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Supply Chain Risk Management: Identification, Evaluation and Mitigation Techniques

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Abstract

Supply chains have expanded rapidly over the decades, with the aim to increase productivity, lower costs and fulfil demands in emerging markets. The increasing complexity in a supply chain hinders visibility and consequently reduces one's control over the process. Cases of disruption such as the ones faced by Ericsson and Enron, have shown that a risk event occurring at one point of the supply chain can greatly affect other members, when the disruption is not properly controlled. Supply chain management thus faces a pressing need to maintain the expected yields of the system in risk situations. To achieve that, we need to both identify potential risks and evaluate their impacts, and at the same time design risk mitigation policies to locate and relocate resources to deal with risk events.

This dissertation aims to analyse how supply chain risks could be effectively managed. This is done firstly by positioning the research agenda in supply chain risk management (SCRM). Then, methods for effective management of supply chain risk are identified and analysed. In order to find these, we develop a research framework in which the supply chain system is divided into subsystems based on the operations of *make*, *source* and *deliver*; as well as on *material*, *financial* and *information flows*. Furthermore, research questions are raised in order to understand the impact of risks on supply chains, to identify the performance measures for monitoring supply chains, and to determine risk mitigation strategies for improving system performances.

This dissertation includes a bibliometric analysis of relevant literature of SCRM published in recent years. Based on the co-citation analysis, we identify the changing interest in SCRM, from performance-focused individual issues in the early years to integrated system issues with management perspective in recent years. We also identify the growing importance of information issues in SCRM. However, there is a relative lack of research into risk mitigation focusing on information flows in the literature.

This dissertation also develops a conceptual model for analysing supply chain risk. The adoption of tools from the established field of reliability engineering provides a systematic yet robust process for risk analysis in supply chains. We have found that the potential use of a stand-alone tool of Failure Modes and Effect Analysis (FMEA) or a hybrid application of Fault Tree Analysis (FTA) and Analytical Hierarchy Process (AHP), will be most appropriate in SCRM.

Apart from above mentioned studies, this dissertation then includes three manuscripts respectively investigating the risk mitigation policies in SCRM. First, we suggest a dynamic pricing policy when facing supply yield risk, such as price postponement, where price is determined only after receiving the delivery information. This postponed pricing, can improve the balance between supply and demand, especially when the delivery quantity is small, demand has a low uncertainty and there is a wide range when demand is sensible to price change. In another paper, a system dynamics model is developed to investigate the dispersion of disruption on the supply chain operation as well as along the network. Based on this simulation model, policies are tested to observe their influence to the performance of the

supply chain. The study results support the benefit of a dual-sourcing strategy. Furthermore, information sharing, appropriate order splitting and time to react would further improve the supply chain performance when disruption strikes. In the last paper, we study how capacity should be expanded when a new product is introduced into the market. The major risk here is due to a quick capacity expansion with large investments which could be difficult to recover. Using the Bass diffusion model to describe demand development, we study how capacity expansion, together with sales plan could affect the economics of the system. Using sales information for the forecast, delaying the sales and adding initial inventories, should create a better scheme of cash flows.

This dissertation contributes in several ways to the research field of SCRM. It plots research advancements which provide further directions of research in SCRM. In conjunction with the conceptual model, simulations and mathematical modelling, we have also provided suggestions for how a better and more robust supply chain could be designed and managed. The diversified modelling approaches and risk issues should also enrich the literature and stimulate future study in SCRM.

Keywords: supply chain risk management, risk analysis, risk control, co-citation, system dynamics, modelling

Riskhantering i Försörjningskedjor: Tekniker för Identifiering, Värdering och Bemötande

Ibland blir man försenad till arbetet eller skolan på grund av trafikstörningar. En förälder måste ställa in ett viktigt arbetsmöte eftersom ett barn är sjukt och kan inte få tag på någon barnvakt. En rapport som ska vara klar vid lunchtid kanske lämnas in för sent eftersom datorn som användes för att skriva rapporten gick sönder. Mat som beställts på resturangen blev över huvud taget inte serverad eftersom kocken blev akut sjuk och måste åka till sjukhus. Störningar uppstår överallt och drabbar alla på ett eller annat sätt. Ingen kommer undan. Men, innebär det verkligen världens undergång?

Trots allt brukar man ändå kunna komma i tid till jobbet om det finns alternativa transportmedel eller om man kan ta en annan väg. Mötet kan kanske genomföras som en telekonferens. Data sparade på en extern hårddisk kan kanske användas på en annan dator och du kommer i slutänden att hinna lämna in rapporten i tid. En kort promenad till en annan restaurang i närheten kan hålla hungern borta och kanske t.o.m. rädda livet på dig, man vet trots allt inte vad det var som gjorde att kocken på den första resturangenen behövde åka till sjukhus! Det här är några exempel som visar hur viktig och närvarande hantering av risk är för att tillvaron ska fungera på ett bra sätt.

Liknande händelseförlopp finns i försörjningskedjor men de får vanligtvis större konsekvenser eftersom försörjningskedjor med tiden har blivit allt mer omfattande. Den ökande komplexiteten i försörjningskedjor gör det svårare att följa vad som händer, vilket minskar möjligheten att styra processen. Exempel på störningar som t.ex. de som drabbade Ericsson och Enron har visat att en störning som drabbar ett led i en försörjningskedja kan få stora konsekvenser för andra led när störningen inte hanteras på ett bra sätt. Ledningen av försörjningskedjor ställs därför inför allt större utmaningar för att kunna säkerställa systemets funktion i situationer med risk. För att uppnå det behöver vi både identifiera potentiella risker och utvärdera deras betydelse, samtidigt som riktlinjer utformas för att bemöta risk genom att använda resurser för hantering av riskhändelser på ett bra sätt.

Avhandlingens mål är att analysera hur risk på ett effektivt sätt kan hanteras i försörjningskedjor. Först positioneras arbetet i förhållande till forskningen i riskhantering i försörjningskedjor (supply chain risk management, SCRM). Därefter identifieras och analyseras metoder för effektiv ledning av försörjningskedjor. Den här avhandlingen bidrar på flera olika sätt till forskningsområdet kopplat till SCRM. Den visar på hur forskningen inom SCRM har utvecklats och pekar på så sätt ut områden för vidare forskning. I samband med konceptuell modellering, simulering och matematisk modellering har vi också undersökt flera olika verktyg för bemötande av risk och kommit med förslag på hur en bättre och mer robust försörjningskedja kan utformas och ledas ur ett systematiskt perspektiv. Dessa olika modelleringsansatser och riskfrågor kan också berika litteraturen och stimulera till fortsatta studier inom SCRM.

Acknowledgements

"Be kind, for whenever kindness becomes part of something, it beautifies it. Whenever it is taken from something, it leaves it tarnished." ~ Prophet Muhammad S.A.W. as narrated by Imam Bukhari

This work benefited immensely from the advice, criticism and encouragement of many, which includes (but is not limited to) the followings:

An immeasurable gratitude goes to my supervisor, *Professor Ou Tang*, who has supported me throughout my dissertation with his patience and great knowledge whilst continuously encouraging me to work in my own way. I have been extremely lucky to have a supervisor who cared so much about my work, and who responded to my queries so promptly.

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The Division of Production Economics has provided the support and facilities I have needed to produce and complete my dissertation and the *Ministry of Higher Education, Malaysia* together with *University of Malaya* has funded my studies. Thank you!

In my daily work, I have been blessed with a friendly and cheerful group of *fellow colleagues*, especially the *fellow doctoral students*, who have lightened up most of my dark and cold days in Sweden! I will always cherish the *fika* breaks (thank you Sweden for the great tradition!), *lunch-train*, mini-golf tournaments, research seminars and many more.

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Last but not least, *Alhamdulillah*.

To my mom.

Asiah Che Yah

(22nd March 1946 ~ 30th November 2008)

"I carry your heart with me (I carry it in my heart)
I am never without it
(anywhere I go you go, my dear;
and whatever is done by only me is your doing, my darling)

I fear no fate (for you are my fate, my sweet)
I want no world (for beautiful you are my world, my true)
and it's you are whatever a moon has always meant
and whatever a sun will always sing is you

here is the deepest secret nobody knows
(here is the root of the root and the bud of the bud
and the sky of the sky of a tree called life;
which grows higher than the soul can hope or mind can hide)
and this is the wonder that's keeping the stars apart

I carry your heart (I carry it in my heart)"

~ E.E. Cummings

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Dissertation Outline

"The ink of the scholar is more holy than the blood of the martyr." ~ Prophet Muhammad S.A.W.

This dissertation entitled "Supply Chain Risk Management: Identification, Evaluation and Mitigation Techniques" consists of two parts. Part I comprises an introduction and a summary of the research. Firstly, it presents research background, objectives and limitations. Then, a thorough literature review in Section 2 has carefully positioned the dissertation in the field of Supply Chain Risk Management. Section 3 summarises the approaches and methods for managing supply chain risks which are used in the dissertation. Part I is concluded with Section 4 which discusses the linkage between Part I and Part II, and which also highlights research gaps and potential work to be conducted in future research.

To complement this dissertation, Part II consists of a collection of papers which are related to the issues described in Part I and which were completed during the doctoral study programme. There are five papers and these cover the research agenda (***Paper 1***), risk analysis (***Papers 2*** and ***4***) and risk control (***Papers 3, 4*** and ***5***).

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

An earlier version of this article was selected and presented as plenary paper in the 15th International Symposium on Inventories Research (ISIR) in Budapest, Hungary on 22nd till 26th August, 2008.

Paper 2:
Musa, S.N., Cocca, P. and Tang, O., 2012. Assessing supply chain risk adopting reliability tools. Working paper, Department of Management and Engineering, Linköping University.

An earlier version of this paper has appeared in the Proceeding for the International Conference on Advances in Production Management Systems (APMS2010) which was held in Cernobbio, Lake Como, Italy on 11th ~ 13th October, 2010.

Paper 3:
Tang, O., Musa, S.N. and Li, J., 2011. Dynamic pricing in the newsvendor problem with yield risks. The manuscript has been accepted for publication in the *International Journal of Production Economics*, doi:10.1016/j.ijpe.2011.01.018.

Paper 4:
Musa, S.N., Wei, S. and Tang, O., 2012. Information flow and mitigation strategy in a supply chain under disruption. Working paper, Department of Management and Engineering, Linköping University.

An earlier version of this paper has appeared in the Proceeding for the International Conference on Production Research (ICPR 21), held on July 31st ~ August 4th, 2011 in Stuttgart, Germany.

During the ICPR21, the author was selected as one of the ten recipients of the Young Scientist Award (YSA). From among the papers selected for the award, this paper was chosen as Best Paper.

Paper 5:
Musa, S.N. and Tang, O., 2012. Capacity expansion policy and its risk in new product diffusion. Working paper, Department of Management and Engineering, Linköping University.

PART I:

SUPPLY CHAIN RISK MANAGEMENT: IDENTIFICATION, EVALUATION AND MITIGATION TECHNIQUES

1. Introduction

"Never walk away from failure. On the contrary, study it carefully and imaginatively for its hidden assets."~ Michael Korda

One may be late to work or school due to a transportation delay. A parent might have to cancel an important meeting at work when her child is sick with no babysitter in sight. A report due at noon might need to be turned in a little late if the laptop used in preparing it is corrupted. Food ordered may not arrive when the only chef in the restaurant suddenly needs to be rushed to the hospital. Disturbances occur everywhere and to everyone. It does not play favourites. Yet, does this mean the end of the world?

Nonetheless, if alternative transportation is readily available, you will still be at work in-time. The meeting could still be conducted via a teleconference. Data saved in secondary data storage can be used in another workstation and you might still meet the deadline. A short walk to a neighbouring restaurant would keep your hunger away, and might even save your life, for you never know what caused the chef from the previous restaurant to the hospital anyway! For these reasons and many more, managing risk is important to have to go on in life.

1.1. Background

Similar stories happen in supply chains. Many industrial cases have shown different outcomes after risk events due to diverse actions (or lack of action) taken in facing supply chain disturbances and disruptions. One typical example is Ericsson's crisis in 2000. Since Ericsson used a single-sourcing policy, a fire accident in its chips' supplier immediately disrupted the material supply. Ericsson's loss was estimated to reach USD 400 million for its T28 model (Norrman and Jansson, 2004). On the other hand, Nokia which also used the same supplier, managed to avoid further disruption impact by quickly switching to backup sources. This eventually resulted in an increase of up to 30% market share (Sheffi, 2005).

In June 2008, Volvo Cars reported a 28% reduction in sales compared with the same period in previous year, with the biggest loss of about 50% in its SUVs. Fredrik Arp, then CEO of Volvo Cars stated that "the weak dollar reduces the revenue and it will further reduce the opportunities for R&D". Another example is the Taiwan earthquake in December 2006, which caused a breakage in the undersea cables and slowed down the internet. One immediate effect was a prolonged waiting time for containers in the Shanghai sea port in China, since all claim procedures rely on information systems.

The above examples show that any material, financial or information risk can create problems in a supply chain. In the fire accident that occurred at Ericsson's supplier, the material flow in Ericsson was disrupted, and eventually affected the financial flow, while in the second case, the volatility in the exchange rate disrupted Volvo Cars' financial flow. Finally, a natural disaster affected the flow of information, which resulted in turn in the disruption of port

operations. A single risk event can easily disrupt at least one of the supply chain flows. In most cases, the impact of disruption can be observed along the supply chain. Any hiccup within the supply chain will cause delays and even disruption (Buzacott, 1971). Most recent incidents, such as the Arab Spring protests, the Sendai earthquake and the Thailand floods in 2011 have shown how such disruptions can severely affect even the most stable supply chain.

These are only a few examples from the numerous disruption cases affecting supply chains in the last decade. The increasing numbers of research studies on supply chain disruptions resulting from economic and political instability, volatile market dynamics, natural disasters or human actions, have shown that risk issues are becoming the new norm in supply chain operations (Berger et al., 2004; Christopher and Lee, 2004; LaLonde, 2004; Norrman and Jansson, 2004; Poirier et al., 2007; Quinn, 2006; Tang, 2006a).

Similarly, practitioners have also shown increasing concern about the volatility of supply chains. In a series of analysis on predicting supply chains for 2012, Gartner Inc. has indicated the increasing importance of supply chain executives where the number of supply chain executives elected as or reporting directly to the CEO has increased from 30% in 2005 to 68% in 2010 (Gartner Inc., 2011). More interestingly, the same study has observed intensified emphasis on scalable risk assessment and management. Moreover, there is increased interest in utilizing advanced technology to better manage diverse supply chains activities.

Despite the increasing concern for risks shown by all members in a supply chain, different disruption impacts affecting them are observed. An individual's recognition of a problem and preparedness when facing it, alter the impact of disruption and maintain the continuity of the supply chain. On the other hand, without preparation and precaution, it requires time for the system to recover from the impact (Hendricks and Singhal, 2005; Sheffi and Rice, 2005).

From the supply chain disruption cases presented here, as well as many others available in the literatures, the question of what actually causes the vulnerabilities in a supply chain and how to ensure its resilience, intrigued us. Therefore, the background above provides the motivation for exploring risk issues affecting supply chain operations, and investigating how risk can be managed. The following subsections will highlight the research objectives and limitations. Next, in Section 2, the literature review of supply chain risk management is presented. Based on the existing literature, risk definitions and supply chain risk management processes are discussed. Then, in Section 3, the approaches and methods used in this dissertation are presented. The correct application of these approaches and methods is a potential aid in analysing different risks and mitigating the impact of disruption in supply chains. Finally, in Section 4, the papers accompanying this dissertation are summarised.

1.2. Research objectives

This dissertation aims to analyse how supply chain risks can be effectively managed. Firstly, this is done by positioning the research agenda in supply chain risk management (SCRM). Then, methods for effective management of supply chain risk are identified and analysed. In order to do this, the supply chain system is divided into subsystems based on the supply chain

operations of *make*, *source* and *deliver*; as well as on *material*, *financial* and *information flows*. We believe that analysing smaller parts of the system in terms of flows is an alternative and comprehensive way of dealing with the complicated risk issues in supply chains.

From these subsystems, we attempt to develop a framework, as presented in Figure 1, for further exploration. This figure shows that the continuity of supply chain operations can be affected by various risk events. A solid risk analysis process could identify the impact of disruption on supply chains. This could be established by monitoring supply chain performance, for example the production or financial performances. With a proper implementation of risk control, for instance via risk mitigation strategies, the impact of disruption on flows could be diminished, or even avoided.

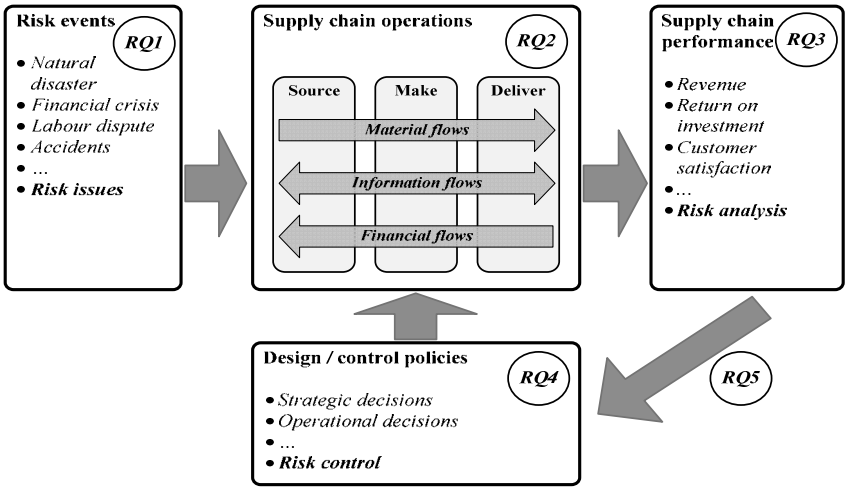


Figure 1: A supply chain research framework

Also based on this framework, we specifically develop the following research objectives and research questions (RQ) for this dissertation.

Objective I: Identifying Supply Chain Risk Management Agenda

To position this dissertation in the field of SCRM, it is important to identify the current agenda in this field. The exploration of various definitions, for both terminology and processes involved in this area, helps to clarify our research scope. The discovery of gaps between practitioners and researchers should further identify the research opportunities in this field. To achieve this objective, we hereby raise two research questions as follows:

RQ1: What risk issues should be considered in supply chain operations?

RQ2: How does a risk event affects supply chain operations?

Objective II: Identification of Effective Management of Supply Chain Risk

The second research objective focuses on finding how supply chain risk can be effectively managed. To achieve this objective, an investigation of selected approaches and methods will be conducted to analyse their competency and robustness in sustaining supply chain operations. Using the selected mitigation policies, such studies will investigate the consequence of supply chains under the influence of risks; both of mismatch risk and disruptive operational risk.

We identify two main processes of SCRM, namely risk analysis and risk control. Hence, to achieve the above objective, we raised three research questions. RQ3 focuses on risk analysis and RQ4 and RQ5 on risk control. The research questions are as follows:

RQ3: How can we analyse supply chain performance from a risk management viewpoint?

RQ4: What kind of mitigation policies should be used for managing risk in supply chains?

RQ5: What modelling techniques and approaches are possible in this research area?

1.3. Limitations

Many articles have been published about SCRM, but our literature search is limited to selected frequently cited journals and focuses on one database. These journals have been categorised by us into business review journals, operations management journals, and management science or operations research type of journals, while the database is limited to Web of Science. The list of journals falling into these categories is referred to Table 1 in Tang and Musa (2011). Although only selected journals and one database have been used, the selections based on high-cited journals provide sufficient data and also help to eliminate noise (Pilkington and Meredith, 2009).

There are many approaches and policies have been introduced and implemented in the industries to ensure the robustness of complex supply chain. To explore all of them would be an extensive task and require a lot more resources. Hence, in modelling the supply chain, only selected mitigation policies are investigated. However, the selected policies are sufficient to give the essence of how supply chains are affected in certain disruptive events. The selection of research approaches and mitigation policies is also based on the results obtained from Research Objective I.

This dissertation includes both conceptual and quantitative models. Data used in these analyses are mainly second-hand. It is difficult to validate the models with real cases, for data relating to risk issues is information which is confidential to the industry. Even when we were given permission to investigate risk issues at a company for this research study, the discussion is classified. Presenting risk issues affecting the company is like revealing the vulnerabilities of the company as well as the supply chain.

2. Literature Review in Supply Chain Risk Management

"Everyone sees the unseen in proportion to the clarity of his heart, and that depends upon how much he has polished it. Whoever has polished it more sees more – more unseen forms become manifest to him" ~ Jalal ad-Din Rumi

In this section, we provide an introduction to supply chain risk management. By presenting the relevant definitions and summarizing the important literature, we describe the background to the field of this study.

2.1. A general framework

Earlier supply chain management focused on the material flows of the network and broadened to include other flows, such as financial and information flows. We believe that a risk event can create disruption in either one or a combination of these flows. Supply chain risk could be mitigated if we have a detailed investigation and description of the root causes of disruption from the aspect of these flows.

Similar ideas have been presented by Chopra and Sodhi (2004), Johnson (2001) and Spekman and Davis (2004), who all identify the dimension of risk in the form of supply chain flows. Spekman and Davis (2004) however go further, and concentrate on information sharing and network relationships and add the security of internal information systems, relationships forged among supply chain partners and corporate social responsibility to their risk dimensions. Arlbjörn and Halldorsson (2002) share this idea of viewing risk on the flows of material and information, but view the third perspective in terms of flow of services.

One important change in managing supply chain is the emphasis on integrating activities into key supply chain processes instead of looking at individual functions. In the SCRM literature too, we note that managerial aspects may not be the same for the inbound and outbound sides. For instance, when discussing the risk in terms of supplier selection, a major concern is to sustain the flow of raw material, whereas on the demand side, financial risk, such as a customer's possibility of bankruptcy, may become important.

However, there is no clear evidence of interlinking flows and of integrating activities in previous studies. Therefore, in this study, we identify the flows in the form of material, financial and information flows. In addition, we analyse the system as a process model of source (supply), make (production) and deliver (demand). The foundation of this process model is the Supply Chain Operations Reference (SCOR) model, for it has been widely used among supply chain practitioners as well as researchers (Supply Chain Council, 2008). For any supply chain irrespective of its complexity, these aspects, as well as the three flows, provide a framework to describe the system. Risk issues will also be discussed based on these perspectives.

From a perspective of flows, we define the material flow as physical movement of products from suppliers to customers. Letters of credit, timely payment of bills, bankruptcy, payment schedules, credit terms and suppliers' contracts fall under the category of financial flows. Information flow is used to keep all supply chain elements updated and hence provides resources for decision making in the supply chain. Examples of information flow are order status, order delivery and inventory status, among others.

Our vision of SCRM is illustrated in a framework presented in Section 1 (refer to Figure 1). As mentioned above, supply chain operations are described as both flows and processes. Decision variables such as design and control policies are determined and improved on the basis of analysing performance measures just as in any supply chain. The only difference to conventional supply chain management is that we also need to define how the external risk events may influence supply chain operations.

2.2. Definitions of risk

In reviewing risk management literature, the first difficult question is, what is supply chain risk? It is particularly difficult to distinguish risk and uncertainty in supply chain operations management. In this section we therefore present relevant definitions.

Risk used to be simply linked to unexpected events. Christopher and Lee (2004) view risk as the "effect of external events such as wars, strikes or terrorist attacks and impact of changes in business strategy". Kleindorfer and Saad (2005) follow the same line and relate risk to i) operational contingencies; ii) natural hazards, earthquakes, hurricanes and storms; and iii) terrorism and political instability. Quinn (2006) also refers the natural and man-made disasters, to "catastrophic events" which are the source of risk.

Tang (2006a) defines risk as an operational as well as a disruption risk, but he however does not distinguish between them. Looking at various perspectives of risk, Spekman and Davis (2004) claim that risk definition can either be objective or subjective. Risk which relies on probability alone, such as coin flipping or dice throwing, is considered to be objective. However, when the consequences of risk need to be assessed along with its expectation of occurrence, it is categorised as subjective risk.

Chopra and Sodhi (2004) present nine risk categories, which include disruptions, delays, systems, forecast, intellectual property, procurement, receivables, inventory and capacity. They also discuss the impact of implementing a single or combination of mitigation strategies towards supply chain flows. There is no simple solution to managing supply chain risk. The implementation of one strategy in mitigating a particular risk may cause the supply chain to face another risk. Therefore it is important for all members of the supply chain to have a common understanding of supply chain risk. Chopra and Sodhi (2004) propose the use of 'stress testing'. Since each supply chain is unique, the risk mitigation strategies should be tailored accordingly to suit the entire supply chain. Even though they are not explicitly distinguished, the risk categories discussed by Chopra and Sodhi (2004) are established on the basis of supply chain flows. However, a clear definition of the fundamentals of risk seems to be lacking. In some of the risk categories, such as the forecast risk, where the authors

highlight the issues of the bullwhip effect, one may argue whether this could be considered as operational uncertainty and could be managed with correctly operating supply chain.

We note that in operations management literature, the terms 'uncertainty' and 'risk' have been used interchangeably. Supply risk usually refers to the occurrence of uncertainties that may halt the inward flow of the supply chain (Harland et al., 2003; Tang, 2006a; Zsidisin, 2003). Zsidisin (2003) classifies supply risk as "the probability of an incident associated with inbound supply from individual supplier failures or the supply market occurring, in which it outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety". On the demand side, even more cases of referring demand risk to uncertainties, for example, the trend of rapid changes of customer demand and the short life cycle of product resulting in fluctuated demand can be noticed. Johnson (2001) defines risk in terms of operational deviations, such as "unpredictable demand, short product life, rapid product turnover and seasonal changes". In our opinion, these should be considered to be the drivers for demand fluctuation.

Apart from supply and demand, uncertainty can take other forms, for instance technology (Chen and Paulraj, 2004). There also exist different viewpoints on uncertainty. Instead of looking at demand uncertainty as a fluctuation of demand volume, Lee (2002) believes that demand uncertainty should be "the predictability of the demand". A comparison of risk and uncertainty is made by Khan and Burnes (2007). They conclude that risk is measurable and manageable. On the other hand, however, uncertainty may not be measurable. Furthermore, risk emerges as measurable "in the sense that estimation can be made of the probabilities of the outcome". These definitions follow the tradition in the research field of decision analysis.

Due to the fact that there is no clear guideline in defining risk, Khan and Burnes (2007) suggest an in-depth study to define supply chain risk. Furthermore, with the expansion of global supply chain, the orthodox definition of supply chain risk needs urgent revision (Barry, 2004; Quinn, 2006).

In another set of literature, risk is viewed as the negative outcome after the impact of events. Christopher and Lee (2004) look at it broadly as any negative consequence resulting from any external event, whereas Paulson (2005) specifically identifies risk as "an event with negative economic consequences". However, some authors view risk as the variance of outcome, no matter whether it affects the organisation positively or negatively (Spekman and Davis, 2004; Crone, 2006).

Recent studies of supply chain risk discuss the elasticity of supply chain performance, which Sheffi (2005) calls Supply Chain Resilient. With the aim of avoiding a risk event, minimizing the effect as well as quickly returning to business, Sheffi defines risk as events with "high-impact/low-probability". Another significant development in this research is the introduction of supply chain preparedness to risk events. Sheffi illustrates eight phases of disruption profile. What distinguishes one disruption case from another is the severity and duration of the disruption and this depends on the level of preparedness.

In our opinion, a better definition of supply chain risk should refer to i) probable events which may occur suddenly, and ii) these events bring substantial negative consequences to the system. Based on this definition, in this research we focus our study on two types of risk: supply and demand mismatch, and unforeseen disruptive risk. In this dissertation which discusses ways to manage supply chains, we tackle the individual risk, as well as the combination of supply and demand risks as suggested by Johnson (2001).

2.3. Supply chain risk management

Kouvelis et al. (2006) view SCRM in terms of managing the uncertainty of demand, supply and costs. Carter and Rogers (2008) define SCRM as "the ability of a firm to understand and manage its economic, environmental, and social risks in the supply chain" which could be materialised by the adoption of contingency planning and having a resilient and agile supply chains.

There are also other notations related to risk management in supply chains. Rice and Caniato (2003) define supply chain resilience as the ability of an organisation "to react to an unexpected disruption and maintain operations after the event". Resilience can be achieved by employing high flexibility and adequate redundancy in the organisation. A more content-oriented definition of resilience as "the ability of a system to return to its original state or move to a new, more desirable state after being disturbed" is provided by Christopher and Peck (2004). To Peck (2006), resilience brings the concept of an organisation's "ability to absorb or mitigate the impact of the disturbance".

Contingency planning, which is interchangeably referred to as business continuity planning, is an approach to prepare for the possibility of future emergency or disruption. This approach involves continuous supplier assessment, development and maintenance of alternative capacities, mirrored and backup information systems and specific emergency response plans (Rice and Caniato, 2003).

In a recent study, Sodhi et al. (2012) claim that there are three gaps in SCRM. Similar to the study presented by Tang and Musa (2011), they identify that there is no clear definition of SCRM definitions, a lack in research on mitigating supply chain risk and a clear deficiency of empirical studies in this area.

In this dissertation, we follow the definition of SCRM as provided by Tang (2006a), in which SCRM is viewed as "the management of supply chain risk through coordination or collaboration among the supply chain partners so as to ensure profitability and continuity". He separates the mitigation approaches into supply, demand, product and information management.

After a fire incident affected their operations, Ericsson revised their SCRM which now consists of a feedback-loop of risk identification, risk assessment, risk treatment and risk monitoring (Norrman and Jansson, 2004). In addition, their new approach also includes incident handling and contingency planning in parallel to the basic loop. Neiger et al. (2009) categorise SCRM into the process of risk identification, risk assessment, risk analysis and

risk treatment. Knemeyer et al. (2009) identify Risk Management as a process of risk analysis subsequently followed by risk perception. The elements of risk identification and risk estimation fall into the process of risk analysis.

Especially in the case of a global supply chain, Manuj and Menzer (2008) believe that managing risk should at least comprise the processes of identification, evaluation and mitigation. Interestingly, they include time and the frequency of risk along with the common risk dimensions, probability and impact. Risk dimension of time is viewed as the speed of event, the speed of losses and the time for detection of the events. This time perspective follows the same ideas as in Sheffi and Rice (2005), where the authors describe the disruption profile by associating supply chain performance with time. Both studies stress the significance of time to risk impact.

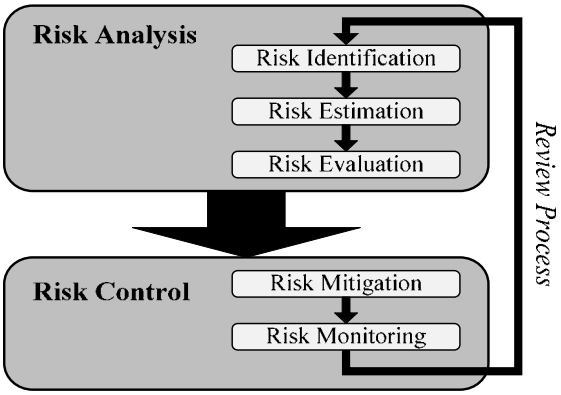


Figure 2: SCRM process

In Figure 2 we present our SCRM process which is constituted of two main elements; supply chain risk analysis and supply chain risk control, henceforth referred to risk analysis and risk control respectively. Note that the term risk assessment is also interchangeably used in referring to risk analysis. The first process covers the identification, estimation and evaluation of risk. Proper implementation of all stages in this process will result in the recognition of potential risk events affecting supply chain. However, not all risk events fall under the category of disruption risk events, and therefore the potential impact caused by an individual risk event needs to be carefully estimated and evaluated according to the individual supply chain operation's definition. ***Paper 2*** which is included in this dissertation, presents a further discussion of the risk analysis stage and suggests the adoption of Reliability Engineering approaches to provide a more structured and robust analysis.

With the completion of the risk analysis process, the supply chain will have a list of potential risk events and an evaluation of how risks could impact it. In order to control a supply chain, we then need to decide how to act upon the risks when the need arises. Various mitigation strategies can be implemented to tackle different types of risk. It is vital to evaluate and identify which mitigation strategy should be deployed and manipulated. In order to ensure the

continuity of all flows in a supply chain and the adaptability of mitigation processes, a supply chain should be closely monitored and continuously reviewed. ***Papers 3***, ***4*** and ***5***, present different strategies for risk mitigation and control.

2.4. Supply chain risk issues

In subsection 2.2 we presented risk definitions in general as well as from the perspectives of supply chain. In this subsection, we present important and common risk issues in supply chain operations. The discussion will be based on the three flows that connect the supply chain operations; *material flow*, *financial flow* and *information flow* (refer to Figure 1 and Figure 3).

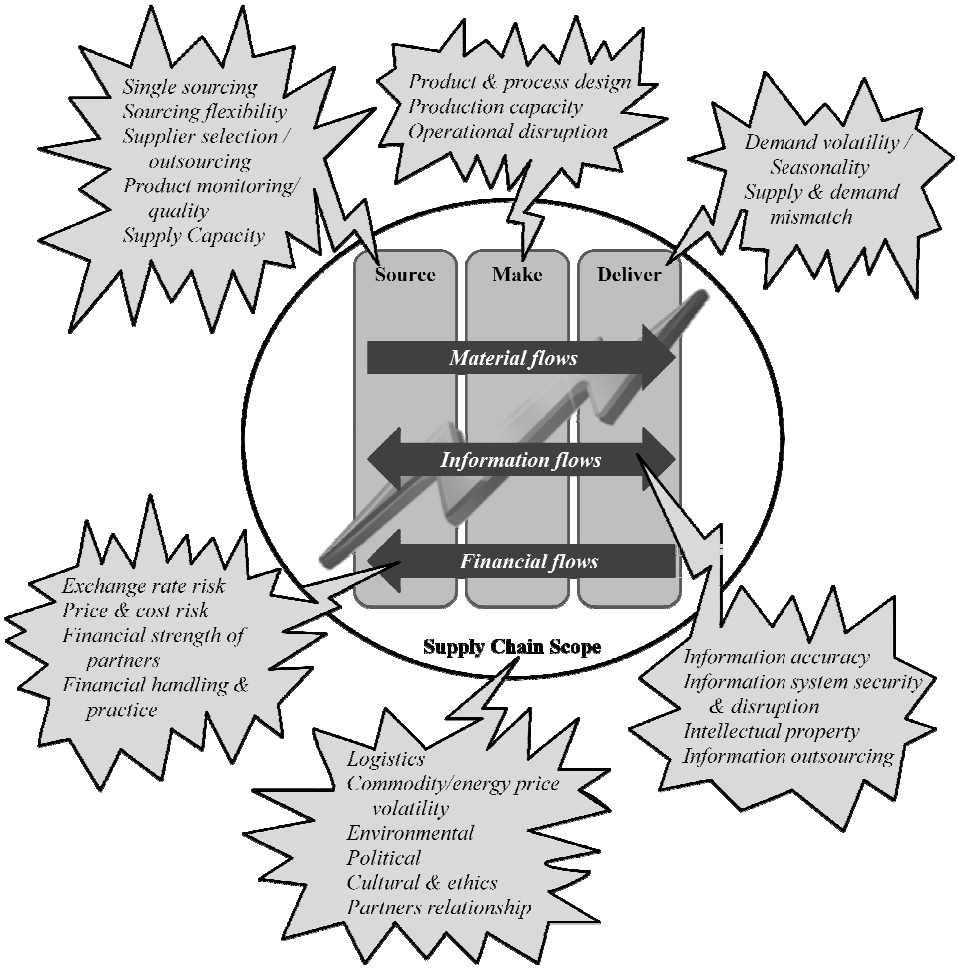


Figure 3: Risk issues in supply chain

In the following, we will first present the material flow risk. We categorise perspectives of risk events in material flow by the supply chain operations; *source*, *make* and *deliver*. Apart from these, we also add the *supply chain scope* to include essential issues such as the logistics, political and cultural issues (Figure 3).

Then we discuss supply chain risk from the view points of financial flow and information flow. We acknowledge that it is impossible not to link one individual issue to others. The flows are related and interconnected, therefore cases of one flow disruption obstructing the others are common. In fact, disruption creates a domino effect, as stated by Peck et al. (2003) "given the interdependencies, it may be the business that is at risk from its supply chain or the supply chain that is at risk from a business". Therefore, when discussing the financial and information flows, we present the risk events affecting the flows in general to avoid the need in discussing the issues presented earlier.

2.4.1. Material flow risk

Material flow involves the physical movement within and between supply chain elements. These include the transportation of goods, delivery movement, storage and inventories. In the event of risk, the material flow will be disrupted due to transportation incapability, halted manufacturing, lack of capacity, inability to access inventories and so on.

Source

Sourcing involves the acquisition of physical products or services. This segment will cover: single sourcing risk, sourcing flexibility risk, supplier selection/outsourcing, supply product monitoring/quality, and supply capacity (Figure 3).

Single sourcing risk: A minor fire accident in Philips' clean room in March 2000 caused Ericsson a major loss of USD400 million (Norrman and Jansson, 2004). Philips Electronics N.V. is a Dutch firm in Albuquerque, New Mexico, USA that supplies 40% of their production to Ericsson and Nokia (Peck et al., 2003). Ericsson's failure, however, was not because of not being responsive, but was mainly due to their single sourcing strategy. Unlike Nokia, who quickly turned to alternative suppliers in the USA and Japan, Ericsson had no substitute supplier (Peck et al., 2003). The Albuquerque accident provided Ericsson with a wakeup call to develop and implement a better SCRM approach (Norrman and Jansson, 2004). Ericsson has now developed a risk management process that has a feedback-loop. The process involves risk identification, risk assessment, risk treatment, risk monitoring, incident handling and contingency planning and it runs by using a SCRM matrix to ensure that responsibility is spread fairly (Norrman and Jansson, 2004).

While discussing the firm's motivation and actions with regards to environment-related supplier initiatives, Cousins et al. (2004) mention two potential exposures: technological and strategic. Technological exposure is caused by over-reliance on a single or limited source for a product, process or technology, whereas strategic exposure is due to high dependencies on a sole supplier. Further, Cousins et al. (2004) perceive financial, performance, physical, social, psychological and time loss, to be due to the risks of a single supplier "that may impact upon

the environment in a harmful way and that may fall foul of environmental legislation, regulation or public opinion".

Sourcing flexibility risk: Flexible supplier sourcing provides firms alternatives in the case of capacity constraint or hazardous disruption. Despite the benefit in safeguarding and preventing operations from coming to a halt, Kamrad and Siddique (2004) and LaLonde (2000) note that switching suppliers involves hidden costs. The cost of switching is related to relationship establishment among supply chain partners. While LaLonde (2000) views the relationship risk from the perspective of the producer, Kamrad and Siddique (2004) analyse the supply contracts from the perspective of the supplier's reaction to sourcing flexibility. A supply contract usually focuses on the profit maximization of the producer, ignoring the reactions of the supplier in protecting their profit, for example, suppliers face 'quantity risk' when order levels change due to exchange rate fluctuations. Therefore, Kamrad and Siddique (2004) focus on the dual optimization problems for both the suppliers and the producer, and posit that for profit sharing, a supply chain should include supplier-switching options, order-quantity flexibility, and reaction options.

Supplier selection/outsourcing: To facilitate focusing core competencies, outsourcing has rapidly become a trend. However, challenges also come with opportunities. While outsourcing in some way lowers manufacturing costs and provides better responsiveness to many situations, on the other hand, it increases the variety of choices and concerns during the supplier selection process. Hence selecting the right supplier has become more difficult. The supplier selection process requires many parameters to be considered. At the very least, supplier reliability, country risk, transport reliability and supplier's suppliers' reliability should be accounted for during the selection process (Levary, 2007). This has urged Levary (2007), Kremic et al. (2006), Kirkwood et al. (2005) and Cigolini and Rossi (2006) to develop various methods, models and systems.

When most companies started to outsource globally, the move was mainly cost-driven. However, it did not take long before the unseen cost of outsourcing was unveiled (Crone, 2006; Fitzgerald, 2005; Kremic et al., 2006; Murphy, 2007; Stalk, 2006). Various taxes, fluctuating currency exchange rates, import/export fees, the costs of longer transportations, and suppliers' audit costs are among the subjects of discussion.

Crone (2006) acknowledges the increasing problems of global supply chains especially on the logistics. He claims that the cost risks on the supply side could be the result of "inputs to transportation" (i.e. fuel) and "forced mode shifting". In addition to the present major concern of rising fuel prices, changing the mode of transportation to satisfy customer demand in a timely manner would substantially increase the cost of outsourcing. Crone suggests using transportation more effectively and re-examining sourcing strategy in order to "increase stocking locations in order to be closer to the point of manufacture and/or use inventory to reduce the need for product movement". Kremic et al. (2006) identify the trends and benefits of outsourcing and present its potential risks. They list additional indirect and social costs, which respectively include contract monitoring/oversight, contract generation/procurement, intangibles, and transition costs, and costs due to different culture and living styles. In

addition, they warn that the country's dynamic evolvement must be taken into account, where low-cost countries may not keep offering low-cost services and products when they experience advances in development, achievement and demand (Fitzgerald, 2005).

Supply product monitoring/quality: Sourcing has limited producer's control over the process and decisions, especially if the supply network is extended. Lack of control usually results in jeopardizing quality, especially when sourcing from low-cost countries (Murphy, 2007; Fitzgerald, 2005). Murphy (2007) illustrates quality risk with the product safety and contamination cases in China. Fitzgerald (2005) links poor quality to the incapability of the supplier to produce according to the standard demanded. This lack of capability due to limited skills and technology can be overcome when time and resources are invested in developing the required standard.

Supply capacity: Taking the toy industry as the case, Johnson (2001) explores supply chain risk and concludes that capacity limitation together with currency fluctuations are the major risks for major supply disruptions. In order to reduce capacity constraints, the toy industry outsources in two ways. First, outsourcing is used as a strategic solution which provides companies the opportunity to focus on their core competencies. Secondly, outsourcing is the answer to overcoming demand overflow. In both cases, manufacturers enhance the capability of handling the volatility of demand due to seasonality, new product introduction and rapid changes of customer demand. Nevertheless, outsourcing may also create the risk of lost control in manufacturing fashion products with a short life cycle, as claimed by Johnson (2001). Zsidisin and Smith (2005) believe that the risk of supplier capacity constraints can be mitigated by implementing early supplier involvement (ESI). With this approach, the supplier's capacity and production flexibility be known beforehand, leading to a better supplier selection. . This implementation also benefits the suppliers in that they can improve planning with better forecast information.

Make

The major issues in this segment involve: product and process design risk, production capacity risk, and operational disruption (Figure 3).

Product and process design risk: As mentioned before, the risk of inability to adapt to product and process changes has urged the industry to involve suppliers at an early stage. Motivated by "if you fail to plan, you plan to fail", many have applied the principle of concurrent engineering with suppliers involved in new product development. While Zsidisin and Smith (2005) study this early involvement at the new product development stage, Bowersox (1999) discusses this issue for product launch activity. Due to the large sum of capital spent in positioning products on the market, it is important to involve suppliers and customers early in order to obtain a robust design for product and process. With the computer and apparel industries as examples, studies have illustrated that integrating supply chain members in new product development will result among other things in aligned supply and demand. Suppliers can improve the decisions about their capacity (Bowersox, 1999; Handfield et al., 1999; Zsidisin and Smith, 2005).

While others examine product or process design separately, Peck (2005) attempts to integrate both using value stream design. An efficient and seamless logistics pipeline would be useful, but deceptively seductive. Using an extensive case study in the U.K., she reports that the "adoption of lean and agile practises has made them increasingly reliant on the existence of a reliable, secure and efficient communication, transport and distribution infrastructure". Based on a case study of Marks and Spencer, Khan et al. (2008) also investigate product and process design and propose a framework for design-led supply chain risk management. Khan et al. conclude that a well designed product and process flow will help an organisation to mitigate risks which arise with production and suppliers.

Production capacity risk: In manufacturing, identifying resource capacity is crucial. One important resource is technological capacity and skills. Handfield et al. (1999) claim that technological risk could be mitigated with early supplier involvement. However, it is necessary to acknowledge that this involves both advantages and disadvantages. If there is "greater experience or expertise with the technology, (they) may have better information about where the technology can be successfully applied". With experience, some may absorb the risk well, so it won't flow to the rest of the supply chain. On the other hand, early supplier involvement may result in a more difficult supplier selection process, because it is necessary to ensure that the suppliers will develop with the technology evolvement.

Operational disruption: Kleindorfer and Saad (2005) study the variations of supply chain design and relate them to supply chain disruption. They categorise operational disruptions into three main sources; operational contingencies, natural disasters and political instability. Focusing on these disruption risks and vulnerabilities, they develop a framework for mitigating disruption risk in a cost-effective manner. This framework (SAM-SAC) includes assessment and mitigation of risk, action strategies and conditions for implementation. In total, ten principles should be understood and applied collectively for SAM-SAC framework.

Deliver

Demand uncertainties are still the major problem discussed in the supply chain (Abernathy et al., 2000; Agrell et al., 2004; Ding et al., 2007; Fang and Whinston, 2007; Johnson, 2001; Li et al., 2001; Sodhi, 2005; Yu, 1997; Zhang, 2006). The major issues are: demand volatility / seasonality and balance of unmet demand and excess inventory (Figure 3).

Demand volatility / Seasonality: Johnson (2001) summarises the demand side risk as "seasonality, volatility of fads, new product adoptions, and short product life". To mitigate demand risk, the toy industry can implement licenses, increase the number of channels and increase product varieties. A successful licensing of Star Wars: Episode 1 led to high demand for toys during a low demand period, and resulted in increased net earnings (Johnson, 2001). Using multiple channels and placing products closer to customers at checkouts, cinemas, restaurants and gas stations can neutralise demand levels and reduce the seasonality of a product. Variation strategy can be realised for instance in rolling mix, when a new product is introduced in small time intervals. The aim of the rolling mix is to produce collector's items with high variety and planned shortages, so that it will eventually create demand from collectors. This has been successfully introduced by Mattel in their Hot Wheels range

(Johnson, 2001). Taking a similar industry as a case, Wong and Hvolby (2007) relate both seasonality and volatility to production responsiveness and coordination, and further indicate the importance of having quick response, accurate response and coordination.

Balance of unmet demand and excess inventory: Inventories allow manufacturers to be more responsive to demand. However, an inaccurate demand forecast may result in excessive inventories, which subsequently lead to capital tied up. Yu (1997) develops robust economic order quantity (EOQ) models with significant uncertainties. The aim is to find an inventory policy that performs well under different scenarios indicated by different outcomes of the demand rate, order cost and holding cost rate. Yu proposes robustness criteria for performance measure, which is minimizing the maximum of total inventory costs and percentage deviation from optimality.

Another inventory risk is obsolescence, which is associated with rapid technology evolvement and changes of customer demand. One famous case of inventory write-off is Cisco's $2.5 billion misread demand (Narayanan and Raman, 2004). Abernathy et al. (2000) suggest differentiating the stock-keeping unit (SKU) within a production line when dealing with risk associating to inventory. They support their argument with four different tests: i). keeping stocks for major customer group, ii). having lower inventories, iii). having a balance between the risk of stockout and inventories, and iv). differentiating the SKU where each SKU is assigned with individual policy. Using simulation, they reinforce that by differentiating SKU, manufacturers not only ease the risk of obsolete inventories, but also secure higher profits.

Sodhi (2005) explores the risk of unmet demand and the point of having excess inventories in tactical supply chain planning. He proposes "demand-at-risk" to quantify unmet demand and "inventory-at-risk" to measure excess inventories. He also introduces deterministic and stochastic linear programming models for capacity planning and reallocation.

Supply chain scope

In the above subsections, we focus on elements of the supply chain operations. Here we describe issues associated from supply chain scopes: logistics, price volatility of commodity and alternative energy, environment degradation and awareness, political risk, culture and ethics, and supply chain partners' relationships (Figure 3).

Logistics: The interconnection between nodes in a supply chain requires a well-designed logistics to allow smooth operations. The extended network has an increased number of logistics elements, such as transportation. Risks relating to transportation include rising fuel costs, labour shortage, service reliability reduction, capacity constraint and port congestion (Hauser, 2003; LaLonde, 2004, 2005). When logistics activities need to cross international borders, custom delays (Hauser, 2003) and long queues from tighter security (LaLonde, 2005) are also common phenomena.

Price volatility of commodity/alternative energy: Tohamy (2008) reports an industrial survey which claims that high price and instable commodity are the main issues in supply chain risk.

Such price hikes, especially those directly linked to logistics, have increased immediately the cost of operating an extended supply chain.

Cudahy et al. (2008) realise that to become competitive in global operations, a company has to be adaptable and responsive to changes. However, they also claim that "unfortunately, the ability to predict and willingness to manage supply chain risk has not grown at the same pace as supply chain extension". According to Tohamy (2008), in mitigating commodity volatility risk, manufacturers have to move away from the traditional supply chain management tools to managing their supply chain by "explicitly accounting for risk and making decision based on the potential costs and value that each risk introduces". The expected financial impact and the opportunity costs associated with each decision, must be considered.

Environment degradation and awareness: There is an increased public awareness of environmental degradation, especially in the low-cost sourcing countries as China. Water scarcity, earthquakes and thunderstorms have resulted in lost production capacity and halted supply chain operations for months (Economy and Lieberthal, 2007). In the same study, the authors categorise the environmental risks into four areas: water, energy, soil erosion and air pollution. To continue sourcing in China, foreign companies are recommended to be well aware of the risk associated with environmental degradation. Foreign companies should also be proactive in implementing environmental protection efforts by introducing programmes to build facilities and develop technologies that China requires for environmental protection. Also many leading companies such as Hawlett Packard and Mattel, have required their suppliers to comply with their standards on global corporate environment, operations and quality.

Political risk: Many studies, such as that by Cudahy et al. (2008) view political risk from the perspective of the sourcing country's political instability, whereas Stalk (2006) has a different viewpoint on political risk. He believes that the outsourcing risk to China has little to do with the politics of import restriction, but that the main concerns now are political and environmental barriers to port expansion. Meanwhile, Checa et al. (2003) emphasise the risk associated with administration transition in a government. From the era of Bush *Sr.* to Bush *Jr.*, the US international policy has shifted from economic concern to broad security protection. This has forced radical changes to our perceptions of which countries are and are not safe for business. With the new order, more effort is required to evaluate political status and assess the links between the political, economic, and financial factors of risk prior to business venture.

Culture and ethics: Reputation damage due to unethical misconduct puts a big hole in a company's pocket. In February 2005, Wal-Mart was convicted guilty of using child labour and of allowing them to use hazardous equipment. Even though they were fined a small penalty by the U.S. Labor Department (USD135,540), the cost of damaged reputation is immeasurable (Los Angeles Times, 2005). With manufacturing ventures in multiple countries, it is necessary to be prepared for the risk of cultural difference and different ethical values. There is distinctly different work culture and ethics between developed and developing countries. Something which might be extremely unethical in developed countries,

might not be an issue for developing countries. Underage labour is considered as a normal means for survival in Bangladesh, India and China, but it is an unacceptable to the ethics of many other countries.

Supply chain partners' relationships: The *Enron Scandal* that was first revealed in October 2001 not only caused Enron to file for its bankruptcy, but also severely affected their auditors, Arthur Andersen LLP, which was then alongside PricewaterhouseCooper and Ernst & Young, one of the biggest consulting firms. It was probably the biggest breach of trust and proved that trust is the bedrock of a supply chain relationship (LaLonde, 2002). Securing relationships with good contracts among supply chain partners can avoid misaligned incentives which can cause hidden action and lead to profit loss (Narayanan and Raman, 2004). A secured relationship can be built by adopting monetary incentives especially when there is limited insight into the other's action, limited information or knowledge of the other partners. Using the relationships between Whirlpool and Sears as an example, they argue that a supply chain works well if its companies' incentives are aligned, i.e. if the risks, costs, and rewards of doing business are distributed fairly across the network. Better contracts, information sharing systems and trusting partners can improve supply chain partnership (Reichheld and Schefter, 2000; Faisal et al., 2006).

2.4.2. Financial flow risk

Also known as cash flow, financial flow represents the received and spent cash streams. Disruption in financial flow involves the inability to settle payments and improper investment. In this part, we will discuss issues as illustrated in Figure 3 covering exchange rate risk, price and cost risk, the financial strength of supply chain partners, and financial handling/practise.

Exchange rate risk: A study of global sourcing strategies, in particular the impact of flexible sourcing under the influent of uncertain exchange rates, is presented by Kouvelis (1999). He proposes a framework to select suppliers and determine the quantity required from each supplier in the presence of exchange rate uncertainty. He analyses sourcing strategies from two approaches; first based on constant switchover cost and the second on the basis of time and quantity flexibility. Time flexibility, quantity flexibility and risk sharing contracts are considered in selecting suppliers and determining order quantity. Kouvelis (1999) claims that in most cases, firm tends to continue sourcing from an expensive supplier due to the trade-off of "hysteresis band".

Other studies on the exchange rate and its influence on financial flow can be found in Carr (1999), Goh et al. (2007) and Li et al. (2001), among many others. Li et al. (2001) discuss the exchange rate risk and propose when to switch suppliers or facilities on the basis of the fluctuation of the exchange rate. Goh et al. (2007) propose a stochastic model to maximise a company's global after-tax profit, which influences the financial flow. This is achieved by acknowledging market demand uncertainties, exchange rates, tax rates and tariffs. While many study the risk of exchange fluctuation, Carr (1999) discusses the opportunities of a single currency. The transition from domestic currencies to the single Euro currency has removed the worries of currency risks from among the European Union's new challenges.

However, this transition has above all exposed the challenges of dealing with multiple cultures and languages.

Price and cost risk: This risk may be associated with the exchange rate as indicated previously. However, price and cost may also change due to various manufacturing strategies. Papadakis (2006) studies the supply disruption effect on financial flows with regard to the make-to-order and make-to-stock systems. She investigates the performance of the personal computer industry during the Taiwan 1999 earthquake, and concludes that component prices increased in the pull-type supply chains. van Putten and MacMillan (2004) also explore the risk issue of cost and price. They discuss the inaccurate evaluation of cash flows if managers tend to use real options and discounted cash flow (DCF) approaches separately; real options tend to overestimate while DCF is more likely to underestimate the value of uncertain projects.

Financial strength of supply chain partners: Hendricks and Singhal (2005) report the vulnerability of financial flow and the long term effects associated with supply chain disruptions. Their findings indicate that the affected firm's stock price could be negatively influenced before the disruption announcement is made, whereas during the post-announcement period, the firm's stock price may have positive or negative development depending on their corrective actions. Many cases have shown that the vulnerability of the financial strength of a supply chain member may easily affect the entire supply chain (Peck et al., 2003; Tang, 2006b). For instance, the Asian financial crisis of 1997 caused many manufacturing companies to operate in debt, or to declare bankruptcy (Hartley-Urquhart, 2006). The consequences spread to the entire supply chain. Their suppliers suffer from unsettled raw material flow and costs while their customers endure market loss due to unsatisfied order fulfilment.

Financial handling and practise: Hartley-Urquhart (2006) and Kerr (2006) discuss the risk arising from the way in which financial flows are managed and handled. Associated with global sourcing and outsourcing is also the increasing velocity and quantity of payments. The adoption of supply chain financing includes early-payment programmes, inventory-ownership solutions and consignment financing. The lack of control and visibility of the procure-to-pay process further led Saks Inc. to an alleged illegal collection of excess vendor markdown and suffer a total market capitalization drop by 20 percent. Further concerns raised are the bank-clearing system, commercial laws and cross-border security measures. Extended supply chains complicate financial flows. However, there is limited research in this area, as pointed out by Hartley-Urquhart (2006), who believes that despite the pressing needs, researchers tend to avoid this area due to highly integrated knowledge base required.

2.4.3. Information flow risk

Value adding activities in a supply chain are often triggered by information flows such as demand information, inventory status and order fulfilment. Product and process design changes and capacity status are other examples of information flows. Information flow may also be seen as the bonding agent between material flow and the financial flow, for example, when the physical part is delivered, the recipient will be informed of the delivery in terms of

delivery order and how much payment is due in the form of invoice to sender. This information will trigger the recipient to make an appropriate payment to the sender. Hence cash will flow in the opposite direction of the material flow. As presented in Figure 3, we will discuss the following risk issues of information flows: information accuracy, information system security and disruption, intellectual property and information outsourcing risk.

Information accuracy: Information accessibility, accuracy and efficiency are major discussions relating to information flows (Bradley, 2001; Faisal et al., 2006, 2007; Geary et al., 2002; Giermanski, 2000; Lee, 2002, 2004, 2007; Raman et al., 2001; Zsidisin and Ellram, 2003). Lee (2002) studies uncertainty from the perspectives of supply and demand. Demand characteristics and uncertainty can be distinguished on how functional and innovative a product is. On the other hand, the nature of the supply process can be stable for a mature and established environment, or evolving for manufacturing processes and technology that are still developing and changing. Lee (2004) argues that to be among the top supply chains, it is necessary to have the triple-A characteristics: to be agile to changes, adaptable to evolvement, and align the interest of all the firms in the supply network. The inaccuracy of information could be mitigated by the adoption of information sharing and transparency, taking the advantage of internet advancement. Despite acknowledging the increasing risks in the information, material and financial flows, Lee (2007) looks at these challenges as opportunities through advances in information technology. The foe could become friend by creating awareness of the real situation.

Raman et al. (2001) discuss how the wrong use of action and policies dealing with inventory data could trigger information inaccuracies. The inaccuracy could be at the checkout, where the cashier carelessly assumes that two "similar" products are the same, for example assuming honey flavoured and citron flavoured yogurt as the same. Data inaccuracy could also be the result of reducing paperwork, for instance Giermanski (2000) highlights the difficulty of moving materials across the US border to Mexico due to the non-existence of custody documentation. The lack of a bill of lading increases the risk of bearing costs for material damage and lost. Using the agency theory to investigate supply risk management, Zsidisin and Ellram (2003) argue that a well aligned information flow results in more symmetric information which could further reduce the risk sources.

Many companies have lost business due to inability to match supply and demand (Bradley, 2001; Chopra and Sodhi, 2004; Faisal et al., 2007). Bradley (2001) illustrates his personal experience in getting an extra snow shovel, right after hearing a snow storm warning. Shovels were sold out at the particular store he visited, while at other stores nearby, there are plenty of them. If the store owner had been able to forecast accurately, he might have made more profit that day. Using chaos theory, Bradley (2001) identifies that information flow should be faster and allow compressing cycle times to avoid any lost business. Geary et al. (2002) suggest implementing a flawless information and material flow system that should be used by all supply chain members to combat uncertainty and improve performance

Information system security and disruption: A survey was conducted in India to ascertain what seems to be obstructing supply chain partners in facilitating an information system. The

study results show that the threat of information security ranks fourth after trader's capability, resistance to changing the system and a low level of supply chain integration (Jharkharia and Shankar, 2005). Furthermore, according to the survey, fear of information breakdown ranks sixth after trust deficiency. The results of a correlation matrix show that information security and breakdowns are a major concern of supply chain information disruption.

Finch (2004) defines an information system on three levels: application, organisational and inter-organisational. He classifies data information security risks as application level risk, when it is associated to the technical or implementation failure of an application resulting from either internal or external factors. Finch also identifies hackers, viruses and destruction and denial of access as information system security risks.

An information system is frequently at risk from hackers illegally accessing the company's information system. Excess bandwidth consumption, resource starvation, and resource exploitation can also interrupt an information system by flooding it, thereby resulting in system shut down and denial of access to legitimate users. There is also threat from internal employee frauds of intentional/unintentional disclosure of proprietary information. A series of supply chain disruptions due to natural disasters and terrorist attacks stress the need of data backup (Faisal et al., 2007). Meanwhile, Finch (2004) foresees information system disruption risk from the lack of a proper implementation of standard operating procedure for the backups.

Intellectual property: To ensure a smooth network, a high visibility of information flow is required. However, inability to protect information sharing will increase the risk of trade secret exposure. Barry (2004) highlights the risk of technology transfer which results in the company competing side by side with their former subcontractors. He raises the question: what is the impact of the compromise of intellectual properties from global sourcing? Faisal et al. (2007) believe that the vulnerability of intellectual property right is especially in jeopardy in the software industry.

Information outsourcing: Information technology or information system outsourcing has enabled a company to focus on its core-competence. However, leaving this to third party increases risk for opportunism among vendors, information security apprehension, hidden costs, loss of control, service debasement, disagreements, disputes and litigation, and poaching (Faisal et al., 2007). Spekman and Davis (2004) suggest that protection from inappropriate illegal or unethical access to the information system should be established to prevent unintended exposure of a company's data. Christopher and Lee (2004) call for improved accuracy, visibility and accessibility for improvising of information sharing. Furthermore, they stress the need for an information system, which can alert the supply chain members on any out of control conditions. Murphy (2007) predicted that the trend in supply chain technology in 2008 would be using information system as a service which provides better security. By using this application, fear of sharing sensitive data to a third party should no longer be a problem, since companies have the access to the third-party's server and have full control of the information system.

Table 1: Main issues discussed over the years

Issues	References
1995~1999	
Financial risk management	Paradine (1995); Carr (1999)
Operation strategies	MacDuffie and Helper (1997); Williamson (1997); Yu (1997); Wilding (1998); Bowersox et al. (1999); Handfield et al. (1999)
2000~2004	
Environmental	Barry (2004); Cousins et al. (2004)
Financial risk management	LaLonde (2000); Cachon (2004); van Putten and MacMillan (2004)
Information management	Reichheld and Schefter (2000); Bradley (2001); Geary et al. (2002); Christopher and Lee (2004); Finch (2004); Lee (2004)
Operation strategies	Abernathy et al. (2000); Johnson (2001); Li et al. (2001); Raman et al. (2001); Tummala and Mak (2001); Svensson (2002); van der Vorst and Beulens (2002); Van Landeghem and Vanmaele (2002); Harland et al. (2003); Hauser (2003); Morales and Geary (2003); Peck et al. (2003); Rice and Caniato (2003); Berger et al. (2004); Chopra and Sodhi (2004); Christopher and Peck (2004); Svensson (2004)
Political and cultural practises	Giermanski (2000); Checa et al. (2003); Cousins et al. (2004)
Supply chain partners relationship	Svensson (2001); Hallikas et al. (2002); LaLonde (2002); Lee (2002); Zsidisin and Ellram (2003); Agrell et al. (2004); Hazra et al. (2004); Kamrad and Siddique (2004); Narayanan and Raman (2004)
2005~2009	
Environmental	LaLonde (2005); Peck (2005); Stalk (2006); Economy and Lieberthal (2007); Murphy (2007)
Financial risk management	Callioni et al. (2005); Hendricks and Singhal (2005); Bovet (2006); Choi and Krause (2006); Hartley-Urquhart (2006); Kerr (2006); Papadakis (2006); Fang and Whinston (2007); Smith et al. (2007); Xiao and Qi (2008)
Information management	Jharkharia and Shankar (2005); Faisal et al. (2006, 2007); Ratnasingam (2007)
Operation strategies	Elkins et al. (2005); Hale and Moberg (2005); Jüttner (2005); Sheffi and Rice (2005); Zsidisin and Smith (2005); Zsidisin et al. (2005); Gattorna (2006); Hillman (2006); Kiser and Cantrell (2006); Khan et al. (2008)
Outsourcing to low cost countries	Fitzgerald (2005); Amaral et al. (2006); Cigolini and Rossi (2006); Crone (2006); Kumar et al. (2007)
Political	Kleindorfer and Saad (2005); de Waart (2006); Stalk (2006); Economy and Lieberthal (2007); Ferrer et al. (2007); Cudahy et al. (2008)
Supply chain partners relationship	Martínez-de-Albéniz and Simchi-Levi (2005); Levary (2007)

2.4.4. Summary of supply chain risk issues

The risk issues affecting supply chain flows discussed above are some examples from the many and mostly unique cases affecting today's industry. In Table 1, we provide the summary of issues discussed over the years. We divide these studies into three time segments. We observe that risk issues in supply chains have received increasing attention from researchers and practitioners, especially after 9/11.

In the early years, studies in SCRM mainly focused on financial risk and operational strategies. Then, in the later time segments, research areas extended the scope to risk issues affecting the entire supply chain. We also observe an emerging interest in analysing information management. We refer to the accompanying ***Paper 1*** for further discussion on trends and advancement in SCRM.

2.5. Research methods and approaches in literature

In reviewing the current research and trends in this field, articles were gathered by means of a literature search and a bibliometric analysis of selected journals (business review journals, operations management journals, management science or operations research (MS/OR)) and a database (Web of Science) from 1995 until 2009. After a series of selection and filtration, a total of 138 related articles were reviewed (Tang and Musa, 2011).

Besides the definition and scope of SCRM presented earlier, it is also important to indentify the research methods and approaches used in evaluating and managing risk issues. We identify that the existing studies on SCRM are mainly based on a qualitative approach (78%) and merely a small fraction fall under the category of quantitative approach (see Figure 4). In the following, we will discuss the two respective approaches.

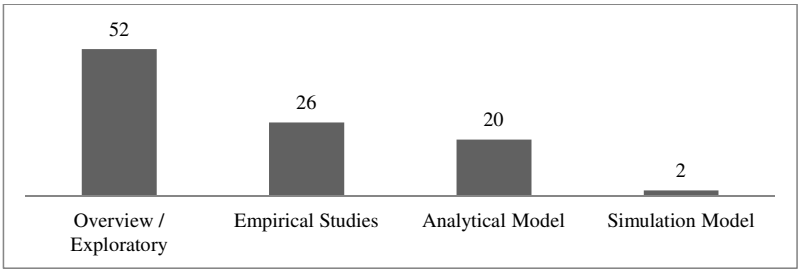


Figure 4: Percentage of publication by types of research method

2.5.1. Qualitative approach

We categorise qualitative studies into two groups. The first group consists of conceptual models, overviews and exploratory reviews, while the latter comprises empirical studies such as industrial cases, interviews and surveys.

More than half of total articles reviewed fall under the category of the first group, qualitative approach. From this group, the vast majority cover some perspectives of supply chain risk. Harland et al. (2003) view risk from the supply side. Peck et al. (2003) investigate the same

and include the additional perspectives of process risk, demand risk and control risk. Taking a wider view of the supply chain, Lee (2004) and Gattorna (2006) analyse the risk of misalignment of supply chain partners' relationship, while Barry (2004) analyses risk in the global supply chain environment. Other perspectives include process-based risk (Neiger et al., 2009), information visibility and controls (Christopher and Lee, 2004), technological capability, and policy risks (Johnson, 2006).

Frameworks have also been developed to explore the risk issues in supply chains, for example for identifying supply chain risk (Bovet, 2006). The strategies proposed aim to mitigate risks in their respective areas, from postponement in order to mitigate demand uncertainties to early warning system in order to monitor critical product development.

A large number of the articles in the first group cover the sourcing issue with or without a combination of other supply chain elements. Hartley-Urquhart (2006) proposes the early-payment programmes whereas Cachon (2004) suggests discount contracts to secure the supplier relationship. Lee (2002, 2007) proposes taking advantage of information technology for the supply chain to tackle supply and demand risks. Fitzgerald (2005) suggests a secondary manufacturing plan which includes sourcing in less risky regions and in the same country as the focal company, in order to mitigate supply disruption.

Other solutions involve the risk protection of buyer's credit (Kerr, 2006), stress testing (Chopra and Sodhi, 2004), a resilience supply chain (Christopher and Peck, 2004) and to increase flexibility (Bovet, 2006; Chopra and Sodhi, 2004; Sheffi and Rice, 2005; Tang, 2006b). We note that the most commonly discussed and implemented methods found in the literature are associated with material flow risk in supply chains.

The empirical studies have predominantly focused on sourcing policies which arise from the practitioner's problem (Amaral et al., 2006; Crone, 2006; Norrman and Jansson, 2004; Sinha et al., 2004). In this study group, inventory is another important issue with common topics such as the reduction of inventory holding (Jüttner, 2005), allocation of buffer inventory (Baker, 2007), application of inventory-driven cost metrics (Callioni et al., 2005) and the implementation of lean production (Abernathy et al., 2000). Frameworks are proposed to encourage early supplier involvement to improve control capacity, demand and process (Khan et al., 2008; Zsidisin and Smith, 2005). Rice and Caniato (2003) stress the significance of redundancy in an organisation facing disruption strikes.

2.5.2. Quantitative approach

Only a quarter of the articles in our review apply a quantitative method including analytical models and simulation. With regard to supply selection, there are decision-tree based optimization models (Berger et al., 2004), risk ranking systems, (Levary, 2007), an IBM supplier evaluation model (Kirkwood et al., 2005) and incentive models (Agrell et al., 2004). With a focus on flexible sourcing and supplier relationships, there are dual optimization using real options (Kamrad and Siddique, 2004), decision support systems with multivariate analysis (Kremic et al., 2006) and procurement contracts models (Martinez-de-Albeniz and Simchi-Levi, 2005).

Various methods are used to mitigate risk associated with uncertainty. Among them are a robust economic order quantity model (Yu, 1997), an optimization model for operating policy (Li et al., 2001), an options contract model (Fang and Whinston, 2007), a linear dynamic system model (Zhang, 2006), a two-stage stochastic model combining real option and financial option (Ding et al., 2007), a financial model (Hauser, 2003), an equilibrium model to counter supply and demand risk (Nagurney et al., 2005), a stochastic location model with risk pooling (Snyder et al., 2007), a stochastic programming for identifying loss risks (Sounderpandian et al., 2008) and a value-at-risk (VaR) model (Tapiero, 2005, 2007).

Simulation modelling covers a very small fraction of the quantitative approaches and most of these models have been designed recently. Dual optimization using real options simulation-based decision support system has been developed for selecting the best collaboration level between partners (Cigolini and Rossi, 2006) and relocating the order penetration points (OPP) (Wong and Hvolby, 2007). A recent application of ARENA simulation (Kull and Closs, 2008) assesses supply risk, and it also claims that small order quantities bring resilience to the supply chain.

Tang (2006a) presents an excellent review on quantitative approaches for supply chain risk management. He proposes robust supply chain strategies which aims both to improve a firm's capability to manage supply and demand under normal operation, and to enhance a firm's capability to sustain its operations when a major disruption hits. Tang (2006a) also proposes nine key policies for mitigating risks: postponement, strategic stock, flexible supply base, make-and-buy, economic supply incentives, flexible transportation, revenue management, dynamic assortment planning and silent product rollover. However, it is acknowledged that studies applying quantitative methods in supply chain risk management are still very limited in number (Khan and Burnes, 2007; Tang, 2006a, 2006b). From our review, we note there is an obvious lack of quantitative approaches, particularly in modelling risk associated with information flows.

2.5.3. Summary on research methods and approaches in literature

The literature search shows that early studies in SCRM focus on a conceptual analysis (52%) of risk issues, mainly on the supply side. There is also increasing SCRM awareness from practitioners, which is translated into an increase of interest in empirical studies (26%). Over the years, we have observed a growing interest in handling risk issues by combining risk perspectives and risk flows. However, these studies are still mainly limited to conceptual and overview studies.

Research conducted in how to deal with technical problems are very few (22%). Although there has been an increase in research in quantitative studies, a big portion of these studies still focus on a specific area, and ignore the need to handle supply chain as an integrated system. This may be due to the challenge of analysing and managing risk issues in a complex, integrated supply chain system. The application of simulation models could be an alternative way to promote quantitative analysis in resolving technical problems in SCRM.

3. Approaches and Methods Adopted in this Research Project

"Where there are things to be done the end is not to survey and recognize the various things, but rather to do them; with regard to excellence, then, it is not enough to know, but we must try to have and use it, or try any other way there may be of becoming good." ~ Aristotle, Nicomachean Ethics

This dissertation aims to investigate the general concern for and perception of risks affecting supply chains and how risk flows in a supply chain can be effectively managed. To achieve our research objectives, we have employed various approaches and methods as presented in the shaded area in Figure 5.

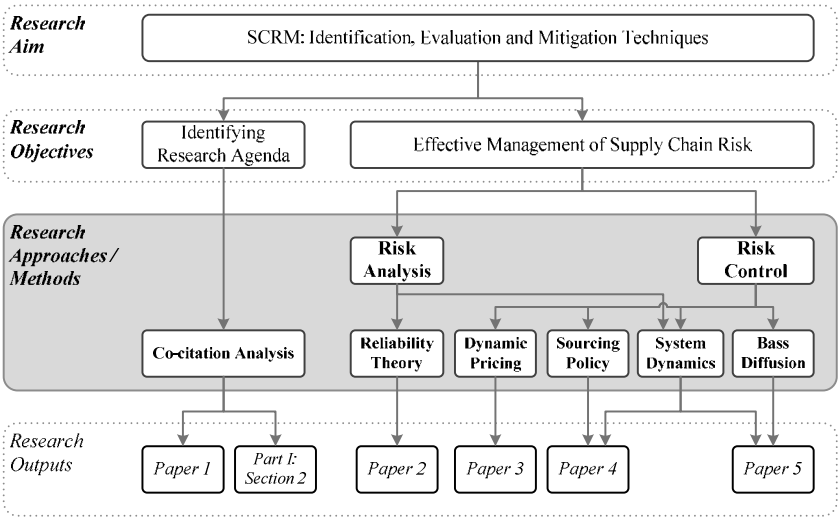


Figure 5: Approaches and methods adopted in the dissertation

Firstly, we identify the agendas in supply chain risk management by using a bibliometric analysis. Bibliometric analysis, specifically co-citation analysis, helps to identify the research agenda and trends in the field of SCRM. The findings of this investigation are presented in ***Paper 1*** and complemented with ***Section 2*** of Part I in this dissertation.

Then, we investigate how supply chain risk could be effectively handled. We use the SCRM process, comprising of risk analysis and risk control stages as the framework (refer to Figure 2 in Section 2). To present how risk in a supply chain can be analysed, we include ***Paper 2***, in which we adopt well-established tools and approaches that have been introduced in Reliability Engineering. These tools and approaches have been widely used in product/process development.

The application of System Dynamics modelling also helps in analysing risk in a supply chain. This is presented in ***Paper 4***. This paper shows how when disruption occurs at one node of the supply chain, the effect of this disruption flows along the supply chain can be identified. These effects could be observed for instance by monitoring the production performance. Any discrepancy in supply chain performance helps to identify a potential risk of disruption. An individual supply chain has to compromise on estimating and evaluating the risk to allow effective risk control processes.

Meanwhile, for risk control, we investigate selected mitigation policies: dynamic pricing, dual-sourcing, and delayed diffusion process. The applications of these policies are presented in ***Paper 3***, ***Paper 4*** and ***Paper 5***. We use system dynamics modelling in ***Paper 4*** and ***Paper 5*** to cater for the complexity and dynamics of a supply chain facing risks. Below, we present some basic facts of the above mentioned approaches and methods.

3.1. Co-citation analysis

Bibliometric analysis is a quantitative approach used in analysing the impact of a particular research field. Two approaches can be applied, either patent analysis or citation/co-citation analysis. Patent analysis is more commonly used for product related analysis, and is therefore excluded from our research. Citation/co-citation analysis is an established approach which has the advantage of identifying the development and trend in a research field.

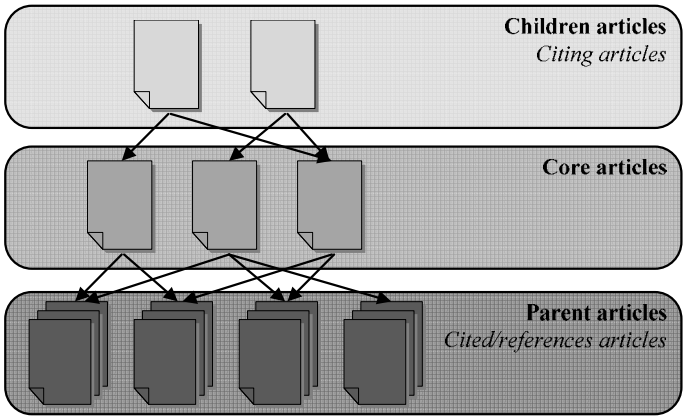


Figure 6: Co-citation Terminology

We first explain the basic terminology in citation/co-citation analysis as illustrated in Figure 6. Articles of interest are referred as core articles. The references obtained from the core articles (the cited references) are referred to as parent articles, while articles citing the core articles are known as children articles.

Citation analysis is the process of examining the frequency, patterns and graphs drawn of citations in publications. The process involves identifying core articles and the appearance of parent articles. From this approach, one may identify the significance of articles, authors, or

journals for the particular field of interest. This is usually performed in the articles' database by classifying the highly cited articles, authors or journals. It is important to carefully select the core articles by referring to databases such as Web of Science or Scopus, where one can easily export the citation data of each article.

To further investigate the impact of articles on research development, co-citation analysis is a preferred method. Co-citation analysis allows the mapping of scientific topics based on the relation between and among core (articles of interest), parent (cited references) and children (citing articles) articles (refer to Figure 6). The aim of co-citation analysis is to find the co-occurrence of parent articles through finding common themes between the core articles and consequently, uncovering the development of research field of interest.

In preparing for co-citation analysis, we first identify the core articles. Then all the references used in these core articles are extracted. These references are known as the parent articles and will be used in the co-citation analysis. When two common parent articles are cited together by a core article, this suggests that the core article has combined the knowledge from these two earlier articles. It also reflects the correlation between the two parent articles as they both have influenced the existence of this core article. The topic relatedness can be analysed by investigating the contents of the parent articles, either by the co-existence of authors or by keywords, journal or research area, even though co-citation of author is the most common method (Bayer et al., 1990; Culnan et al., 1990; Lunin and White, 1990; McCain, 1990; Paisley, 1990; Pilkington and Meredith, 2009).

Data from both citation and co-citation is then used to develop matrices and clusters in order to present a visual network of the research field. Computer aided statistics tools such as SPSS, BibExcel, UCINET and Pajek are commonly used in developing citation and co-citation matrices and network clustering (Pilkington and Meredith, 2009; White and McCain, 1998).

In the field of Operations Management, citation analysis has been used to define the influence of journals (Cote et al., 1991) and journal ranking (Vokurka 1996; Kumar and Kwon 2004). This method helps researchers to realign their focus in the literature review and to know where to send your own work for publication. Co-citation analysis is relatively new for analysing the development of Operations Management. Attempts to identify intellectual structures in the field of Operations Management (Pilkington and Fitzgerald, 2006; Pilkington and Meredith, 2009; Ramon-Rodriguez and Ruiz-Navarro, 2004) and Supply Chain Management (Charvet et al., 2008) have been made. ***Paper 1*** which accompanies this dissertation (Tang and Musa, 2011) is the first attempt to identify research advances in Supply Chain Risk Management.

3.2. Reliability theory

Consumers increasing demands for product quality and performance leads to a growing complexity of product development processes. This higher complexity calls for an interdisciplinary approach to enable the realisation of successful products. Thus, the field of System Engineering and Concurrent Engineering have emerged. System Engineering is a

disciplined, orderly, top-down process for managing project risks while defining customer requirements, translating those into performance requirements, selecting balanced solutions to the design problems revealed, verifying that the solution responds adequately to the problems, and validating that the solution fulfils the original needs. One important sub-field in System Engineering is Reliability Engineering, where the focus is on ensuring product reliability, quality and safety.

Even though reliability and quality are often used interchangeably, there is a distinct difference between these two qualities. Reliability concerns the performance of a product over its entire lifetime, while quality control focuses on the performance of a product at one point in time, usually during the manufacturing process. Safety is usually defined as a "conservation of human life and its effectiveness, and the prevention of damage to items as per specified mission requirement" (Dhillon, 2005). While reliability and quality focus on failures and their prevention, safety focuses on those failures that create hazards. Hence, these three qualities are closely knit together to satisfy customers' needs for highly reliable, good quality and safe products.

To achieve high quality, a product has to reflect customers' needs as well as be robust (Lewis, 1996). One common approach for measuring product and process performance is to assess its risk by means of the three above mentioned qualities.

To perform a fundamental risk assessment in Reliability Engineering requires an understanding of probability and sampling to ensure the accuracy of the assessment. Concepts in representing failure behaviour include the bathtub hazard rate curve, hazard rate function, reliability function and mean time to failure (Dhillon, 2005; Lewis, 1996). Risk assessment can be divided into three stages; preparing for the assessment, carrying out the assessment and post-assessment activities (Gadd et al. 2004).

Many methods and approaches have been developed for assessing risk. Some examples of commonly and interchangeably used methods in reliability, quality and safety assessment are the fault tree analysis (FTA), the failure modes and effect analysis (FMEA), the Markov method, the network reduction method, the decomposition method, and various types of quality control charts, the Pareto diagram, the quality function deployment (QFD), the cause and effect diagram (CAED), the design of experiments (DOE) and the hazards and operability analysis (HAZOP). The applications of these tools range from software to aircraft engine developments (Yacoub and Ammar, 2002; Yang et al., 2011).

Based on a literature search and case studies, an extensive study on risk assessment of health and safety at work in the UK has identified several pitfalls in implementing risk assessment (Gadd et al., 2004). Among others, the pitfalls include "considering risk from one activity" and failure to identify all problems as well as consequences. Meanwhile, in a comparative study, Backlund and Hannu (2002) identify results obtained from three different risk analysis approaches (from three different teams) applied to a specific hydro-plant, and conclude that these approaches produce dissimilar results. Based on these pitfalls, factors affecting the quality of risk analysis are identified (Backlund and Hannu, 2002; Arunraj and Maiti, 2007).

These factors are risk assessment, hazard identification and initial consequence analysis. Sub factors include frequency estimation, consequence estimation, method, data and information, and results.

We believe that there are similarities between system engineering and supply chain management. Both concepts require a holistic perspective of the network, as if there is a case of failure in one of the members, the whole network will be affected. Therefore, we aim to investigate the suitability of adopting reliability engineering risk analysis tools in the perspective of supply chain risk (see ***Paper 2***).

3.3. Dynamic pricing

Pricing strategy plays a main role in maximizing profit, especially when competition is high or in the case of limited supplies. Advances in information technologies have enabled the sharing and real-time processing of various pieces of information, e.g. customers' demands and competitors' strategies. With this development, dynamic pricing has become more attractive to apply.

Dynamic pricing affects customers demand by making flexible adjustments to price based on changing circumstances, such as demand and market conditions. One approach in dynamic pricing is to offer goods according to customers' willingness to pay. For example, a new product can be labelled with a high price to gain a high profit margin at the introductory stage, and then later have a price markdown in order to maintain revenue by increasing the sales volume. Another common application of dynamic pricing which is based on time of purchase is practised by airline companies.

The early development of dynamic pricing can be traced back to the research conducted by Gallego and van Ryzin (1994) where they present the structural properties of the optimal policies of dynamic pricing. They formulate an elegant model in which the vendor starts with a finite number of identical products in the inventory. Customers arrive according to a Poisson process, with independent, identically distributed reservation prices. In the case of exponentially distributed reservation prices, the optimal pricing strategy is easily derived. Gallego and van Ryzin (1994) conclude that with homogenous demand, at any given time the optimal price decreases as the inventory increases, and with any given initial inventory level, the optimal price increases over time. The above work has been further extended in studies by Bitran and Mondschein (1997), Zhao and Zheng (2000) and Chatwin (2000).

Petruzzi and Dada (1999) present a review of the newsvendor model with pricing policies. They investigate multiplicative, additive demand cases and present a unified framework for both. This study demonstrates how optimal policy varies when different demand uncertainties are introduced to the model. It also demonstrates that the profit function is unimodal and is determined by i) pricing, as well as ii) both pricing and order quantity. In this model, a high confidence in supply is assumed, and demand is realised after order quantity and pricing have been determined.

In the industries of today, the strategic, the tactical as well as the operational planning of an organisation is developed under various uncertainties. For example, in the case of new product introduction, the organisation has to determine resources' capacity and estimate the payoffs of investment in that capacity without knowing the actual demand for the new product. These issues, in which a firm evaluates profit based on i) price or ii) production quantity or iii) price and production quantity determined after demand is realised, are discussed by Van Mieghem and Dada (1999) in a very interesting way. Another extension of dynamic pricing is presented by Biller et al. (2005) who present dynamic pricing in association with production scheduling and inventory controls for non-perishable products. They demonstrate that dynamic pricing promotes market shares.

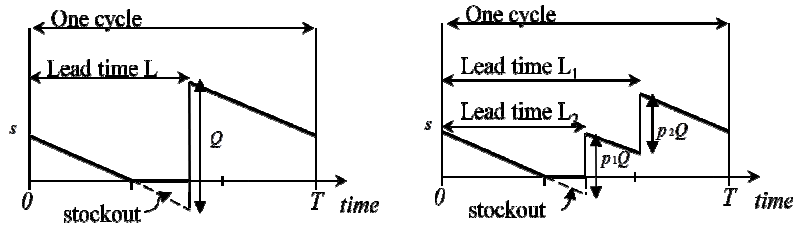
An extension of dynamic pricing in newsvendor policy in the case of yield risks is presented in this dissertation (see ***Paper 3***).

3.4. Sourcing policy

The role of sourcing has changed from being simply a tactical decision to becoming a strategic one. Sourcing policy is used as a guideline in decision making to ensure the success of procurement practises, which include finding, evaluating and engaging suppliers of goods and services. In order to develop a fully integrated supply chain, it is important to know the capabilities and activities of each member of the supply chain, such as the design aspect, process flows and data management. However, aligning its diverse components is a challenge, particularly as supply chain grows wider.

There is no simple sourcing policy that can fit everywhere. Instead, a policy is very much related to the specific situations, opportunities and intentions of the supply chain. Enarsson (2008) discusses the different needs and practises of sourcing. Single sourcing is preferable for it is easier to monitor and control. This strategy is particularly common in industries that require high confidentiality with their products and processes. However, with a single sourcing policy, the supplier has the upper hand, something which eventually could influence the price and operations of its buyer. Furthermore, the buyer is more exposed to the risk of supply shortages, especially within a global sourcing environment. Therefore multiple sourcing is preferable particularly when global sourcing involves high-risk countries, even though using redundant suppliers is against the principles of lean manufacturing.

In order to both minimize risk and control the production process, industries are now more prone to having a smaller supplier base, such as a dual sourcing policy. Dual sourcing requires a rigorous and boring process in supplier selection. It also limits customer/supplier relationships as suppliers' loyalty towards customers is reduced because they need to cater for greater numbers of customers. However, the benefits of dual sourcing overshadow these limitations. With dual sourcing, the supply chain gains supply reliability and benefits from a better price and quality due to supply redundancy and competition. Figure 7 shows the operational advantages of using dual sourcing. Assuming the same replenishment level (or reorder point s) and order quantity (Q) in both single sourcing and dual sourcing systems, we note that in the dual sourcing system, both the stockout and inventory holding can be reduced if two suppliers offer different lead times.



(i) Single sourcing (ii) Dual sourcing

Figure 7: Sourcing policy

Early literature on dual sourcing includes studies investigating the benefits of dual sourcing over sole sourcing under various conditions (Mohebbi and Posner, 1998; Ramasesh et al. 1991). Ramasesh et al. (1991) evaluate the sourcing policy by varying demand variability, shortage cost, holding cost ratio and ordering costs. They conclude that with the implementation of dual sourcing, savings increase as demand variability increases. Taking lost sales into consideration, Mohebbi and Posner (1998) investigate under which conditions sole and dual sourcing outperform each other. When both suppliers are equally reliable, dual sourcing is superior to sole sourcing especially in saving inventory holding costs.

Another group of literature focuses on finding the optimal order splitting strategy (Kelle and Miller, 2001; Lau and Zhao, 1993; Tang and Grubbström, 2005). Lau and Zhao (1993) investigate optimal splitting assuming a stochastic demand and lead time environment, while Kelle and Miller (2001) focus on constant demand and investigate the stockout risk with even and uneven order splitting in dual sourcing. Kelle and Miller conclude that the uneven splitting of order lowers the risk of stockout even in the case that one supplier is not reliable. The application of the dual sourcing splitting strategy is also found in the remanufacturing supply chain system (Tang and Grubbström, 2005).

Existing literature in dual sourcing focuses on uncertainties in demand, supply or lead time (Anupindi and Akella, 1993; Chopra et al. 2007). Assuming one supplier is more reliable than the other, Lu et al. (2011) study the optimal product substitution in case of disruption. In ***Paper 4*** of this dissertation (Musa et al., 2012), we investigate the benefits of dual sourcing when one of the supply chain members faces disruption. This study highlights the information flow and its impact on the dual sourcing policy.

3.5. Bass diffusion

The Bass diffusion model was developed by Frank Bass (Bass, 1969). It describes the process by which new products and services are adopted as an interaction between customers (existing users) and potential customers.

The model is built on the basic assumption that potential adopters of an innovative product are influenced by two types of communication: broadcast media and interpersonal channels. Individuals adopt a new product partly because of what they see or hear from mass media

advertising messages, while, in interpersonal channels, individuals adopt based on what they see or hear from earlier adopters. Bass specifies the probability of adoption as a linear function of the total potential market (m), the coefficient of innovation (p), and the coefficient of imitation (q). The diffusion at time t is described as:

$$d(t) = p\big(m - D(t)\big) + \frac{q}{m} D(t)\big(m - D(t)\big)$$

where $D(t)$ is the cumulative number of customers who have already adopted the product. Various extensions have been made to this model (Bass et al., 1994; Kamakura and Balasubramanian, 1987; Mahajan and Peterson, 1978).

One area of extension considers the effect of marketing variables. Kamakura and Balasubramanian (1987) find that the role of price seems to be heterogeneous across products. Meanwhile, Bass et al. (1994) include price and advertising to develop a Generalised Bass model to reflect the current marketing effort. A number of parameters of the Bass model can change over time due to factors such as the changing characteristics of the population, products, or economy. Another similar extension is by Mahajan and Peterson (1978), in which the authors formulate market potential as a function of time-varying exogenous and endogenous factors such as socioeconomic conditions, population changes, and government or marketing actions.

The classic Bass model includes only the first purchases, but market growth could also be due to the repeat purchases by the original buyers. Hahn et al. (1994) develop a four-segment trial-repeat purchase model in which the four segments comprise nontriers, triers, post-trial nonrepeaters, and post-trial repeaters. They find that word-of-mouth from earlier adopters and marketing efforts influence trial, and that product quality, marketing activity, and market familiarity influence the repeat rate.

Taking into account the supply restrictions, Jain et al. (1991) model the impact of capacity restrictions on the diffusion process. They model the customer flow from potential adopters to waiting applicants and from waiting applicants to adopters. Both Ho et al. (2002) and Kumar and Swaminathan (2003) allow some waiting applicants to abandon their adoption decisions to reflect supply and demand dynamics. However, in these studies, capacity is considered as constant and restricted, without the possibility of expansion.

In this dissertation, we include one paper investigating the capacity expansion policy and its risk when introducing new products. The Bass diffusion model provides a theoretical framework for model development (see ***Paper 5***).

3.6. System dynamics

Industrial dynamics studies behaviour and its impact on the interactions between various functional areas (Forrester, 1958). Towill (1996) later extends this approach to the supply chain systems where he claims that for an effective supply chain model, there are four essential inputs that need to be integrated: industrial engineering, control engineering, simulation and business re-engineering. Figure 8 illustrates the supply chain modelling

methodology which is developed based on the flow diagram in Towill (1996). An effective industrial dynamics model should be able to address a system's conceptual and technical problems (Figure 8).

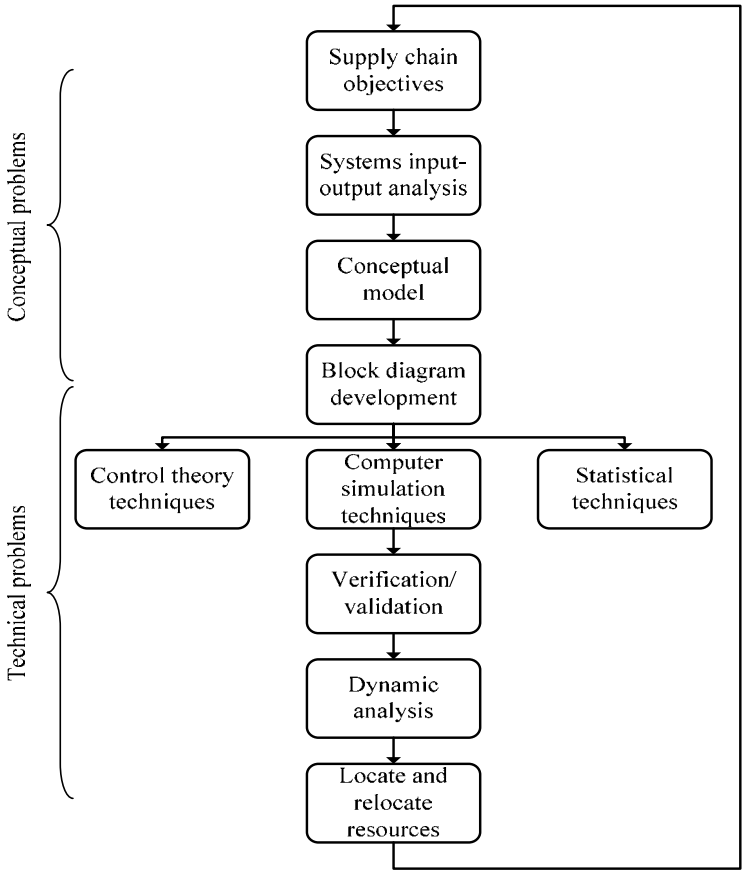


Figure 8: Supply chain modelling methodology (adapted from Towill, 1996)

When addressing this modelling process, Towill (1996) suggests applying systems-knowledge-based information to address conceptual problems (top part of Figure 8). In systems-knowledge modelling, it is important to analyse system input and output. This is usually presented by a causal loop diagram (Figure 9) or by a stock and rate diagram (Figure 10). Another alternative is to use a block diagram to link the conceptual and technical problems. A block diagram is a control theory approach which could be represented in either a time-domain (Figure 11) or a frequency domain (Figure 12). In the frequency domain, Laplace transform (or z-transform) technique can have the advantage of developing transfer functions for further analysis (Ogata, 1997).

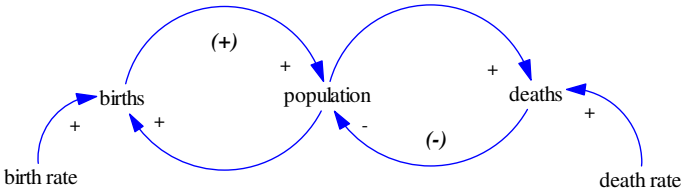


Figure 9: Causal loop diagram

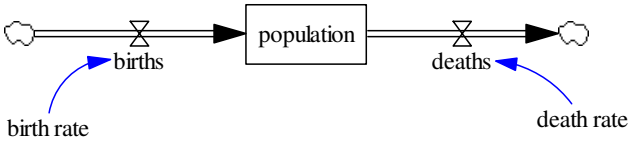


Figure 10: Stock and rate diagram

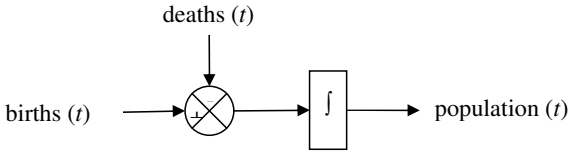


Figure 11: Block diagram in time domain

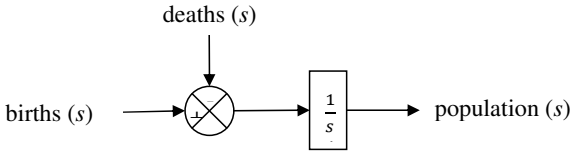


Figure 12: Block diagram in frequency domain

Figures 9-12 show that the level of population relies on the difference between the rate of births and the rate of deaths. The level of population will increase with an increase in birth rates. Meanwhile, as the level of the population increases, the number of deaths will increase and will eventually reduce the population size. The integral in the time domain can be substituted with the Laplace transform $\frac{1}{s}$ in the frequency domain as presented in Figure 12.

To further investigate the technical problems of the supply chain system, dynamic analysis should be conducted (Towill, 1996, Figure 8). The application of system dynamics modelling is renowned for its capability to address this type of analysis (Sterman, 2000).

The basis of a system dynamics lies in a system of coupled, nonlinear, differential (or integral) equations

$$\frac{d}{dt}\mathbf{x}(t) = f(\mathbf{x}, \mathbf{p})$$

where **x** is a vector of levels, **p** a set of parameters, and f a nonlinear vector-valued function (Ogata, 1997). Though the original development of system dynamics is based on continuous time, development has shown how system dynamics can be used on discrete difference equations combined with continuous differential equation or integral equations (Forrester, 1958; Sterman, 2000; Wilson, 2007).

System dynamics applies a feedback approach to understand the system structure and its impact upon performance behaviour. It has recently been successfully applied for analysing a supply chain and its inherent control policies. A typical example is to apply such a method to investigate the bullwhip effect in a supply chain (Croson and Donohue, 2006; Disney and Towill, 2005, 2006; Wang and Huang, 2010).

Most research into system dynamics application focuses on information flow (Fiala, 2005; Wikner et al., 1991; Wilson, 2007). However, a recent development has seen a combination of financial and information flows (De Marco et al., 2012). We refer to Sarimveis et al. (2008) for an extensive review on modelling techniques used in controlling the dynamics characteristics of supply chains. In this dissertation, we refer to ***Paper 4*** and ***Paper 5*** for a presentation of the system dynamics application.

4. Overview and Summary of Papers

"The learning process is something you can incite, literally incite, like a riot."~ Audre Lorde

4.1. Overview

As mentioned before, this dissertation consists of two parts. In ***Part I***, we present the background and an introduction to SCRM, as well as essential information about the approaches and methods used in this research field. In ***Part II***, the five individual (but connected) papers each answer one or more of the research questions presented in ***Part I***. In Figure 13, we show how these five papers are positioned according to their relationships to the research objectives and questions raised in Section 1. This figure also shows the links between research outputs and research approaches/methods used.

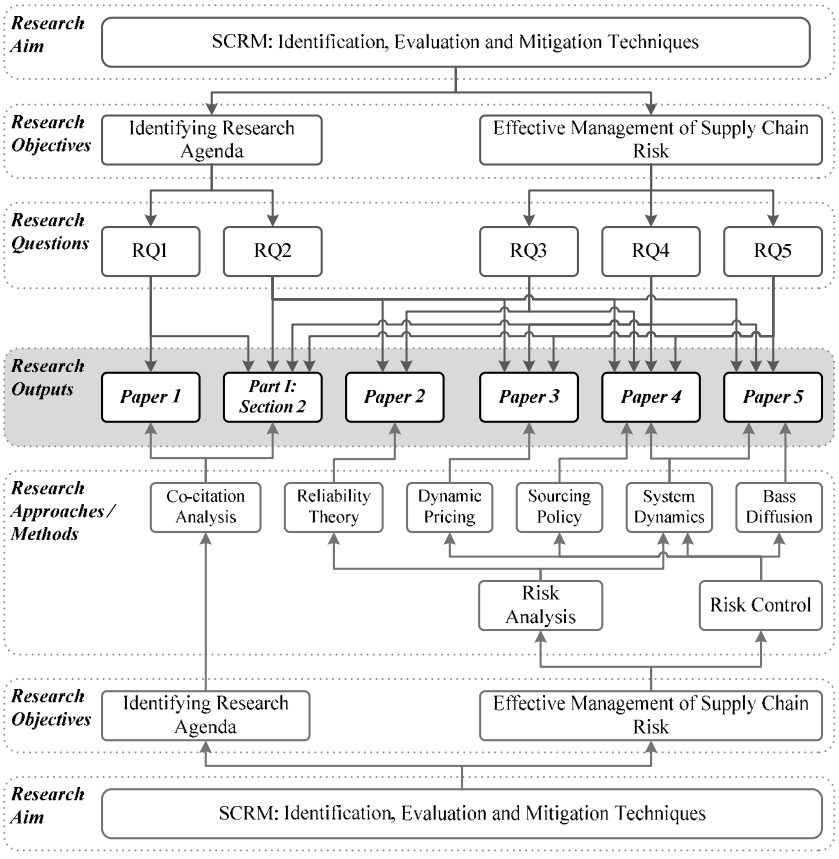


Figure 13: Positioning of the papers within the research objectives and research questions

We identify two research objectives in this dissertation. The first focuses on identifying the research agenda in SCRM. Under this objective we raised two questions. First we ask "*What risk issues should be considered in supply chain operations?*"; follow by "*How does a risk event affects supply chain operations?*".

For the first research question, ***RQ1***, we present our answer in ***Paper 1*** and Section 2 of Part I (henceforth we referred to as ***Section 2***). We first discuss several definitions and perceptions of risk in supply chains. In both, we define a risk as an event that has a low probability of occurrence, but which results in highly negative consequences to a system. There are two main types of risk that we consider; supply and demand mismatch, and unforeseen disruptive risk. Further, we present these risk issues from the perspective of major flows in supply chain; material, financial and information.

Our findings for the effect of risk event connection to supply chain operations (***RQ2***) can be found in ***Section 2***, ***Paper 2***, ***3***, ***4***, and ***5***. In ***Section 2***, where supply chain risk issues are presented, we show that one risk event may disrupt more than one node and/or flow in the supply chain. ***Paper 2*** discusses the importance of analysing risk from the holistic perspective of the supply chain, for any single incident affecting or changes made to the supply chain can easily affect the entire supply chain. In the other three papers we provide further evidence of various risk events affecting supply chain operations. ***Paper 4*** focuses on supply chain operations in the face of supply side risk, and investigates operational disruption. ***Paper 3*** and ***5*** on the other hand analyse supply chain operations on both supply and demand risk, and ***Paper 3*** focuses more specifically on random demand and random yield, while ***Paper 5*** investigates the correlation between capacity augmentations (supply) on new product diffusion (demand).

For the second research objective, we focus on the identification of effective management of supply chain risk. Under this objective three research questions are tabled; RQ3: *How can we analyse supply chain performance from a risk management viewpoint?*, RQ4: *What kind of mitigation policies should be used for managing risk in supply chains?* and RQ5: *What modelling techniques and approaches are possible in this research area?*

We answer ***RQ3*** in ***Paper 2*** and ***Paper 4***. In ***Paper 2*** we investigate the opportunities for analysing supply china risk using the readily available and commonly applied tools in product/process development, the reliability engineering tools. We analyse the suitability of adopting such tools from the perspective of assessing supply chain risk. In ***Paper 4***, we present a partial risk analysis process, the risk identification. With the application of system dynamics modelling, the adaptability of a supply chain to changes is monitored. According to this study, in order to reduce negative effects, it is important to monitor the performance of the entire supply chain to allow quick response in case of a risk event.

In ***RQ4*** and ***RQ5*** we raise the questions of what are the mitigation policies and what possible techniques in this area. In ***Section*** 2, we present various mitigation policies as well as techniques used in literatures. We identify the fact that there are many supply chain management policies that could be adopted in dealing with risk issues, from managing the

material flow, to managing the information flow and the financial flow. With regards to approaches, many existing research studies still focus on conceptual and qualitative models. We find there is a research gap in quantitative research especially in risk issues relating to supply chain information flow.

To further investigate ***RQ4***, in ***Papers 3***, ***4*** and ***5*** we present some selected mitigation policies. ***Paper 3*** uses pricing policy to deal with the risk of a mismatch between supply and demand. ***Paper 4*** investigates sourcing policy to face unforeseen disruptive risk. In ***Paper 5***, we investigate the information risk of forecasting demand and consequently risk of capacity expansion when new product is introduced into a market.

Papers 3, ***4*** and ***5*** also answer ***RQ5***. In ***Paper 3*** we use mathematical modelling on a newsvendor problem to investigate different pricing policies. Due to the complexity of the problem, we further develop the managerial insights by using numerical examples. In ***Paper 4*** and ***Paper 5*** we apply the system dynamics approach. In ***Paper 4***, a system dynamics model is built to illustrate a 3-echelon supply chain system. We investigate the complicated (non-linear) system behaviour in such a supply chain when it faces disruption. We use AnyLogic™ (XJ Technologies, 2011) simulation software which helps to enhance the integration and visual impact of complicated models. In ***Paper 5*** differential equations are used to show information flow, decision making and system dynamics. This paper also discusses the conditions for optimal control with regards to production and sales decisions. The studies in ***Papers 3***, ***4*** and ***5*** illustrate some mitigation policies and analysis tools for supply chains reacting to risk events, either from the supply side or from the demand side.

4.2. Summary of the contributions

In this section we summarise the contribution of each paper included in this dissertation.

Paper 1: Identifying risk issues and research advancements in supply chain risk management

Paper 1 presents a review of risk issues and supply chain risk management. A combination of a literature survey and co-citation analysis was conducted on journal articles published up to the year 2009. Issues in Supply Chain Risk Management are categorised according to the operations and flows of the supply chain.

This paper identifies the major risk issues investigated by fellow researchers and practitioners. From the co-citation analysis, we identify only a few distinct clusters in the early development of this field, from 1995 to 1999. The number of individual clusters increases over the next 5 years (2000-2004) and there is a shift towards more integrated clusters in the following 5 years (2005-2009).

To identify issues in supply chain risk management, we use co-citation analysis based on keywords. Over the three time segments that we have investigated, the research focus on performance is replaced by innovation, which later is replaced by management. This shows the shifting of interest in the research area from that of a separate issue of risk to an integrated viewpoint of managing risk in a system. We also identify the growing importance of

information issues in this field. However, there is relatively little research on risk mitigation concerning disruption in information flows.

This article has now been published in the International Journal of Production Economics, Vol. 133, pp. 25-34, 2011. An earlier version of this article entitled "Analysing Risk Flows in Supply Chains", was selected and presented as plenary paper in the 15th International Symposium on Inventories Research (ISIR) in Budapest, Hungary on 22nd till 26th August, 2008.

Paper 2: Assessing supply chain risk adopting reliability tools

Reliability engineering is a well known approach in addressing risk issues in systems development. The tools used in this approach have a long history and have shown to tackle the problem well. From a wide list of tools and approaches in reliability engineering risk analysis, we select five tools based on their commonality in the industries that show good potential for use in supply chain. With these selected tools, we evaluate their applicability and adopt them to managing supply chain risk. The application of these tools has also provided the interconnection between risk events and supply chain operations.

We identify the potential of FMEA to be used as a standalone tool for analysing risks in a supply chain as it can identify, estimate and evaluate risk events. However, FTA and AHP can complement each other, and a hybrid application of these two tools offers a less complicated process for analysing supply chain risk. FTA carries excellent criteria for identifying risk issues, while AHP's pairwise computational analysis has shown to be the best option for both risk estimation and evaluation. In short, this paper contributes alternatives for risk assessment in supply chain in a structured way.

An early draft of this paper was presented at the International Conference on Advances in Production Management Systems (APMS2010) which was held in Cernobbio, Lake Como, Italy between 11th and 13th October, 2010.

Paper 3: Dynamic pricing in the newsvendor problem with yield risks

Supply yield would affect a supply chain during the disruption event as well as during its recovery period. When this happens, a supply chain faces a potential loss of market and profit if the mismatch between supply and demand is not managed properly. This was what happened for many personal computer producers when their suppliers needed to operate at partial capacity during the Taiwan earthquake in 1999. In order to reduce the impact of supply shortage, Dell offered lower prices on products using alternatives memories, in order to redirect consumers' choice.

In this paper, the focus is on how uncertainties in supply can be manipulated with the application of a postponed and dynamic pricing policy in a newsvendor problem. There are three circumstances where dynamic pricing brings more economic benefits to the system: first, when the quantity delivered is fairly small compared with the ordered quantity; second, when demand side has a low uncertainty; and third, when there is a wide range in which demand is sensitive to price change. This article provides insights into when and how a dynamic pricing policy can be implemented for mitigating risk of supply yield.

The paper has been accepted for publication in the International Journal of Production Economics in 2011. It is currently available online (doi:10.1016/j.ijpe.2011.01.018).

Paper 4: Information Flow and Mitigation Strategy in a Supply Chain under Disruption
This paper investigates the effect of disruption in a supply chain where a dual-sourcing strategy is used. A system dynamics model is used to illustrate 3-echelon supply chain operations. Two inventory replenishment policies, APIOBPCS and APVIOBPCS, are investigated to identify which reacts better in a disruption event.

The impacts of disruption occurring at echelon 2 are visible throughout the 3-echelon supply chain network. APIOBPCS shows a lower variation of inventory levels. This model has also verified that the application of dual-sourcing causes less turbulence in the system. Reacting to the disruption by immediately transferring part of the order to its backup supplier further dampens the disruption impact. In order to react appropriately to the disruption event, extensive information sharing along the supply chain is necessary. This paper shows that system dynamics has the advantage of analysing supply chain disruption, even though the system needs to be modelled as a non-linear one.

An earlier version of this paper was presented at the International Conference on Production Research (ICPR 21), held between July 31st and August 4th, 2011 in Stuttgart, Germany.

During ICPR21, the author was selected as one of the ten recipients of Young Scientist Award (YSA). From among the papers selected for the award, this paper was chosen as Best Paper.

Paper 5: Capacity expansion policy and its risk in new product diffusion
Overinvestment in capacity often occurs when companies are introducing new products into markets. This reduces a company's profit, even if the new product can be well accepted by the customer with good profit margin. A fast and large capacity expansion can be caused by the diffusion speed of the product. Based on the Bass diffusion model, we analyse result from two principles of capacity augmentation: progressive expansion and lumping expansion. Decision for capacity expansion also relies on the four scenarios of colleting forecast information which consists of either one or of a combination of market demand, backlogs and sales information.

In the case of both capacity augmentation policies, this paper suggests relying on sales information. Using sales information creates a drift of the diffusion curve, and consequently, it reduces the pressure of overinvesting in capacity. It is also important to define the initial capacity level, which should ideally be near the level of initial demand in the market. In the worst case, with too low initial capacity, delaying sales and adding initial inventory can significantly improve the system performance, in particular when capacity expansion is based on a sales' forecast. This paper provides robust strategies for planning capacity, which is important for business success both from marketing and production perspectives, when a new product is introduced into the market.

4.3. Future research

As mentioned in Figure 1, Supply Chain Operations can be represented in two different ways, either by the flows of information, material and finances; or by its processes. In the current study, we focus mainly on the information flow aspect. Expanding the simulation model by taking into consideration other aspects of supply chain operations and the interaction of operations, would definitely be of interest for further investigation, since this would extend our understanding of risk issues.

Current investigations mainly focus on selected mitigation strategies, i.e. dual-sourcing, dynamic pricing and capacity expansion. It would be very interesting to investigate the impact of disruption on a supply chain by implementing different mitigation strategies on individual entities as well as comparing the robustness of different strategies under the same disruption signal (for example dual-sourcing vs. reinforced co-operation).

Current studies focus on the impact of disruption on the supply chain. An extension of studying the behaviour of entities in facing supply chain disruption would also be of great interest. One possible approach is to combine two simulation modelling approaches, the Agent Based Modelling to study entity behaviour and System Dynamics to represent system performance.

Validating the policies and approaches used with industrial data would provide insight from the practitioners' perspectives. Furthermore, it would be interesting to identify how effective the proposed mitigation strategies such as the SCRM approach introduced in Ericsson post supplier fire incident are to the company. Do they help to avoid risk issues in supply chain or are they just another *Band-Aid* solution? How effective are these to the entire supply chain, or does it require a high level of compromise from the upstream supply chain? These are still open questions for future investigation.

Nowadays, people have a higher awareness of environmental issues than previously. Industries have to accommodate this concern together with commodities and energy volatilities. These issues, together with a number of few other factors such as short product life cycles, have motivated research on risk issues in reverse manufacturing. Nevertheless, can be expected that risk issues in reverse manufacturing to be more complicated to manage for they involve more complicated flows and decisions.

Managing supply chain risks is a complicated task. This dissertation provides some answers to difficult questions and it provides some suggestions as to how a better and more robust supply chain could be designed and managed. We hope that the diversified modelling approaches and risk issues presented in this dissertation will enrich the literature and also stimulate future study in supply chain risk management.

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