., Bamford, C., Steen, N., Thomas, R., Harvey, E., Garratt, A. and Bond, J. (2001) Design and use of questionnaires: a review of best practice applicable to surveys of health service staff and patients. *Health Technology Assessment*, 5(31), pp. 1-256.

Janamanchi, B. and Burns, J.R. (2007) Reducing bullwhip oscillation in a supply chain: a system dynamics model-based study. *International Journal of Information Systems and Change Management*, 2(4), pp. 350-371.

Jereb, B., Ivanuša, T. and Rosi, B. (2013) Systemic thinking and requisite holism in mastering logistics risks: the model for identifying risks in organizations and supply chain. *Amfiteatru economic Journal*, 15(33), pp. 56-73.

Jiang, N. and Huo, J.Z. (2008) Supply risk identification and analysis of iron and steel enterprises supply chain based on social system theory. *Proceedings of the 4th Wireless Communications, Networking and Mobile Computing* [online] Dalian, China, 12-14 October. pp. 1-4.

Available at: https://www.infona.pl/resource/bwmeta1.element.ieee-art-000004680659

[Accessed: 15th January 2016]

Johnson, J.K. (2010) Transforming the chemical supply chain: chemical management services offer a new business model that can reduce cost and keep companies compliant with regulatory challenges. *Tobacco Control*, 19(2), pp. 104–109.

Jüttner, U., Peck, H. and Christopher, M. (2003) Supply chain risk management: outlining an agenda for future research. *International Journal of Logistics: Research and Applications*, 6(4), pp. 197-210.

Jüttner, U. (2005) Supply chain risk management: Understanding the business requirements from a practitioner perspective. *International Journal of Logistics Management*, 16(1), pp. 120-141.

Kaggwa, M. (2008) *Modelling South Africa's Incentives under the Motor Industry Development Programme*, 2005-2008. Ph.D. thesis, University of Pretoria.

Karimi, I.A., Sharafali, M. and Mahalingam, H. (2005) Scheduling tank container movements for chemical logistics. *Aiche Journal*, 51(1), pp. 178-197.

Kenne, J.P., Dejax, P., and Gharbi, A. (2012) Production planning of a hybrid manufacturing-remanufacturing system under uncertainty within a closed-loop supply chain. *International Journal of Production Economics*, 135(1), pp. 81-93.

Khan, F.I. and Abbasi, S.A. (2001) Risk analysis of a typical chemical industry using ORA procedure. *Journal of Loss Prevention in the Process Industries*, 14(1), pp. 43-59.

Khan, O. and Burnes, B. (2007) Risk and supply chain management: creating a research agenda. *The International Journal of Logistics Management*, 18(2), pp. 197-216.

Kirschstein, T. (2015) *Integrated supply chain planning in chemical industry: potentials of simulation in network planning*. New York: Springer.

Kleindorfer, P.R. and Saad, G.H. (2005) Managing disruption risks in supply chains. *Production and Operations Management*, 14(1), pp. 53-68.

Knemeyer, A.M., Zinn, W. and Eroglu, C. (2009) Proactive planning for catastrophic events in supply chains. *Journal of Operations Management*, 27(2), pp. 141-153.

Koji, M. and Macgregor, J.F. (2008) Optimal purchasing of raw materials: a data-driven approach. *Aiche Journal*, 54(54), pp. 1554-1559.

Kothari, C.R. (2004) *Research methodology: methods and techniques*. Delhi: New Age International.

Kroes, J.M. and Ghosh, S. (2010) Outsourcing congruence with competitive priorities: Impact on supply chain and firm performance. *Journal of Operations Management*, 28(2), pp. 124-143.

Kumar, S., Himes, K.J. and Kritzer, C.P. (2014) Risk assessment and operational approaches to managing risk in global supply chains. *Journal of Manufacturing Technology Management*, *25*(6), pp. 873-890.

Kumar, S. and Yamaoka, T. (2007) System dynamics study of the Japanese automotive industry closed loop supply chain. *Journal of Manufacturing Technology Management*, 18(2), pp. 115-138.

Lahmar, M., Assavapokee, T. and Ardekani, S.A. (2006) A dynamic transportation planning support system for hurricane evacuation. *Acta Psychiatrica Scandinavica*, 94(4), pp. 106-107.

La ńez, J.M., Puigjaner, L. and Reklaitis, G.V. (2009) Financial and financial engineering considerations in supply chain and product development pipeline management. *Computers & Chemical Engineering*, 33(12), pp. 1999-2011.

La ńez, J.M. and Puigjaner, L. (2012) Prospective and perspective review in integrated supply chain modelling for the chemical process industry. *Current Opinion in Chemical Engineering*, 1(4), pp. 430-445.

Lam, J. (2003) *Enterprise risk management: From incentives to controls*. New Jersey: Wiley.

Lane, D.C., Monefeldt, C., and Rosenhead, J.V. (2000) Looking in the wrong place for healthcare improvements: a system dynamics study of an accident and emergency department. *The Journal of the Operational Research Society*, 51(5), pp. 518–531.

Lasschuit, W. and Thijssen, N. (2004) Supporting supply chain planning and scheduling decisions in the oil and chemical industry. *Computers & Chemical Engineering*, 28(6-7), pp. 863-870.

Lavastre, O., Gunasekaran, A. and Spalanzani, A. (2012) Supply chain risk management in French companies. *Decision Support Systems*, 52(4), pp. 828-838.

Lee, C.F., and Chung, C.P. (2012) An inventory model for deteriorating items in a supply chain with system dynamics analysis. *Procedia-Social and Behavioral Sciences*, 40, pp. 41-51.

Leonelli, P., Bonvicini, S. and Spadoni, G. (2000) Hazardous materials transportation: a risk-analysis-based routing methodology. *Journal of Hazardous Materials*, 71(1-3), pp. 283-300.

Leppelt, T., Foerstl, K., Reuter, C. and Hartmann, E. (2013) Sustainability management beyond organizational boundaries-sustainable supplier relationship management in the chemical industry. *Journal of Cleaner Production*, 56(1), pp. 94-102.

Lertpattarapong, C. (2002) *Applying System Dynamics Approach to the Supply Chain Management Problems*. Msc. Thesis, Massachusetts Institute of Technology.

Leveson, N. (2004) A new accident model for engineering safety systems. *Safety Science*, 42(4), pp. 237-270.

Li, C.Y., Fu, S.S., Ren, J. and Wang, H.Y. (2015) A preliminary research methodology on chemical supply chain risk management using system dynamics approach. *Proceedings of International Conference on Transportation Information and Safety (ICTIS)*, 3th, Wuhan, China, 25-28, June. IEEE. pp. 739-745.

Li, D.X. (2013) The 2013 annual report of Guoqiang Logistics Company. Wuhan: Guoqiang Logistics Company.

Li, D.X. (2014) The 2014 annual report of Guoqiang Logistics Company. Wuhan: Guoqiang Logistics Company.

Liu, L. Liu, S. and Chang, X. (2011) A study on framework of chemical industry supply chain risk management based on 3S and the internet of things. *International Conference on Artificial Intelligence, Management Science and Electronic Commerce (AIMSEC)*, 2nd, Zhengzhou, China, 8-10 August. *IEEE*. pp. 4541-4543.

Liu, L., Li, S. Fan, T. and Chang, X. (2011) Transportation risk assessment of chemical industry supply chain based on a dual model. *Procedia Environmental Science*, 11(Part A), pp. 393-397.

Liu, S. and Papageorgiou, L.G. (2013) Multiobjective optimisation of production, distribution and capacity planning of global supply chains in the process industry. *Omega*, 41(2), pp. 369-382.

Liu, Z. and Nagurney, A. (2011) Supply chain outsourcing under exchange rate risk and competition. *Omega*, 39(5), pp. 539-549.

Lohse, J., Lißner, L., Lundie, S., Ahrens, A. and Wirts, M. (2003) Never change a running process? Substitution of hazardous chemicals in products and processes: Definition, key drivers and barriers. *Greener Management International*, 41, pp. 57-76.

Lu, Y. (2015) Supply chain risk assessment based on AHP and fuzzy comprehensive assessment mode: a case study of the chemical supply chain. *International Journal of u-and e-Service. Science and Technology*, 8(2), pp. 227-234.

Lynch, G.S. (2012) Supply chain risk management. In: Gurnani, H., Mehrotra, A. and Ray, S. (eds.) *Supply chain disruptions: Theory and practice of managing risk*. London: Springer, pp. 319-336.

Lyneis, J.M. and Ford, D.N. (2007) System dynamics applied to project management: a survey, assessment, and directions for future research. *System Dynamics Review*, 23(2-3), pp. 157-189.

Manuj, I. and Mentzer, J.T. (2008a) Global supply chain risk management. *Journal of Business Logistics*, 29(1), pp. 133-155.

Manuj, I. and Mentzer, J.T. (2008b) Global supply chain risk management strategies. *International Journal of Physical Distribution & Logistics Management*, 38(3), pp. 192-223.

Mapes, J., New, C. and Szwejczewski, M. (1997) Performance trade-offs in manufacturing plants. *International Journal of Operations & Production Management*, 17(10), pp. 1020-1033.

Marhavilas, P. K., Koulouriotis, D. and Gemeni, V. (2011) Risk analysis and assessment methodologies in the work sites: On a review, classification and comparative study of the scientific literature of the period 2000-2009. *Journal of Loss Prevention in the Process Industries*, 24(5), pp. 477-523.

Markmann, C., Darkow, I.L. and von der Gracht, H. (2013) A Delphi-based risk analysis-Identifying and assessing future challenges for supply chain security in a multi-stakeholder environment. *Technological Forecasting and Social Change*, 80(9), pp. 1815-1833.

Marley, K.A., Ward, P.T. and Hill, J.A. (2014) Mitigating supply chain disruptions-A normal accident perspective. *Supply Chain Management: An International Journal*, 19(2), pp. 1-34.

Mashayekhi, A.N. and Ghili, S. (2012) System dynamics problem definition as an evolutionary process using the concept of ambiguity. *System Dynamics Review*, 28(2), pp. 182-198.

Mason-Jones, R., Naylor, B. and Towill, D.R. (2000) Lean, agile or leagile? Matching your supply chain to the marketplace. *International Journal of Production Research*, 38(17), pp. 4061-4070.

Massey, R., Jacobs, M, Gallagher, L.A., Dlugolecki, A., Geiser, K. and Edwards, S. (2012) Global Chemicals Outlook: Towards Sound Management of Chemicals. United Nations Environment Program.

McCormack, B. and Hill, E. (1997) *Conducting a survey: The SPSS workbook*. London: Thompson.

Mckinnon, A. and Braithwaite, A. (2005) European chemical supply-chain: threats and opportunities. *Logistics & Transport Focus*, 7(3), pp. 30.

Mehrjoo, M. and Pasek, Z.J. (2016) Risk assessment for the supply chain of fast fashion apparel industry: a system dynamics framework. *International Journal of Production Research*, 54(1), pp. 28-48.

Meixell, M.J. and Gargeya, V.B. (2005) Global supply chain design: A literature review and critique. *Transportation Research Part E: Logistics and Transportation Review*, 41(6), pp. 531-550.

Meric, F., Bernstam, E.V., Mirza, N.Q., Hunt, K.K., Ames, F.C., Ross, M.I., Kuerer, H.M., Pollock, R.E., Musen, M.A. and Singletary, S.E., (2002) Breast cancer on the World Wide Web: cross sectional survey of quality of information and popularity of websites. *British Medical Journal*, 324(7337), pp. 577-581.

Micheli, G.J.L., Mogre, R. and Perego, A. (2014) How to choose mitigation measures for supply chain risks. *International Journal of Production Research*, 52(1), pp. 117-129.

Milgate, M. (2001) Supply chain complexity and delivery performance: an international exploratory study. *Supply Chain Management: An International Journal*, 6(3), pp. 106-118.

Miller, A. (1991) Competitive advantages in new corporate ventures: The impact of resource sharing and reporting level. *Journal of Business Venturing*, 6(5), pp. 335-350.

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,* 207(3), pp. 1147-1161.

Mele, F.D., Kostin, A.M., Guillén-Gosálbez, G. and Jiménez, L. (2011) Multiobjective model for more sustainable fuel supply chains. a case study of the sugar cane industry in Argentina. I*ndustrial & Engineering Chemistry Research*, 50(9), pp. 4939-4958.

Moffatt, I. (1991) *Causal and simulation modelling using system dynamics*, Norwich: CATMOGS.

Mont, O., Singhal, P. and Fadeeva, Z. (2006) Chemical management services in Sweden and Europe: Lessons for the future. *Journal of Industrial Ecology*, 10(1-2), pp. 279-292.

Moizer, J.D. (1999) *System Dynamics Modelling of Occupational Safety: A Case Study Approach*, 1997-1999. Ph.D. thesis, University of Stirling.

Mokhtari, K., Ren, J., Roberts, C. and Wang, J. (2012) Decision support framework for risk management on sea ports and terminals using fuzzy set theory and evidential reasoning approach. *Expert Systems with Applications*, 39(5), pp. 5087-5103.

Mullai, A. (2009) Risk management system-A conceptual model. In: Zsidisin, G.A. and Ritchie, B. (eds.) *Supply chain risk: A handbook of assessment, management, and performance*. New York: Springer. pp. 83-101.

Naraharisetti, P.K., Karimi, I.A. and Srinivasan, R. (2011) *Chemical supply chain redesign*. Weinheim: Wiley-VCH Verlag GmbH & Co.

Narasimhan, R. and Talluri, S. (2009) Perspectives on risk management in supply chains. *Journal of Operations Management*, 27(2), pp. 114-118.

Nikolopoulou, A. and Ierapetritou, M.G. (2012) Optimal design of sustainable chemical processes and supply chain: A review. *Computer & Chemical Engineering*, 44(44), pp. 94-103.

Oehmen, J., Ziegenbein, A., Alard, R., and Schönsleben, P. (2010) System-oriented supply chain risk management. *Production Planning Control*, 20(4), pp. 343-361.

Oliveira, F. and Hamacher, S. (2012) Optimization of the petroleum product supply chain under uncertainty: A case study in Northern Brazil. *Industrial & Engineering Chemistry Research*, 51(11), pp. 4279-4287.

Oliveira, F., Gupta, V., Hamacher, S. and Grossmann, I.E. (2013) A Lagrangean decomposition approach for oil supply chain investment planning under uncertainty with risk considerations. *Computers & Chemical Engineering*, 50(7), pp. 184-195.

Olson, D.L. and Wu, D. (2011) Risk management models for supply chain: a scenario analysis of outsourcing to China. *Supply Chain Management: An International Journal*, 16(6), pp. 401-408.

Oxelheim, L. and Wihlborg, C.G. (1987) *Macroeconomic uncertainty: International risks and opportunities for the corporation*. Chichester: John Wiley and Sons.

Özbayrak, M., Papadopoulou, T.C. and Akgun, M. (2007) System dynamics modelling of a manufacturing supply chain system. *Simulation Modelling Practice and Theory*, 15(10), pp. 1338-1355.

Owen, C., Love, D. and Albores, P. (2008) Selection of simulation tools for improving supply chain performance. *Proceedings of the 50th Conference of Operational Research Society*. York, UK, 8-10 September, pp. 199-207.

Pai, R. R., Kallepalli, V.R., Caudill, R.J. and Zhou, M. (2003) Methods toward supply chain risk analysis. *IEEE International Conference on Systems, Man and Cybernetics*. Washington, USA, 5-8 October, pp. 4560-4565.

Papageorgiou, L.G. (2009) Supply chain optimisation for the process industries: Advances and opportunities. *Computer & Chemical Engineering*, 33(12), pp. 1931-1938.

Park, Y.W., Hong, P. and Roh, J.J. (2013) Supply chain lessons from the catastrophic natural disaster in Japan. *Business Horizons*, 56(1), pp. 75-85.

Pasman, H.J. and Rogers, W.J. (2012) Risk assessment by means of Bayesian network: A comparative study of compressed and liquefied H_2 transportation and tank station risks. *International Journal of Hydrogen Energy*, 37(22), pp. 17415-17425.

Peterson, D.W. and Eberlein, R.L. (1994) Reality check: A bridge between systems thinking and system dynamics. *System Dynamics Review*, 10(2-3), pp. 159-174.

Peng, M., Peng, Y. and Chen, H. (2014) Post-seismic supply chain risk management: A system dynamics disruption analysis approach for inventory and logistics planning. *Computer Operations Research*, 42(1), pp. 14-24.

Pet-Armacost, J.J., Sepulveda, J. and Sakude, M. (1999) Monte Carlo sensitivity analysis of unknown parameters in hazardous material transportation risk assessment. *Risk Analysis*, 19(6), pp. 1173-1184.

Ponomarov, S. and Holcomb, M.C. (2009) Understanding the concept of supply chain resilience. *International Journal of Logistics Management*, 20(1), pp. 124-143.

Qudrat-Ullah, H. and Seong, B.S. (2010) How to do structural validity of a system dynamics type simulation model: The case of an energy policy model. *Energy Policy*, 38(5), pp. 2216-2224.

Rangel, D.A., de Oliveira, T.K., and Leite, M.S.A. (2014) Supply chain risk classification: discussion and proposal. *International Journal of Production Research*, 53(22), pp. 6868-6887.

Rao, S. and Goldsby, T.J. (2009) Supply chain risks: a review and typology. *International Journal of Logistics Management*, 20(1), pp. 97-123.

Reiskin, E.D., White, A.L., Johnson, J.K. (1999) Servicizing the chemical supply chain. *Journal of Industrial Ecology*, 3(2-3), pp. 19-31.

Ren, J., Wang. J., Jenkinson, I., Xu, D.L., and Yang, J.B. (2009) An offshore risk analysis method using fuzzy Bayesian network. *Journal of Offshore Mechanics and Arctic Engineering*, 131(4), pp. 1-12.

Ritchie, B. and Brindley, C. (2007) Supply chain risk management and performance. *International Journal of Operations & Production Management*, 27(3), pp. 303-322.

Robb, S.P. and Bailey, A. (2003) *Risky business: Corruption, fraud, terrorism and other threats to global business*. London: Kogan Page Ltd.

Robert, C.P. and Casella, G. (2013) *Monte Carlo statistical methods*. New York: Springer-Verlag.

Rozman, Č., Pažek, K., Prišenk, J., Škraba, A., & Kljajić, M. (2012) System dynamics model for policy scenarios of organic farming development. *Organizacija*, 45(5), pp. 212-218.

Ruiz-Femenia, R., Guillén-Gosálbez, G., Jiménez, L. and Caballero, J.A. (2013) Multi-objective optimization of environmentally conscious chemical supply chains under demand uncertainty. *Chemical Engineering Science*, 95(24), pp. 1-11.

Ryan, J. and Silvanto, S. (2013) The critical role of corporate brand equity in B2B marketing: An example and analysis. *The Marketing Review*, 13(1), pp. 38-49.

Saunders, M., Lewis, P. and Thornhill, A. (2007). *Research methods for business students*, 4th edition. Harlow: Pearson Education.

Samvedi, A., Jain, V. and Chan, F.T. (2012) An integrated approach for machine tool selection using fuzzy Analytic hierarchy process and grey relational analysis. *International Journal of Production Research*, 50(12), pp. 3211-3221.

Sarkar, A. and Mohapatra, P.K.L. (2006) Evaluation of supplier capability and performance: A method for supply base reduction. *Journal of Purchasing and Supply Management*, 12(3), pp. 148-163.

Sarkis, J., Zhu, Q. and Lai, K. (2011) An organizational theoretic review of green supply chain management literature. *International Journal of Production Economics*, 130(1), pp. 1-15.

Schildhouse, J. (2006) One on one: an interview with Willis D. Pugh. *Journal of Supply Chain Management*, 42(1), pp. 2-4.

Schmidt, G. and Wilbert, E.W. (2000) Strategic, tactical and operational decisions in multi-national logistics networks: A review and discussion of modelling issues. *International Journal of Production Research*, 38(7), pp. 1501-1523.

Schmitt, A.J. and Singh, M. (2012) A quantitative analysis of disruption risk in a multi-echelon supply chain. *International Journal of Production Economics*, 139(1), pp. 22-32.

Schreckenberg, M., Pottmeier, A., Hafstein, S.F., Chrobok, R. and Wahle, J. (2005) Simulation of the autobahn traffic in North Rhine-Westphalia. In: Kitamura, R. and Kuwahara, M. (eds.) *Simulation approaches in transportation analysis*. New York: Springer, pp. 205-233.

Scruggs, C.E, Ortolano L, Schwarzman, M.R. and Wilson, M.P. (2014) The role of chemical policy in improving supply chain knowledge and product safety. *Journal of Environment Study Science*, 4(2), pp. 132-141.

Sharda, B. and Akiya, N. (2012. Selecting make-to-stock and postponement policies for different products in a chemical plant: a case study using discrete event simulation. *International Journal of Production Economics*, 136(1), pp. 161-171.

Shubik, M. (1983) Auctions, bidding, and markets: an historical sketch. In: Engelbrecht-Wiggans R., Shubik, M. and Stark, R.M. (eds.) *Auctions, bidding, and constructing: Uses and theory*. New York: New York University Press, pp. 33-52.

Sijtsma, K. (2009) On the use, the misuse, and the very limited usefulness of Cronbach's alpha. *Psychometrika*, 74(1), pp. 107-120.

Simangunsong, E., Hendry, L.C. and Stevenson, M. (2012) Supply chain uncertainty: a review and theoretical foundation for future research. *International Journal of Production Research*, 50(16), pp. 4493-4523.

Singhal, P., Agarwal, G. and Mittal, M.L. (2011) Supply chain risk management: review, classification and future research directions. *International Journal of Business Science and Applied Management*, 6(3), pp. 15-41.

Sodhi, M.S. and Tang, C.S. (2012) Managing supply chain risk. *International Series in Operations Research & Management Science*, 172, pp. 3-11.

Sodhi, M.S., Son, B. and Tang, C.S. (2012) Researchers' perspectives on supply chain risk management. *Production and Operations Management*, 21(1), pp. 1-13.

Srinivasan, R. and Karimi, I.A. (2002). Unlock supply chain improvements through effective logistics often an overlooked component of the chemical business, an examination of logistics practices can result in substantial savings. *Chemical Engineering Progress*, 98(5), pp. 32-39.

Stave, K.A. and Kopainsky, B. (2015) A system dynamics approach for examining mechanisms and pathways of food supply vulnerability. *Journal of Environmental Studies and Sciences*, 5(3), pp. 321-336.

Sterman, J.D. (2000) *Business dynamics: System thinking and modelling for a complex world*. New York: McGraw-Hill Higher Education.

Swafford, P.M., Ghosh, S. and Murthy, N. (2006) The antecedents of supply chain agility of a firm: scale development and model testing. *Journal of Operations Management*, *24*(2), pp. 170-188.

Tako, A. and Robinson, S. (2014) An empirical study comparing model development in discrete-event simulation and system dynamics. In: Brailsford, S., Churilov, L. and Dangerfield, B. (eds.) *Discrete-event simulation and system dynamics for management decision making*. Chichester: John Wiley & Sons, Ltd., pp. 140-164.

Tang, C.S. (2006) Perspectives in supply chain risk management. *International Journal of Production Economics*, 103(2), pp. 451-488.

Tang, O. and Musa, S.N. (2011) Identifying risk issues and research advancements in supply chain risk management. *International Journal of Production Economics*, 133(1), pp. 25-34.

Thakkar, J., Kanda, A. and Deshmukh, S.G. (2009) Supply chain performance measurement framework for small and medium scale enterprises. *Benchmarking: An International Journal*, 16(5), pp. 702-723.

The European Chemical Industry Council (CEFIC) (2012a*) The chemical industry in Europe: Towards* sustainability 2011/12 Report [Online].

Available at:

http://www.cefic.org/Documents/Learn%20and%20Share/Cefic_Sutainability_Report2011-2012.pdf

[Accessed: 15th January 2016].

The European Chemical Industry Council (CEFIC) (2012b) *Facts and figures: The European chemicals industry from a worldwide perspective* [Online].

Available at:

http://www.cefic.org/Documents/FactsAndFigures/2012/Facts-and-Figures-2012-The-Leaflet.pdf

[Accessed: 15th January 2016].

The white paper of Advisen Insurance Intelligence (2013) *Addressing risk management issues faced by the financial industry* [Online].

Available at: http://www.advisenltd.com/research/white-papers/aig/

[Accessed: 15th January 2016].

World Economic Forum (2014) *The global competitiveness report* [Online].

Available at: http://www3.weforum.org/docs/WEF_GlobalCompetitivenessReport_2013-14.pdf

[Accessed: 15th January 2016].

Thun, J. and Hoenig, D. (2011) An empirical analysis of supply chain risk mmanagement in the German automotive industry. *International Journal of Production Economics*, 131(1), pp. 242-249.

Thun, J., Drüke, M. and Hoenig, D. (2011) Managing uncertainty-an empirical analysis of supply chain risk management in small and medium-sized enterprises. *International Journal of Production Research*, 49(18), pp. 5511–5525.

Ting, W. (1988) *Multinational risk assessment and management*, Westport: Quorum Books.

Tong, K., Feng, Y. and Rong, G. (2011) Planning under demand and yield uncertainties in an oil supply chain. *Industrial & Engineering Chemistry Research*, 51(2), pp. 814-834.

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*, *119*(2), pp. 247-258.

Tsai, W. (2013) A review on environmental distributions and risk management of phenols pertaining to the endocrine disrupting chemicals in Taiwan. *Toxicological & Environmental Chemistry*, 95(5), pp. 723-736.

Tse Y.K. (2012) *Supply Chain Quality Risk Management: An Empirical Study of Its Dimensions and Impact on Firm Performance*, 2009-2012. Ph.D. thesis, University of Nottingham.

Tsiakis, P. and Papageorgiou, L.G. (2008) Optimal production allocation and distribution supply chain networks. *International Journal of Production Economics*, 111(2), pp. 468-483.

Tsiakkouri, M. (2010) *Risk Management Processes for Managing Disruptions in Supply Chains*, 2007-2012. Ph.D. thesis, University of Southampton.

Tummala, R. and Schoenherr, T. (2011) Assessing and managing risks using the supply chain risk management process. *Supply Chain Management: An International Journal*, 16(6), pp. 474-483.

Tuncel, G. and Alpan, G. (2010) Risk assessment and management for supply chain networks: A case study. *Computers in Industry*, 61(3), pp. 250-259.

Udenio, M., Fransoo, J.C. and Peels, R. (2015) Destocking, the bullwhip effect, and the credit crisis: empirical modelling of supply chain dynamics. *International Journal of Production Economics*, 160, pp. 34-36.

Upton, R., Zsidisin, G.A., and Panelli, A. (1986) Purchasing organization involvement in risk assessments, contingency plans, and risk management: an exploratory study. *Supply Chain Management*, 19(5), pp. 187-198.

van den Heijden, K. (1997) *Scenarios: The art of strategic conversation*. Chichester: John Wiley & Sons.

van der 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 & Logistics Management*, 32(6), pp. 409-430.

Van Wyk, J. and Baerwaldt, W. (2005) External risks and the global supply chain in the chemicals industry. *Supply Chain Forum: an International Journal*, 6(1), pp. 2-15.

Verboven, H. (2011) Communicating CSR and business identity in the chemical industry through mission slogans. *Business and Professional Communication Quarterly*, 74(4), pp. 415-431.

Viana, J., Brailsford, S. C., Harindra, V., and Harper, P. R. (2014) Combining discrete-event simulation and system dynamics in a healthcare setting: a composite model for chlamydia infection. *European Journal of Operational Research*, 237(1), pp. 196-206.

Vilko, J.P.P. and Hallikas, J.M. (2012) Risk assessment in multimodal supply chains. *International Journal of Production Economics*, 140(2), pp. 586-595.

Waters, D. (2011) *Supply chain risk management: Vulnerability and resilience in logistics*. London: Kogan Page.

Wagner, S.M. and Bode, C. (2006) An empirical investigation into supply chain vulnerability. *Journal of Purchasing and Supply Management*, 12(6), pp. 301-312.

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*, 49(13), pp. 4063-4084.

Weiler, S., Páez, D., Chun, J.H., Graves, S.C. and Lanza, G. (2011) Supply chain design for the global expansion of manufacturing capacity in emerging markets. *Cirp Journal of Manufacturing Science & Technology*, 4(3), pp. 265-280.

Wilson, M.C. (2007) The impact of transportation disruptions on supply chain performance. *Transportation Research Part E: Logistics and Transportation Review*, 43(4), pp. 295-320.

Waring, A. (1996) *Safety management systems*. London: Chapman and Hall.

Wong, K.T., Antonio, G.E., Hui, D.S., Lee, N., Yuen, E.H., Wu, A., Leung, C.B., Rainer, T.H., Cameron, P., Chung, S.S. and Sung, J.J. (2003) Severe acute respiratory syndrome: radiographic appearances and pattern of progression in 138 patients. *Radiology*, 228(2), pp. 401-406.

Woodruff, J.M. (2005) Consequence and likelihood in risk estimation: A matter of balance in UK health and safety risk assessment practice. *Safety Science*, 43, pp. 345-353.

Wu, D.D. and Olson, D.L. (2013) Computational simulation and risk analysis: An introduction of state of the art research. *Mathematical and Computer Modelling*, *58*(9), pp. 1581-1587.

Wulan, M. and Petrovic, D. (2012) A fuzzy logic based system for risk analysis and evaluation within enterprise collaborations. *Computers in Industry*, 63(8), pp. 739-748.

Yang, C.C. (2010) Impact of the container security initiative on Taiwan’s shipping industry. *Maritime Policy and Management*, 37(7), pp. 699-722.

Yang, C.C. and Chen, B.S. (2006) Supplier selection using combined Analytic hierarchy process and grey relational analysis. *Journal of Manufacturing Technology Management*, 17(7), pp. 926-941.

Yang, C.S., Lu, C.S., Haider, J.J. and Marlow, P.B. (2013) The effect of green supply chain management on green performance and firm competitiveness in the context of container shipping in Taiwan. *Transportation Research Part E: Logistics and Transportation Review*, 55(6), pp. 55-73.

Yang, J.B. and Xu, D.L. (2002) On the evidential reasoning algorithm for multiple attribute decision analysis under uncertainty. *Systems, Man and Cybernetics-Part A: Systems and Humans, IEEE Transactions on*, *32*(3), pp. 289-304.

Yang, Z.L., Bonsall, S. and Wang, J. (2008) Fuzzy rule-based Bayesian reasoning approach for prioritization of failures in FMEA. *Reliability, IEEE Transactions on*, 57(3), pp. 517-528.

Yang, Z.L., Bonsall, S. and Wang, J. (2010) Facilitating uncertainty treatment in the risk assessment of container supply chains. *Journal of Marine Engineering & Technology*, *9*(2), pp. 23-36.

Yeo, G., Pak, J., and Yang, Z.L. (2013) Analysis of dynamic effects on seaports adopting port security policy. *Transport Research Part A-Policy and practice*, 49(1), pp. 285-301.

Yin, R.K. (2013) *Case study research-design and methods*. 5th Edition, Thousand Oaks: Sage publications.

You, F., Wassick, J.M. and Grossmann, I.E. (2009) Risk management for a global supply chain planning under uncertainty: models and algorithms. *American Institute of Chemical Engineers Journal*, 55(4), pp. 931-946.

Yu, X., Yan, H. and Cheng, T.C.E. (2001) Benefits of information sharing with supply chain partnerships. *Industrial Management & Data Systems*, 101(3), pp. 114-121.

Yu, H., Zeng, A.Z. and Zhao, L. (2009) Single or dual sourcing: decision-making in the presence of supply chain disruption risks. *Omega*, *37*(4), pp. 788-800.

Zhu, Q., Cordeiro, J. and Sarkis, J. (2013) Institutional pressures, dynamic capabilities and environmental management systems: Investigation the ISO 9000-Environmental management system implementation linkage. *Journal of Environmental Management*, 114(15), pp. 232-242.

Zsidisin, G.A. and Ritchie, B. (2008) *Supply chain risk: A handbook of assessment, management, and performance*. New York: Springer.

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 & Logistics Management*, *34*(5), pp. 397-413.

APPENDICES

Appendix One

Risk Management of the Transportation Process in the Chemical Supply Chain Questionnaire (Part A)

Dear Sir/Madam,

My name is Chaoyu Li; I am currently pursuing a PhD degree at the Liverpool Logistics Offshore and Marine Research Institute (LOOM) in Liverpool John Moores University. My research topic is "Risk Modelling and Simulation of the Chemical Supply Chain using System Dynamics Approach", which intends to provide a novel, systematic and structured approach to conduct hazard identification, risk analysis, risk evaluation and risk reduction in chemical supply chain. The purpose of the questionnaire to examine the identified hazards involved in the transportation operations of the chemical supply chain.

I am writing to elicit your opinion as an executive in the transportation process of the chemical supply chain with expert knowledge on hazard identification. Your participation is voluntary; however, your assistance would be greatly appreciated in making this a meaningful questionnaire. The information gathered in this survey will be treated in the **strictest confidence**, as this has always been the policy of the Liverpool John Moores University. This survey will take you about 10-15 minutes. This questionnaire is anonymous, thus your response can not be attributed to you or your company.

If you have any questions about this research please contact me at +44 (0) 759 334 1528, or by email C.Li@2012.ljmu.ac.uk or my supervisor, Dr. Jun Ren, at +44 (0) 151 231 2236, or by email j.ren@ljmu.ac.uk.

Please accept my thanks for your anticipated co-operation. If you wish to receive a copy of the research results, please email me at C.Li@2012.ljmu.ac.uk (regardless of whether you participate or not).

Yours faithfully,

Chaoyu Li,
PhD Candidate,

Liverpool Logistics Offshore and Marine Research Institute (LOOM)
Tel: +44-(0)759 334 1528
Email: C.Li@2012.ljmu.ac.uk
Room 121, James Parsons Building
Liverpool John Moores University, Byrom Street, Liverpool, L3 3AF, UK

Section A: Respondent Profile

We would like to ask you about how your research or business involves chemical supply chain transportation operations.

1. What is the type of your organisation?

Goods Provider (e.g. Manufacturing)	Service Provider (e.g. Distribution, Warehousing)	Infrastructure Provider (e.g. Port)	Other
☐	☐	☐	☐

2. What types of transportation methods are you involved in? We are thinking particularly of four transportation methods (please tick all that apply):

- Road transportation - Involving the transport of chemical substances on roads.
- Rail transportation - Involving the transport of chemical substances through train routes.
- Air transportation - Involving the transport of chemical substances through freight flights.
- Waterborne transportation - Involving the transport of chemical substances by ship.

Road Transport	Rail Transport	Air Transport	Waterway Transport
☐	☐	☐	☐

3. What is your organisation's gross revenue?

   ☐ $0-$1M ☐ $1M-$5M ☐ $5M-$10M ☐ $10M-$20M ☐ >$20M

4. What is your job title?

____

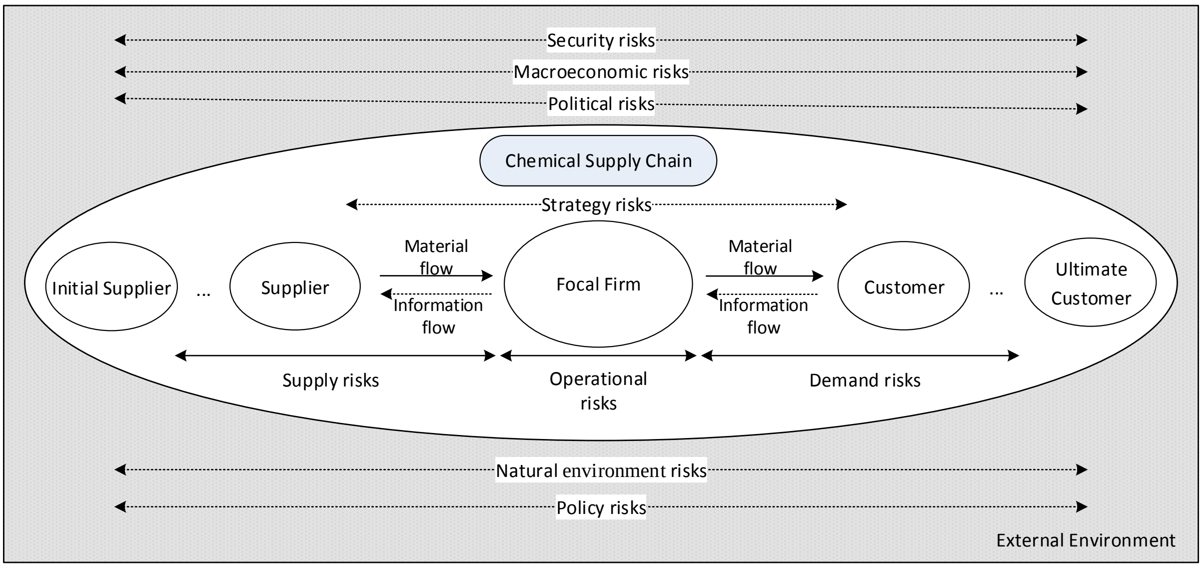
5. What is your research area or related to the professional role?

____

6. For how many years have you worked in the chemical industry or chemical supply chain?

   ☐ 1-5 years ☐ 6-10 years ☐ 11-15 years ☐ 16-20 years ☐ >20 years

Based on our research, the propose categorising the risks in chemical supply chain into nine categories: supply risks, operational risks, demand risks, strategic risks, security risks, macroeconomic risks, political risks, natural environment risks and policy risks (see the figure below for a schematic of where these risks are focused). The following questions are related to the **Identified Hazards** in the chemical supply chain.



<u>Section B:</u> Supply risks refer to the potential or actual disturbances surrounding the supply procedure in supply chain operations. From detailed synthesis of the literature in this discipline, the components of supply risks are listed below. For the identified supply risks in the chemical supply chain, what is the importance do you think to transportation operations, and thus analyse the risks in transportation? (1=Extremely Unimportant; 2=Very Unimportant; 3= Minor Unimportant; 4= Moderate; 5=Minor Important, 6=Very Important, 7=Extremely Important)

Identified Hazards		**How important is this hazard to transportation?**
Supply risks	Supply market uncertainty	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	High sourcing cost	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Supply activities disruptions	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Low supplier reliability	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Low supplier flexibility	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Complexity of material types	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Unavailability of materials	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Low material quality	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Lack of supply process monitoring	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
Please add that any other risks should be considered?		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7

<u>Section C:</u> Operational risks refer to the specialized operational features in the internal supply chain that may cause production, transportation or services delay. Through a detailed synthesis of the literature in this discipline, the components of operational risks are listed below. For the identified operational risks in the chemical supply chain, what is the importance do you think to transportation operation to analyse the risks in transportation?

(1=Extremely Unimportant; 2=Very Unimportant; 3= Minor Unimportant; 4= Moderate; 5=Minor Important, 6=Very Important, 7=Extremely Important)

Identified Hazards		**How important is this hazard to transportation?**
Operational risks	Hazardous nature of materials	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Breakdown in core operations	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Improper operational procedure selection	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Inadequate process capacity	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	High level of process variation	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Complexity of product types	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Lack of/inappropriate inventory management	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Lack of/inappropriate container management	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Problem of product quality	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Lack of qualified staffs	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Technology innovation	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Information sharing delay	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Information sharing inaccuracy	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Financial problems	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
Please add that any other risks should be considered?		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7

<u>Section D:</u> Demand risks are specific to the possibility of unexpected changes in the downstream of the supply chain. After detailed synthesis of the literature, the components of demand risks are listed below. For the identified demand risks in the chemical supply chain, what is the importance do you think to transportation operations, thus analysing the risks in transportation?

(1=Extremely Unimportant; 2=Very Unimportant; 3= Minor Unimportant; 4= Moderate; 5=Minor Important, 6=Very Important, 7=Extremely Important)

Identified Hazards		**How important is this hazard to transportation?**
Demand risks	Demand uncertainty	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Customer requirement changes	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Forecasting errors	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Product substitution	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Competition changes	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
Please add that any other risks should be considered?		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7

<u>Section E:</u> Strategic risks represent the risks related to the supply chain strategic characteristics that the strategic actions influence the whole supply chain context. Through a detailed synthesis of the literature in this discipline, the components of strategic risks are listed below. For the identified strategic risks in the chemical supply chain, what is the importance do you think to the transportation operations?

(1=Extremely Unimportant; 2=Very Unimportant; 3= Minor Unimportant; 4= Moderate; 5=Minor Important, 6=Very Important, 7=Extremely Important)

Identified Hazards		**How important is this hazard to transportation?**
Strategic risks	Improper supply chain network design	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Lack of information sharing	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Lack of partner relationship management	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Location selection of facilities	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Improper supply chain strategy selection	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
Please add that any other risks should be considered?		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7

<u>Section F:</u> Security risks refer to third party elements that surround the internal or external environment and intend to steal proprietary, data or knowledge, or interrupt supply chain operations. After detailed synthesis of the literature in this discipline, the components of security risks are listed below. For the identified security risks of the chemical supply chain, what is the importance do you think to transportation operations?

(1=Extremely Unimportant; 2=Very Unimportant; 3= Minor Unimportant; 4= Moderate; 5=Minor Important, 6=Very Important, 7=Extremely Important)

Identified Hazards		**How important is this hazard to transportation?**
Security risks	Information system security problems	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Infrastructure security problems	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Transportation security problems	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Labour strikes	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Criminal acts	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Terrorism	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
Please add that any other risks should be considered?		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7

<u>Section G:</u> Macroeconomic risks are a broad term referring to the economic fluctuations in the economic activity and price changes. Through a detailed synthesis of the literature in this area, the components of macroeconomic risks are listed below. For the identified macroeconomic risks of the chemical supply chain, what is the importance do you think to transportation operations?

(1=Extremely Unimportant; 2=Very Unimportant; 3= Minor Unimportant; 4= Moderate; 5=Minor Important, 6=Very Important, 7=Extremely Important)

Identified Hazards		How important is this hazard to transportation?
Macroeconomic risks	Economy fluctuation	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Financial crisis	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Price fluctuation	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Inflation	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Exchange rate arbitrages	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
Please add that any other risks should be considered?		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7

<u>Section H:</u> Political risks refer to the uncertainty and instability when major change happens in political regimes. From a detailed synthesis of the literature in this discipline, the components of political risks are listed below. For the identified political risks of the chemical supply chain, what is the importance do you think to transportation operations?

(1=Extremely Unimportant; 2=Very Unimportant; 3= Minor Unimportant; 4= Moderate; 5=Minor Important, 6=Very Important, 7=Extremely Important)

Identified Hazards		How important is this hazard to transportation?
Political risks	Government instability	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Revolution	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	War	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Government attitude	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
Please add that any other risks should be considered?		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7

<u>Section I:</u> Natural environment risks include the various natural phenomena that could impair supply chain operations in the affected region. After detailed synthesis of the literature, the components of natural environment risks are listed below. For the identified natural environment risks of the chemical supply chain, what is the importance do you think to transportation operations?

(1=Extremely Unimportant; 2=Very Unimportant; 3= Minor Unimportant; 4= Moderate; 5=Minor Important, 6=Very Important, 7=Extremely Important)

Identified Hazards		How important is this hazard to transportation?
Natural environment risks	Natural disaster	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Infectious disease	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Weather risk	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
Please add that any other risks should be considered?		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7

<u>Section J:</u> Policy risks refer to the uncertainty and instability of the policies, laws, regulations and other available policy materials. From a detailed synthesis of the literature in this area, the components of policy risks are listed below. For the identified policy risks of the chemical supply chain, what is the importance do you think that impact transportation operations?

(1=Extremely Unimportant; 2=Very Unimportant; 3= Minor Unimportant; 4= Moderate; 5=Minor Important, 6=Very Important, 7=Extremely Important)

Identified Hazards		**How important is this hazard to transportation?**
Policy risks	Changes in legislation/ regulations/ policies	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	The requirement of environment protection	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
	Stakeholders'/society's attitudes	□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
Please add that any other risks should be considered?		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7
		□ 1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7

THANK YOU ONCE AGAIN FOR YOUR KIND PARTICIPATION IN THIS SURVEY.

YOUR ANSWERS WILL BE KEPT CONFIDENTIAL.

化工供应链中运输过程的风险管理

调查问卷 (第一部分)

尊敬的专家：

您好！我是英国利物浦约翰莫尔斯大学(LJMU)利物浦物流和海洋研究所的一名博士研究生，名叫李超宇。LJMU与武汉理工大学共同参加欧盟第七框架计划“玛丽居里行动计划”中的《风险评估与决策科学》研究项目。作为此欧盟项目的参与者，我希望能提出一种全新的、系统化与结构化的方法对化工供应链进行风险识别、评估以及控制的研究。目前，我正在武汉理工大学开展交流研究工作，希望借此机会通过此次问卷调查得到化工供应链在运输过程中的一些风险指标信息，为今后的研究提供宝贵的数据支持。

需要提出的是，本次问卷调查采取自愿形式。我们非常感激您在问卷填写中给予的帮助。本次调查的信息将会完全保密，这也是利物浦约翰摩尔斯大学一直以来所严格要求的。本次调查需要10到15分钟的时间。

如果您有任何疑问，请通过电话 +44 (0) 759 334 1528、 +86 186 0606 3710或电子邮件C.Li@2012.ljmu.ac.uk 联系我。您也可以通过电话 +44 (0) 151 231 2236 或电子邮件J.Ren@ljmu.ac.uk联系我的导师Jun Ren博士。

请接受我们由衷的感激。如果您想知道调查的最终结果，请通过电子邮件C.Li@2012.ljmu.ac.uk与我联系。

李超宇
博士研究生
Liverpool Logistics Offshore and Marine Research Institute (LOOM)
Tel: +44-(0)759 334 1528; +86-186 0606 3710
Email: C.Li@2012.ljmu.ac.uk
Room 121, James Parsons Building
Liverpool John Moores University, Byrom Street, Liverpool, L3 3AF, UK

第一部分：基本情况

下列问题是针对您以及您所在的企业或公司，请根据您以及您所在的企业或公司的实际情况进行选择。

1. 您所在机构的在化工供应链中扮演的角色是？

货物供应方 如：工厂	服务提供方 如：配送、存储	基础设施提供方 如：港口	其它
☐	☐	☐	☐

2. 您所在的企业在运营过程中是否曾经遭遇过危害事件？ 后果是否严重？

   ☐没有 ☐有，后果不严重 ☐有，后果严重

3. 您所在的企业有没有对雇员和管理人员进行过风险管理培训？

   ☐专门进行过 ☐有，但是附带性的 ☐没有

4. 针对供应链风险管理，要系统掌握风险管理方面的知识，您认为最需要解决的问题是什么？

   ☐如何对供应链风险进行系统的识别和分析 ☐掌握针对供应链风险的管理措施

   ☐专门成立供应链风险管理部门 ☐公司领导的重视程度

   ☐其它（请说明）

5. 您的职位是？

   ____

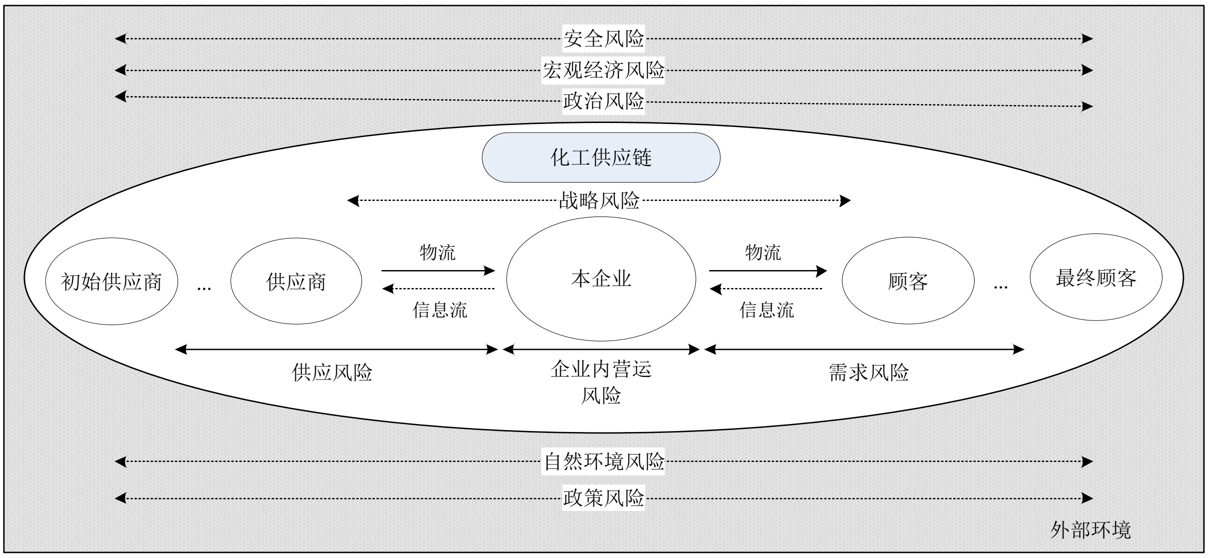
6. 您所从事的研究领域或专业领域是？

   ____

7. 您在化工行业或化工供应链行业中工作了多久？

   ☐ 1-5 年 ☐ 6-10 年 ☐ 11-15 年 ☐ 16-20 年 ☐ >20 年

在前期的研究中，我们将化工供应链的风险分为 9 类：供应风险、企业内营运风险、需求风险、战略风险、安全风险、政治风险、自然环境风险和政策风险。接下来的问题是针对化工供应链中的相关的风险进行识别。



第二部分：供应风险是指围绕供应链运营中的供应过程的潜在的和实际的风险。经过多方面的综合考虑分析，我们认为供应风险大致有以下几种（见下表）。为帮助辨识这些风险，您认为在化工供应链中，这些风险各自的重要性得分是？

（1 完全不重要，2 不重要，3 不是很重要，4 一般重要，5 比较重要，6 很重要，7 十分重要）

辨识出的风险因素		**风险因素对化工供应链的影响程度**
供应风险	供应市场的不确定	□1 □2 □3 □4 □5 □6 □7
	高采购成本	□1 □2 □3 □4 □5 □6 □7
	供应行为中断	□1 □2 □3 □4 □5 □6 □7
	供应方可靠性低	□1 □2 □3 □4 □5 □6 □7
	供应方灵活性低	□1 □2 □3 □4 □5 □6 □7
	货物种类繁多	□1 □2 □3 □4 □5 □6 □7
	材料短缺	□1 □2 □3 □4 □5 □6 □7
	材料质量低	□1 □2 □3 □4 □5 □6 □7
	缺乏对供应过程的监控	□1 □2 □3 □4 □5 □6 □7
您是否认为还有其它因素？		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7

第三部分：根据供应链中企业内可能导致产品或服务延迟的运营特征考虑其企业内营运风险。经过多方面的综合考虑，我们认为企业内营运风险大致有以下几种（见下表）。为帮助辨识这些风险，您认为在化工供应链中，这些风险的各自的重要性得分是？

（1 完全不重要，2 不重要，3 不是很重要，4 一般重要，5 比较重要，6 很重要，7 十分重要）

辨识出的风险因素		**风险因素对化工供应链的影响程度**
企业内营运风险	货物具有易燃易爆等危险性质	□1 □2 □3 □4 □5 □6 □7
	服务商选择不当	□1 □2 □3 □4 □5 □6 □7
	运营方法选择不当	□1 □2 □3 □4 □5 □6 □7
	企业内主要设备失效或发生故障	□1 □2 □3 □4 □5 □6 □7
	企业供应 / 生产 / 运输能力不足	□1 □2 □3 □4 □5 □6 □7
	运营过程复杂多变	□1 □2 □3 □4 □5 □6 □7
	货物种类复杂	□1 □2 □3 □4 □5 □6 □7
	库存管理缺乏/不当	□1 □2 □3 □4 □5 □6 □7
	容器管理缺乏/不当	□1 □2 □3 □4 □5 □6 □7
	合格的工作人员缺乏	□1 □2 □3 □4 □5 □6 □7
	技术革新的挑战	□1 □2 □3 □4 □5 □6 □7
	供应链信息共享水平低	□1 □2 □3 □4 □5 □6 □7
	供应链信息共享延误 / 不准确	□1 □2 □3 □4 □5 □6 □7
	企业内财务问题	□1 □2 □3 □4 □5 □6 □7
您是否认为还有其它因素？		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7

第四部分：需求风险是指供应链下游中不可预知的变化所导致的风险。经过多方面的综合考虑，我们认为需求风险大致有以下几种（见下表）。为帮助辨识这些风险，您认为在化工供应链中，这些风险的各自的重要性得分是？

（1 完全不重要，2 不重要，3 不是很重要，4 一般重要，5 比较重要，6 很重要，7 十分重要）

辨识出的风险因素		**风险因素对化工供应链的影响程度**
需求风险	需求的不确定性	□1 □2 □3 □4 □5 □6 □7
	顾客要求的变化	□1 □2 □3 □4 □5 □6 □7
	预测错误	□1 □2 □3 □4 □5 □6 □7
	可替代产品	□1 □2 □3 □4 □5 □6 □7
	竞争的变化	□1 □2 □3 □4 □5 □6 □7
您是否认为还有其它因素？		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7

第五部分：战略行为影响整个供应链体系，战略风险可根据其战略特征得到。经过多方面的综合考虑，我们认为战略风险大致有以下几种（见下表）。为帮助辨识这些风险，您认为在化工供应链中，这些风险的各自的重要性得分是？

（1 完全不重要，2 不重要，3 不是很重要，4 一般重要，5 比较重要，6 很重要，7 十分重要）

辨识出的风险因素		**风险因素对化工供应链的影响程度**
战略风险	供应网络设计不完善	□1 □2 □3 □4 □5 □6 □7
	共享信息缺乏	□1 □2 □3 □4 □5 □6 □7
	合作伙伴管理缺乏	□1 □2 □3 □4 □5 □6 □7
	位置选择不合理	□1 □2 □3 □4 □5 □6 □7
	供应链策略选择不完善	□1 □2 □3 □4 □5 □6 □7
您是否认为还有其它因素？		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7

第六部分：安全风险是指由于第三方盗取物品、数据、知识或中断供应链运营而产生的风险。经过多方面的综合考虑，我们认为安全风险大致有以下几种（见下表）。为帮助辨识这些风险，您认为在化工供应链中，这些风险的各自的重要性得分是？

（1 完全不重要，2 不重要，3 不是很重要，4 一般重要，5 比较重要，6 很重要，7 十分重要）

辨识出的风险因素		**风险因素对化工供应链的影响程度**
安全风险	信息系统安保问题	□1 □2 □3 □4 □5 □6 □7
	基础设施安保问题	□1 □2 □3 □4 □5 □6 □7
	运输安保问题	□1 □2 □3 □4 □5 □6 □7
	罢工	□1 □2 □3 □4 □5 □6 □7
	犯罪	□1 □2 □3 □4 □5 □6 □7
	恐怖主义	□1 □2 □3 □4 □5 □6 □7
您是否认为还有其它因素？		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7

第七部分：宏观经济风险是在经济波动和价格调整中对经济活动的影响。经过多方面的综合考虑，我们认为宏观经济风险大致有以下几种（见下表）。为帮助辨识这些风险，您认为在化工供应链中，这些风险的各自的重要性得分是？

（1 完全不重要，2 不重要，3 不是很重要，4 一般重要，5 比较重要，6 很重要，7 十分重要）

辨识出的风险因素		**风险因素对化工供应链的影响程度**
宏观经济风险	经济波动	□1 □2 □3 □4 □5 □6 □7
	经济危机	□1 □2 □3 □4 □5 □6 □7
	价格波动	□1 □2 □3 □4 □5 □6 □7
	通货膨胀	□1 □2 □3 □4 □5 □6 □7
	汇率套利交易	□1 □2 □3 □4 □5 □6 □7
您是否认为还有其它因素？		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7

第八部分：政治风险是指主要政治体系改变的不确定性和不稳定性。经过多方面的综合考虑，我们认为政治风险大致有以下几种（见下表）。为帮助辨识这些风险，您认为在化工供应链中，这些风险的各自的重要性得分是？（如过以下问题有欠妥或不方便回答之处，请您跳过）

（1 完全不重要，2 不重要，3 不是很重要，4 一般重要，5 比较重要，6 很重要，7 十分重要）

辨识出的风险因素		**风险因素对化工供应链的影响程度**
政治风险	政府不稳定性	□1 □2 □3 □4 □5 □6 □7
	革命	□1 □2 □3 □4 □5 □6 □7
	战争	□1 □2 □3 □4 □5 □6 □7
	执政理念的冲突或改变	□1 □2 □3 □4 □5 □6 □7
您是否认为还有其它因素？		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7

第九部分：自然环境风险主要是指自然现象在其影响区域对供应链运营的损害。经过多方面的综合考虑，我们认为自然环境风险大致有以下几种（见下表）。为帮助辨识这些风险，您认为在化工供应链中，这些风险的各自的重要性得分是？

（1 完全不重要，2 不重要，3 不是很重要，4 一般重要，5 比较重要，6 很重要，7 十分重要）

辨识出的风险因素		**风险因素对化工供应链的影响程度**
自然环境风险	自然灾害	□1 □2 □3 □4 □5 □6 □7
	传染病	□1 □2 □3 □4 □5 □6 □7
	天气风险	□1 □2 □3 □4 □5 □6 □7
您是否认为还有其它因素？		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7

第十部分：政策风险是指由税务政策，法律，规定和现有的政策条文引起的不确定性和不稳定性。经过多方面的综合考虑，我们认为政策风险大致有以下几种（见下表）。为帮助辨识这些风险，您认为在化工供应链中，这些风险的各自的重要性得分是？

（1 完全不重要，2 不重要，3 不是很重要，4 一般重要，5 比较重要，6 很重要，7 十分重要）

辨识出的风险因素		**风险因素对化工供应链的影响程度**
政策风险	政策，法律，法规的改变	□1 □2 □3 □4 □5 □6 □7
	社会对环境保护的要求	□1 □2 □3 □4 □5 □6 □7
	利益相关人的态度	□1 □2 □3 □4 □5 □6 □7
您是否认为还有其它因素？		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7
		□1 □2 □3 □4 □5 □6 □7

再次感谢您在此次调查中提供的帮助。

您的回答将会被保密。

Appendix Two

Risk Management of the Transportation Process in the Chemical Supply Chain Questionnaire (Part B)

Dear Sir/Madam,

My name is Chaoyu Li; I am currently pursuing a PhD degree at the Liverpool Logistics Offshore and Marine Research Institute (LOOM) in Liverpool John Moores University. My research topic is "Risk Modelling and Simulation of the Chemical Supply Chain using System Dynamics Approach", which intends to provide a novel, systematic and structured approach to conduct hazard identification, risk analysis, risk evaluation and risk reduction in the chemical supply chain.

The purposes of the questionnaire are:

1. To examine the likelihood of the identified operational hazards that influence transportation operations in the chemical supply chain.
2. To analyse the interaction sites of the hazards in the transportation process and investigate the consequence severity and consequence probability of these hazards.

I am writing to elicit your opinion as an executive in the chemical supply chain with expert knowledge on risk management. Your participation is voluntary; however, your assistance would be greatly appreciated in making this a meaningful questionnaire. The information gathered in this survey will be treated in the **strictest confidence**, as this has always been the policy of the Liverpool John Moores University. This survey will take you about 15-20 minutes. This questionnaire is anonymous, thus your response can not be attributed to you or your company.

If you have any questions about this research please contact me at +44 (0) 759 334 1528, or by email C.Li@2012.ljmu.ac.uk or my supervisor, Dr. Jun Ren, at +44 (0) 151 231 2236, or by email j.ren@ljmu.ac.uk.

Please accept my thanks for your anticipated co-operation. If you wish to receive a copy of the research results, please email me at C.Li@2012.ljmu.ac.uk (regardless of whether you participate or not).

Yours faithfully,

Chaoyu Li,
PhD Candidate,

Liverpool Logistics Offshore and Marine Research Institute (LOOM)
Tel: +44-(0)759 334 1528
Email: C.Li@2012.ljmu.ac.uk
Room 121, James Parsons Building
Liverpool John Moores University, Byrom Street, Liverpool, L3 3AF, UK

Section A: Respondent Profile

We would like to ask you about how your research or business involves chemical supply chain transportation operations.

1. What is the type of your organisation?

Goods Provider (e.g. Manufacturing)	Service Provider (e.g. Distribution, Warehousing)	Infrastructure Provider (e.g. Port)	Other
☐	☐	☐	☐

2. What types of transportation methods are you involved in? We are thinking particularly of four transportation methods (please tick all that apply):

- Road transportation - Involving the transport of chemical substances on roads.
- Rail transportation - Involving the transport of chemical substances through train routes.
- Air transportation - Involving the transport of chemical substances through freight flights.
- Waterborne transportation - Involving the transport of chemical substances by ship.

Road Transport	Rail Transport	Air Transport	Waterway Transport
☐	☐	☐	☐

3. What is your organisation's gross revenue?

☐ $0-$1M ☐ $1M-$5M ☐ $5M-$10M ☐ $10M-$20M ☐ >$20M

4. What is your job title?

____

5. What is your research area or related to the professional role?

____

6. For how many years have you worked in the chemical industry or chemical supply chain?

☐ 1-5 years ☐ 6-10 years ☐ 11-15 years ☐ 16-20 years ☐ >20 years

<u>Section B:</u> The following questions are related to the **Operational Risks** associated with **Transportation Operations** in the chemical supply chain. According to your experience and opinion about the degree of the **Occurrence Likelihood** of a hazardous event, please fill the appropriate score in each of the following:

(The **occurrence likelihood** of a hazardous event refers to the frequency of the hazardous event occurring in a certain time period, which interrupts transportation operations in the chemical supply chain)

<table>
<tr><th colspan="4">Identified Hazards in Chemical Supply Chain</th></tr>
<tr><th>No</th><th>Source of operational hazards</th><th>Likelihood of Occurrence</th><th></th></tr>
<tr><td>1</td><td>Hazard nature of materials</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td><td rowspan="14">How likely is it that the hazardous event will occur?

0= Rare: Has never or rarely happened
1= Very Low: Only likely to happen within 2-3 years
3= Low: May occur within one year
5= Medium: Likely to happen at some point within a few months
7= High: Circumstances frequently encountered on a monthly basis
9= Very High: Circumstances frequently encountered almost daily</td></tr>
<tr><td>2</td><td>Breakdown in core operations</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td>3</td><td>Improper operational procedure selection</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td>4</td><td>Inadequate process capacity</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td>5</td><td>High level of process variation</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td>6</td><td>Complexity of product types</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td>7</td><td>Lack of/inappropriate inventory management</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td>8</td><td>Lack of/inappropriate container management</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td>9</td><td>Problem of product quality</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td>10</td><td>Lack of qualified staffs</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td>11</td><td>Technology innovation</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td>12</td><td>Information sharing delay</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td>13</td><td>Information sharing inaccuracy</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td>14</td><td>Financial problems</td><td>□ 0 □ 1 □ 3 □ 5 □ 7 □ 9</td></tr>
<tr><td colspan="2">Comments:</td><td colspan="2">Examples:
If Breakdown in core operations has rarely happened in years then please tick 0.
If Breakdown in core operations has frequently happened and could be encountered monthly then please tick 7.</td></tr>
</table>

<u>Section C:</u> Through impacting on the core activities of transportation operations, both actual and potential risks influence supply chain operations. The following questions are related to the **Risks** associated with the **Core Elements** of transportation operations. According to your experience and opinion about the degree of **Consequence Severity** and **Consequence Probability**, please tick the appropriate score in each of the following:

(**Consequence Severity** refers to the magnitude of possible consequences caused by the hazardous event; **Consequence Probability** refers to the probability of the consequence given the hazardous event occurred)

Consequence Severity and Consequence Probability Analysis

	Core Elements	Consequence severity	Consequence probability
Hazard nature of materials	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9

Comments:

Examples:

If Hazard nature of materials has an insignificant effect on the available infrastructure capacity, then please tick 0.

If the consequence probability of Hazard nature of materials impacting on the available infrastructure capacity will never happen then please tick 0.

What is the severity level of the impact on the core elements of the transportation process?

0= Negligible: An insignificant effect on this core activity
1= Minor: Causing some inconvenience with minor impacts
3= Moderate: Causing some disruption with medium impacts
5= Major: Causing major disruptions to transportation operations
7= Critical: Causing failure of transportation operations
9= Catastrophic: Causing complete and irrecoverable failure of transportation operations

What is the consequence probability of the risk impact on the core activities of the transportation process?
0= Impossible: Will never occur
1= Rare: Rarely to occur
3= Low: Unlikely to occur
5= Medium: About an even chance of occurring
7= High: Likely to occur
9= Definite: Definitely will occur

Consequence Severity and Consequence Probability Analysis

	Core Elements	Consequence severity	Consequence probability
Breakdown in core operations	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
Improper operational procedure selection	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9

What is the severity level of the impact on the core elements of the transportation process?

0= Negligible: An insignificant effect on this core activity
1= Minor: Causing some inconvenience with minor impacts
3= Moderate: Causing some disruption with medium impacts
5= Major: Causing major disruptions to transportation operations
7= Critical: Causing failure of transportation operations
9= Catastrophic: Causing complete and irrecoverable failure of transportation operations

What is the consequence probability of the risk impact on the core activities of the transportation process?

0= Impossible: Will never occur
1= Rare: Rarely to occur
3= Low: Unlikely to occur
5= Medium: About an even chance of occurring
7= High: Likely to occur
9= Definite: Definitely will occur

Comments:

Examples:

If Breakdown in core operations has an insignificant effect on the available infrastructure capacity, then please tick 0.

If the consequence probability of Breakdown in core operations impacting on the available infrastructure capacity will never happen then please tick 0.

Consequence Severity and Consequence Probability Analysis

	Core Elements	Consequence severity		Consequence probability
Inadequate process capacity	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
High level of process variation	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9

Comments:

Examples:

If Inadequate process capacity has an insignificant effect on the available infrastructure capacity, then please tick 0.

If the consequence probability of Inadequate process capacity impacting on the available infrastructure capacity will never happen then please tick 0.

What is the severity level of the impact on the core elements of the transportation process?

0= Negligible: An insignificant effect on this core activity
1= Minor: Causing some inconvenience with minor impacts
3= Moderate: Causing some disruption with medium impacts
5= Major: Causing major disruptions to transportation operations
7= Critical: Causing failure of transportation operations
9= Catastrophic: Causing complete and irrecoverable failure of transportation operations

What is the consequence probability of the risk impact on the core activities of the transportation process?

0= Impossible: Will never occur
1= Rare: Rarely to occur
3= Low: Unlikely to occur
5= Medium: About an even chance of occurring
7= High: Likely to occur
9= Definite: Definitely will occur

Consequence Severity and Consequence Probability Analysis

	Core Elements	Consequence severity	Consequence probability
Complexity of products types	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
Lack of/inappropriate inventory management	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9

What is the severity level of the impact on the core elements of the transportation process?

0= Negligible: An insignificant effect on this core activity
1= Minor: Causing some inconvenience with minor impacts
3= Moderate: Causing some disruption with medium impacts
5= Major: Causing major disruptions to transportation operations
7= Critical: Causing failure of transportation operations
9= Catastrophic: Causing complete and irrecoverable failure of transportation operations

What is the consequence probability of the risk impact on the core activities of the transportation process?

0= Impossible: Will never occur
1= Rare: Rarely to occur
3= Low: Unlikely to occur
5= Medium: About an even chance of occurring
7= High: Likely to occur
9= Definite: Definitely will occur

Comments:

Examples:

If Complexity of products' types has an insignificant effect on the available infrastructure capacity, then please tick 0.

If the consequence probability of Complexity of products' types impacting on the available infrastructure capacity will never happen then please tick 0.

Consequence Severity and Consequence Probability Analysis

	Core Elements	Consequence severity	Consequence probability
Lack of/inappropriate container management	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
Problem of product quality	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9

What is the severity level of the impact on the core elements of the transportation process?

0= Negligible: An insignificant effect on this core activity
1= Minor: Causing some inconvenience with minor impacts
3= Moderate: Causing some disruption with medium impacts
5= Major: Causing major disruptions to transportation operations
7= Critical: Causing failure of transportation operations
9= Catastrophic: Causing complete and irrecoverable failure of transportation operations

What is the consequence probability of the risk impact on the core activities of the transportation process?

0= Impossible: Will never occur
1= Rare: Rarely to occur
3= Low: Unlikely to occur
5= Medium: About an even chance of occurring
7= High: Likely to occur
9= Definite: Definitely will occur

Comments:

Examples:

If Lack of/inappropriate container management has an insignificant effect on the available infrastructure capacity, then please tick 0.

If the consequence probability of Lack of/inappropriate container management impacting on the available infrastructure capacity will never happen then please tick 0.

Consequence Severity and Consequence Probability Analysis

	Core Elements	Consequence severity	Consequence probability
Lack of qualified staffs	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
Technology innovation	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9

Comments:

Examples:

If Lack of qualified labours has an insignificant effect on the available infrastructure capacity, then please tick 0.

If the consequence probability of Lack of qualified labours impacting on the available infrastructure capacity will never happen then please tick 0.

What is the severity level of the impact on the core elements of the transportation process?

0= Negligible: An insignificant effect on this core activity
1= Minor: Causing some inconvenience with minor impacts
3= Moderate: Causing some disruption with medium impacts
5= Major: Causing major disruptions to transportation operations
7= Critical: Causing failure of transportation operations
9= Catastrophic: Causing complete and irrecoverable failure of transportation operations

What is the consequence probability of the risk impact on the core activities of the transportation process?

0= Impossible: Will never occur
1= Rare: Rarely to occur
3= Low: Unlikely to occur
5= Medium: About an even chance of occurring
7= High: Likely to occur
9= Definite: Definitely will occur

Consequence Severity and Consequence Probability Analysis

	Core Elements	Consequence severity		Consequence probability
Information sharing delay	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
Information sharing inaccuracy	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9		□ 0 □ 1 □ 3 □ 5 □ 7 □ 9

What is the severity level of the impact on the core elements of the transportation process?

0= Negligible: An insignificant effect on this core activity
1= Minor: Causing some inconvenience with minor impacts
3= Moderate: Causing some disruption with medium impacts
5= Major: Causing major disruptions to transportation operations
7= Critical: Causing failure of transportation operations
9= Catastrophic: Causing complete and irrecoverable failure of transportation operations

What is the consequence probability of the risk impact on the core activities of the transportation process?

0= Impossible: Will never occur
1= Rare: Rarely to occur
3= Low: Unlikely to occur
5= Medium: About an even chance of occurring
7= High: Likely to occur
9= Definite: Definitely will occur

Comments:

Examples:

If Information sharing delay has an insignificant effect on the available infrastructure capacity, then please tick 0.

If the consequence probability of Information sharing delay impacting on the available infrastructure capacity will never happen then please tick 0.

Consequence Severity and Consequence Probability Analysis

	Core Elements	Consequence severity	Consequence probability
Financial problems	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
Please all another risks should be considered	Available Infrastructure Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Available Vehicle Capacity	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quality)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transported Object Damage (Quantity)	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Time	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Timeliness of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Accuracy of Information sharing	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9
	Transportation Cost	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9

Comments:

Examples:

If a Financial problem has an insignificant effect on the available infrastructure capacity, then please tick 0.
If the consequence probability of Financial problems impacting on the available infrastructure capacity will never happen then please tick 0.

What is the severity level of the impact on the core elements of the transportation process?

0= Negligible: An insignificant effect on this core activity
1= Minor: Causing some inconvenience with minor impacts
3= Moderate: Causing some disruption with medium impacts
5= Major: Causing major disruptions to transportation operations
7= Critical: Causing failure of transportation operations
9= Catastrophic: Causing complete and irrecoverable failure of transportation operations

What is the consequence probability of the risk impact on the core activities of the transportation process?

0= Impossible: Will never occur
1= Rare: Rarely to occur
3= Low: Unlikely to occur
5= Medium: About an even chance of occurring
7= High: Likely to occur
9= Definite: Definitely will occur

THANK YOU ONCE AGAIN FOR YOUR KIND PARTICIPATION IN THIS SURVEY.
YOUR ANSWERS WILL BE KEPT CONFIDENTIAL.

化工供应链中运输过程的风险管理

调查问卷 (第二部分)

尊敬的专家：

您好！我是英国利物浦约翰莫尔斯大学(LJMU)利物浦物流和海洋研究所的一名博士研究生，名叫李超宇。LJMU与武汉理工大学共同参加欧盟第七框架计划"玛丽居里行动计划"中的《风险评估与决策科学》研究项目。作为此欧盟项目的参与者，我希望能提出一种全新的、系统化与结构化的方法对化工供应链进行风险识别、评估以及控制的研究。目前，我正在武汉理工大学开展交流研究工作，希望借此机会通过此次问卷调查得到化工供应链在运输过程中的一些风险指标信息，为今后的研究提供宝贵的数据支持。

本次调查问卷的目的是：

1. 针对已经识别出存在于化工供应链运输过程中的企业内营运风险，根据专家的经验与看法评价其发生于运输过程中的概率。
2. 企业内营运风险作用于供应链运输过程中的节点，评价带来危害的后果以及产生此后果的可能性。

需要提出的是，本次问卷调查采取自愿形式。我们非常感激您在问卷填写中给予的帮助。本次调查的信息将会完全保密，这也是利物浦约翰摩尔斯大学一直以来所严格要求的。本次调查需要15到20分钟的时间。

如果您有任何疑问，请通过电话 +44 (0) 759 334 1528, +86 186 0606 3710或电子邮件C.Li@2012.ljmu.ac.uk联系我。您也可以通过电话+44 (0) 151 231 2236或电子邮件J.Ren@ljmu.ac.uk联系我的导师Jun Ren博士。

请接受我们由衷的感激。如果您想知道调查的最终结果，请通过电子邮件C.Li@2012.ljmu.ac.uk和我联系。

李超宇
博士研究生,
Liverpool Logistics Offshore and Marine Research Institute (LOOM)
Tel: +44-(0)759 334 1528; +86-186 0606 3710
Email: C.Li@2012.ljmu.ac.uk
Room 121, James Parsons Building
Liverpool John Moores University, Byrom Street, Liverpool, L3 3AF, UK

第一部分：基本情况

下列问题是针对您以及您所在的企业或公司，请根据您以及您所在的企业或公司的实际情况进行选择。

1. 您所在机构的在化工供应链中扮演的角色是？

货物供应方 如：工厂	服务提供方 如：配送，存储	基础设施提供方 如：港口	其它
☐	☐	☐	☐

2. 以下四个运输方式中，您涉及到哪些运输方式？（可多项）

道路运输	铁路运输	航空运输	水路运输	管道运输	其他
☐	☐	☐	☐	☐	☐

3. 您所在的企业是否曾经遭遇过危害事件？ 后果是否严重？

   ☐没有 ☐有，后果不严重 ☐有，后果严重

4. 您所在的企业有没有对雇员和管理人员进行过风险管理培训？

   ☐专门进行过 ☐有，但是附带性的 ☐没有

5. 针对供应链风险管理，要系统掌握风险管理方面的知识，您认为最需要解决的问题是什么？

   ☐如何对供应链风险进行系统的识别和分析 ☐掌握针对供应链风险的管理措施

   ☐专门成立供应链风险管理部门 ☐公司领导的重视程度

   ☐其它（请说明）

6. 您的职位是？

   ____

7. 您所从事的研究领域或专业领域是？

   ____

8. 您在化工行业或化工供应链行业中工作了多久？

   ☐ 1-5 年 ☐ 6-10 年 ☐ 11-15 年 ☐ 16-20 年 ☐ >20 年

第二部分：以下问题是根据与化工供应链运输过程相关的企业内营运危害事件进行设计的。根据您的专业经验与看法，请分别对危害事件影响运输过程的可能性程度在相应分值的方框内打勾。

（**危害事件发生的可能性**指危害事件在特定时间内发生可能影响运输操作的频率）

化工供应链运输过程危害事件分析			
序号	**已识别出的企业内营运危害事件**	**危害事件影响运输过程的可能性 (极少发生——非常高)**	
1	被运输货物具有易燃易爆等危险性质	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	危害事件发生的可能性？ 0= 极少发生：从未或者很难发生 1= 很低：两三年内会发生一次 3= 低：可能每年发生一次 5= 中等：有时候每几个月会发生一次 7= 高：可能每个月都会发生 9= 非常高：可能每天都会频繁的发生
2	化工供应链运输服务商选择不当	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
3	化工供应链节点间运输线路选择不当	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
4	运输过程中主要设备失效或发生故障	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
5	运输能力不足	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
6	运输过程复杂多变	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
7	被运输货物种类复杂	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
8	库存管理缺乏/不当	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
9	容器管理缺乏/不当	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
10	合格的工作人员缺乏	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
11	技术革新的挑战	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
12	供应链信息共享水平低	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
13	供应链信息共享延误 / 不准确	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
14	运输服务提供商财务问题	□ 0 □ 1 □ 3 □ 5 □ 7 □ 9	
备注：		例子： 如果核心操作部分故障好几年都不可能发生，请选择 0 如何核心操作部分故障频繁发生甚至每个月都会发生请选择 7	

<u>第三部分：</u>实际与潜在的危害事件都可能通过影响**运输操作中的核心活动**进而影响整个运输过程的。基于前期研究，我们认为运输过程中的核心活动包括：可用的基础设施能力、可用的运输工具运输能力、运输对象质量损坏、运输对象数量损坏、运输时间增加、信息共享实效性降低、信息共享准确性下降、运输成本增加。以下问题是根据识别出的危害事件与运输过程的核心活动设计的。 危害事件作用于运输过程的核心活动并产生一定的后果，根据您的专业经验与看法，请您对此后果的严重性与产生此后果的可能性在相应分值的方框中打勾。

（**后果的严重性**是根据危害事件导致可能后果的等级确定的，**产生此后果的可能性**则根据灾害发生后该后果发生的概率确定的）

<table>
<tr><td colspan="6">危害事件作用于运输过程中的核心元素所导致的后果严重程度和出现此后果的可能性分析</td></tr>
<tr><td>危害事件</td><td>运输过程的核心元素</td><td>后果的严重性
（可忽略 ——灾难）</td><td></td><td>出现此后果的可能性
（不可能——极高）</td><td rowspan="10">危害事件发生并且影响运输过程核心元素的后果是什么？

0= 可忽略：对此核心活动的影响不重要
1= 较小：对此核心活动带来轻微影响
3= 中等： 对此核心活动带来中等的影响
5= 较大：对此核心活动带来较大的影响
7= 严重：导致运输过程失败
9= 灾难：对运输过程带来灾难性的影响

危害事件发生并且产生此影响运输过程核心元素的后果的可能性是什么？

0= 不可能：从未发生
1= 极少发生：很难发生
3= 低：不是很可能发生
5= 中等：有一定的可能发生
7= 高：很可能发生
9= 极高：一定发生</td></tr>
<tr><td rowspan="8">1. 被运输货物具有易燃易爆等危险性质</td><td>可用的基础设施能力降低</td><td>□0 □1 □3 □5 □7 □9</td><td rowspan="8"></td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>可用的运输工具运输能力降低</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输对象质量损坏</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输对象数量损坏</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输时间增加</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>信息共享时效性降低</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>信息共享准确性下降</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输成本增加</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td colspan="2">备注：</td><td colspan="3">例子：
<u>后果的严重性：</u>
如果危害事件 （1）被运输货物具有易燃易爆等危险性质对于可用的基础设施能力降低的影响较小，那么请选择 1。

<u>出现此后果的可能性：</u>
如果危害事件（1）被运输货物具有易燃易爆等危险性质对于可用的基础设施能力降低的影响较小，但发生的可能性高，那么请选择 7。</td></tr>
</table>

危害事件作用于运输过程中的核心元素所导致的后果严重程度和出现此后果的可能性分析

危害事件	运输过程的核心元素	后果的严重性 （可忽略——灾难）		出现此后果的可能性 （不可能——极高）
2. 化工供应链运输服务商选择不当	可用的基础设施能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	可用的运输工具运输能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象质量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象数量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输时间增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享时效性降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享准确性下降	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输成本增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
3. 化工供应链节点间运输线路选择不当	可用的基础设施能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	可用的运输工具运输能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象质量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象数量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输时间增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享时效性降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享准确性下降	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输成本增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9

危害事件发生并且影响运输过程核心元素的后果是什么？

0= 可忽略：对此核心活动的影响不重要
1= 较小：对此核心活动带来轻微影响
3= 中等： 对此核心活动带来中等的影响
5= 较大：对此核心活动带来较大的影响
7= 严重：导致运输过程失败
9= 灾难：对运输过程带来灾难性的影响

危害事件发生并且产生此影响运输过程核心元素的后果的可能性是什么？

0= 不可能：从未发生
1= 极少发生：很难发生
3= 低：不是很可能发生
5= 中等：有一定的可能发生
7= 高：很可能发生
9= 极高：一定发生

备注：

例子：

后果的严重性：

如果危害事件（2）**化工供应链运输服务商选择不当**对于**可用的基础设施能力降低**的影响较小，那么请选择 1。

出现此后果的可能性：

如果危害事件（2）**化工供应链运输服务商选择不当**对于**可用的基础设施能力降低**的影响较小，但发生的可能性高，那么请选择 7。

<table>
<tr><td colspan="6">危害事件作用于运输过程中的核心元素所导致的后果严重程度和出现此后果的可能性分析</td></tr>
<tr><td>危害事件</td><td>运输过程的核心元素</td><td>后果的严重性
（可忽略 ——灾难）</td><td></td><td>出现此后果的可能性
（不可能——极高）</td><td rowspan="21">危害事件发生并且影响运输过程核心元素的后果是什么？

0= 可忽略：对此核心活动的影响不重要
1= 较小：对此核心活动带来轻微影响
3= 中等： 对此核心活动带来中等的影响
5= 较大：对此核心活动带来较大的影响
7= 严重：导致运输过程失败
9= 灾难：对运输过程带来灾难性的影响

危害事件发生并且产生此影响运输过程核心元素的后果的可能性是什么？

0= 不可能：从未发生
1= 极少发生：很难发生
3= 低：不是很可能发生
5= 中等：有一定的可能发生
7= 高：很可能发生
9= 极高：一定发生</td></tr>
<tr><td rowspan="8">4. 运输过程中主要设备失效或发生故障</td><td>可用的基础设施能力降低</td><td>□0 □1 □3 □5 □7 □9</td><td rowspan="8"></td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>可用的运输工具运输能力降低</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输对象质量损坏</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输对象数量损坏</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输时间增加</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>信息共享时效性降低</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>信息共享准确性下降</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输成本增加</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td rowspan="8">5. 运输能力不足</td><td>可用的基础设施能力降低</td><td>□0 □1 □3 □5 □7 □9</td><td rowspan="8"></td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>可用的运输工具运输能力降低</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输对象质量损坏</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输对象数量损坏</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输时间增加</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>信息共享时效性降低</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>信息共享准确性下降</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输成本增加</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td colspan="2">备注：</td><td colspan="3">例子：
后果的严重性：
如果危害事件（4）运输过程中主要设备失效或发生故障对于可用的基础设施能力降低的影响较小，那么请选择 1。
出现此后果的可能性：
如果危害事件（4）运输过程中主要设备失效或发生故障对于可用的基础设施能力降低的影响较小，但发生的可能性高，那么请选择 7。</td></tr>
</table>

危害事件作用于运输过程中的核心元素所导致的后果严重程度和出现此后果的可能性分析				
危害事件	**运输过程的核心元素**	**后果的严重性** （可忽略 ——灾难）		**出现此后果的可能性** （不可能——极高）
6. 运输过程复杂多变	可用的基础设施能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	可用的运输工具运输能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象质量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象数量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输时间增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享时效性降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享准确性下降	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输成本增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
7. 被运输货物种类复杂	可用的基础设施能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	可用的运输工具运输能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象质量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象数量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输时间增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享时效性降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享准确性下降	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输成本增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9

危害事件发生并且影响运输过程核心元素的后果是什么？

0= 可忽略：对此核心活动的影响不重要
1= 较小：对此核心活动带来轻微影响
3= 中等： 对此核心活动带来中等的影响
5= 较大：对此核心活动带来较大的影响
7= 严重：导致运输过程失败
9= 灾难：对运输过程带来灾难性的影响

危害事件发生并且产生此影响运输过程核心元素的后果的可能性是什么？

0= 不可能：从未发生
1= 极少发生：很难发生
3= 低：不是很可能发生
5= 中等：有一定的可能发生
7= 高：很可能发生
9= 极高：一定发生

备注：

例子：

<u>后果的严重性：</u>

如果危害事件（**6**）**运输过程复杂多变**对于**可用的基础设施能力降低**的影响较小，那么请选择 1。

<u>出现此后果的可能性：</u>

如果危害事件（**6**）**运输过程复杂多变**对于**可用的基础设施能力降低**的影响较小，但发生的可能性高，那么请选择 7。

<table>
<tr><td colspan="6">危害事件作用于运输过程中的核心元素所导致的后果严重程度和出现此后果的可能性分析</td></tr>
<tr><td>危害事件</td><td>运输过程的核心元素</td><td>后果的严重性
（可忽略 ——灾难）</td><td></td><td>出现此后果的可能性
（不可能——极高）</td><td rowspan="20">危害事件发生并且影响运输过程核心元素的后果是什么？

0= 可忽略：对此核心活动的影响不重要
1= 较小：对此核心活动带来轻微影响
3= 中等： 对此核心活动带来中等的影响
5= 较大：对此核心活动带来较大的影响
7= 严重：导致运输过程失败
9= 灾难：对运输过程带来灾难性的影响

危害事件发生并且产生此影响运输过程核心元素的后果的可能性是什么？

0= 不可能：从未发生
1= 极少发生：很难发生
3= 低：不是很可能发生
5= 中等：有一定的可能发生
7= 高：很可能发生
9= 极高：一定发生</td></tr>
<tr><td rowspan="8">8. 库存管理缺乏/不当</td><td>可用的基础设施能力降低</td><td>□0 □1 □3 □5 □7 □9</td><td rowspan="8"></td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>可用的运输工具运输能力降低</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输对象质量损坏</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输对象数量损坏</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输时间增加</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>信息共享时效性降低</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>信息共享准确性下降</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输成本增加</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td rowspan="8">9. 容器管理缺乏/不当</td><td>可用的基础设施能力降低</td><td>□0 □1 □3 □5 □7 □9</td><td rowspan="8"></td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>可用的运输工具运输能力降低</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输对象质量损坏</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输对象数量损坏</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输时间增加</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>信息共享时效性降低</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>信息共享准确性下降</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输成本增加</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td colspan="2">备注：</td><td colspan="3">例子：
后果的严重性：
如果危害事件（8）库存管理缺乏/不当对于可用的基础设施能力降低的影响较小，那么请选择 1。
出现此后果的可能性：
如果危害事件（8）库存管理缺乏/不当对于可用的基础设施能力降低的影响较小，但发生的可能性高，那么请选择 7。</td></tr>
</table>

危害事件作用于运输过程中的核心元素所导致的后果严重程度和出现此后果的可能性分析

危害事件	运输过程的核心元素	后果的严重性 （可忽略 ——灾难）		出现此后果的可能性 （不可能——极高）
10. 合格的工作人员缺乏	可用的基础设施能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	可用的运输工具运输能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象质量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象数量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输时间增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享时效性降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享准确性下降	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输成本增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
11. 技术革新的挑战	可用的基础设施能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	可用的运输工具运输能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象质量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象数量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输时间增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享时效性降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享准确性下降	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输成本增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9

危害事件发生并且影响运输过程核心元素的后果是什么？

0= 可忽略：对此核心活动的影响不重要
1= 较小：对此核心活动带来轻微影响
3= 中等： 对此核心活动带来中等的影响
5= 较大：对此核心活动带来较大的影响
7= 严重：导致运输过程失败
9= 灾难：对运输过程带来灾难性的影响

危害事件发生并且产生此影响运输过程核心元素的后果的可能性是什么？

0= 不可能：从未发生
1= 极少发生：很难发生
3= 低：不是很可能发生
5= 中等：有一定的可能发生
7= 高：很可能发生
9= 极高：一定发生

备注：

例子：

后果的严重性：

如果危害事件（**10**）**合格的工作人员缺乏**对于**可用的基础设施能力降低**的影响较小，那么请选择 1。

出现此后果的可能性：

如果危害事件（**10**）**合格的工作人员缺乏**对于**可用的基础设施能力降低**的影响较小，但发生的可能性高，那么请选择 7。

危害事件作用于运输过程中的核心元素所导致的后果严重程度和出现此后果的可能性分析

危害事件	**运输过程的核心元素**	**后果的严重性** （可忽略 ——灾难）		**出现此后果的可能性** （不可能——极高）
12. 供应链信息共享水平低	可用的基础设施能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	可用的运输工具运输能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象质量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象数量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输时间增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享时效性降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享准确性下降	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输成本增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
13. 供应链信息共享延误／不准确	可用的基础设施能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	可用的运输工具运输能力降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象质量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输对象数量损坏	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输时间增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享时效性降低	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	信息共享准确性下降	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9
	运输成本增加	□0 □1 □3 □5 □7 □9		□0 □1 □3 □5 □7 □9

危害事件发生并且影响运输过程核心元素的后果是什么？

0= 可忽略：对此核心活动的影响不重要
1= 较小：对此核心活动带来轻微影响
3= 中等： 对此核心活动带来中等的影响
5= 较大：对此核心活动带来较大的影响
7= 严重：导致运输过程失败
9= 灾难：对运输过程带来灾难性的影响

危害事件发生并且产生此影响运输过程核心元素的后果的可能性是什么？

0= 不可能：从未发生
1= 极少发生：很难发生
3= 低：不是很可能发生
5= 中等：有一定的可能发生
7= 高：很可能发生
9= 极高：一定发生

备注：

例子：

后果的严重性：

如果危害事件（**12**）**供应链信息共享水平低**对于**可用的基础设施能力降低**的影响较小，那么请选择 1。

出现此后果的可能性：

如果危害事件（**12**）**供应链信息共享水平低**对于**可用的基础设施能力降低**的影响较小，但发生的可能性高，那么请选择 7。

<table>
<tr><td colspan="6">危害事件作用于运输过程中的核心元素所导致的后果严重程度和出现此后果的可能性分析</td></tr>
<tr><td>危害事件</td><td>运输过程的核心元素</td><td>后果的严重性
（可忽略 ——灾难）</td><td></td><td>出现此后果的可能性
（不可能——极高）</td><td rowspan="10">危害事件发生并且影响运输过程核心元素的后果是什么？

0= 可忽略：对此核心活动的影响不重要
1= 较小：对此核心活动带来轻微影响
3= 中等： 对此核心活动带来中等的影响
5= 较大：对此核心活动带来较大的影响
7= 严重：导致运输过程失败
9= 灾难：对运输过程带来灾难性的影响

危害事件发生并且产生此影响运输过程核心元素的后果的可能性是什么？

0= 不可能：从未发生
1= 极少发生：很难发生
3= 低：不是很可能发生
5= 中等：有一定的可能发生
7= 高：很可能发生
9= 极高：一定发生</td></tr>
<tr><td rowspan="8">14. 运输服务提供商财务问题</td><td>可用的基础设施能力降低</td><td>□0 □1 □3 □5 □7 □9</td><td rowspan="8"></td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>可用的运输工具运输能力降低</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输对象质量损坏</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输对象数量损坏</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输时间增加</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>信息共享时效性降低</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>信息共享准确性下降</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td>运输成本增加</td><td>□0 □1 □3 □5 □7 □9</td><td>□0 □1 □3 □5 □7 □9</td></tr>
<tr><td colspan="2">备注：</td><td colspan="3">例子：
<u>后果的严重性：</u>
如果危害事件（14）运输服务提供商财务问题对于可用的基础设施能力降低的影响较小，那么请选择 1。
<u>出现此后果的可能性：</u>
如果危害事件（14）运输服务提供商财务问题对于可用的基础设施能力降低的影响较小，但发生的可能性高，那么请选择 7。</td></tr>
</table>

再次感谢您在此次调查中提供的帮助。

您的回答将会被保密。

Appendix Three

Research Deliverables Arising from this Research

1) Li, C., Ren, J. and Wang. H.Y. (2016) A system dynamics simulation model of chemical supply chain transportation risk management systems. Computers & Chemical Engineering, 89, pp. 71-83. (DOI: 10.1016/j.compchemeng.2016.02.019)

2) Fu, S.S., Yan, X.P., Zhang, D., Li, C. and Zio, E. (2016) Framework for the quantitative assessment of the risk of leakage from LNG-fueled vessels by an event tree-CFD. Journal of Loss Prevention in the Process Industry, 47, pp. 42-52. (DOI: 10.1016/j.jlp.2016.04.008)

3) Li, C., Fu, S.S., Ren, J. and Wang. H.Y. (2015) A preliminary research methodology on chemical supply chain risk management using system dynamics approach. International Conference on Transportation Information and Safety. IEEE. 28-30 June 2015, Wuhan, China. (DOI: 10.1109/ICTIS.2015.7232196)

4) Li, C., Yang, Z.L., Ren, J. and Wang, J. (2016) Dynamic risk management of chemical supply chains, IAME. Accepted

5) Li, C., Yang, Z.L., Ren, J. and Wang, J. (2016) Hazard identification in chemical supply chains: The development of a novel taxonomy. International Conference on Logistics, Informatics and Services Sciences (LISS 2016). Accepted