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A Computer-Based Simulation Investigation of Environment-Strategy Fit for Risk Management in Global Supply Chains

Ila Manuj

To the Graduate Council:

I am submitting herewith a dissertation written by Ila Manuj entitled "A Computer-Based Simulation Investigation of Environment-Strategy Fit for Risk Management in Global Supply Chains." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Business Administration.

John T. Mentzer, Major Professor

We have read this dissertation and recommend its acceptance:

Theodore P. Stank, Terry L. Esper, Melissa R. Bowers

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Vice Provost and Dean of the
Graduate School

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A COMPUTER-BASED SIMULATION INVESTIGATION OF ENVIRONMENT-STRATEGY FIT FOR RISK MANAGEMENT IN GLOBAL SUPPLY CHAINS

A Dissertation
Presented for
Doctor of Philosophy Degree
The University of Tennessee

Ila Manuj
August 2007

DEDICATION

This dissertation is dedicated to my husband,
Manuj Naman

For giving me wings to fly and pursue my dreams.

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ABSTRACT

The purpose of this dissertation is to examine the phenomenon of risk management in global supply chains. Drawing from logistics, supply chain management, operations management, economics, international business, and strategy literatures and a qualitative study, a comprehensive conceptual model of environment-strategy fit for risk management in global supply chains was developed. External environmental conditions comprising of supply and demand risks, four risk management strategies, namely hedging, assuming, postponement, and speculation, and a moderator in the form of a port disruption were chosen for further investigation. The model was quantitatively tested using a simulation.

The findings from this dissertation study reflect mixed results. Findings that conform to existing research, primarily related to hedging and speculation strategies, provide empirical support for extant knowledge that is primarily conceptual or experience-based. On the other hand, findings that are contrary to existing knowledge or are supported under very select conditions, primarily related to assuming and postponement strategies, provide interesting new insights into the phenomenon. The findings add to both theoretical and practical understanding of the phenomenon. This research opens up several new research directions that indicate that continued research is needed to facilitate both theoretical and empirical progress in better understanding of risk management in global supply chains.

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CHAPTER I : DEFINING THE PROBLEM

INTRODUCTION

Global supply chains are a source of competitive advantage. The global configurations of firms provide benefits such as access to cheap labor and raw materials, subsidized financing opportunities, larger product markets, arbitrage opportunities, and other incentives offered by host governments to attract foreign capital (AlHashim 1980; Kogut and Kulatilaka 1994). These benefits are available to firms today because of unprecedented transnational mobility of capital, information, people, products, and services; tremendous leaps in information and communications technology; and increased opportunities and willingness of businesses to engage in e-commerce (Harland, Brenchley and Walker 2003). However, today's supply chains are becoming not only more efficient, but also riskier, due to the tight interconnectedness of numerous chain links that are prone to breakdowns, disruptions, bankruptcies, and disasters. Some events described below substantiate this observation:

> A dramatic cargo ship accident off the Alaskan coast in July 2006 highlighted that problems at sea can result in big losses for companies relying on the products on board. For Japanese automaker Mazda, this incident could mean the loss of nearly 4,800 cars and trucks headed for Canada and the United States. About half the cars on board are the compact Mazda3, which had a 16.4% sales jump in July. (Source: www.usatoday.com).

> The foot-and-mouth disease in the United Kingdom in 2001 not only affected the local agriculture industry but also regional and international industries. It affected luxury car manufacturers such as Volvo and Jaguar which had to stop deliveries due to lack of quality leather supply. It led to a reduced number of and expenditure by overseas visitors in the UK (Norrman and Jansson 2004; Thompson et al. 2002).

> On 21 September 1999, an earthquake of magnitude 7.6 struck Chichi, Taiwan with devastating consequences. Total industrial production losses were estimated as $1.2 billion. Twenty-eight semiconductor fabrication facilities accounting for an estimated 10 percent of world consumption lost significant quantities of work in progress. The world markets of memory chips reacted very fast to this news. The spot price of memory chips went up fivefold. Contract prices went up by 25 percent. This negatively affected Dell, Compaq, and IBM who had to revise earnings estimates for the last quarter of 1999 downward, in part, because of supply shortages made worse by the Taiwan earthquake (Papadakis 2003; Shameen and Healy 1999)

> Victor Fung describes a typical order for a supply chain managed by his Hong Kong-based company, Li & Fung. A European retailer ordered garments from his company. Decisions regarding styles and colors were not initially determined; however, anticipated demand was communicated up and down the chain. The firm purchased yarn in Korea. A supplier wove and dyed the fabric in Taiwan. Zippers, buttons, and the fabric were transferred to Thailand for sewing, and the garments were in the European retail outlets in five weeks from the start of production. The transaction is both financially and logistically complex involving over half a dozen countries and currencies (Magretta 1998).

The situations described above indicate that a firm operating globally is part of a complex supply chain that requires highly coordinated flows of goods, services, information, and cash within and across national boundaries (Mentzer 2001). Maximizing profits in a global environment includes sourcing from locations that offer the lowest total procurement cost, manufacturing and assembling products in least cost countries, and marketing in high potential demand centers (AlHashim 1980). As supply chains are restructured to operate on a global basis to take advantage of the international product, human resource, and capital markets, managers must address several concerns, including economic, political, logistical, competitive, cultural, and infrastructural challenges (Schmidt and Wilhelm 2000).

Economic challenges include such considerations as transfer prices, tax rates, duties, exchange rates, and inflation (Nelson and Toledano 1979). Infrastructural differences such as available modes; quantity, quality, and type of documentation; and the number and nature of intermediaries and facilitators (banks, warehouses, transport agencies, etc.) may require organizations to alter and/or reconsider strategies used in home countries. The infrastructural limitations in some developing economies may impose constraints on the efficiency of logistical systems (Mentzer and Samli 1981). The competitive environment, coupled with relatively high resource requirements, may create significant challenges in terms of customer service levels, anticipated costs, and desired profitability. Political factors such as stability of government, law and order, and sanctions have implications for supply chain structure and related costs. Many firms, however, do not understand inherent challenges involved in formulating and implementing global supply chain decisions. As Biederman (2006) puts it, "*It's been a rude awakening. The same strategic initiatives that have enabled thousands of companies to slash costs – outsourcing, single sourcing, lean inventories and just-in-time manufacturing – have introduced risk, Trojan-Horse style, into global supply chains on which those companies depend*."

Administering and managing a global supply chain also creates conflict between central management of the entire system and local management of each division of the total system (Nelson and Toledano 1979). In sum, global supply chains have greater uncertainties, and potentially more delay and disruption points, and hence the need for greater coordination, communication, and monitoring (Mentzer 2001), and most importantly, better risk management (Berger, Gerstenfeld and Zeng 2005; Jüttner, Peck and Christopher 2003; Spekman and Davis 2004).

IMPORTANCE OF RISK MANAGEMENT TO STAKEHOLDERS

There is wide acknowledgement in the literature of the risks and uncertainties in global supply chains (Norrman and Jansson 2004). The anecdotes presented earlier also point to the presence of greater risks in global supply chains as compared to domestic ones, and highlight the fact that managers are struggling to understand and manage the risk-benefit trade-offs. Although risk management in multinational enterprises was brought to the forefront in the mid 1980s and early 1990s (Baird and Thomas 1985; Baird and Thomas 1991; Ghoshal 1987; Kahneman and Tversky 1979; Kogut 1985; Lessard and Lightstone 1986; Miller 1992; Ogden et al. 2005), supply chain risk management was relegated to the background until recently when several researchers (Barry 2004; Cavinato 2004; Christopher and Lee 2004; Giunipero and Eltantawy 2004; Jüttner 2005; Manuj and Mentzer 2007a; Norrman and Jansson 2004; Spekman and Davis 2004; Swaminathan, Smith and Sadeh 1998; Zsidisin 2003b; Zsidisin et al. 2004) revived the interest in risk management, particularly in global supply chains. In fact, in the recent past, a leading logistics journal, *International Journal of Physical Distribution & Logistics Management*, devoted two special issues (2004, Vol. 34, Issue 5 and 2004, Vol. 34, Issue 9) to risk management in domestic and global supply chains. Similarly, *Production and Operations Management Journal* came out with a special issue on risk management (Spring 2005). Several leading conferences such as INFORMS have announced tracks or special sessions on risk management.

On the managerial front, there is a lack of knowledge on important issues related to supply chain risk management. Therefore, there is a need for investigating risk management in supply chains from the perspective of the practitioner community (Jüttner 2005). Chopra and Sodhi (2004) contend that most companies develop plans to protect against recurrent, low-impact risks in their supply chains. Many, however, ignore high-impact, low-likelihood risks. They suggest that by understanding the variety and interconnectedness of supply chain risks, managers can tailor balanced, effective risk-reduction strategies for their companies. Hauser (2003) suggests that in today's increasingly complex environment, risk adjusted supply chain management can translate into improved financial performance and competitive advantage.

On the shareholder front, results from the analytical study by Amit and Wernerfelt (1990) support the thesis that lowering business risk is valuable because, ceteris paribus, it allows firms to increase cash flows. Reduced risk enhances efficiency in that it allows for smooth production and low input costs. Furthermore, investors are willing to accept lower levels of return on stocks with lower business risks. Hendricks and Singhal (2005) investigated the effect of supply chain disruptions – many of them caused by the supply chain's inability to better manage and control supply chains – and found that these disruptions could seriously depress the financial performance of a firm for three years or longer. On the other hand, if managers are compensated solely on the basis of their firm's earnings, they prefer a stable earnings stream and may take a variety of risk reducing actions at the expense of shareholders. Therefore, managing risks is also of concern to stockholders.

In sum, identifying, understanding, and managing risks is of importance to researchers, practitioners, and stockholders.

FOUNDATIONAL RESEARCH AND RESEARCH GAPS

This section focuses on the past research that provides the foundation for this study. Recently, Manuj and Mentzer (2007a) combined the existing literature from supply chain and related disciplines to suggest a 5-step model for risk management and mitigation in global supply chains. It consists of the following steps:

Step 1: Risk Identification
Step 2: Risk Assessment and evaluation
Step 3: Selection of appropriate risk management strategies
Step 4: Implementation of supply chain risk management strategy(s)
Step 5: Mitigation of supply chain risks

For step 1, Manuj and Mentzer (2007a) classify risks in global supply chains into supply, operational, demand, and security risks. A review of the literature reveals that much research effort has been devoted to risk identification including identification of supply risks (e.g., Hallikas, Virolainen and Markku Tuominen 2002; Harland, Brenchley and Walker 2003; Zsidisin 2003b; Zsidisin and Ellram 2003), demand risks (e.g., Fisher 1997; Johnson and Anderson 2000; Jüttner, Peck and Christopher 2003; Svensson 2002; Wilding 1998), operational risks (e.g., Kogut 1985; Kogut and Kulatilaka 1994; Lessard and Lightstone 1986; Lewis 2003; Simons 1999), and security risks (e.g., Spekman and Davis 2004; Downey 2004).

For step 2, Manuj and Mentzer (2007a) provide an extensive review of risk assessment tools and frameworks for supply chains that can be divided into three broad categories: decision analysis (e.g., Berger, Gerstenfeld and Zeng 2004; Treleven and Schweikhart 1988), case-study (e.g. Harland, Brenchley and Walker 2003; Hauser 2003), and perception based (Simons 1999). Although appropriate for the specific use for which they are designed, adopting any one of the frameworks suggested above limits the scope of risk management in global supply chains.

Steps related to selecting and implementing strategies - steps 3 and 4 - have not been given enough attention, and step 5 on mitigating risks has been given limited attention in a global supply chain context. The key to risk mitigation is identifying the possible losses that may happen from an unexpected event. For example, if delivery issues are critical to a business, a risk mitigation plan should include identifying a back-up service provider, and developing a relationship with that provider to replace and/or pick up the capacity crunch caused by any unexpected event (Manuj and Mentzer 2007a).

However, as Jüttner, Peck, and Christopher (2003) suggest, the main emphasis in practice as well as research on supply chain risk management should shift from the current focus on minimizing detrimental effects through contingency planning and crises management, i.e., step 5, to a more proactive approach aimed at strategic management of risks. Several other researchers (e.g., Norrman and Jansson 2004) also assert that the link between risk and implications for supply chain management is poorly understood, and identify selection and implementation of risk management strategies, i.e., steps 3 and 4, as areas in need of further exploration. This dissertation primarily focuses on step 3 by delving deeper into selection of supply chain risk management strategies. It also identifies the factors critical to implementation of risk, and therefore, contributes to our understanding of step 4. Major research that provides the foundation for this research is compiled in Table I-1.

TABLE I-1: OVERVIEW OF FOUNDATIONAL RESEARCH

Study (Author and Year)	Focus of Research	Uncertainties and Risks Studied	Con-text	Risk Management Strategies Discussed	Conclusions and/or Gaps
Studies providing overarching framework for this research					
Jüttner, Peck, and Christopher (2003)	Outlining a future agenda for SC risk management	Environmental, Network, and Organization	SC	Avoidance, Control, Cooperation, and Flexibility	Suggest investigating risk-benefit trade-off and developing tools to support situation specific decision making
Ghoshal (1987)	Framework for developing global strategies	Macro, Policy, Resource, and Competitive	IB	Flexibility, and Diversification (Hedging)	Provides a framework for reviewing and analyzing strategies in an international business context
Miller (1992)	Integrated risk management in IB	Environmental, Industry, and Firm	IB	Avoidance, Control, Cooperation, Imitation, and Flexibility	Presents a review of uncertainties facing international business that serves as a foundation for this research
Lee (2002)	Aligning SC strategies with product uncertainties	Product	SC	Information Sharing, Coordination, Flexibility, Postponement	Provides a typology of supply chains that serve as a foundation for this research
Baird and Thomas (1985)	Contingency model of strategic risk taking	Environmental, Industry, and Organization	Org.	X	Provide a detailed discussion on important elements of strategic risk and process for risk assessment; make a plea for not ignoring risk just because it is too complex.

TABLE I-1. Continued.

Study (Author and Year)	Focus of Research	Uncertainties and Risks Studied	Con-text	Risk Management Strategies Discussed	Conclusions and/or Gaps
Jüttner (2005)	Practitioner perspective on risk management	Environmental, Supply, and Demand	Global SC	Sharing risks; Process and control mechanisms	Findings suggest that risks will increase, concept of supply chain risk management is in infancy, traditional approaches from a single company perspective are not suitable for a supply chain
Examples of research focusing on specific risks					
Zsidisin (2003a and b); Zsidisin et al. (2004);	Perception and assessment of supply risks	Supply	SC	X	Discussion on factors affecting supply risks, risk assessment techniques, and definition of supply risk
Birou and Fawcett (1993)	Overview of international sourcing	Supply	Global SC	X	Survey-based review of benefits, requirements, and challenges to international sourcing
Fisher (1997)	Matching supply chain type with product	Demand	SC	X	Efficient supply chain for functional products, and responsive supply chain for innovative products
Agrawal and Seshadri (2002)	Risk intermediation	Demand	SC	Sharing risks	Suggest reducing financial risks faced by suppliers using a menu of contracts

TABLE I-1. Continued.

Study (Author and Year)	Focus of Research	Uncertainties and Risks Studied	Con-text	Risk Management Strategies Discussed	Conclusions and/or Gaps
Kogut and Kulatilaka (1994)	Global operational flexibility	Operations	IB	Hedging	Suggest building a global network of facilities to shield against wage rate and exchange rate fluctuations
Simons (1999)	Directional evaluation of risk of a company	Internal corporate risk	Org.	Communication, Monitoring Systems, Interactive control systems	Calculating risk exposure because of growth, culture, and information systems
Amit and Wernerfelt (1990)	Motivations for reducing business risk	Business risk	Org.	X	Identification of stock-holder interest in business risk
Spekman and Davis (2002)	Security risks related to flow of goods, information, and money	Security, opportunistic behavior, and corporate social responsibility	Global SC	Better partner selection and building trust	Underline the importance of risk management across the global supply chain

Key: IB: International Business; SC: Supply Chain; Org.: Organization

UNCERTAINTIES IN GLOBAL SUPPLY CHAINS

Uncertainties are sources of risk (Jüttner 2003). Miller (1992) divides uncertainties facing international businesses into environmental, industry, and organizational or firm uncertainties. Environmental uncertainties include political, government policy, macroeconomic, social, and natural uncertainties. Industry uncertainties include input market uncertainties, product market, and competitive uncertainties. Firm uncertainties include operating, liability, R&D, credit, and behavior uncertainties. Adapting Miller's classification to a supply chain context, the uncertainties are divided into environmental and supply chain related uncertainties.

Environmental uncertainties affect businesses across industries (Miller 1992) and include components of government policy and macroeconomic uncertainties (Ghoshal 1987). Supply chain uncertainties include input market and supply, product market and demand, operational, competitive, and behavioral uncertainties. Input market and supply uncertainties refer to uncertainties surrounding the acquisition of adequate quantities and qualities of inputs into the production process (Miller 1992) at expected costs and in expected time. Product market and demand uncertainties refer to changes in or an inability to meet demand for a supply chain's output. Operational uncertainties refer to firm-specific factors such as labor and production uncertainties that can arise due to labor unrest, employee safety, and machine failures, and confused lines of responsibility(Kogut and Kulatilaka 1994; Lessard and Lightstone 1986). Competitive uncertainty refers to inability to predict the amount and type of goods available in the market (Miller 1992), and lack of history about competitor activities and moves (Ghoshal 1987). Behavioral uncertainty refers to a manager's or an employee's propensity to act in their own self interest to maximize their wealth at the expense of the firm (Williamson 1985; Williamson 1979).

Often the terms uncertainty and risk are used interchangeably. However, uncertainty, although closely related to risk, is different. Uncertainty is the perceived inability to predict something accurately, and risk is the distribution of the outcomes that result because of uncertainties. Uncertainties are sources of risks (Miller 1992; Jüttner 2003), i.e., risks exist because of uncertainty in the environment and the supply chain.

RISKS IN GLOBAL SUPPLY CHAINS

Reflecting the different and often conflicting objectives of functions and firms within supply chains, and because of industry-related differences, several conceptualizations of risk exist in the literature. The finance literature looks at risk primarily in terms of probabilities of expected outcomes; variability of returns on a portfolio of investments; or risk of default, bankruptcy, and/or ruin (Beaver 1966). In the strategy literature, risk has been defined by using risk adjusted rates of return on capital investment (Christensen and Montgomery 1981), variability of expected and actual returns (Bettis 1981), risks of strategic actions such as doing business with incompetent partners, and relational risks such as opportunistic behavior like cheating, distorting information, and/or partner firms stealing customers (Baird and Thomas 1985; Bettis and Mahajan 1985). Marketing looks at risk in terms of customer behavior and is primarily concerned with the nature and importance of buying goals and failure in meeting psychological or performance goals (Cox 1967). Management and psychology literature dealing with managerial preferences explores the link between individual disposition to risk, probabilities of outcomes, and the expected outcome values. In a supply chain context, Harland, Brenchley, and Walker (2003) define risk as a chance of danger, damage, loss, injury, or any other undesired consequences. However, no definition of supply chain risk has been offered so far. The following excerpt from Sykes (2006) illustrates:

> *"Ask an insurance professional to define risk, and he'll characterize it as a condition of the real world in which there is a possibility of loss. In insurance professionals' lingo, the term "risk" is also used as a noun to refer to physical property to be protected by an insurance contract, or to refer to an entity (an individual or a company) for whom or which an insurance contract is written.*
>
> *Ask a financial or investment advisor to define risk, and you'll be given a litany of risk categories to define and understand risk and risk management. At the highest level, all types of risk can be divided into two categories – systemic and unsystemic risk...*
>
> ***Ask a supply chain professional to define risk…and you will either get a layman's twist on the above two risk definitions, or you will get a disoriented, blank stare.*** *The subject of supply chain risk is coming to the forefront of our profession today, and it has not adopted the mathematical and statistically-driven methods of our professional counterparts in the fields of finance and trade."*

The complicated nature of the supply chain makes it difficult for supply chain practitioners and scholars to define risk. A supply chain is defined as "*the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole*" (Mentzer 2001). The one thing common to all definitions of risk is the variability of outcomes of interest. Therefore, as a working definition, ***risk is defined as the distribution of performance outcomes.***

Because of the broad scope of a supply chain, uncertainties and risks can exist in so many different functions and firms that it is often not possible to come up with a definition of risk that captures all dimensions of risks in a supply chain. A definition of risk that incorporates the complex nature of global supply chain is still a research gap. **An objective of this dissertation is to provide a definition of risk in a supply chain context.** A new definition of risk more appropriate to a global supply chain context is developed and presented in Chapter II. Meanwhile, the working definition provided above is adopted.

RISK MANAGEMENT IN GLOBAL SUPPLY CHAINS

Managing supply chain risks is more difficult than managing organizational or functional risks because apart from focusing on risks within an organization or function, global supply chain managers must focus on risks to the various links in their supply chain (Souter 2000). Since companies in a supply chain are interdependent, individual risks in supply chains are often interconnected, and as a result, actions that mitigate one risk can end up exacerbating another (Chopra and Sodhi 2004). Not surprisingly, a study by Bradford (2003) indicated that more than one-third of the finance executives and risk managers surveyed do not feel that they are adequately prepared for disruptions to their business. Ghoshal (1987) recognized risk management as one of the goals of organizations operating globally. He stated that the strategic task of managing globally is to use three sources of competitive advantage – namely national differences, scale economies, and scope economies to – to optimize efficiency, risk, and learning in a world-wide business. With the increasing fragmentation of supply chains and mounting dynamism of global environment, an even more explicit assessment and management of risks in the supply chain is warranted.

Several definitions of risk management in a supply chain context have been offered. Hauser (2003) states that supply chain risk management means keeping an increasingly complex process moving efficiently at the lowest total cost and without compromising the quality of the product or customer satisfaction. Put simply, supply chain risk management is focused on identifying and assessing the probabilities and consequences of risks, and selecting appropriate risk strategies to reduce the probability of, or losses associated with, adverse events.

A definition by Jüttner (2005) and Jüttner, Peck and Christopher (2003), that combines the major elements of risk management definitions discussed above, is adopted as a working definition. They define supply chain risk management as, ***"the identification of potential sources of risk and implementation of appropriate strategies through a coordinated approach among supply chain members, to reduce supply chain vulnerability."*** Here, supply chain vulnerability is defined as an exposure to serious disturbance arising from supply chain risks affecting the supply chain's ability to effectively serve the end customer market (Jüttner 2005; Jüttner, Peck and Christopher 2003).

A definition of risk management that incorporates the complex nature of global supply chain is still a research gap. **An objective of this dissertation is to provide a definition of risk management in a supply chain context.** A new definition more appropriate to a global supply chain context is developed and presented in Chapter II. Meanwhile, the working definition provided above is adopted.

RISK MANAGEMENT STRATEGIES IN GLOBAL SUPPLY CHAINS

Eleven broad supply chain risk management strategies have been identified after an extensive cross-disciplinary literature review: avoidance, control, cooperation, imitation, flexibility, hedging, assuming, postponement, speculation, sharing and transferring, and security (Agrawal and Seshadri 2000; Bucklin 1965; Cachon 2004; Downey 2004; Jüttner, Peck and Christopher 2003; Miller 1992). Since there are multiple interpretations of risk, Pablo (1999) advises that care and attention should be given to the context in which the variable “risk” is used as it affects the meaning of risk management for a manager. Therefore, appropriate strategies are contextual and should be structured based on the characteristics of the situation in question. This entails recognizing the factors motivating the choice of a particular strategy and determining appropriate strategies for a given situation. To this end, Jüttner, Peck and Christopher (2003) suggest investigating risk management in different supply chains and industries, and developing relevant strategies based on industries and environments facing supply chains as a direction for future research.

Rephrasing Ghoshal (1987), global strategies aimed at optimizing any one of three – efficiency, learning, or risk – may compromise the others. Therefore, a supply chain manager's task is to build a multidimensional and adaptable strategy that is robust to different assumptions in global environments. **Investigation of supply chain risk management strategies in terms of which strategy works best under certain environmental conditions is a major research gap, and is the main focus of this dissertation.** A model of environment-strategy fit for risk management in global supply chains is developed and presented in Chapter II.

RESEARCH PURPOSE

In light of call for more research on supply chain risk management, importance of the topic to both theory and practice, and some research gaps discussed in the preceding sections, this research focuses on the selection of appropriate risk management strategies based on the environment faced by a supply chain. Accordingly, the research objectives for this dissertation are to (a) define risk and risk management in a supply chain context, (b) build a theory of environment-strategy fit for risk management in the global supply chain, and (c) test the theory. To achieve these objectives, the questions that drove this research are:

1. What do supply chain managers mean by risks?
2. What strategies do managers with responsibilities for making or executing global supply chain decisions use to manage risks?

3. What factors facilitate or hinder the process of risk management in global supply chains?
4. How does performance of global supply chains vary under different combinations of environmental conditions and the strategy selected?

ORGANIZATION OF THE DISSERTATION

This dissertation is organized in five parts. Following the introduction in Chapter I, Chapter II describes the steps in building the theory. It begins with an initial literature review to provide theoretical sensitivity to the researcher for execution of qualitative study and data collection from the field (Maxwell 1996; Strauss and Corbin 1998). The initial literature review explores existing research on risk and risk management in supply chains. Next, the research design for qualitative study and findings from the qualitative study are presented. Next, an overall conceptual model of environment-strategy fit for risk management in global supply chains is presented based on initial literature review, qualitative study, and additional literature review. The additional literature review acts as supplementary data source to provide further evidence for the theory that emerged from the qualitative study (Glaser and Strauss 1967; Strauss and Corbin 1998). Finally, the part of the comprehensive model that was tested in this research is presented and discussed along with a set of hypotheses.

Chapter III presents the methodology used to test the model developed in Chapter II. The model was tested using computer-based simulation modeling. First, the justification for use of simulation modeling is provided. Next, an eight-step process used for developing the simulation model for this research is presented. Execution of each step for this study and all other aspects of the model including assumptions, independent and dependent variables, and sources of data are described in detail.

This dissertation follows the two-paper format. Chapter IV is the first paper and Chapter V is the second paper.

The first paper presented in Chapter IV is titled, "Improving the Rigor of Discrete-Event Simulation in Logistics and Supply Chain Research." A review of literature reveals that much of the published simulation research in logistics and supply chain journals does not incorporate and/or report the measures taken to maintain the rigor of the study. Part of the reason may be that unlike other methods used in logistics research, such as structural equation modeling, there is no set standard for design, implementation, and evaluation of simulation studies in logistics and supply chain journals. This paper addresses this gap by identifying an eight-step simulation methodology referred to as the Simulation Model Development Process (SMDP). The SMDP is illustrated using the simulation study for this dissertation. The SMDP can be used by researchers to design and execute rigorous simulation research, by reviewers for academic journals to establish the level of rigor when reviewing simulation research, and by practitioners to answer logistics and supply chain system questions.

The second paper is titled, "Investigating the impact of risk management strategies on the performance of global supply chains using computer simulation." This paper presents the results from the simulation study developed for this dissertation. The objective of this paper is to shed light on the impact of risk management strategies on the performance of global supply chains. Four risk management strategies are simulated and the impact of these strategies on performance of global supply chains is measured without-disruption and with-disruption. Risk events such as fluctuations in currency and wage rates, port clearance times, transportation lead times and variability, supplier order processing time and variability, price increases, quality issues, and demand variability are incorporated in the model.

CHAPTER II : BUILDING THE THEORY

INTRODUCTION

> *"On paper it looks like a great return on investment without the risk issue. With the risk, who knows?"*
>
> - Former senior vice president for global outsourcing and supply chain management operations of a leading manufacturing firm.

As the above quote reflects, with the consistent increase in off-shoring (i.e., sourcing raw materials and components from across borders), and international marketing (i.e., marketing products abroad through exporting, licensing, franchising, joint ventures, or wholly owned subsidiaries), managing risk in the supply chain has come to the forefront. Most firms are under extreme pressure to reduce cost to become increasingly efficient and competitive. Today, off-shoring and international marketing are seen more than ever as prime competitive strategies.

In contrast, the interviews conducted for this research revealed that there is reluctance among middle line managers to enthusiastically embrace these global initiatives. There is an intuitive feeling that one is losing control, and taking on risks that are not fully understood. Also, there is the sentiment that global initiatives conflict with other proven concepts like the Lean and Six Sigma tools that have been sweeping across industries and are based on reducing average cycle times and variability. In a nutshell, the dilemma faced by management is how to balance all these factors with risks, and make the best decision for the future health and survival of the firm.

As discussed in Chapter I, there is limited research on the topic within supply chain management and related fields. Therefore, both observations of the phenomenon in practice as well as a literature review were used in the development of the theoretical model. This chapter provides a review of the literature from which the justification for the constructs in the global supply chain risk management strategy model was developed. This is supported and enriched with the qualitative research to obtain detailed information on the constructs of interest in practice. The literature review is an integrative investigation of the following disciplines: **logistics, supply chain management, operations management**, **economics, international business, and strategy.**

To restate, the objectives for this dissertation are to (a) define risk and risk management in a supply chain context, (b) build a theory of environment-strategy fit for risk management in global supply chains, and (c) test the theory. This chapter deals with the first two research objectives. The first three research questions identified in Chapter I drive the literature review, qualitative research, and theory building described in this chapter. These research questions are: what do supply chain managers mean by risks, what strategies do managers with responsibilities for making or executing global supply chain decisions use to manage risks, and what factors facilitate or hinder the process of risk management in global supply chains?

The chapter is organized as follows. First, the literature review is presented that led to the identification of major gaps in the body of knowledge. To address these gaps, a qualitative study was undertaken. The next section presents the design and findings of this qualitative study. Thereafter, a comprehensive model of environment-strategy fit for risk management in global supply chains is presented based on literature review, qualitative study, and additional literature review undertaken after qualitative study. Finally, part of this comprehensive model that will be tested in the dissertation is presented and hypotheses are systematically developed.

LITERATURE REVIEW

Investigation of the interrelationships among the principle concepts of uncertainties, risks, risk management, risk management strategies, and global supply chains drove the literature review. Many disciplines are involved in risk research; hence all of these different disciplines were consulted to obtain a comprehensive a picture of the concepts. The logistics and supply chain management and international business literature describe the different types of uncertainties and risks faced by and risk management strategies used in global supply chains. Operations management literature provides insights into different ways of assessing risks and into the complexity of designing global supply chains. Economics and international business literature provide the basis for research in risk management strategies for global supply chains and the application of TCE to an international context. Finally, strategy research provides the theoretical rationale for matching strategies to the environment.

THEORETICAL FOUNDATIONS

Much of the existing research related to risk management in global supply chains is normative, and primarily based on insights from case studies. There is no accepted theory or framework providing the backdrop on which to base the theory of supply chain risk management. However, two frameworks, Transaction Cost Economics and Political Economy Paradigm have been used in past studies to address phenomena in global supply chains. Although limitations exist in terms of extent of applicability of these paradigms to risk management, they provide the preliminary basis to begin to build a theory of risk management in global supply chains. The following discussion briefly describes the two frameworks, their applications in global contexts, and their limitations.

Transaction Cost Economics

Transaction Cost Economics (TCE) is an economic approach that looks at decision making in terms of choosing the option that minimizes the sum of transaction and production costs. It deals with behavioral and environmental uncertainties, and therefore, provides an appropriate starting point for understanding how uncertainties in the global environment create higher transaction costs and impact economic decisions. TCE assumes that buyers use price as a primary criterion for their purchase decisions. Therefore, the decision to engage in market exchange or vertical integration depends upon the sum of production and transaction costs associated with each option (Klein, Frazier and Roth 1990).

Transaction costs stem from the interaction of a set of dimensions of transactions (asset specificity, degree of uncertainty/complexity surrounding the transaction, and frequency of transaction occurrence), and human factors (bounded rationality and opportunism) (Williamson 1985).

Asset specificity is the degree of investments made in support of particular transactions that cannot be redeployed to other uses. Requirements for specific assets may take the form of physical asset specificity, site specificity, human asset specificity, and dedicated asset specificity. The significance of the asset specificity dimension for transaction costs lies in the fact that both parties (the "buyer" and the "seller") are bound together to some degree. Uncertainty refers to the situation in which the circumstances surrounding an exchange cannot be determined *ex ante*. Uncertainty can occur due to environmental factors such as the inability to specify all dimensions of an exchange *ex ante*, and behavioral factors such as opportunism or difficulty is verifying whether compliance with established agreements has occurred.

Under the assumption of bounded rationality, decision makers have a constraint on their cognitive capabilities and limits on their rationality. Under the assumption of opportunism, there is a possibility that decision makers may unscrupulously seek to serve their self-interests and it is difficult to know *a priori* who is trustworthy and who is not.

Because of behavioral assumptions of bounded rationality and opportunism, transaction costs assume increased significance in the issue of structuring economic activities. Asset specificity facilitates expectations of continued exchange into the future (Heide and John 1990) and represent credible commitments to the relationship that are useful in safeguarding against opportunistic behavior (Anderson and Weitz 1992; Williamson 1985). Uncertainty creates the need for firms to be adaptable (Heide 1994). The higher the need for safeguards and adaptability, the higher the transaction costs, and the more likely firms will move away from arm's length market exchange toward integrated relationships (Heide and John 1988).

Although the instances of application of TCE to global supply chain decisions are mostly limited to choice of modes for foreign market entry decisions (Balakrishnan and Wernerfelt 1986; Dwyer and Welsh 1985; Klein 1991; Walker and Weber 1984), recent efforts have been directed at using TCE to understand phenomena in global supply chains including risk management. For example, Gereffi, Humphrey and Sturgeon (2005) study the governance of global supply chains based on TCE and suggest that variables affecting governance include the complexity of transactions, the ability to codify transactions, and the capabilities in the supply base. Fehle and Tsyplakov (2005) show that the structure of transaction costs can have an important effect on the firm's risk management strategy in terms of the extent of risk management. Total Cost of Ownership (TCO) is a concept in strategic cost management decisions and has its foundations in the TCE (Ellram and Siferd 1998). TCO has been argued to be a useful concept to be applied in global settings as it includes all types of costs including duties, and taxes that are more relevant to global settings (Cirimele 2003).

Although TCE has not been directly applied to study risk management strategies in global supply chains, successful applications of the framework in similar contexts suggest that TCE is a promising framework for this research. From TCE perspective, outcome uncertainty is associated with the variability of outcomes, lack of knowledge about the distribution of potential outcomes, and uncontrollability of outcome attainment.

However, limitations of TCE in explaining global supply chain phenomena have also come into notice. First, apart from economic aspects, the task environment and the socio-political system surrounding the supply chain have increasingly become party to economic decisions in international business; thus, rendering TCE inadequate. For example, Cavusgil, Deligonul and Zhang (2004) found that the relationship between formal contracts (prescribed as a governance tool by TCE), and opportunism was probably moderated by the legal environment. Second, TCE does not recognize factors like product and industry characteristics, and competition that may play a vital role in determining supply chain risk management strategies. Third, although TCE incorporates behavioral and environmental uncertainties, it does not explicitly consider supply chain risks which are the outcomes of these and other uncertainties.

Political Economy Paradigm

Political Economy Paradigm (PEP) addresses some of these limitations of the TCE framework. PEP views a social system as comprising of interacting sets of major economic and sociopolitical forces that affect collective behavior and performance. Therefore, it supplements the TCE framework and can potentially provide valuable insights into the phenomenon of risk management for a supply chain. The political economy framework is comprised of two major systems (Stern and Reve 1980): the internal political economy and the external political economy. The internal economy consists of the internal economic distribution structure processes. The internal polity consists of the internal sociopolitical structure and processes. The external economy is the nature of vertical/horizontal markets and external polity is the sociopolitical system, i.e., use of power by external actors.

Subsequent studies based on the framework in marketing channels have focused on the impact of environmental variables such as environment type (Achrol, Reve and Stern 1983), and uncertainty and dependence constraints (Dwyer and Welsh 1985). Many researchers have explored the PEP and added dimensions to it such as environmental variability (Achrol, Reve and Stern 1983; Klein 1991), environmental uncertainty about information (Walker and Weber 1984), environmental volatility and diversity (Dwyer and Welsh 1985), institutional environment like regulatory, normative and cognitive institutions (Kale and McIntyre 1991), and legal environment (Anderson and Coughlan 1987).

In terms of global supply chain decisions other than foreign market entry decisions, PEP has not been explicitly used. However, all research related to global supply chains has indicated the presence of complex and interacting domestic and global environments that are governed by different economic, physical, cultural, demographic, psychological, political, and technological forces (e.g., Biederman 2006; Ghoshal 1987; Jüttner, Peck and Christopher 2003; Manuj and Mentzer 2007a; Zsidisin et al. 2004).

The strength of the TCE and PEP frameworks that makes it appropriate to the current research is the acknowledgement that forces such as the external economy, i.e., the prevailing and prospective economic environment, and the external polity, i.e., the external sociopolitical system in which an entity operates, need to be incorporated to provide a more comprehensive view of a global supply chains decisions and strategies. Second, these frameworks also guided the literature review by providing an understanding of things to be considered when developing a theory of risk management in global supply chains.

UNCERTAINTIES IN GLOBAL SUPPLY CHAINS

Uncertainty is the inability to predict something accurately, and consists of state uncertainty, effect uncertainty, and response uncertainty (Milliken 1987). State uncertainty is the inability to predict the organizational environment or a component of the environment. Effect uncertainty is an inability to predict the effect on the organization of a change in the environment or a future state of the environment. Response uncertainty is the lack of knowledge of response options and/or an inability to predict the likely consequences of a response choice.

Ghoshal (1987) identifies uncertainties (he calls them risks) faced by the multi-national corporations as: (a) macroeconomic uncertainties associated with significant economic shifts in wage rates, interest rates, exchange rates, and prices; (b) policy uncertainties associated with unexpected actions of national governments; (c) competitive uncertainties associated with uncertainty about competitor activities in foreign markets; and (d) resource uncertainties associated with unanticipated differences in resource requirements in foreign markets.

Schmidt and Wilhelm (2000) discuss the uncertainties at strategic, tactical and operational levels in global supply chains. They argue that strategic level decisions entail a relatively high level of uncertainty because such decisions typically involve a relatively lengthy planning horizon, and therefore, lack information to specify all parameters such as demand, political environment, and exchange rates with certainty. Discussing the tactical level, they say that although near term parameters may be known with certainty, later periods in the tactical horizon may be subject to some degree of uncertainty. Besides, they point out that the tactical level is limited by the network made available by the strategic-level decisions. Finally, at the operational level, the main focus is on where and when to assemble components to minimize the time interval from order arrival to order delivery at the customer site, given the constraints imposed by strategic and tactical levels. Therefore, the operational level faces the lowest uncertainty.

Jüttner, Peck and Christopher (2003) label uncertainties as sources of risk. They divide uncertainties into environmental, network-related, and organizational uncertainties. Environmental risk sources comprise uncertainties arising from the interaction of the supply chain with elements of its environment such as accidents, socio-political events, and acts of God. Organizational risk sources lie within the boundaries of the supply chain parties and include uncertainties from labor, production, and IT systems. Network-related risk sources arise from suboptimal interaction between organizations within the supply chain. In a later article, Jüttner (2005) identified four types of uncertainties and classified environment, demand and supply related uncertainties as sources of risk, and process and control uncertainties as amplifiers or absorbers of risks.

Miller (1992) developed a detailed typology of uncertainties facing global organizations. He divided them into environmental, industry, and organizational or firm uncertainties. Environmental uncertainties include political, government policy, macroeconomic, social, and natural uncertainties. Industry uncertainties include input market uncertainties, product market, and competitive uncertainties. Firm uncertainties include operating, liability, R&D, credit, and behavior uncertainties. This research adopts and builds upon Miller's typology for its multidimensional treatment of uncertainty, inclusion of other classifications, and ready adaptability for application to a global supply chain context. Adapting Miller's typology, uncertainties are divided into environmental and supply chain uncertainties.

Environmental uncertainties

Environmental uncertainties affect businesses across industries (Miller 1992) and include components of government, policy, and macroeconomic uncertainties as identified by Ghoshal (1987). Policy and macroeconomic changes may lead to fundamental shifts in comparative advantages of countries, and therefore, give rise to uncertainty over competitive advantages (Kogut 1985). The basic premise of comparative advantage based competitive advantage is that a firm gains cost advantages by configuring its value-chain so that each activity is located in the country which has the least cost for the factor that the activity uses the most intensely (Ghoshal 1987).

However, for any nation, the availability and cost of factors of production change over time. This is particularly important because global supply chain decisions are often based on wage rate advantages, tax benefits and other financial inducements offered by the governments, exchange rates, trade regulations and import duties, and relative prices (Cho and Kang 2001). Nelson and Toledano (1979) contend that dynamic dimensions of the international environment such as transfer prices, tax rates, duties, exchange rates and inflation have a bearing on the design of a multi-national logistics system. Similarly, capacity planning, i.e., location and capacity of productive facilities in a global supply chain, is often driven by government and policy variables. However, all of these are likely to change, some in the long run as the social and economic performance of nations change, and some in the short run in response to specific policies and regulations of governments.

The other group of uncertainties that has, in recent times, attracted the attention of practitioners and scholars alike are natural disasters. Although until recently natural disasters were thought to be more momentous to the agricultural sector, several recent events such as SARS, bird-flu, the Taiwanese earthquake, and hurricanes Katrina and Rita have demonstrated that such events can impair numerous business functions, disrupt supply chains, and severely affect the profitability of organizations across the supply chains.

Supply Chain Uncertainties (Industry and Firm Uncertainties)

On examining the definition of supply chain stated earlier, it can be inferred that a supply chain is composed of several firms that may belong to and serve multiple industries. Hence, one firm in a supply chain may be subject to idiosyncrasies of numerous industries. Therefore, firm and industry uncertainties are combined and named as supply chain uncertainties. Adapting the classification by Miller (1992) to a supply chain context, uncertainties are divided into: input market and supply, operational, product market and demand, competitive, and behavioral uncertainties.

Supply and input market uncertainties refer to uncertainties surrounding the acquisition of adequate quantities and qualities of inputs into the production process (Miller 1992) at expected costs and in expected time. Components of input market uncertainties are market price, process or technology, volume and mix requirements, number of available suppliers, financial health of suppliers, and product design changes (Chopra and Sodhi 2004; Zsidisin 2003b; Zsidisin and Ellram 2003; Zsidisin et al. 2004).

Operational uncertainties refer to firm-specific factors such as labor and production uncertainties that can arise due to labor unrest, employee safety, and machine failures, and confused lines of responsibility (Kogut and Kulatilaka 1994; Lessard and Lightstone 1986). Apart from these, input supply uncertainties such as shortage of raw materials or defective components may also lead to operational uncertainty.

Product market and demand uncertainties refer to changes in or an inability to meet demand for a supply chain's output. Such uncertainties might result from changes in consumer tastes, availability of better quality or lower cost substitute products, scarcity of complementary goods, misunderstanding of cultural differences, and quality and safety issues (Johnson 2001; Jüttner 2005; Svensson 2002). Furthermore, supply and input market uncertainties as well as operational uncertainties also lead to product market and demand uncertainties.

Competitive uncertainty refers to an inability to predict the amount and type of goods available in the market (Miller 1992), and lack of history about competitor activities and moves (Ghoshal 1987). Competitive uncertainty arises from rivalry among existing competitors, new entrants, and product and process innovations, i.e., technological uncertainty (Porter 1990).

As per TCE, behavioral uncertainty refers to a manager's or an employee's propensity to act in their own self interest to maximize his or her wealth at the expense of the firm (Williamson 1985; Williamson 1979). In the case of a supply chain, behavioral uncertainty may lead to a firm acting in its self-interest at the cost of the overall value to the supply chain.

One may argue that most of the uncertainties discussed above also exist in domestic supply chains. While uncertainties such as macro and policy are less prevalent in a domestic supply chains, uncertainties common to global and domestic supply chains get exacerbated in a global supply chain (Bowersox and Calantone 1998; Ghoshal 1987; Schmidt and Wilhelm 2000) because of lack of information, lack of control**,** infrastructural constraints, cultural differences, greater physical distances, extended lead times and lead-time uncertainty, and increased forecast errors over extended lead times (Birou and Fawcett 1993; Bowersox and Calantone 1998; Ghoshal 1987; Hwarng et al. 2005; Nelson and Toledano 1979). In terms of designing control systems, Lessard and Lorange (1977) contend that global operations can exacerbate the problems of monitoring managerial and partner performance in order to reduce behavioral uncertainty.

In sum, there is a multitude of uncertainties facing global supply chains that can be divided into environmental and supply chain (i.e., firm and industry) uncertainties. Higher levels of environmental uncertainties in a global environment (Birou and Fawcett 1993; Chopra and Sodhi 2004; Hwarng et al. 2005; Zsidisin 2003b) interact with industry and firm uncertainties, thereby increasing the risks in global supply chains.

RISKS IN GLOBAL SUPPLY CHAINS

Uncertainties are sources of risks (Jüttner, Peck and Christopher 2003). Although seemingly overwhelming, the uncertainties in supply chains indicate the opportunities for translating and expressing these uncertainties in terms of supply chain risks and identifying and ranking these risks to (re)design robust global supply chains.

Reflecting different and often conflicting objectives of firms comprising supply chains, and because of industry-related factors, several conceptualizations of risk exist in the literature. The finance literature looks at risk primarily in terms of probabilities of expected outcomes, variability of returns on a portfolio of investments, or risk of default, bankruptcy, and/or ruin (Beaver 1966). In the strategy literature, risk has been defined in terms of risk-adjusted rates of return on capital investment (Christensen and Montgomery 1981), variability of expected and actual returns (Bettis 1981), risks of strategic actions such as doing business with incompetent partners (Das and Teng 1998), and relational risks such as opportunistic behavior like cheating, distorting information, and/or partner firms stealing customers (Baird and Thomas 1985; Bettis and Mahajan 1985). Marketing looks at risk in terms of customer behavior and is primarily concerned with the nature and importance of buying goals and failure in meeting psychological or performance goals (Cox 1967). Management and psychology literature dealing with managerial preferences explores the link between individual disposition to risk, probabilities of outcomes, and the expected outcome values. “When dealing with a risky alternative whose possible outcomes are generally good (e.g., positive monetary outcomes), human subjects appear to be risk averse; but if they are dealing with a risky alternative whose possible outcomes are generally poor, human subjects tend to be risk-seeking” (Kahneman and Tversky 1979). An event has more impact on choice when it turns an impossibility into a possibility or a possibility into a certainty than when it merely makes a possibility more or less likely (Kahneman and Lovallo 1993). Sitkin and Pablo (1992) state that risk is a characteristic of decisions, and define it as "the extent to which there is uncertainty about whether potentially significant and/or disappointing outcomes of decisions will be realized"

Definitions of risks also vary with industry. Baird and Thomas (1991) found that some risk definitions are more significant in high growth than in low growth industries. For example, definitions of risk based on innovation and failure to reach targets were significantly more important in high growth than in low growth industries. Pablo (1999) found that industry influences the way managers interpret risk. In a qualitative study of managers in commercial banking, software, and oil and gas industries, Pablo found three broad categories of risk based on temporal diversity, beliefs about how best to deal with risk, and competitive strategies. The three categories were control, probabilities/uncertainty, and consequences. Whereas managers in commercial banking are most focused on better probability assessment rather than losses, managers in software industry are most concerned about the significance of outcome. Managers in oil and gas exploration industry were found to be most focused on better defining the range of outcomes.

Several objective definitions of risk have also been offered. Harland, Brenchley, and Walker (2003) define risk as a chance of danger, damage, loss, injury, or any other undesired consequences. Mitchell (1995) states that the risk concept contains different types of loss and the risk of a particular type of loss is a combination of the probability of that loss and the significance of that loss to the individual or organization. Miller (1992) defined risk as the variation in the corporate outcomes variables.

The one thing common to all definitions of risk is the variability of outcomes of interest. The outcomes and the ways in which variability is measured, however, vary with the context such as discipline or industry. Therefore, "risk as distribution of performance outcomes" is adopted as a working definition which will be refined and adapted to a supply chain context using qualitative data later in this chapter.

Often the terms uncertainty and risk are used interchangeably. However, uncertainty, although closely related to risk, is different from risk. Uncertainty is the perceived inability to predict something accurately (Milliken 1987), whereas Deloach (2000) defines business risk as "the level of exposure to uncertainties that the enterprise must understand and effectively manage as it executes its strategies to achieve its business objectives and create value." Spekman and Davis (2004) state that risk differs from uncertainty in that risk has associated with it a probability of a loss and uncertainty is, as Williamson (1985) states, an exogenous disturbance. **Hence, uncertainty is the perceived inability to predict something accurately, and risk is the distribution of the outcomes of interest.** Risk exists because of uncertainty of environmental, organizational, and firm variables. Uncertainty may adversely impact organizational performance and therefore, uncertainty is a source of risk (Jüttner, Peck and Christopher 2003; Miller 1992). Since uncertainties lead to risks, higher uncertainties mean greater risks, and therefore more variability in supply chain performance outcomes.

TYPES OF RISKS IN GLOBAL SUPPLY CHAINS

Spekman and Davis (2004) provide an extensive review of risks in global supply chains. They classify risks in supply chains as related to the physical movement of goods and include risks associated with inadequate supply or obsolete or unwanted inventory; flow of money including risks associated with stable pricing, hedging, letters of credit, and timely payment of bills; risks associated with quality, product design and production, supplier development and stability, logistics, and any physical activity that impinges negatively on the supply chain's ability to meet its objectives regarding the delivery of goods or services; risks emerging from the security of a firm's internal information systems associated with who has access to the information and with sharing information outside of the firm's own four walls; and risks associated with the relationships forged among supply chain partners including risks related to degree of interdependence among partners and the tendency of a partner to act in its own self interest to the detriment of other supply chain members.

This research adopts the classification suggested by Manuj and Mentzer (2007a). They provide a framework for holistic consideration of numerous risks in supply chains. They divided the ones put forth by Spekman and Davis (2004) above and several other risks discussed in the literature into supply, operational, demand, and security risks. Zsidisin (2003a) defines supply risk as *"the probability of an incident associated with inbound supply from individual supplier failures or the supply market occurring, in which its outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety."* The four types of risks are defined using this definition as foundation, and the working definition of risk (i.e., distribution of outcomes) developed earlier.

Modifying Zsidisin's definition above, supply risk is the distribution of the outcome of adverse events associated with inbound supply that may cause failures from supplier(s) or the supply market, such that the outcome results in the inability of the focal firm to meet customer demand (in terms of both quantity and quality) within anticipated costs and time, or causes threats to customer life and safety. Sources of supply risk reside in the movement of goods from the suppliers' suppliers to the focal firm. Operations risk is the distribution of the outcome of adverse events associated with the focal firm that may affect the firm's internal ability to produce goods and services, quality and timeliness of production, and/or the profitability of the company. In addition, operations risk may increase because of supply risk. Sources of operations risk reside within the focal firm. Demand risk is the distribution of the outcome of adverse events associated with outbound flows that may affect the likelihood of customers placing orders with the focal firm, and/or variance in the volume and assortment desired by the customer. Sources of demand risk reside in the movement of goods from the focal firm to the customer's customers. Security risk is the distribution of the outcomes associated with adverse events that cause threat to human resource, integrity of operations, and information systems security; and may lead to outcomes such as freight breaches, stolen data or proprietary knowledge, vandalism, crime, and sabotage. Sources of security risk reside across the supply chain from suppliers' suppliers through focal firm, and all the way up to customers' customers.

Table II-1 (adapted from Manuj and Mentzer 2007a) presents a list of representative (but not exhaustive) adverse events that might lead to a particular type of risk. This classification provides a systemic way to look at risks. However, there are two prominent research gaps. First, the dimensions of risk are primarily limited to probability and losses in most of the definitions. There is evidence that there are additional dimensions of risk, such as exposure suggested by Deloach (2000), that need to be incorporated to develop a holistic definition of risk in a supply chain context. Second, there is a need to identify those risk (adverse) events that are the most important in a global supply chain context as it might be impossible for managers to consider all risk events because of resource constraints.

RISK MANAGEMENT

Using the above definitions of supply, demand, operational, and security risks, the literature related to risk management in supply chain was explored.

TABLE II-1: SUMMARY OF RISKS

Type of risk	**Adverse Events**
Supply Risks	Disruption of supply, inventory, schedules, and technology access; price escalation; quality issues; technology uncertainty; product complexity; frequency of material design changes
Operational Risks	Breakdown of operations, inadequate manufacturing or processing capability, high levels of process variations, changes in technology, changes in operating exposure
Demand Risks	New product introductions, variations in demand (fads, seasonality, and new product introductions by competitors), chaos in the system (the Bullwhip Effect on demand distortion and amplification)
Security Risks	Information systems security; infrastructure security; freight breaches from terrorism, vandalism, crime, and sabotage.

Adapted from Manuj and Mentzer (2007a)

For reasons similar to the existence of multiple definitions of risk, several conceptualizations of risk management exist in literature. Industry mindsets and functional orientation affect risk concepts, and as a result, affect ways to manage risks. Norrman and Jansson (2004) define risk management as the process whereby decisions are made to accept a known or assessed risk and/or the implementation of actions to reduce the consequences or probability of occurrence. Adapting this definition of risk management to a supply chain context, they use the following definition in their research: supply chain risk management is to collaborate with partners in a supply chain to apply risk management process tools to deal with risks and uncertainties caused by, or impacting on, logistics related activities or resources. Hauser (2003) states that supply chain risk management means keeping an increasingly complex process moving efficiently at the lowest total cost and without compromising the quality of the product or customer satisfaction.

A counterpart of risk management in project and process management literature is Failure Modes and Effects Analysis (FMEA) approach. FMEA approach is a powerful tool in assessing failures and preventing them (Puente et al. 2002; Sankar and Prabhu 2001). It asks questions such as: What might go wrong? What might cause it to go wrong? What effects would it have? FMEA is used to assign ratings of 1-10 for probability of occurrence (O), detection (D) and seriousness of effects (S) of a failure mode. A Risk Priority Number, which is the product of O, D, and S, is used to prioritize the risks in a project or a process (Sankar and Prabhu 2001).

Adopting any one concept of risk management limits its scope (Jüttner, Peck and Christopher 2003). According to Mentzer et al. (2001), supply chain management involves sharing both risks and rewards between the members of the supply chain. Souter (2000) stresses that companies should focus not only on their own risks, but also on risks in other links in their supply chain. Building on Souter (2000), Norrman and Jansson (2004) suggest that the focus of supply chain risk management is to understand, and try to avoid, the devastating ripple effects that disasters or even minor business disruptions can have in a supply chain. Tentatively, the definition provided (Jüttner (2005) and Jüttner, Peck and Christopher (2003) is adopted for the purpose of literature review as it includes the major elements of the definitions discussed above. They define supply chain risk management as the identification of potential sources of risk and implementation of appropriate strategies through a coordinated approach among supply chain members to reduce supply chain vulnerability. Here, supply chain vulnerability is defined as an exposure to serious disturbances arising from supply chain risks affecting the supply chain's ability to effectively serve the end customer market. This definition is adopted for its broad focus with an understanding that new dimensions of risk explored using qualitative data will lead to a more refined definition of risk management in a global supply chain context.

RISK MANAGEMENT STRATEGIES

In addition to the definition of risk management above, the literature review on risk management strategies is based on Ghoshal (1987), who suggests:

> "The strategic task, with regard to management of risks, is to consider these (macro, policy, competitive, and resource risks) different kinds of risks jointly in the context of particular strategic decisions. However, not all forms of risk are strategic since some of these risks can be easily diversified through a readily available external market. It is only those risks which can not be diversified through a readily available external market that are of concern at the strategic level."

Miller identifies five "*generic responses to environmental uncertainties*" to strategically address risks - avoidance, control, cooperation, imitation, and flexibility. Building on Miller (1992), Jüttner, Peck and Christopher (2003) argue that four of them, i.e., avoidance, control, cooperation, and flexibility, can be easily adapted in a supply chain context, although no rationale is offered for dropping imitation. Other strategies suggested in the literature to counter uncertainty, and thereby help in risk management are postponement, speculation, hedging, assuming, sharing/transferring, and security.

Avoidance strategy is used when the risks associated with operating in a given product or geographical market, or working with particular suppliers or customers, is considered unacceptable. In avoiding risks, managers are aware of the supply-demand and/or operating trade-offs associated with the options and choose to avoid some risks. Avoidance may take the form of exiting through divestment of specialized assets, delay of entry, or participating only in low uncertainty markets (Miller 1992). Another way of avoiding risks is to eliminate the types of events that could trigger the risk (Norrman and Jansson 2004).

Control strategies aim at controlling uncertain variables rather than treating them as constraints. Examples of control strategies include political lobbying, use of market power to deter entry, vertical integration, and mergers and acquisitions. Vertical integration increases the ability of a member of a supply chain to influence processes, systems, methods, and decisions. Vertical integration may take the form of forward (downstream) or backward (upstream) integration. As the supply chain becomes more integrated, control increases. Integration may also be used to create entry or mobility barriers (Bucklin 1965). Benefits of control can also be obtained through virtual supply chain integration and supply chain collaboration.

Unlike control, cooperation involves multilateral agreements, long-term contractual agreements, voluntary restraint of competition, alliances and joint ventures, franchising agreements, technology licensing agreements, and participation in consortia (Miller 1992). Miller contends that such measures improve coordination through behavioral interdependence, and reduction in autonomy of coordinating organizations and thereby reducing uncertainty.

Imitation of product and process technologies is a strategy that firms may adopt to compete in foreign markets. Scholars have suggested the greater the uncertainty of the outcomes of international strategy innovations, the more likely firms are to imitate the strategies of other firms. Technological knowledge imitation is increasingly a competitive behavior, which allows firms to be at the cutting edge of technological development (Katrishen 1994).

Flexibility is the ability of an organization to adapt to substantial, uncertain, and fast-occurring environmental changes that have a meaningful impact on the organization. By enhancing flexibility, supply chains can significantly reduce demand and supply risks (Bowersox, Stank and Daugherty 1999). For example, flexibility in global supply chain context will enable a supply chain to shift production and procurement between multiple countries in response to foreign currency or wage rate fluctuations. Although, Miller (1992) and Jüttner, Peck and Christopher (2003) suggest that flexibility is a strategy, it appears that flexibility is more a characteristic of supply chain than a strategy in itself.

Hedging strategy, originally a term from the area of finance, is based on the law of large numbers. With a large enough population, the expected outcome can be known with considerable accuracy, i.e., the sample mean is highly predictable if the distribution for a group is known. In a supply chain context, hedging involves creating multiple options for production and procurement such that an event like currency fluctuation or natural disaster will not affect all options simultaneously or with an equal intensity.

While hedging is a strategy designed to minimize exposure to risks, assuming is a strategy is designed to take on these risks. When the risks associated with a given option are considered acceptable, the effort is geared toward driving minimization of risks rather than spreading them through hedging. As Wernerfelt And Karnani (1987) suggest, when the future is known with certainty, focusing resources yields more advantages, such as exploiting economies of scale, as compared to spreading the resources across multiple options. In a supply chain context, assuming risks may take the form of sourcing from a single supplier or from a single geopolitical area, or depending on a single manufacturing plant for a particular product or line of products.

Postponement entails delaying the actual commitment of resources to maintain flexibility and delay the incurring of costs (Bucklin 1965). There are two types of postponement – form and time. Form postponement includes labeling, packaging, assembly, and manufacturing. Time postponement refers to the movement of goods from manufacturing plants only after customer orders are received (Zinn and Bowersox 1988).

Speculation (also called assumption or selective risk taking) is the opposite of postponement (Bucklin 1965). In speculation, decisions are made on anticipated customer demand. The resources in the supply chain need to be directed to those specific products and customers that are going to provide the firm with a competitive advantage (Perry 1991).

Sharing risks entails paying premiums to risk-taking members for assuming risks and penalizing risk-averse members. For example, a portfolio of contracts can be used to persuade intermediaries in supply chains with different levels of risk aversion to select unique contracts. This induces the retailers in the supply chain to order quantities that maximize the expected value. Since there are a variety of contracts from which to choose, contracting can be used to counter the inefficiencies created by the risk aversion of the retailers (Agrawal and Seshadri 2000; Cachon 2004).

Security strategy refers to increasing a supply chain's ability to sort out what is moving, identify unusual or suspicious elements and concentrate on them, and deal with the rest of the movements through a sampling-based process. Security of a global supply chain encompasses issues such as information systems security, freight breaches, terrorism, vandalism, crime, and sabotage.

In sum, eleven strategies were found in the literature. However, there are two major research gaps with respect to this study. First, there was not much evidence of when to use what strategies. Second, there is a need for identification of strategies that are the most important for managers to understand.

FACTORS AFFECTING THE IMPLEMENTATION OF RISK MANAGEMENT IN GLOBAL SUPPLY CHAINS

A review of literature reveals four factors that affect implementation of risk management strategies in global supply chains – supply chain complexity, information systems, inter-organizational learning, and flexibility.

Supply Chain Complexity

Supply chains are made up of elements that have intimate connections, and counterintuitive and non-linear links, and as a consequence, present self-emerging, often chaotic results and hence are complex as well as adaptive (Choi and Hong 2002). Supply chain complexity is a measure of volume, structure, and types of interdependent activities, transactions, and processes in the supply chain and the constraints and environmental uncertainties under which these (activities, transactions, and processes) operate (Manuj and Sahin 2007). Complexity leads to suboptimal interaction between elements of the supply chain systems, issues such as lack of ownership, chaos like the bullwhip effect, and inertia (Wilding 1998). Complexity has been shown to have a negative impact on supply chain performance in terms of cycle time (Vachon and Klassen 2002).

Information Systems

Information systems are an enabler of the entire process of supply chain risk management (Manuj and Mentzer 2007a) and hence affect both choice and outcome of strategy. Information systems are critical for effective management of supply chains and performance measurement (Bowersox and Daugherty 1995; Edwards, Peters and Sharman 2001), as well as to the choice of strategy as strategic initiatives in supply chains such as just-in-time, quick response, and collaborative planning, forecasting and replenishment (Bowersox and Calantone 1998). Moreover, the process of supply chain risk management – from identifying risks, through selecting appropriate risk management strategies, and making necessary structural changes in the supply chain – is an information-intensive process (Manuj and Mentzer 2007a). Hence, information systems are an enabler of the entire process and affect both choice and outcome of strategies.

Inter-organizational Learning

Inter-organizational learning is a process by which supply chain partners share and combine information and knowledge in novel ways that lead to enhanced supply chain outcomes. It helps a firm in a supply chain to develop its knowledge base (Holmqvist 2003; Huber 1991), and gain fresh insights into strategies, markets, and relationships (Hult et al. 2000). Learning can also provide a platform for building dynamic capabilities (Teece, Pisano and Shuen 1997). Ghoshal (1987) contends that to exploit the potential advantages of diversity, an organization must consider learning as an explicit objective and must create mechanisms and systems for such learning to take place. Inter-organizational learning has been shown to be negatively related to cycle time (Hult, Ferrell and Hurley 2002) .

Flexibility

Flexibility was earlier discussed as a risk management strategy. However, literature also suggests that apart from being a strategy, flexibility positively impacts a supply chain's ability to enhance comparative performance relative to leading industry competitors in executing the same strategies. Flexibility helps a firm reallocate resources quickly and smoothly in response to change (Buckley and Casson 1998). Fawcett, Calantone and Sheldon (1996) found that firms that achieved higher levels of flexibility significantly outperformed their less flexible counterparts. Flexibility helps a firm reallocate resources quickly and smoothly in response to change (Buckley and Casson 1998). Supply chain flexibility provides an inherent capacity to respond to emerging circumstances, and therefore, a capacity to change strategies based on circumstances that cannot be fully anticipated in the planning cycle (Welch and Welch 1996). In sum, flexibility might lead to better and faster implementation of strategies.

SUMMARY AND GAPS

The review of literature discussed above revealed several gaps that need to be addressed before a sound theory of risk management in global supply chains could be developed. A qualitative study was designed to address the gaps identified during the literature review.

First, a major focus of the qualitative study was to discover and explore the dimensions of risk in a global supply chain context.

Second, as the discussion above illustrates, there are numerous risks in global supply chains, and addressing all of these may not be feasible because of resource constraints. There is a need to identify those risks that are the most important in a global supply chain context. Therefore, the qualitative study also focused on identifying risks that are the most salient to supply chain managers.

Third, as discussed earlier, a tentative definition of risk management was adopted for the purpose of literature review with an understanding that new dimensions of risk explored using qualitative study will lead to a more refined definition of risk in a global supply chain context. Therefore, the qualitative study also focused on understanding the meaning of risk management in a global supply chain context.

Fourth, eleven risk management strategies for supply chains were found in the literature but there was not much evidence of when to use what strategies in a global context. From this perspective, qualitative study was aimed at looking for evidence of these strategies, as well as identification of strategies that were the most important for managers to understand.

Fifth, the literature on factors affecting risk management in supply chains is sparse. Therefore, the qualitative study was aimed at looking for the evidence of existence and importance of these factors, and to explore any new factors discovered. Also, literature suggested that flexibility is both a strategy as well as a factor that affects risk management in supply chains. Therefore, qualitative study also focused on managers' understanding of flexibility.

Finally, since TCE and PEP do not provide adequate theoretical background to build a theory of risk management in global supply chains, the qualitative study also focused on the risk management process, i.e., findings patterns of how the different elements of risk and risk management fit together.

QUALITATIVE STUDY

In order to address the research gaps and objectives identified above, and to supplement the existing research in constructing the theory for this dissertation, qualitative research was conducted. Qualitative methods are ideally suited to research substantive areas about which little is known (Stern 1989). The qualitative research was meant to help clarify the main constructs and support the relationships among them so that a stronger theory and subsequent test of the theory could be constructed. Content analysis of depth interviews and a focus group discussion with supply chain managers with global supply chain responsibilities were chosen to accomplish these objectives. The qualitative study was designed to explore the process of supply chain risk management as carried out by managers of global manufacturing firms with responsibilities for making and executing various facets of global supply chain decisions, with particular emphasis on interpretation of risk, the strategies for risk management, and drivers of the strategy selection and implementation process.

RESEARCH DESIGN

The nature of the research problem should drive the choice of a research strategy (Creswell 1998; Denzin and Lincoln 1998). One objective of this study is to build a theory of environment-strategy fit for risk management in global supply chains. Therefore, this qualitative study borrows heavily from the grounded theory methodology, which involves an inductive process for analysis of data allowing theory to emerge from the data. It goes beyond thick description to build theory. Furthermore, an advantage of grounded theory is the ability to handle complex phenomenon such as risk management because the methodology emphasizes the need for developing multiple concepts and their linkages in order to capture a great deal of the central phenomenon.

Grounded theory incorporates a series of structured steps for data analysis. It involves the systematic comparison of small units of data (incidents) and the gradual construction of a system of "categories" that describes the phenomena being observed. The categories may have several "subcategories," and associated "dimensions" and "properties," which are gradually elaborated and refined as incidents are examined, systematically coded, and compared (Strauss and Corbin 1998). Using grounded theory to analyze process data demands a fairly large number of comparable incidents that are all richly described. Thus, while one setting may be sufficient, there should at least be several distinct processes that can be compared in depth (Langley 1999). Therefore, using carefully selected participants who can provide meaningful data on multiple incidents is very critical for a grounded study.

A semi-structured interview protocol was used to guide data collection (see Appendix). Initial interview questions were purposefully broad and were not always asked in the same sequence. As data collection progressed, questions with a higher degree of focus were added to adapt to emergent findings (Strauss and Corbin 1998). Some consistency in the interview questions was maintained as data collection progressed in order to facilitate systematic comparisons of categories; however, the interview format was sufficiently flexible to allow the informant to offer relevant information unconstrained by interview questions.

SAMPLE AND DATA COLLECTION

To maximize the variations in the phenomenon, managers involved in making and executing global supply chain decisions from a variety of manufacturing companies that include home appliances, electronic component suppliers, manufacturers, and assemblers, pharmaceuticals and over-the-counter products, office products, heavy equipment, and consumer goods were interviewed. The sample included managers who have worked in several different companies and industries, as well as those that have worked with one organization over an extended period of time and have witnessed the company move through several transformations. The sample also included one manager whose responsibilities include developing solutions to supply chain problems for both in-house and external clients. . In total, the study had 16 unique participants. The number and content of in-depth interviews was based on the concept of "theoretical sampling" and continued until "theoretical saturation" was reached. This means that successive respondents were chosen based on the emerging theory, and interviews continued until further interviews did not reveal any new information. Details of participants in the study are provided in Figure II-1. The data for this research comes primarily from 14 in-depth qualitative interviews with senior supply chain executives across 8 companies. Apart from interviews, a focus group meeting involving 7 senior executives of a global manufacturing firm was conducted. Five of these 7 executives were later interviewed separately for this study and are a part of the 14 in-depth interviews

TRUSTWORTHINESS

The method of analysis, grounded theory, was chosen in order to provide a framework for methodically relying on the data to provide insights and understanding rather than imposing a preconceived theoretical framework (Glaser and Strauss 1967; Strauss and Corbin 1998). In view of the fact that the researcher has a good understanding of the extant literature on risk management, a conscious attempt was made to keep this knowledge away from the ongoing research to prevent the interference of what the researchers know and believe about phenomenon. The researcher wrote down all that she knew or believed to be true about the phenomenon of risk management. This list was used during the drafting of the interview protocol to make sure the presuppositions were not forced into the interview questions. This list also proved useful both during data collection and data analysis. The data collected from the field were audiotaped and transcribed verbatim by a professional transcriptionist in order to assure accuracy and completeness in data collection (Maxwell 1996; McCracken 1988).

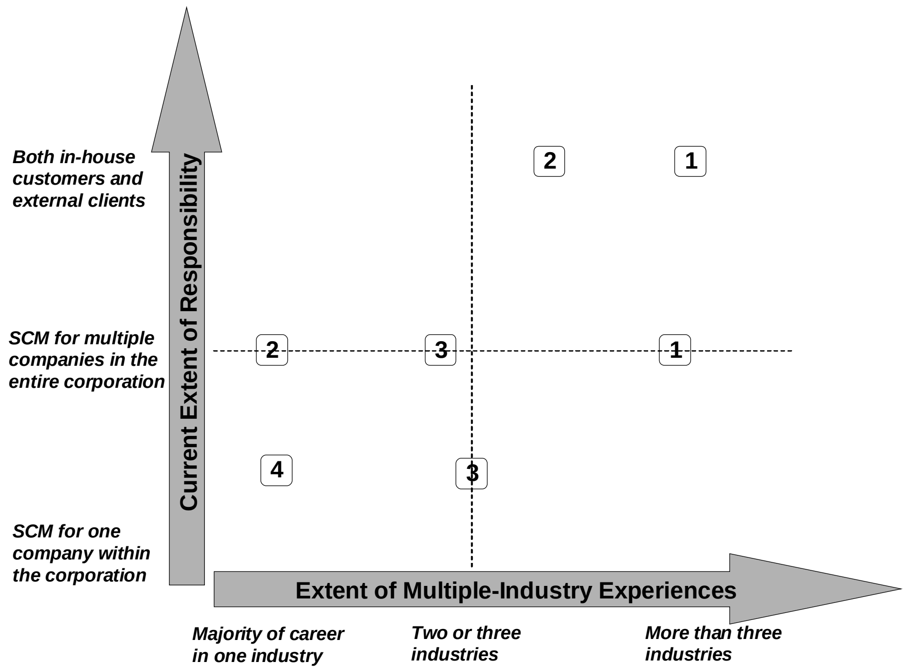


FIGURE II-1 : CHARACTERISTICS OF STUDY PARTICIPANTS

Note: The numbers in the boxes represent the number of participants in a particular category.

The software tool, ATLAS.ti, provided a mechanism for systematic organization of the data and consistent application of codes throughout the coding process. A combination of software and manual coding was used.

Additional steps to maintain the credibility, dependability, transferability, confirmability, integrity, fit, understanding, generality, and control (Hirschman 1986; Lincoln and Guba 1985; Wallendorf and Belk 1989) are presented in Table II-2.

FINDINGS OF THE QUALITATIVE STUDY

The major findings from the qualitative study are divided into three headings: Risk, Risk Management, and Factors Affecting Risk Management. Some additional findings are presented in the context of the existing literature later in this chapter under the section titled "Comprehensive Conceptual Framework." Furthermore, insights from the qualitative study were also used in the selection of constructs for this research.

Risk

As discussed earlier, no all-encompassing definition exists that identifies important dimensions of risks in global supply chains. Furthermore, global business initiatives have not only exacerbated traditional domestic supply chain risks but have also created new ones such as foreign exchange, and political risks (Biederman 2006).

TABLE II-2: EVALUATION CRITERIA FOR THE QUALITATIVE STUDY

Criteria (and explanation)	**Step(s) taken**
Credibility (extent to which the results appear to be acceptable representations of the data)	Member Checks: Selected informants reviewed a summary of the researcher's interpretations of their interviews to ensure the data analysis was both complete and credible
Transferability (extent to which the findings from one study in one context will apply to other contexts)	Purposive Sampling: The data were collected from 16 individuals across multiple companies to minimize the possibility of chance associations.
Dependability (extent to which the findings are unique to time and place; the stability or consistency of explanations)	Participants reflected as far back as 20 years, core categories existed across industries
Confirmability (extent to which interpretations are the result of the participants and the phenomenon as opposed to researcher biases)	Bracketing-type exercise and journal-keeping. Quotes presented to substantiate interpretation. Colleagues familiar with the constructs consulted throughout the project and reviewed final results to ensure they were confirmable
Integrity (extent to which interpretations are influenced by misinformation or evasions by participants)	Confidentiality assurance; Multiple informants from a company, where possible.
Fit (extent to which findings fit with the substantive area under investigation)	Addressed through the methods used to address credibility, dependability, and confirmability. Concepts deeply described, capturing the multifaceted nature of the phenomenon
Understanding (extent to which participants buy into results as possible representations of their worlds)	Similar to credibility; participants and colleagues were asked to confirm if researcher's interpretations were accurate.
Generality (extent to which findings discover multiple aspects of the phenomenon)	Interviews were of sufficient length and openness to elicit many facets of the phenomenon and related concepts.
Control (extent to which organizations can influence aspects of the theory)	Participants can control some theory variables so as to be able to influence and manage risk in supply chains

Adapted from Flint and Mentzer (2000) and Flint, Woodruff and Gardial (2002)

The objective of the qualitative study was to identify the dimensions of risk in a supply chain context, and to identify those risks that are the most important for global supply chain managers. Therefore, insights from the qualitative study were used to develop a definition of risk relevant to global supply chains. An example quote from a senior executive in a leading home appliance manufacturing firm is provided below:

> ***"****Risks are all those things that keep you away from the perfect path and perfect outcomes and (you) got to be able to translate (risks) into dollars somehow."*

Manuj and Mentzer (2007a) put forth the following three components of risk: the potential losses (i.e., what losses will result if the risk is realized); likelihood of those losses (i.e., the probability (likelihood) of the occurrence of an event that leads to realization of the risk); and the significance of the consequences of the losses. While probability and impact of losses are the two most commonly discussed dimensions of risk (e.g., Mitchell 1995), Harland, Brenchley and Walker (2003) suggest that the likelihood of an event occurring depends partly on the extent of *exposure* to risk. Exposure refers to sensitivity of a firm or project's cash flows to changes in any of a number of interrelated uncertain variables (Miller 1992). This definition of exposure is extended to a supply chain context to suggest that exposure is the sensitivity of a supply chain's outcomes to changes in uncertain variables that may change the number of different types of adverse events to which the supply chain is susceptible.

Apart from losses, probability, and exposure, the qualitative study reveals two more dimensions of risk that gain critical importance in global supply chains, namely speed, and frequency. Speed of risk may further be divided into the speed at which the event leading to loss happens, the speed at which losses happen (i.e., losses per unit time), and the time for detection of a risk event. Speed is of critical importance in global supply chains because of increased lead times, lead time variability, physical distances from sources of risk, lesser control over the supply chain, and other global challenges. The following quote from a manager who participated in the qualitative study below elaborates:

> *"We're three levels down into the supply chain here and we design the (circuit) board, we get it contract manufactured, and sometimes we're buying the components, sometimes the contract manufacturer is buying the components. But a component supplier, their process for making capacitors went out of control. Capacitors got integrated into our boards and you know, months later, unfortunately, in this case, you're finding field failures because, it wasn't immediate failure, it was a failure over time. So, even though all the reliability work had been done on this and it was in the field and working great, now you get three months of supply all of a sudden, which is a huge number, in the field, where now we have problems."*

Frequency is a measure of how often a similar kind of risk event happens. For example, a one-time big-volume loss due to a quality defect may be tolerable and correctable. However, frequent small-volume quality defects leading to supply and demand risks can potentially lead to a company losing its reputation and even going out of business. In sum, the events leading to a risk have the dimensions of losses, probability, speed of event, speed of losses (losses per unit time), time for detection of a risk event, frequency, and exposure (Manuj and Mentzer 2007b; Miller 1990; Mitchell 1995). This conceptualization of risk is similar to Failure Mode and Effects Analysis (FMEA). FMEA is often used in engineering design analysis to identify and rank the potential failure modes of a design or manufacturing process, and to determine its effect on other components of the product or processes in order to document and prioritize improvement actions (Sankar and Prabhu 2001).

It is important to note that different risks are linked to each other in complex patterns with one risk leading to another, or influencing the outcome of other risks. For example, as the quote below illustrates, the risks of transit time, cycle time variability, and forecasting error seem to be intricately related to each other.

> *So there's the forecast error issue, too, over a long lead times. And the forecast error multiplies exponentially as you extend the lead time. I mean you're trying to forecast, it's like trying to forecast the weather tomorrow versus next month. You can do it tomorrow. You have no idea what's going to happen next month. That's the situation here, too. So you have this huge risk of forecasting incorrectly and it happens over and over. So what happens is companies tend to overreact. They run into a supply shortage and they add in a whole bunch of inventory so it won't happen to them again, and then they realize, oh my gosh, I've got a year's supply here of product. Now we need to shut down the factory. By the time they shut it down they're in a shortage again. So they go through this big pendulum swing between shortage and out of stock versus excessive inventory.*

It can be inferred from the above discussion that one common feature of all definitions of risk is "variation or distribution" of a performance measure, which if less than the expected outcome is termed as a "loss." If there are multiple expected outcomes, and some are less desirable than others, there is risk. Based on the preceding discussion, risk in supply chain context is defined as **the distribution of performance outcomes of interest related to supply, operations, demand, and security in a supply chain, such that there is a possibility of lower than desired returns. These outcomes are expressed in terms of losses, probability, speed of event, speed of losses, the time for detection of the events, frequency, and exposure.** While, the definition retains the basic essence of risk as, "variation or distribution of outcomes," it specifies the scope, i.e., supply, operations, demand, and security, as well as identifies the dimensions of outcomes, i.e., losses, probability, speed of event, speed of losses, the time for detection of the events, frequency, and exposure. Therefore, this definition is adopted for this research.

Finally, it is important to note that risk can be objective or perceptual/subjective. Objective risk is inherent in certain situations such as throwing dice or playing cards. Subjective risk is an individual's assessment of a situation that motivates him/her to action or not (Spekman and Davis 2004). Pablo (1999) suggests "*As such, they (managers) may not be aware of the extent to which they are focusing on some risk elements and ignoring others. By providing tools to heighten manager's cognizance of their own risk-related theories-in-use and where these fail to account for potentially important risk elements, managers may be able to identify other avenues for dealing with risk that were not apparent previously*." This implies that objective risk assessment is important for robust risk management. Therefore, this research focuses on objective risk. To recapitulate, the dimensions of risk are losses, probability, speed of event, speed of losses (losses per unit time), the rate at which (i.e., how quickly) the risk event is discovered, frequency, and exposure.

The qualitative research revealed that risk events most salient to global supply chain managers are related to currency, transit time, forecast, quality, safety, business disruption, survival, inventory (and tools such as machining tools) ownership, legal, culture, dependency and opportunism, oil prices, and similar risk events affecting suppliers and customers.

Table II-3 presents interesting quotes from interviews supporting the existence of these risk events. Subsets of these risk events have been considered by scholars investigating risks in supply chains (Giunipero and Eltantawy 2004; Jüttner, Peck and Christopher 2003; Spekman and Davis 2004).

As defined in this paper, operations risks are within the control of the focal organization, whereas supply and demand risks are not. In the qualitative study, global supply chain managers were most concerned about risks beyond their control as these are more difficult to manage. Therefore, this research focuses on the ones that are beyond the direct control of the supply chain managers, i.e., supply and demand risks.

Risk Management

Based upon risk management definitions in existing literature, FMEA, definition of risk developed above, and qualitative interviews, the following definition of supply chain risk management is proposed:

Supply chain risk management is the identification of risks and consequent losses in the supply chain and implementation of appropriate strategies through a coordinated approach among supply chain members with the objective of reducing one or more of the following for the supply chain outcomes – losses, probability, speed of event, speed of losses, the time for detection of the events, frequency, and exposure – that in turn lead to close matching of the actual cost savings and profitability targets with the desired ones.

TABLE II-3: RISK EVENTS

Risk Events	Definition	Quotes from interviews
Currency	Changes in exchange rates	*When you're dealing with international trade, certainly introduce the currency risk*
Transit Time	In-transit time including port clearance and transportation	*"The problem with these long supply lines is they're also highly variable. I mean, it's not just the mean, it's the standard deviation of cycle time."*
Forecast	Incorrect demand predictions causing stock-outs or excess stock	*"There's the forecast error issue, too, over a long lead times* (of global supply chains). *And, you know, the forecast error multiplies exponentially as you extend the lead time."*
Quality	Defective, damaged, or incorrect supply; differences across multiple sites	*"the assumption is that quality is a given, but, the reality of it is, you do have quality difference between suppliers because, you have variation across people as far as who's doing the audit and you don't necessarily have the same guy doing every audit everywhere around the world, so, there's difference there."*
Safety	Products causing safety hazards	*"the problem is that when these suppliers are half a world away from you, they are not necessarily used to operating with the same quality and the same safety standards as we adhere to over decades because quality and safety standards have been developed in the U.S and they have become almost natural to domestic suppliers. But look at people in the east, they are just starting up factories. They don't have that history."*
Business Disruption	Inability to produce goods or sell to customers	*"I always used to put in my analyses some money for air freight. I would assume that eventually we're going to encounter a disruption"*
Survival	Firm going out of business/bankrupt	*"And what if you're outsourcing some component and right safety standards weren't exactly* (followed)*, or right testing wasn't done and you bring in a component that starts burning down people's houses, I mean, can you imagine the lawsuits? So it could put an entire company at risk for survival"*
Inventory and tools ownership	Confusion and/or dispute over inventory ownership; Dispute over use and IP of tools provided by one partner	*"It's not unusual for* (company name) *to actually supply or own the tooling that make the parts. What do you do if you own a tool in China and all of a sudden you want to buy from Thailand or Mexico? Do you move the tooling? The tool is built in China and you pay for it, it goes to the supplier and then you say, you're charging too much. We're going to build it somewhere else. We want our tool. Will they let you have your tool? How long will it take to go through the courts?"*
Culture	Inadequate knowledge about people, culture, and language	*"With both those points of reference* (two different companies where this participant worked), *I'll say*, (there are) *common risk elements. One is language and culture barriers. You have to work, probably, a lot harder at overcoming some of those than a lot of people anticipate."*
Dependency and Opportunism	Opportunistic acts by supplier/customer	*"I need some flexibility and I can't have the risk of only being with one…If I absolutely know I'm dependent on you, then I lose some kind of leverage."*
Oil price increase	Changes in oil price	*"So many different things you have to be concerned with when you start looking at risk. Transportation costs increases because of oil. Oil has a big impact. We're seeing it now."*

Factors Affecting Risk Management in Global Supply Chains

The qualitative study pointed to the importance of the four factors affecting risk management in global supply chain that were identified earlier in the literature review section, namely, supply chain complexity, information systems, inter-organizational learning, and flexibility. In addition to finding the evidence of importance and existence of these factors, qualitative research identified one factor that has not been awarded enough attention in the literature, i.e., Team Composition. Supply chain complexity, information systems, inter-organizational learning, flexibility, and team composition are all factors that are internal to the supply chain and to a large extent within the control of supply chain managers. In addition to internal factors, qualitative study revealed an external critical factor, namely disruption, which can significantly influence the anticipated outcome of supply chain risk management process. These two factors are discussed below with support from qualitative study and existing literature.

Team Composition

Although there is not much research in logistics and supply chain literature on the composition and role of teams in selecting and implementing supply chain strategy, Williams et al. (1997) found evidence that when logisticians are included on cross-functional teams, there is a positive correlation with the integration of logistics into overall corporate strategy. Andre (1999) suggests that management teams in logistics today are comprised of a diverse group of people, and current demographics indicate that this diversity will increase as the labor pool changes. Therefore, it is important to understand the importance of team composition and set up processes to manage unproductive conflict in diverse work groups.

The first step in identifying risk typically starts when an opportunity to reduce costs or increase revenues is recognized by a focal firm. This opportunity may be realized by sourcing from, producing in, or supplying across the borders of the domestic market. Such decisions are usually capital intensive and have major cost or strategic implications. It is reasonable to assume (and the in-depth interviews support the assertion) that such decisions tend to be team-based efforts. Team members bring different perspectives to solving a problem. Hence, the team composition becomes an important determinant of the quality of risk identification and management. However, for the team to effectively and efficiently reach a risky decision, it is important to understand the trade-offs and counteractive forces that may exist in a group. The following quote from a senior supply chain executive provides an example:

> *"... in addition to supply chain we had procurement involvement, legal, customs, material control involved in decision making for off-shore procurement. Factory material control was a key player in this. They're the ones that are impacted. They're sitting there running the factories and if they don't have the parts they're the ones who feel the pain when the parts aren't there so they had a vested interest in doing everything they could to stop this project."*

Insights derived from the in-depth interviews suggest the following important trade-offs and counteractive forces:

- Members having stakes for and against the decision in question;
- Members having risk-averse versus risk-taking attitudes;

- Trade-off between inclusion of members from outside the organization, and the time and cost of such an effort. For example, making suppliers (and other supply chain members) a part of the solution may pay off in the long run but may involve significant investment by the focal firm; and
- Getting the most functionally proficient managers versus managers with long term vision.

Disruption

Disruption is defined as non-availability of products or components for a given length of time at any level of the supply chain that severely hampers a supply chain's ability to meet customer demand within given cost parameters and while maintaining satisfactory profitability. Disruptions can manifest themselves in a variety of forms including transportation delays, port closures, accidents, natural disasters, capacity shortages, quality problems, facility shut-downs, and terrorism (Blackhurst et al. 2005). Craighead et al. (2007) contend that supply chain disruptions and the associated operational and financial outcomes represent the most urgent concern facing supply chains that compete globally. In light of their findings that link the severity of disruptions to supply chain design characteristics, they question the usefulness of pursuing current practices such as supply base reduction, global sourcing, and sourcing from supply clusters. In particular, closure of a US port was a big concern for several managers. The following quotes illustrate:

> *"There is risk of supply disruptions, slowness of getting things through ports…What if there is a dirty bomb that explodes in the port of Los Angeles tomorrow? What would we do?"*
>
> *"Anything that would shut down a U.S. port, for example, would fall under that* (catastrophic) *category and there are all kinds of scenarios that would do it."*

Apart from clarifying the concepts of risk, risk management, and factors affecting risk management in global supply chains, qualitative study also provided insights into the process of supply chain risk management, and how managers deal with supply chain risks. These insights combined with literature review were used to develop a comprehensive model of environment-strategy fit for risk management in global supply chains. The following section elaborates on this model.

COMPREHENSIVE CONCEPTUAL FRAMEWORK

Based on the preliminary literature review, qualitative study, and additional literature review undertaken after the qualitative study, a comprehensive model of environment-strategy fit for risk management in global supply chains was developed (See Figure II-2). The second round of literature review was used as a source of data to provide evidence for or against the emerging theory.

ENVIRONMENT-STRATEGY FIT

Global supply chains are constantly engaged in a three-way tug-of-war between the objectives of maintaining product leadership (both technologically and operationally), meeting customer requirements, and achieving cost efficiencies.

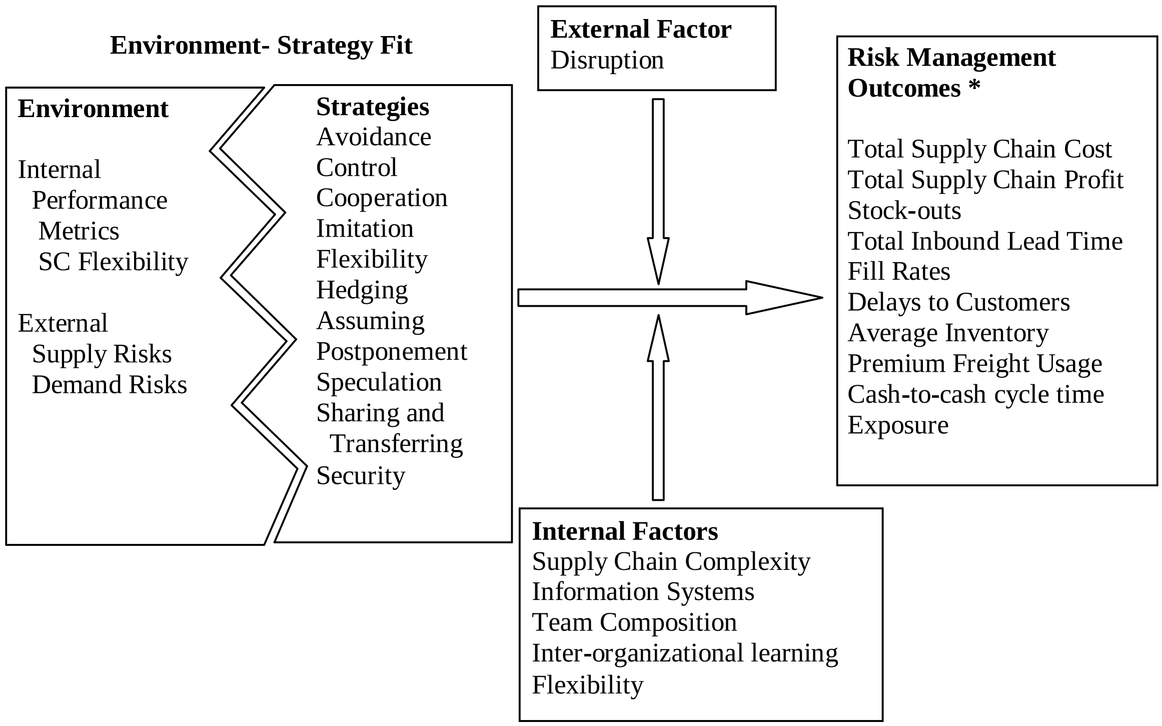


FIGURE II-2 : A COMPREHENSIVE CONCEPTUAL FRAMEWORK OF ENVIRONMENT-STRATEGY FIT FOR RISK MANAGEMENT IN GLOBAL SUPPLY CHAINS

The resources of a firm are limited and need to be distributed among these conflicting objectives such that the profitability of the supply chain is maximized. A resource's capacity to generate profits or to prevent losses depends, to a large extent, on the fit of a given strategy to the external environment (Porter 1991; Sachan and Datta 2005; Wernerfelt and Karnani 1987).

Strategy, Structure, and Performance (SSP), a theory widely used is strategy research and has been suggested as an appropriate theoretical basis to study supply chain phenomena (Defee and Stank 2005; Rodrigues, Stank and Lynch 2004; Stank, Daugherty and Autry 1999). SSP deals with the concept of fit. It suggests that a firm's performance depends on the degree of fit between its strategy and the structural elements developed to support the strategy. However, changing environmental factors such as customer requirements, competition, the state of the economy, and governmental regulations (Christensen and Montgomery 1981; Porter 1985) affect the appropriateness of this fit. Performance results from the degree of fit between strategy and structure taken within the context of internal and external environmental factors.

Venkatraman (1989) identifies six perspectives of fit – fit as moderation, fit as mediation, fit as matching, fit as gestalts, fit as profile deviation, and fit as covariation. In this research, the concept of fit as matching is used because, in this perspective, fit is defined as the match between two related variables. Subsequently, the effect of this fit on performance variables can be examined. This definition is most suitable for the major objective of this study, i.e., examining the effect of fit between environment and strategy on supply chain outcomes.

Venkatraman (1989) presents an example of fit as matching from Chandler (1962). Based on SSP, Chandler proposes that, in multinational corporations, a diversification strategy requires a multidivisional structure, whereas a geographical expansion strategy requires field units, and the absence of such a match between strategy and structure leads to administrative inefficiency or weaker performance.

Pablo (1999) advises that care and attention should be given to the context in which the variable "risk" is used as it affects the meaning of risk management for a manager. Therefore, appropriate strategies are contextual and should be structured based on the characteristics of the situation in question. This entails recognizing the factors motivating the choice of a particular strategy and determining the appropriate strategies for a given situation. To this end, Jüttner, Peck and Christopher (2003) suggest that future research should be directed at investigating risk management in different supply chains and industries, and developing relevant strategies based on industries and environments facing supply chains. Kleindorfer and Saad (2005) suggest, "*to effectively manage risk, the approach must fit the characteristics and needs of decision environment.*"

To address the second research objective of building a theory of environment-strategy fit for risk management in global supply chains, the concept of risk is extended to a supply chain context. This research builds on the thesis that if a risk management strategy selected by a supply chain fits with its environment, then this supply chain will experience higher performance as compared to the performance of a supply chain that adopts a strategy that is mismatched with the environment.

ENVIRONMENTAL FACTORS

Both internal and external environmental factors and the strategy selected should fit with each other to optimize supply chain performance. Internal environmental factors identified as the most important for risk management in global supply chains, as per the qualitative study, include performance metrics and supply chain flexibility. Most imporant external environmental factors include supply risks and demand risks.

Internal Environmental Factors

Several internal environmental factors (that correspond to structural elements in SSP) have been identified including formal organizational form, lines of authority, role assignments, and management control systems (Defee and Stank 2005). Internal environmental factors identified as most important for risk management in global supply chains, as per the qualitative study, include performance metrics and supply chain flexibility.

As the following quote from a participant in the qualitative study reveals, objectives and performance measures of managers affect the attitudes of managers towards risk management.

> *"…it's not that they don't want to (include risks in analyses). It's not that they don't know they should look at risk. But I think they don't because of the pressures they're under, the goals that they have to meet for the year. They probably figure, hey look, it's a low probability, probably won't happen and, frankly, my boss isn't asking me to look at it. So, why should I be a hero and miss my objectives? It's the right thing to do but they aren't rewarded for doing it. Maybe that's at the heart of this, is no one is compensated or incented in their day to day job to look at and evaluate the risks properly."*

Performance metrics are a determinant of the temporal perspective of managers (Mentzer and Firman 1994). Design of performance metrics is an important factor that influences a manager's inclination to include risks in their analysis of global supply chain decisions. If the reward system rewards only those who achieve their objectives irrespective of giving due attention to risks, then the managers will strive to achieve objectives at the cost of disproportionate risks. In sum, a short term focus of performance metrics leads to adoption of strategies that provide immediate results, and involve lower investments, and vice versa.

The second factor in the internal environment of the supply chain that affects the selection of risk management strategy is flexibility. Upton (1994) defines flexibility as "the ability to change or react with little penalty in time, effort, cost, or performance." Although flexibility was earlier discussed as a strategy and as a factor that affects risk management, flexibility is also a characteristic of the internal environment of the supply chain. Flexibility represents the main driver of competitive advantage and market leadership for several firms and organizations (Fawcett, Calantone and Sheldon 1996). Flexibility is important in a global supply chain because a risk management strategy can only be executed if the level of flexibility required for a given strategy matches the flexibility of the supply chain. The following quote illustrates,

> *"…you need to have the flexibility to do whatever operations you need to do, wherever you need to do them and source whatever you need from wherever you can get it best and the model that we apply today, we literally kind of pick up and move operations. It's a very inflexible move. We kind of replicate the same highly integrated, supply base and manufacturing process, just in a lower wage, lower supply base cost location. So wherever our competition follows us, there is no advantage. And, if there are currency fluctuations or wage increases, we're*

stuck. You know, there's no where to go because we're in the same model that we had before that we had to abandon from where we were before."

Kogut and Kulatilaka (1994) argue that flexibility is an option that is valuable because of uncertainty, time dependence, and discretion. For example, a company may choose (discretion) to exploit exchange rate volatility (uncertainty) by configuring its business to have flexibility to increase production and sourcing in countries where and when currencies become undervalued (time dependence) in real terms (Lessard and Lightstone 1986). This is an example of a hedging strategy which is not a good option for inflexible supply chains. In sum, a strategy should be selected based on the level of flexibility in the supply chain.

External Environmental Factors

External environmental factors include the supply risks and demand risks facing a supply chain. To recapitulate, supply risk is the distribution of the outcome of an adverse event associated with inbound supply that may cause failures from supplier(s) or the supply market, such that the outcome results in the inability of the focal firm to meet customer demand (in terms of both quantity and quality) within anticipated costs, anticipated time, or threats to customer life and safety. Sources of supply risk reside in the movement of goods from the supplier's supplier to the focal firm. Demand risk is the distribution of the outcome of an adverse event associated with outbound flows that may affect the likelihood of customers placing orders with the focal firm, and/or variance in the volume and assortment desired by the customer. Sources of demand risk reside in the movement of goods from the focal firm to the customer's customers.

Table II-4 presents a comprehensive review of research dealing with supply and demand risk events. The risk events that are primarily global in nature are represented by G (Global), those risk events that exist in domestic supply chains but have exacerbated effects in global supply chains are represented by EG (Exacerbated in Global supply chains), and those risk events that have similar effects in domestic and global supply chains are represented by S (Similar).

Fisher (1997) suggested matching a type of supply chain with product and demand uncertainties faced by the supply chain. He stated that efficient supply chains should be used for functional products and responsive supply chains for innovative products. Lee (2002) built upon Fisher's model and included supply uncertainties to suggest four types of supply chains: efficient (high cost efficiency based on low demand and supply uncertainty), responsive (responsive and flexible to high demand uncertainty and low supply uncertainty), risk-hedging (pooling and sharing of resources in a supply chain with low demand uncertainty and high supply uncertainty), and agile (both hedging and responsive to high demand and supply uncertainty). Lee's classification suggests how supply chains operating under conditions of low or high supply and demand uncertainty ought to act, not necessarily how they always act.

TABLE II-4: SUPPLY AND DEMAND RISK EVENTS

Risk Events	References	Scope
Supply Risks		
Culture/Miscommunication /Language Differences	Birou and Fawcett (1993); Cho and Kang (2001)	G
Currency Fluctuations	Birou and Fawcett (1993); Cho and Kang (2001); Chopra and Sodhi (2004)	G
Duty/Customs/Trade Regulations	Birou and Fawcett (1993); Cho and Kang (2001)	G
Political and Economic Stability	Birou and Fawcett (1993); Cho and Kang (2001)	G
Bankruptcy of Supplier	Chopra and Sodhi (2004); Zsidisin and Ellram (2003)	EG
Quality (defects)	Chopra and Sodhi (2004); Berger, Gerstenfeld, and Zang (2004); Min and Zhou (2002); Treleven and Schweikhart (1988); Zsidisin (2003b); Zsidisin and Ellram (2003)	EG
Supplier and Market Capacity Constraint	Chopra and Sodhi (2004); Zsidisin (2003); Zsidisin and Ellram 2003	EG
Market Price Fluctuations	Berger, Gerstenfeld, and Zang (2004); Treleven and Schweikhart (1988); Zsidisin (2003b); Zsidisin and Ellram (2003)	EG
Wage Rate Fluctuations	Ghoshal (1987)	EG
Natural Disasters	Chopra and Sodhi (2004); Zsidisin (2003b)	EG
War and Terrorism	Chopra and Sodhi 2004; Kleindorfer and Saad 2005	EG
Lead times - Length and Variability (Supplier lead time, transportation time, port clearance time)	Birou and Fawcett (1993); Cho and Kang (2001); Chopra and Sodhi (2004); Hult (1997); Zsidisin (2003); Zsidisin and Ellram (2003)	EG
Oil Price Increase	Qualitative Study	EG
Inventory Management	Cho and Kang (2001); Chopra and Sodhi (2004); Zsidisin and Ellram (2003)	S
Information Systems Incompatibility	Chopra and Sodhi (2004); Lee, Padmanabhan and Whang (1997); Min and Zhou (2002); Zsidisin (2003); Zsidisin and Ellram (2003)	S
Product Design Changes	Zsidisin and Ellram (2003)	S
Process/Technological Change	Berger, Gerstenfeld, and Zang (2004); Novak and Eppinger (2001); Treleven and Schweikhart (1988); Walker and Weber (1987); Zsidisin and Ellram (2003)	S
Volume and Mix Requirements Changes	Zsidisin (2003b); Zsidisin and Ellram (2003)	S

TABLE II-4. Continued.

Risk Events	References	Scope
Number of Available Suppliers	Berger, Gerstenfeld, and Zang (2004); Birou and Fawcett (1993); Chopra and Sodhi (2004); Treleven and Schweikhart (1988); Zsidisin (2003); Zsidisin and Ellram (2003)	S
Inability to Reduce Cost	Zsidisin (2003)	S
Supplier Dependency and Opportunism	Spekman and Davis (2004); Bettis and Mahajan (1985); Baird and Thomas (1985)	S
<u>Demand Risks</u>		
Uncertainty of demand (Coefficient of variation)	Childerhouse, Aitken and Towill (2002); Chopra and Sodhi (2004); Johnson (2001); Pagh and Cooper (1998); Sodhi (2005); Wilding (1998)	EG
PLC Duration	Childerhouse, Aitken and Towill (2002); Fisher (1997); Pagh and Cooper (1998); Sodhi (2005)	EG
Product variety	Childerhouse, Aitken, and Towill (2002); Fisher (1997); Pagh and Cooper (1998)	EG
End-of-season markdown	Chopra and Sodhi (2004); Fisher (1997); Sodhi (2005); Johnson (2001); Wilding (1998)	EG
Lead time for made-to-order products	Childerhouse, Aitken and Towill (2002); Fisher (1997)	EG
Product customization	Fisher (1997); Pagh and Cooper (1998)	EG
Forecast error	Chopra and Sodhi (2004); Fisher (1997)	EG
Customer Receivables default	Chopra and Sodhi (2004)	EG
Stock-outs	Fisher (1997); Johnson 2001; Sodhi (2005); Wilding (1998)	EG
Contribution Margin	Fisher (1997)	EG
Product Value	Chopra and Sodhi (2004); Pagh and Cooper (1998)	EG

G: Events primarily Global in nature
E: Events Exacerbated in global supply chains
S: Events with Similar effects in domestic as well as global supply chains

Supply and demand uncertainties lead to risks in supply chains. However, apart from supply and demand uncertainties, other environmental uncertainties can also lead to supply and demand risks. Therefore, the classification suggested by Lee (2002) is adapted. Based upon earlier definitions developed in this paper, instead of naming the two dimensions as supply uncertainties and demand uncertainties, they are named supply risks and demand risks respectively (see Figure II-3). The words in the cells of Figure II-3 denote the environments facing supply chains in terms of the levels of supply and demand risks. "$S_L D_L$" denotes the presence of low supply and low demand risks, "$S_L D_H$" denotes the presence of low supply and high demand risks, "$S_H D_L$" denotes the presence of high supply and low demand risks, and "$S_H D_H$" denotes the presence of high supply and high demand risks.

FACTORS AFFECTING THE OUTCOME OF ENVIRONMENT-STRATEGY FIT

The impact of environment-strategy fit on performance outcomes depends not only on the selection of strategy that fits with the external environment, but also on how well the strategy is executed. As discussed earlier, one external factor and five internal factors influence the process of strategy implementation and, in effect, moderate the link between environment-strategy fit and the risk outcomes. The external factor is disruptions and internal factors are supply chain complexity, information systems, team composition, inter-organizational learning, and flexibility.

		Supply Risks	
		Low	High
Demand Risks	Low	$S_L D_L$	$S_H D_L$
	High	$S_L D_H$	$S_H D_H$

$S_L D_L$: low supply and low demand risks
$S_L D_H$: low supply and high demand risks
$S_H D_L$: high supply and low demand risks
$S_H D_H$: high supply and high demand risks.

FIGURE II-3 : TYPES OF SUPPLY CHAIN ENVIRONMENTS
Adapted from Lee (2002)

RISK MANAGEMENT OUTCOMES

The objective of supply chain risk management is to reduce one or more of the following for the outcomes of risk events – losses, probability, speed of event, speed of losses (losses per unit time), time for detection of a risk event, frequency, and exposure. Supply chain risk management should lead to closely matching the desired cost savings and profitability targets. Therefore, total supply chain cost and profit that account for both benefits and costs of risk management strategies are important outcomes that need to be measured to ascertain the effectiveness of a supply chain risk management strategy (Beamon 1998; Canbolat et al. 2005).

However, total cost and profit do not tell the complete story as other measures of supply chain performance that are most likely to be impacted by global supply and demand uncertainties should be included to evaluate a supply chain risk management strategy holistically. On the supply side, two outcomes of interest in global supply chains have been emphasized by researchers, namely, stock-out (Chopra and Sodhi 2004), and total inbound lead time (Fagan 1991). On the demand side, the outcomes most emphasized in literature include fill rates including order, unit and line fill rates (Beamon 1998; Chang and Makatsoris 2001; Chopra and Sodhi 2004; Fisher 1997), and delays to customers (Chopra and Sodhi 2004). The qualitative study revealed several other outcomes of interest in global supply chains. These include average inventory (Hwarng et al. 2005; Min and Zhou 2002; Van Der Vorst et al. 1998; Zsidisin 2003b), premium freight usage on both the inbound and outbound side (Canbolat et al. 2005), cash-to-cash cycle time (Min and Zhou 2002), and exposure (described below) (Miller 1992).

Total cost is the sum total of costs incurred by the supply chain including transportation, inventory carrying, production, warehousing, and penalty costs such as late delivery or stock-out penalty by customers, if any. Total profit is the difference between total revenues earned and total costs incurred by the supply chain. Stock-out is the inability to meet customer demand for a given quantity by due date because of non-availability of inbound components, products, or raw materials. Total inbound lead time is the sum of supplier lead time, transportation time, and port clearance time. Order fill rate is the number of orders filled complete and on time divided by total number of orders in a given time period. For a given order, unit fill rate is the number of units shipped divided by the total number of units ordered. For a given order, line fill rate is the number of lines filled complete divided by the total number of lines in an order. Delay to customers is a measure of orders delivered late and the length of delays. Average inventory is the average number of units at hand over a given period of time across the entire supply chain. Premium freight usage is the number of times premium freight is used for inbound and/or outbound sides. Cash-to-cash cycle time is length of time for which a company must finance its own inventory, i.e., the number of days between the initial cash outflow (when the company pays its suppliers) to the subsequent cash inflow (accounts receivable). Finally, exposure is the number of different types of risk events that occur in a given time period.

In sum, the following outcomes related to supply and demand risks, measured in terms of probability and losses, time to identify a risk event, speed of losses, and/or frequency of adverse events, are of interest in global supply chains:

1. Total Supply Chain Cost
2. Total Supply Chain Profit
3. Stock-outs
4. Total Inbound Lead Time
5. Fill Rates
6. Delays to Customers
7. Average Inventory
8. Premium Freight Usage
9. Cash-to-cash cycle time
10. Exposure

RATIONALE FOR THE CHOICE OF CONSTRUCTS

Due to the limitation of resources and time, and to keep the model simple but meaningful, this research focuses on selected constructs from the comprehensive model presented in Figure II-2. This research focuses only on the external environmental factors because managers in the qualitative study showed more interest in managing risks arising from the external environment that was out of their direct control. In particular, it was the outcome of the strategies, that if adopted given appropriate internal environmental factors, that was of greatest concern to managers.

Sound risk management is a continual process that involves long-term dedication of supply chain members (Giunipero and Eltantawy 2004) because it requires both capital and human resource investment. As the following example from the qualitative study illustrates, it is driven by performance metrics to a large extent.

"And they (senior management) *will tell you something like I know you're outsourcing $50 million worth of product this year. I want it to be $200 million by the end of the year and you will be evaluated on hitting that number. So people get goals like that, sometimes they (managers) almost view risk analysis as something that might slow them down in trying to work toward that goal if they know they're going to be punished for it if they don't make it at it at the end of the year."*

Performance metrics are under the direct control of the senior managers. It is the outcome of the strategies that will be adopted if appropriate performance metrics are in place that is of more interest to managers. Therefore, it is assumed that performance metrics have long-term orientation, i.e., all strategies are assumed to be adopted for the same "long term period." The length of time period (i.e., length of simulation run) for this study is discussed in Chapter III.

The other internal environmental factor, flexibility, has been conceptualized as a characteristic of a supply chain that should fit with the strategy selected. For example, inflexible supply chains that adopt strategies requiring flexibility, such as postponement, will show poor performance. A supply chain can be made more flexible by investing time, skills, and money. However, it is the outcome of the strategies that can be achieved if the supply chains had the flexibility that is of interest. Furthermore, due to lack of an integrated theory or framework on supply chain flexibility, it is difficult to measure and predict the effect of flexibility in this research. Therefore, for this study, it is assumed that all supply chains have the same high level of flexibility to adopt the desired strategy. In effect, flexibility acts as a control variable and is not directly included in this research.

This research focuses on four selected strategies that are the most important and frequently used strategies: hedging, assuming, speculation, and postponement. The strategies were chosen as they were identified as important based on the views of the participants in the qualitative study. These strategies also came across as the ones that were the most likely to be influenced by the supply chain managers. Incidentally, these strategies are also some of the most frequently mentioned strategies in the context of managing risks in supply chains (e.g., Kogut and Kulatilaka 1994; Chiou, Wu and Hsu 2002). Other strategies have limited mention, and although there is preliminary support from the qualitative study, there is limited theoretical support to develop propositions for the remaining seven strategies at this stage.

Avoidance is not included as it is very similar to speculation in terms of execution, in which an organization decides whether or not to invest in a certain initiative. Control is not included as it is achieved through political lobbying, use of market power to deter entry, vertical integration, and mergers and acquisitions, which is beyond the direct influence of a supply chain manager. Imitation is not included since evidence was found in the qualitative research that imitation is not a preferred strategy as it is unlikely to provide any sustainable competitive advantage. Both the literature and the qualitative study provide evidence that flexibility is a characteristic of the organization or the supply chain that influences the choice of strategies or enables strategy implementation rather than a strategy in itself. Cooperation strategy is implemented through some explicit or implicit contract and is a part of the broader strategy of sharing or transferring risk. Finding optimum contracts under different supply and demand conditions is a separate stream of research. Finally, in light of current security threats and increasing trade, it is expected that supply chains facing all types of environments will increase the use of security strategies largely driven by government guidelines. It is difficult to test the impact on security strategy in this model and is, thus, left to future research. In sum, the strategies included in this research are hedging, assuming, postponement, and speculation.

For the purpose of this dissertation, it is assumed that all internal factors affecting the implementation process, except supply chain complexity, are the same across all supply chains for three reasons. First, the main focus of this research is to understand which supply chain risk management strategy works best under certain external environmental conditions. Since these factors influence the outcome and not the extent of environment-strategy fit, they are not of prime importance to this dissertation. Second, this research is one of the first to test risk-management systematically and in a theoretically sound way in the context of global supply chains. Consequently, it faces a lack of sufficient theoretical basis to hypothesize about the effect of these moderators. Third, as discussed earlier, the focus of this research in on risks and factors outside the direct control of supply chain managers. All internal factors, to a large extent, can be influenced by supply chain managers. Finally, in light of available time and resource constraints, there is need to maintain the simplicity of the model. Supply chain complexity can not be assumed to be constant as adoption of any of the four strategy changes the complexity of the supply chain. However, the effect of complexity is not studied in this research.

The external factor, disruption, is included in this research as disruption can be caused by numerous circumstances that are beyond the direct and indirect control of supply chain managers such as acts of terrorism, strikes, and natural disasters. As mentioned earlier, this research attempts to include factors that are external to the supply chain and beyond the direct control of supply chain managers.

Not all measures can be included as it not only complicates the analysis but is difficult to achieve because of time and resource constraints. A subset of performance measures is used. The measures that are not included are premium freight usage, cash-to-cash cycle time, and exposure. Premium freight usage is not included as it is part of flexibility strategy and flexibility strategy is not part of this study. Cash-to-cash cycle time is not included as it is dependent on the terms of payment set between the partners and terms of payment considerations are not a part of this study. Exposure is the number of different types of risk events that occur in a given time period. As explained in detail in Chapter III, this research uses simulation methodology to test the model and the risk events are built into the model *a-priori*. More about performance measures is discussed in Chapter III. The testing of hypotheses is based on total supply chain profit as it takes into account several other performance measures including total supply chain costs (inventory, transportation, and production costs), total supply chain revenues, and penalty costs associated with late deliveries.

DISSERTATION MODEL AND HYPOTHESES

This section concentrates on the part of the comprehensive model (presented in Figure II-2) that will be tested in this dissertation. Figure II-4 presents the model that identifies the constructs of interest for this research. In this section, hypotheses that will be tested are systematically developed.

First, the concept of environment-strategy fit is explored. Next, hypotheses that specify the effect of one strategy on the performance outcomes are discussed. These are called direct effect hypotheses because they predict the effect of one strategy at a time. The next set of hypotheses is called interaction effect hypotheses because they predict the outcome of a combination of strategies relative to different supply chain environments. Next, hypotheses that are exploratory in nature are proposed for those combinations of strategies for which there is not enough theoretical background to predict the outcomes *a priori*. Finally, hypotheses called disruption hypotheses are presented that predict the outcome of a combination of strategies relative to different supply chain environments in the presence of a disruption.

ENVIRONMENT-STRATEGY FIT

As discussed earlier, the classification suggested by Lee (2002) presented in Figure II-3 is adapted. "S_LD_L" denotes the presence of low supply and low demand risks, "S_LD_H" denotes the presence of low supply and high demand risks, "S_HD_L" denotes the presence of high supply and low demand risks, and "S_HD_H" denotes the presence of high supply and high demand risks.

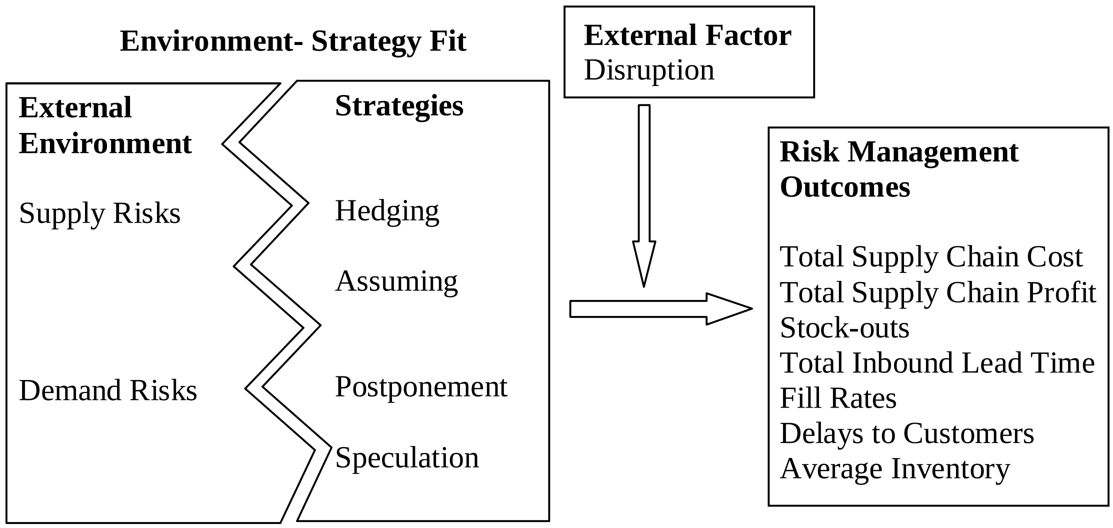
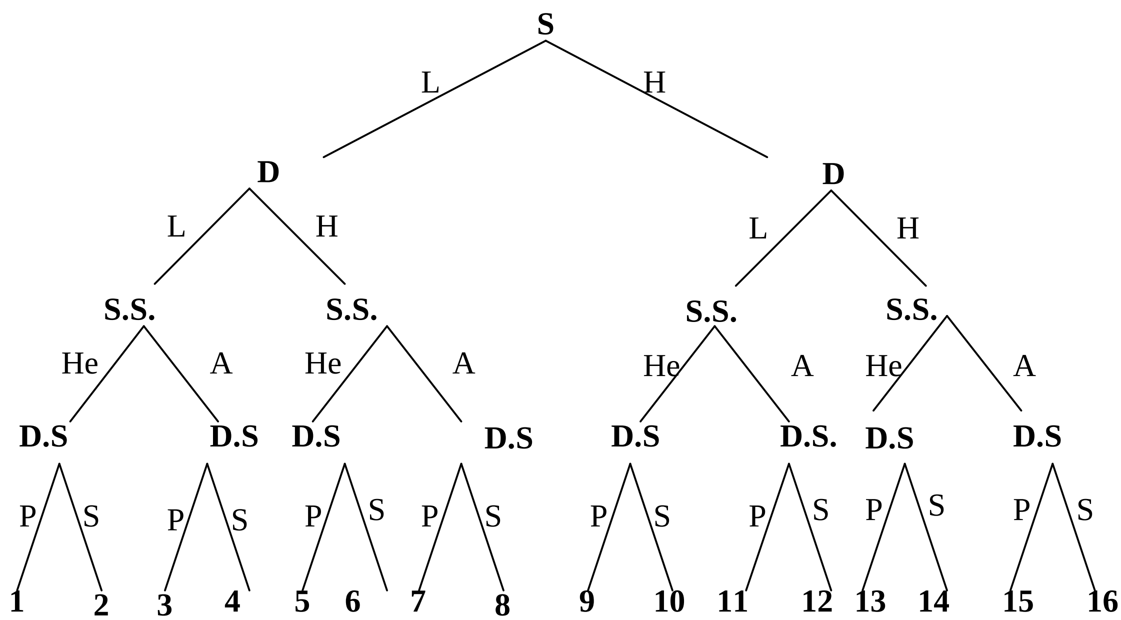


FIGURE II-4 : A MODEL OF ENVIRONMENT-STRATEGY FIT FOR RISK MANAGEMENT IN GLOBAL SUPPLY CHAINS

The concept of fit discussed earlier suggests that a resource's capacity to generate profits or to prevent losses depends very much on the fit of a given strategy to the external environment (Amit and Schoemaker 1993; Porter 1991). This implies that strategies are contextual (Pablo 1999), and based on the characteristics of the situation in question, perform differently for different environmental conditions (Jüttner, Peck and Christopher 2003). Therefore, for a given supply chain environment, a particular combination of supply and demand risk management strategies will be significantly better than all other combinations for that supply chain environment.

Performance implies lower total supply chain costs, and a reduction in one or more of the following for the outcomes identified in the figure: losses, probability, speed of event, speed of losses, the time for detection of the events, frequency, and exposure.

Figure II-5 presents a "tree and branch" diagram that illustrates all possible combinations of supply and demand risks, and supply side strategies and demand side strategies respectively. The figure shows the different paths that can be taken in terms of supply risks, demand risks, supply strategies, and demand strategies. As mentioned earlier, testing of hypotheses is based on total supply chain profit. The numbers 1 through 16 represent the total profit for each path. For example, 3 in Figure II-5 is the total profit for a supply chain that faces low supply risks and low demand risks and adopts an assumption strategy on the supply side, and a postponement strategy on the demand side.



S: Supply; D: Demand; H: High Risks; L: Low Risks
SS: Supply Strategy; He: Hedging; A: Assuming
DS: Demand Strategy; P: Postponement; S: Speculation

FIGURE II-5 : TREE AND BRANCH DIAGRAM FOR ALL POSSIBLE PATHS

DIRECT EFFECT HYPOTHESES

Direct effect hypotheses specify the relative effect on outcomes of the fit of a demand or a supply strategy with the environment.

Hedging and Assuming

In a supply-chain context, hedging is undertaken by having a globally dispersed portfolio of suppliers and facilities such that a single event (like currency fluctuations or a natural disaster) will not affect all the entities at the same time and/or with the same magnitude (Bartmess and Cerny 1993; Ogden et al. 2005).

Hedging works as an option whose value depends on the direction and extent of change in events (Kogut and Kulatilaka 1994). However, not all supply chains will benefit equally from hedging. Supply chains with low supply risks will not gain any substantial benefits because the transaction costs for those supply chains to find alternate sources of supply will be lower as compared to supply chains facing high supply uncertainty. In light of unstable manufacturing schedules or unreliable suppliers, hedging is an appropriate strategy to counter supply risks.

Assuming risks is the opposite of hedging risks. While hedging is a strategy designed to minimize exposure to risk, the assuming strategy is designed to take on these risks. When the risks associated with a given option are considered acceptable, the effort is geared toward driving minimization of risks rather than spreading them through hedging.

As Wernerfelt And Karnani (1987) suggest, when the future is known with certainty, focusing resources yields more advantages, such as exploiting economies of scale, as compared to spreading the resources across multiple options. In assuming risks, managers should be reasonably aware of the operating trade-offs associated with the available options and choose to assume risks associated with a given option. The following quote from a manager who participated in the qualitative study provides an example of assuming risks:

> *"The total amount of initiatives that you would, could potentially work on would far exceed that number (the total number of desirable initiatives). So the difficult decisions were really to place your bets, so to speak, on the right horses. In other words, try to make sure you worked on the things that were really going to deliver the year end objectives."*

Assuming risks in the supply side in a global supply chain may take the form of sourcing from a single supplier or from a single geopolitical area, or depending on a single manufacturing plant for a particular product or line of products when the risks and associated costs can be specified *a priori*. However, such a strategy will not be effective when there are high risks such as those of quality, quantity, disruption, price, variability in performance, and opportunism (Berger, Gerstenfeld and Zeng 2004).

Therefore, for high supply risks, it is proposed that irrespective of the level of demand risks and strategy on the demand side:

> **H1: Supply chains facing high supply risks (S_HD_L and S_HD_H environments) that adopt a hedging strategy will show a higher profit than supply chains hat adopt a assuming strategy.**

In other words, in Figure II-5, 9, 10, 13, and 14 will be greater than 11, 12, 15 and 16 respectively.

For low supply risks, it is proposed that irrespective of the level of demand risks and strategy on the demand side:

H2: Supply chains facing low supply risks ($S_L D_H$ and $S_L D_L$ environments) that adopt a assuming strategy will show a higher profit than supply chains that adopt a hedging strategy.

In other words, in Figure II-5, 3, 4, 7, and 8 will be greater than 1, 2, 5, and 6 respectively.

Postponement and Speculation

Postponement entails delaying the actual commitment of resources to maintain flexibility and delay incurring costs (Bucklin 1965). There are two types of postponement – form and time. Form postponement includes labeling, packaging, assembly, and manufacturing. Time postponement refers to the movement of goods from manufacturing plants only after customer orders are received (Zinn and Bowersox 1988). The focus here is form postponement. Due to the nature of and constraints on global transportation, the extent of time postponement is limited. The extent of form postponement depends on demand customization, component costs, product life cycle, and product modularity (Chiou, Wu and Hsu 2002). The following quote from a manager who participated in the qualitative study illustrates the usefulness of postponement strategy:

> *"It's tough, because our product to begin is really not architected to allow it (late stage differentiation) and that's the opportunity. In some cases, some of our ABC products, we have a high degree of reuse of the control with lots of different user interfaces that go with the control. So you could begin to imagine a late stage differentiation opportunity. But our supply chain really isn't architected to do, to do that. That's the direction that we are heading."*

A major problem faced by supply chains is how to justify the cost of form postponement. Form postponement requires a substantial investment in understanding product design (Van Hoek 2001) and more effort as modular products are more difficult to design than comparable interconnected systems (Baldwin and Clark 1997). The existence of common or overlapping suppliers and customers in different supply chains may affect a firm's ability to invest in the postponement related facilities and training programs. Any investment may provide a free benefit for competitors, i.e., a source of opportunism and hence increase transaction costs. With increasing attention to mass customization, agile operations, and e-business strategies, there is interest in postponement that has led to development of measures to improve coordination through behavioral interdependence, and reduction in autonomy of coordinating organizations and thereby reducing behavioral uncertainty (Appelqvist and Gubi 2005). However, there has been an absence of empirical research supporting either side (Yang, Burns and Backhouse 2004) . Building on Perry (1991), who suggests the potential benefits of postponement depend on the uncertainty projected in the operating environment., it is argued that supply chains facing low demand uncertainty will not benefit as much from form postponement as supply chains facing high demand uncertainty.

Speculation (also called assumption or selective risk taking) is the opposite of postponement (Bucklin 1965). In speculation, decisions are made on anticipated customer demand. The resources in the supply chain need to be directed to those specific products and customers that provide the firm with a competitive advantage (Perry 1991). In the interviews, speculation emerged as the most commonly used strategy to address uncertainty in the business environment. Speculation requires thorough groundwork to develop high-quality estimates of demand in order to accept options with low demand risks. Speculation may involve delaying entry in a foreign market, or serving customers with similar demographics in culturally-similar countries rather than developing customized products for new markets or participating only in low uncertainty markets (Miller 1992). In speculating about cost-risk trade-offs, managers should typically be aware of the supply-demand and/or operating trade-offs associated with the options and choose to avoid certain options. Supply chains facing low demand uncertainty are better suited to achieve benefits of speculation.

Therefore, for high demand risks, it is proposed that irrespective of the level of supply risks and strategy on the supply side:

> **H3: Supply chains facing high demand risks (S_LD_H and S_HD_H environments) that adopt a postponement strategy will show a higher profit than supply chains adopting a speculation strategy.**

In other words, in Figure II-5, 5, 7, 13, and 15 will be greater than 6, 8, 14, and 16 respectively.

For low demand risks, it is proposed that irrespective of the level of supply risks and strategy on the supply side:

> **H4: Supply chains facing low demand risks (S_LD_L and S_HD_L) environments that adopt a speculation strategy will show a higher profit than supply chains that adopt a postponement strategy.**

In other words, in Figure II-5, 2, 4, 10, and 12 will be greater than 1, 3, 9, and 11 respectively.

INTERACTION EFFECT HYPOTHESES

So far, the hypotheses that have been offered deal with a strategy that addresses one type of risk at a time. For example, hedging and assuming strategies deal with supply risks, and postponement and speculation strategies deal with demand risks. However, in reality, global supply chains face different levels of risks on the supply side and demand side. Applying the concept of fit, a supply chain that adopts the strategy combination that fits with demand and supply uncertainty conditions will perform better as compared to a supply chain that adopts a mismatched strategy combination.

Since, hedging is useful in case of high supply risks, assuming in case of low supply risks, postponement in case of high demand risks, and speculation in case of low demand risks, it is proposed that:

H5: Supply chains facing low supply risks and low demand risks (S_LD_L environment) that adopt an assuming strategy on the supply side and a speculation strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.

In other words, in Figure II-5, 4 will be greater than 1, 2, and 3

H6: Supply chains facing low supply risks and high demand risks (S_LD_H environment) that adopt an assuming strategy on the supply side and a postponement strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.

In other words, in Figure II-5, 7 will be greater than 5, 6, and 8.

H7: Supply chains facing high supply risks and low demand risks (S_HD_L environment) that adopt a hedging strategy on the supply side and a speculation strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.

In other words, in Figure II-5, 10 will be greater than 9, 11, and 12.

H8: Supply chains facing high supply risks and high demand risks ($S_H D_H$ environment) that adopt a hedging strategy on the supply side and a postponement strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.

In other words, in Figure II-5, 13 will be greater than 14, 15, and 16.

EXPLORATORY HYPOTHESES

Although, from H1 through H4 above, for each strategy, it is possible to identify the two environments under that strategy works best, there is little guidance on which among those two environments fits the selected strategy better. For example, if a firm has products with different supply and demand risks, and limited resources, then it has to make a decision on identifying those supply chain environments that stand to benefit most from adopting a particular strategy. For example, for H1, it is anticipated that supply chains facing $S_H D_L$ and $S_H D_H$ environments that adopt a hedging strategy perform better than a supply chain adopting a speculation strategy. However, we do not know enough to understand whether a supply chain facing a $S_H D_L$ environment or a $S_H D_H$ environment will gain more by adopting the hedging strategy.

Although we do not know much about other strategies, there is one study in postponement strategy. For the postponement strategy, Lee (2002) suggests, based on empirical evidence from cases studies of HP and IBM, that postponement for innovative products is most applicable with a reliable and stable supply base. Although this evidence is limited, it is proposed:

H_E1: Supply chains facing low supply risks (S_LD_H environment) will show a higher profit than supply chains facing high supply risks (S_HD_H environment) from adopting a form postponement strategy.

In other words, in Figure II-5, 5 will be greater than 3 and 7 will be greater than 15.

The research by Lee discussed above suggests that there is a possibility of differential performance for the other three strategies also relative to a supply chain environment. Since there is not much guidance on the relative impact of the other three hypotheses, we assume the performance to be equal. Therefore, for hedging, assuming, and speculation strategies, it is proposed:

H_E2: Irrespective of the level of demand risks, all supply chains facing high supply risks (S_HD_L and S_HD_H environment) will show an equal profit from adopting a hedging strategy.

In other words, in Figure II-5, 9 will be equal to 13 and 10 will be equal to 14.

H_E3: Irrespective of the level of demand risks, supply chains facing low supply risks (S_LD_L and S_LD_H environments) will show an equal profit from adopting an assuming strategy.

In other words, in Figure II-5, 3 will be equal to 7 and 4 will be equal to 8.

H_E4: Irrespective of the level of supply risks, supply chains facing low demand risks (S_LD_L and S_HD_L environments) will show an equal profit from adopting a speculation strategy.

In other words, in Figure II-5, 2 will be equal to 10 and 4 will be equal to 12.

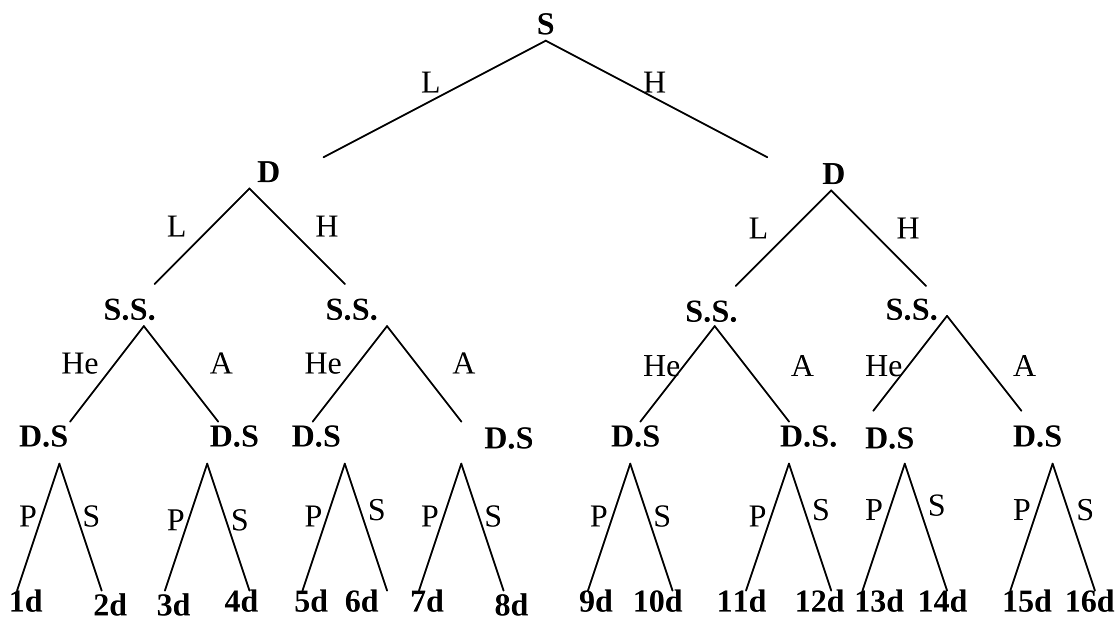
DISRUPTION HYPOTHESES

As discussed earlier, disruptions can manifest themselves in a variety of forms including transportation delays, port closures, accidents, natural disasters, capacity shortages, quality problems, facility shut-downs, and terrorism (Blackhurst et al 2005).

Figure II-6 presents a "tree and branch" diagram that illustrates all possible combinations of supply risks and demand risks, and supply side strategies and demand side strategies respectively under conditions of disruption. As mentioned earlier, testing of hypotheses is based on total supply chain profit. Similar to Figure II-5, the numbers 1d through 16d in Figure II-6 represent the total profit for each path. For example, 3d in Figure II-6 is the total profit for a supply chain that faces low supply risks and low demand risks and adopts an assumption strategy on the supply side, and a postponement strategy on the demand side under conditions of disruption.

Two sets of hypotheses related to disruption are developed. The first set compares the outcomes or total profit between with-disruption and without-disruption scenarios. The second set compares the effect of hedging versus assuming strategy within with-disruption scenarios.

Several disruption events were discussed by the participants in the study. A port closure was very salient to several practitioners who still remember the consequences of port closures at the ports of Los Angeles and Long Beach in 2002 and expressed concern about future supply disruptions caused by congested ports or other factors such as terrorism or strikes.



S: Supply; D: Demand; H: High Risks; L: Low Risks
SS: Supply Strategy; He: Hedging; A: Assuming
DS: Demand Strategy; P: Postponement; S: Speculation

FIGURE II-6 : TREE AND BRANCH DIAGRAM FOR ALL POSSIBLE PATHS UNDER DISRUPTION

The following quote aptly summarizes the concerns expressed by several mangers in the study:

> *"Port of Long Beach shut down this past December had well over 100 big container ships waiting to be unloaded sitting out in the harbor. Good grief. That was days and days worth of unloadings and that was just normal business. What happens if you shut down a port for a few days?"*

Therefore, in this study, the focus is on a supply disruption, namely post disruption. All types of disruptions are likely to negatively affect supply chain outcomes. Outcomes of combinations of environment and strategies under non-disruption scenarios will always be better than outcomes under disruption scenarios. Therefore it is proposed that:

H9: The total profit for a given combination of environment conditions and strategies under non-disruption condition will always be higher than total profit for the corresponding environmental conditions and strategies combination under disruption conditions.

For all non-disruption and disruption scenarios, this translates into the following 16 sub-hypotheses:

a. Profit for path 1 > Profit for path 1d
b. Profit for path 2 > Profit for path 2d
c. Profit for path 3 > Profit for path 3d
d. Profit for path 4 > Profit for path 4d
e. Profit for path 5 > Profit for path 5d
f. Profit for path 6 > Profit for path 6d
g. Profit for path 7 > Profit for path 7d
h. Profit for path 8 > Profit for path 8d
i. Profit for path 9 > Profit for path 9d
j. Profit for path 10 > Profit for path 10d
k. Profit for path 11 > Profit for path 11d
l. Profit for path 12 > Profit for path 12d
m. Profit for path 13 > Profit for path 13d
n. Profit for path 14 > Profit for path 14d
o. Profit for path 15 > Profit for path 15d
p. Profit for path 16 > Profit for path 16d

Any disruption or disruptions will have potentially less severe outcomes if there is some sort of buffer against a given disruption. As mentioned earlier, in this study we focus on a supply disruption. A buffer in the form of multiple suppliers, i.e., hedging strategy, should lessen the impact of a supply disruption as compared to a single source arrangement, i.e., assuming strategy. Therefore, it is proposed that:

H10: Under the condition of a supply disruption, hedging will always be better than an assuming strategy under corresponding environmental conditions and demand side strategy.

For all disruption scenarios, this translates into the following 8 sub-hypotheses:

a. Profit for path 1d > Profit for path 3d
b. Profit for path 2d > Profit for path 4d
c. Profit for path 5d > Profit for path 7d
d. Profit for path 6d > Profit for path 8d
e. Profit for path 9d > Profit for path 11d
f. Profit for path 10d > Profit for path 12d
g. Profit for path 13d > Profit for path 15d
h. Profit for path 14d>Profit for path 16d

SUMMARY

This chapter provided the theoretical justification supported by the qualitative study from which the model of environment-strategy fit for risk management in global supply chains was built. The theoretical justification was based on a review of literature from various disciplines, including logistics, supply chain management, economics, operations management, international business, and strategy disciplines; and the qualitative study. The qualitative study comprised of 14 in-depth interviews and a focused group discussion. Both provided justification for each of the constructs and their associated relationships that comprise the model. The hypotheses tested in this dissertation are summarized in Table II-5:

TABLE II-5: SUMMARY OF HYPOTHESES

Number	Hypothesis
H1	Supply chains facing high supply risks (S_HD_L and S_HD_H environments) that adopt a hedging strategy will show a higher profit than supply chains that adopt an assuming strategy.
H2	Supply chains facing low supply risks (S_LD_H and S_LD_L environments) that adopt an assuming strategy will show a higher profit than supply chains that adopt a hedging strategy.
H3	Supply chains facing high demand risks (S_LD_H and S_HD_H environments) that adopt a postponement strategy will show a higher profit than supply chains adopting a speculation strategy.
H4	Supply chains facing low demand risks (S_LD_L and S_HD_L) environments that adopt a speculation strategy will show a higher profit than supply chains that adopt a postponement strategy.
H5	Supply chains facing low supply risks and low demand risks (S_LD_L environment) that adopt an assuming strategy on the supply side and a speculation strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.
H6	Supply chains facing low supply risks and high demand risks (S_LD_H environment) that adopt an assuming strategy on the supply side and a postponement strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.
H7	Supply chains facing high supply risks and low demand risks (S_HD_L environment) that adopt a hedging strategy on the supply side and a speculation strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.
H8	Supply chains facing high supply risks and high demand risks (S_HD_H environment) that adopt a hedging strategy on the supply side and a postponement strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.
H_E1	Supply chains facing low supply risks (S_LD_H environment) will show a higher profit than supply chains facing high supply risks (S_HD_H environment) from adopting a form postponement strategy.
H_E2	Irrespective of the level of demand risks, all supply chains facing high supply risks (S_HD_L and S_HD_H environment) will show an equal profit from adopting a hedging strategy.
H_E3	Irrespective of the level of demand risks, supply chains facing low supply risks (S_LD_L and S_LD_H environments) will show an equal profit from adopting an assuming strategy.
H_E4	Irrespective of the level of supply risks, supply chains facing low demand risks (S_LD_L and S_HD_L environments) will show an equal profit from adopting a speculation strategy.
H9	The total profit for a given combination of environment conditions and strategies under without-disruption condition will always be higher than total profit for the corresponding environmental conditions and strategies combination under with-disruption conditions.
H10	Under the with-disruption condition, hedging will always be better than an assuming strategy under corresponding environmental conditions and demand side strategy.

CHAPTER III : RESEARCH METHODOLOGY

INTRODUCTION

The model presented in Chapter II (Figure II-4) depicts the interrelationships between the external environment, supply chain risk management strategies, and outcomes in a global supply chain context. This chapter describes the methodology to test the model. The first section describes the research design, i.e., simulation methodology, and its appropriateness to study the phenomenon of global supply chain risk management. The next section discusses the procedure for simulating a system. This is followed by a discussion of previous applications of computer simulation to logistics and supply chain management topics. Next, the proposed simulation study is discussed in detail.

RESEARCH DESIGN

According to McGrath and Brinberg (1983), all research methods possess limitations in terms of both external and internal validity. In their words, "all methods are flawed, but different methods are flawed differently" (p.116). In recommending the use of multiple methods for investigating research questions, McGrath and Brinberg point out that the use of multiple methods is essential for statistical power as "differently flawed methods shore up each others' vulnerabilities" (p. 116). According to McGrath (1982), methodological strategies for conducting research fall into four generic classes -

I, II, III, and IV (see Figure III-1). These classes differ according to which one of the following three research goals (A, B, and C, in Figure III-1) is maximized:

A. Maximum Generalizability, i.e., the ability to generalize to the population(s) of interest

B. Maximum Precision/Control, i.e., precision in control/measurement/manipulation of variables

C. Maximum Realism of Context, i.e., existential realism, or whether or not the research "(takes) place in settings that are existentially 'real' for the participants (or the objects of the system of interest)" (p.74).

Research goal A addresses one dimension of external validity, i.e., the ability to generalize to a population contingent on how much the chosen sample represents the population. Research goal B addresses the construct validity of a concept, as reflected in the convergent and discriminant validity of some particular set of operationlizations of the concept (McGrath and Brinberg 1983). Research goal C addresses a second dimension of external validity, i.e., that of realism, or whether or not the context of the research closely matches some real world counterpart (Lynch 1982).

McGrath (1982) argues that a single research study, through the methodological choices that must be made with the purpose of study in mind, will necessarily emphasize one research goal over the other two.

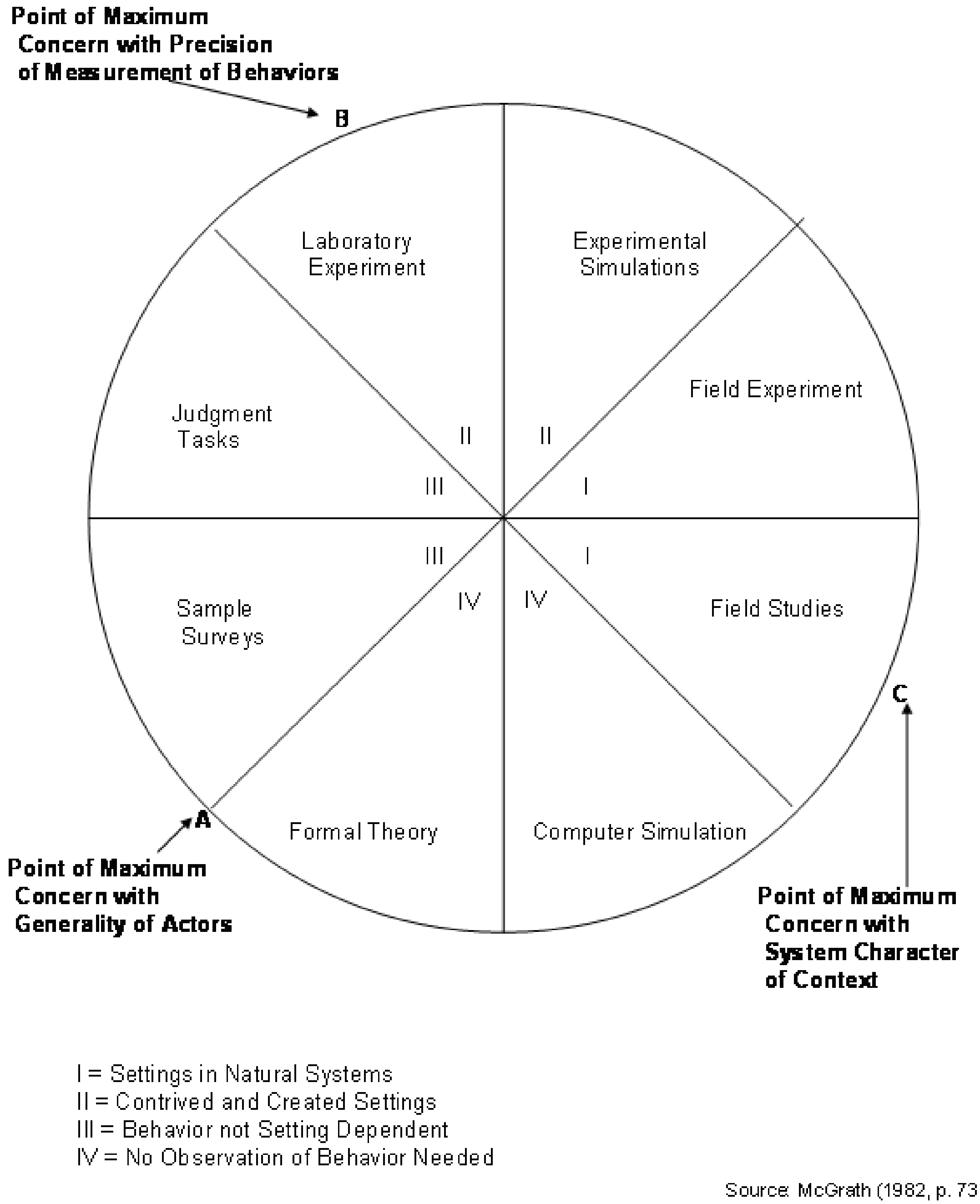


FIGURE III-1 : RESEARCH STRATEGIES

Source: McGrath (1982, p.73)

For example, survey research emphasizes representative sampling, and seeks to maximize population generalizability (research goal A). However, surveys are not able to address realism of context since they rely on participants' furnishing responses "after the fact" in an existential sense.

This study used computer simulation, which partially addresses the realism of context goal (research goal C). In this study, a computer simulation model is used as a basis for experimental analysis. Thus, it offers high precision in manipulation of variables, and therefore, primarily addresses research goal B.

In sum, a computer-simulation model used as the basis of an experimental design addresses research goal B (precision in control/measurement/manipulation of variables), and partially research goal C (existential realism or realism of context), but not research goal A (ability to generalize to a population of interest) (Bienstock 1994).

Simulation has emerged as a tool for analysis of logistics and supply chain systems because in these systems, uncertainties and resulting variances are significant considerations (Bowersox and Closs 1989). The capability of simulation to include stochastic situations makes it a powerful decision-making tool for supply chain managers. Simulation also enhances decision making by offering the flexibility to understand system behavior when cost parameters and policies are changed (Rosenfield, Copacino and Payne 1985). Simulation also permits time compression so that timely decisions can be made (Chang and Makatsoris 2001). Often, simulation runs representing years can be accomplished in a matter of hours.

Logistics and supply chain systems lend themselves to simulation because of the following characteristics of activities involved in these systems: a network of fixed facilities and connecting linkages, complex and stochastic linkages between components of a logistics system, and the ability to generate data that are relatively quantifiable (Mentzer and Cosmas 1979). The size and complexity of global supply chains, their stochastic nature, level of detail necessary for investigation, and the inter-relationships between system components make simulation modeling a particularly appropriate approach. In particular, simulation models are useful when a limited number of alternatives are to be considered, and the objective is to understand the effects of change due to a single or a limited number of variables (Rosenfield, Copacino and Payne 1985).

In terms of experimental design, the fact that "real life" controlled experimentation of logistics and supply chains is extremely difficult makes experimental designs using computer simulation models an attractive alternative for understanding system behavior (Chang and Makatsoris 2001). Even when such "real life" experiments are possible, cost and organizational disruptions may not permit extensive revisions of the systems (Rosenfield, Copacino and Payne 1985). As Shubik (1960, p.909) explains, "the model is amenable to manipulation which would be too expensive or impractical to perform on the entity it portrays. The operation of a model can be studied, and from it, properties concerning the behavior of the actual system, or its subsystems can be inferred."

In a global supply chain, the choice of a risk management strategy is a decision that is expensive to implement, and difficult to alter in the short term. Further, an incorrect choice can lead to costly mistakes. A quote from a manager who was a participant in the qualitative study illustrates an off-shoring decision, the cost of which could be reasonably estimated *a priori* using simulation. This manager was comparing domestic and global supply chains of two different products for his company. This problem also provides an example of a type of global supply chain problem, i.e., off-shoring, which this research attempts to address.

> *"The X Division is a big washing machine factory of Company Y. This factory employees 3000 people, covers two million square feet and it makes 20,000 washers a day in three shifts. Now that's one every five seconds, 24 hours a day, that come out of this factory on a conveyor over to the warehouse. That factory is flexible enough to be able to only operate with a seven day from schedule. In other words, what that means is they want to fix their schedule for seven days in order to provide some stability to the operation. But on the eighth day they allow the corporate planners to change their schedule any way that's necessary in order to react to the orders.*
>
> *Compare that to getting microwave ovens from China. You've got thirty days on the water alone. I mean, not on the water, but from point to point you've got thirty days of just transit time. You've got then the factory itself is not nearly as flexible as X in that they have one month from schedules, not seven days, one month. So suddenly you're two months away from demand and that doesn't count the additional inventory that you're putting in the system as well. So you can see the enormous loss of flexibility that you have when you start globally sourcing versus our local factories. Our systems weren't prepared to deal with that kind of environment. We didn't know how to optimize it or really to deal with it. So certainly a number of projects that I've worked on then and now at Company Y to deal with that issue of how do you deal with a supply chain that is suddenly many times longer than it was, when we were just a domestically sourced business."*

In addition to recognizing simulation modeling as a viable and appropriate means of studying complex logistics and supply chain problems, several scholars have made explicit calls for increased usage of simulation modeling to study supply chains. Bowersox and Closs (1989) called for refining existing and building new simulation tools to identify and improve logistics system performance, and to obtain better understanding of cost-service trade-offs. Allen and Emmelhainz (1984) contend that conventional managerial judgment may not always result in effective decision making, thereby making simulation-based research a worthy endeavor. More recently, Min and Zhou (2002) call for a resurgence of simulation models to evaluate dynamic decision rules for managing supply chains.

In particular, for supply chain risk management, Sykes (2006, p.13) makes a case for developing mathematical models for risk management in supply chains by contending that, "The subject of supply chain risk is coming to the forefront of our profession today, and it has not adopted the mathematical and statistically driven methods of our professional counterparts in the fields of finance and insurance." Kleindorfer and Saad (2005) argue that good crises management (i.e., mitigation planning) is not enough; linking risk assessment and quantification with risk management options *ex ante* is of fundamental importance in understanding the potential for ultimate harm to the organization and the supply chain. Without such quantification, there might be a general sense of alarm in the firm and the supply chain, but it will not be directed towards the effective strategies for managing risks.

In sum, computer-based simulation is ideally suited to study the phenomenon for two reasons. First, the strengths of the methodology are ideally suited to model a global supply chain and accomplish the second objective of this dissertation, i.e., build a theory of environment-strategy fit for risk management in the global supply chain. Second, the general sentiment echoed by researchers interested in studying supply chains is to move toward development of simulation models that adequately reflect the stochastic nature of the supply chains, and can assist in theory building as well as decision-making.

SIMULATION PROCESS

On the basis of Law and Kelton (1982), and Banks (1998), the process of simulating a system may be divided into 8 steps (see Figure III-2). This discussion here is brief and focuses largely on the objectives of each step. A detailed discussion on how each step is performed for this research is presented later in the section entitled, "Methodological Approach of This Research."

The first step is to formulate the problem. The problem may not initially be stated precisely or in quantitative terms. Often, an iterative process is necessary. As the problem of interest becomes clearer, overall objectives, specific questions that need to be answered, performance measures of interest, scope of the model, and time frame and resources required for the study need to be determined.

The second step is to specify performance criteria (or response variables), and system parameters (or independent variables). In a simulation model, independent variables are manipulated and their effect on dependent variables is recorded and analyzed.

The third step is to construct a conceptual model and validate it. The real-world system under investigation is abstracted by a conceptual model.

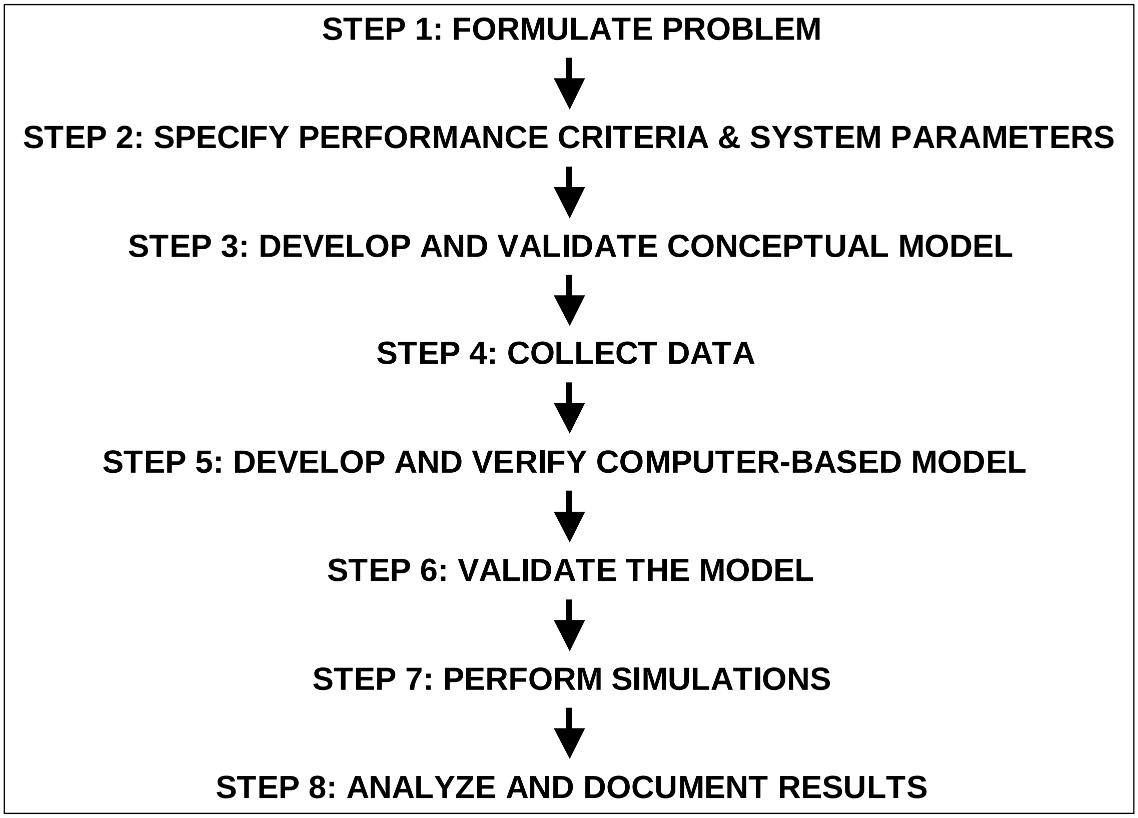


FIGURE III-2 : SIMULATION PROCESS

Developed based on Law and Kelton (1982), Banks (1998), Gomes (1988), and Bienstock (1994).

The conceptual model includes mathematical and logical relationships concerning the components and structure of the system (Banks 1998). This step involves documenting the model concepts, assumptions, algorithms, data summaries, and model components. In general, a dynamic event driven stochastic model has the following components (Law and Kelton 1982):

> System state: the collection of state variables necessary to describe the system at a particular time
> Simulation clock: a variable giving the current value of a simulated clock
> Event list: a list containing the next time each type of event will occur
> Initialization routine: a subroutine used to initialize the model at time zero
> Timing routine: a subroutine which determines the next event from the event list and advances the simulation clock to the time when the event is to occur
> Event routine: a subroutine which updates the system when an event occurs
> Main program: a subprogram which calls the timing routine to determine the next event and then transfers control to the event routine
> Statistical counters: variables used to store statistical information about system performance
> Report generator: a subroutine which computes estimates (from the statistical counters) of desired measures of performance and prints reports when simulation ends

The fourth step is to collect data. Data collection may follow or proceed concurrently with conceptual model development. Data have to be collected to specify model parameters, system layout and operating procedures, and probability distributions of variables of interest. Data may come from company databases, interviews, surveys, books, and/or other published sources. Data may be made up depending upon the requirements of the model and the objectives of the study. Collecting data can be challenging in many cases as data may not be readily available in required formats or in an appropriate level of detail. Before use in the model, data may need to be scanned, cleaned, and updated to account for discrepancies and/or missing data.

The fifth step is to develop and verify the structure of the computer-based simulation model. This means examining the substructure outputs and determining whether they behave acceptably (Fishman and Kiviat 1968), as well as making sure that the complete simulation model structure is executing as intended (Law and Kelton 1982). This is achieved by debugging the programming logic and code (Mentzer and Gomes 1991). Fishman and Kiviat (1968) identify two important benefits of verification: identifying unwanted system behavior, and determining whether an analytical or simple simulation substructure can be substituted for a complex one. Banks (1998) strongly advises that verification should be a continuous process rather than waiting until the entire model is coded.

The sixth step is to validate the model. Model validation is the process of determining whether a simulation is an accurate representation of the system of interest (Law and Kelton 1982). All simulation models need to be validated, or any decisions made with the model may be erroneous. A "valid" model can be used to make decisions similar to those that would be made if it were feasible and cost-effective to experiment with the system itself (Law 2005). A simulation model of a complex system can only be an approximation to the actual system, no matter how much time and money is spent on model building (Law and McComas 2001) .

The seventh step is to perform simulations. For each system configuration of interest, decisions have to be made on tactical issues such as run length, warm-up period, and the number of independent model replications. In simulation, the benefits of additional model replications, i.e., increased sample size, may be gained by (1) increasing the number of replications (simulation runs) for each experimental condition (each cell), (2) decreasing the length of subinterval, i.e., reducing the time unit to provide more subintervals for the same length of run, and (3) increasing the length of the run to increase the number of subintervals (Mentzer and Gomes 1991; Bienstock 1994). It is also important to note here that the power of a test to detect an effect increases with the number of replications (Mentzer and Gomes 1991). This must be weighed against the cost in time and money to make additional runs.

The eighth and final step is to analyze and document the results. Model runs are used to estimate performance measures. Several tests may be performed to test for statistical significance of results. These are discussed at several places throughout this chapter including in the descriptions of past studies. The documentation for the simulation study should include the conceptual model (critical for future reuse of the model), a detailed description of the computer program, and the results of the study.

PAST SIMULATION MODELING RESEARCH

This section provides a discussion of past studies that mark significant advancements in simulation methodology application to logistics and supply chain problems, particularly in the context of uncertainties faced by the logistics and supply chain systems. First, three major landmark studies – Industrial Dynamics Model (1961), Long Range Environmental Planning Software (1972), and Strategic Planning Model (1991) are discussed. Next, a review of nine simulation studies is presented to assist in the rigorous development of this model. Finally, how each step of the simulation process described in the previous section was executed for this study is described in full detail.

INDUSTRIAL DYNAMICS MODEL (1961)

Forrester (1961) developed one of the first large scale production and distribution models of the firm for experimental use. The principal contribution of this model was its demonstration of the effect of variation in customer demand on inventory levels throughout the system. To investigate system response, he introduced the following:

1. a demand increase of 10%
2. a 10% rise and fall in sales over one year
3. an irregular sales pattern
4. a reduction in available clerical delays

Forrester considered each independent variable (1 though 4 above) in turn with all others held constant. Forrester's output was graphical without any statistical analysis, and did not utilize experimental design. Without any sample size and statistical tests of the significance of the results, statistical conclusion validity (i.e., the extent that the statistical conclusions are true) is non-existent. Concerning model validation, Forrester felt that the primary purpose of the model was to facilitate the design of better management systems. According to this criterion, the validity of the model could be determined only after it had been used for system redesign (Bienstock 1994). His work generated considerable interest in simulation and led to future methodological improvements in simulation approaches. Forrester's model had around forty relationships involving factors such as inventory levels, orders, shipments, purchasing rates, mailing delays, transportation times, and factory lead times.

LONG RANGE ENVIRONMENTAL PLANNING SIMULATION (LREPS) MODEL (1972)

LREPS, developed by Bowersox et al. (1972), was a dynamic simulation model to evaluate system cost and service response to different distribution system designs. The model incorporated the logistics elements of transportation, warehousing, inventory, and communication for three echelons of a distribution system (one manufacturer, to two wholesalers, to four retailers each) and measured system responses of total cost and customer service (delivery performance). This model was the first truly large scale event-driven, dynamic (stochastic) temporally integrated analysis tool to probe the complex and subtle intricacies of alternative operating policies.

The LREPS model dealt with variations in both demand and lead times, which formed the independent variables used for a full factorial design. As demand was varied, lead time was held constant, and as lead times varied, demand was held constant. Four control runs were made with both demand and lead time constant as a basis for system performance under uncertainty. The response variables included measures of system cost and service. Analytical techniques included analysis of variance using the f-test, Chi-square tests, Theil's Inequality coefficient, Tukey's test of multiple comparisons, Dunnett's method of multiple comparisons, spectral analysis, graphical analysis, and factor analysis.

The results indicated that uncertainty of both lead time and demand reduced service, with lead time uncertainty having a greater impact. Similarly, for total system cost, high demand uncertainty did not significantly increase total system cost, while high lead time uncertainty did.

This study showed considerable advancement in experimental design and methodology over its predecessors. Bowersox et al. performed an array of analyses to examine the model's validity, which they maintained was indicated by: 1) the model's long-term stability, 2) sensitivity of model response to model assumptions, and 3) comparison of model output with historical output. LREPS appeared to possess long-term stability and the model's response variables (total cost and delivery performance) proved to be relatively insensitive to the methods used for generating demand and the selection of product categories used in the analyses. However, the results for the comparison of model output with historical output were less conclusive, leading the authors to state, "...the validity of model's predictive ability has not been established" (p.184).

STRATEGIC PLANNING MODEL (1991)

Mentzer and Gomes (1991) developed a PC-based multi-echelon, stochastic, simulator intended to act as an adaptive strategic decision support system (DSS) generator which they termed the Strategic Planning Model (SPM). SPM could be configured to present detailed functioning of operating systems, production or distribution facilities, and even entire channels. Models of the type represented by SPM are multi-echelon as they represent a number of consecutive levels in a channel or a supply chain. The model was designed to accommodate any number of sources of supply, distribution centers, markets, products, and branches (retail locations). A model is termed stochastic if it contains randomly generated variables. The stochastic nature of the SPM was important as average values do not adequately reflect the real world random behavior that affects the system performance. The SPM had the ability to accept initial information on system, plant, and channel configuration and operation, and be repeatedly configured according to the requirements. Therefore, it qualifies as an adaptive DSS generator. SPM retained the LREPS advantage of large-scale but expanded the range of application. Since it was the first PC-based simulation model in logistics, it also built upon improved capabilities in data preparation efficiencies, user friendliness, and computing speed.

Mentzer and Gomes (1991) extensively validated and verified the model using the following procedure suggested by Meier, Newell and Pazer (1969):

1. Compare short pilot model runs to hand calculation
2. Verify model segments separately
3. Replace stochastic elements with deterministic
4. Use simplified probability distributions
5. Use simple test data input

For verification (debugging) of the model, random number generators were tested for uniformity of distribution by a “chi-square” test for independence. Similarly, a “chi-square” test was used to test the distribution function by which the random number generators created random variables (e.g., demand distributions) in the model. Since SPM was applied to several real-life systems, other techniques, such as Kolmogorov-Smirnov tests, factor analysis, spectral analysis, regression analysis, and Theil's inequality coefficient, were used to test whether a particular SPM generated model matched the historical reality of corporate systems under investigation. In addition, Mentzer and Gomes (1991) provide details on addressing other issues such as start-up time, stochastic convergence, and sample size determination. Gomes and Mentzer (1991) utilized the SPM to investigate Just-In-Time system performance under uncertainty. This study is one of the nine summarized later in the next section.

SUMMARY OF NINE SIMULATION STUDIES

To find examples of rigorous studies, simulation studies published in the last 20 years in a wide variety of logistics, supply chain, and related journals were reviewed. As a result of this review, a summary of nine studies is presented. These nine studies were chosen based on the following criteria: The first step in the selection process limited the pool of simulation studies to only those that dealt with simulating more than one echelon in logistics, supply chain, or distribution systems. Next, from this pool of studies, those that reported in detail on the steps taken during the model development process were chosen. These studies provide insights into the measures taken to maintain the rigor of the research at each step in the simulation model development process, thereby providing guidance for this research.

Tables III-1 (A), (B), and (C) specify the manner in which each of these nine studies addressed all eight but the third step in the process. Step 3 is omitted because only one study in our sample set provided documentation of this important step in model development. The only exception, Appelqvist and Gubi (2005), specify that their model was compared to actual supply chain performance and reviewed in a structured walk-through with company management. However, it is not clear when the walk-through was conducted. It appears that even in this case conceptual validation was done during the actual simulation model validation (i.e., step 6). In general, if researchers omit conceptual validation early in the model development process and attempt to validate the computer or computational model directly, it may be too late, too costly, or too time-consuming to fix the errors and omissions in the computational model.

Following the tables, the method of execution of each step for this research is explained.

METHODOLOGICAL APPROACH OF THIS RESEARCH

This section elaborates on how each step in the simulation process was executed to maintain a high degree of rigor for this research.

TABLE III-1: SUMMARY OF PAST SIMULATION STUDIES

(Part A)

Author and Year	**Objective / Problem Formulation (Step 1)**	**Dependent Variable(s) (Step 2)**	**Independent Variable(s) (Step 2)**
Canbolat et al. (2005)	Estimating off-shoring risk for automotive components for an auto manufacturer (Ford)	Dollar value of risks, i.e., expected total costs after adjusting for risks	Around 40 risk factors can be specified in the model Delay, and duration of delay are key ones
Appelqvist and Gubi (2005)	Quantifying the benefits of postponement for a consumer electronics company as well as Supply Chain of Bang and Olefsun	Fill rate Total inventory	Demand Order-up-to levels for retail-outlet inventory Number of basic units Number of colored fronts
Shang, Li, and Tadikamalla (2004)	Identifying the best operating conditions for a supply chain to optimize performance	Total supply chain cost Service Levels	Extent of differentiation Extent of information sharing Capacity limit Reorder quantity Lead time Reliability of the suppliers Inventory holding costs Demand variability
Holland and Sodhi (2004)	Quantifying the effect of causes of Bullwhip Effect in a Supply Chain	Observed variance of manufacturer's order size Observed variance of retailer's order size	Demand autocorrelation Variance of forecast error Retailer's lead time Manufacturer's lead time Retailer's order batch size Manufacturer's order batch size Standard deviation of the deviation from the retailer's optimal order size Standard deviation of the deviation from the manufacturer's optimal order size
Bienstock and Mentzer (1999)	Investigating outsourcing decision for motor carrier transportation (applied to company H)	Mean total shipment cost	Structure (private/leased or for-hire carrier) Asset specificity Variation in loading, line-haul, and transportation times Volume and Frequency of shipments

TABLE III-1. Continued.

(Part A)

Author and Year	**Objective / Problem Formulation (Step 1)**	**Dependent Variable(s) (Step 2)**	**Independent Variable(s) (Step 2)**
Van der Vorst et al. (1998)	Improving performance in a real food supply chain	Inventory level at DC Inventory level at test outlet Product freshness at DC Product freshness at test outlet Total supply chain costs	5 improvement principles identified but the only ones discussed are: Delivery frequency Lead times
Mentzer and Gomes (1991)	Developing a strategic decision-support system called Strategic Planning Model which can be configured to simulate different logistics systems. Illustrated using one academic and one managerial application.	Depends on the system being simulated. (As an example, see Gomes and Mentzer (1991) below who used Strategic Planning Model (SPM) for their study)	Depends on the system being simulated.
Gomes and Mentzer (1991)	Understanding influence of JIT Systems on Distribution Channel Performance	Profit Order cycle time Standard deviation of order cycle time Percent customer orders filled	Materials management JIT (with or without) Physical distribution JIT (with or without) Materials management uncertainty Demand uncertainty
Powers and Closs (1987)	Understanding impact of trade incentives on a simulated grocery products distribution channel	Average distribution center inventory level Shipment size pattern Total number of shipments Customer service level Total financial performance	Response increase (% increase in sales during the incentive period) Demand uncertainty Payback (reduction in sales level from normal at the conclusion of the incentive) Incentive level

TABLE III-1. Continued.

(Part B)

Study (Author and Year)	**Sources of Data (Step 4)**	**Programming Environment (Step 5)**	**Model Verification (Step 5)**
Canbolat et al (2005)	Personal interviews or surveys (questionnaire) of company executives, and subject matter experts	MS Excel with @RISK add-in	Three case studies (one with Ford die cast component illustrated in this paper)
Appelqvist and Gubi (2005)(2005)	Historical data and made-up data Qualitative data from interviewing managers at the headquarters and retailers downstream	Not Specified	Not specified
Shang, Li and Tadikamalla (2004)(2004)	Bass (1969) Model for generating demand Existing research for inventory holding costs	ARENA	Verifying model architecture with literature and other researchers
Holland and Sodhi (2004)(2004)	Made-up data	Gauss 5.0	Not specified
Bienstock and Mentzer (1999)(1999)	Real companies Published sources such as books, and statistics from American Trucking Association	SLAMSYSTEM, a FORTRAN based simulation software	Mentions that model was verified but the process is not specified
Van Der Vorst et al. (1998)	Actual data from a producer, a distributor, and retailer outlets of chilled salads	Not specified	Not specified
Mentzer and Gomes (1991)	Depends on the system being simulated	Not specified	Testing random number generators using chi-square test Compare short pilot model runs to hand calculation Verify model segments separately Replace stochastic elements with deterministic Use simplified probability distributions Use simple test data input
Gomes and Mentzer (1991)	Real companies, and published sources such as books	Not specified	Verified as per Fishman and Kiviat (1968) Verification of uniformity and independence of model's random number generators
Powers and Closs (1987)	Made-up data built on Simulated Product Sales Forecasting model	Not specified	Testing programming logic through statistical output

TABLE III-1. Continued.

(Part C)

Study (Author and Year)	**Validation (Step 6)**	**Sample Size and Sample Size Determination (Step 7)**	**Analysis Techniques (Step 8)**	**Other important details**
Canbolat et al (2005)	Validation using case studies	Not Specified	Ranking of failure modes Mean, lower and upper limits, standard deviation, and 5^{th} and 95^{th} percentile of dollar value of risks	
Appelqvist and Gubi (2005)	Using input-output transformation, i.e., comparing simulation data to real world data, on performance measures such as delivery times, delivery accuracy, and inventory levels. Structured walk-through with company management.	Five replications for each unique scenario Each replication consisted of a 100 day warm-up period and a 1,000 day steady-state run	Inspection of graphical outputs Percentage changes in performance measures	Same demand data sets used for all replications. This technique is known as correlated sampling and provides a high statistical confidence level.
Shang, Li, and Tadikamalla (2004)	Comparing simulation results with analytical models for simple known cases	1000 replications of the system for 20 months	Visual inspection of graphical output Taguchi (1986) method for parameter design Response surface methodology, i.e., fitting regression models to simulation output	
Holland and Sodhi (2004)	Not specified	186 time intervals (weeks) of which middle 152 weeks were used	Regression Analysis	
Bienstock and Mentzer (1999)	Testing face validity using literature, and review of distribution system simulation models Interviews with employees of company H Comparison of model output with actual company data	10 runs per cell determined as per Law and Kelton (1982) relative precision method	ANOVA	Tested for bias created by initial starting conditions

TABLE III-1. Continued.

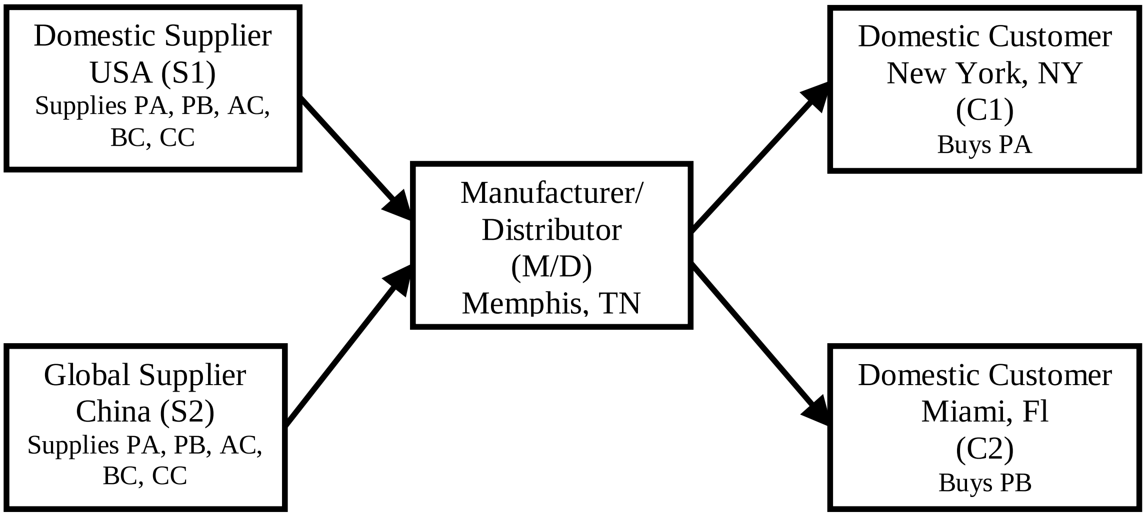
(Part C)

Study (Author and Year)	Validation (Step 6)	Sample Size and Sample Size Determination (Step 7)	Analysis Techniques (Step 8)	Other important details
Van der Vorst (1998)	Implementation of one scenario to two retail outlets, and measurement against a control outlet as well as simulated results	Not specified	Percentage changes in performance measures (such as inventory levels and remaining product freshness) at distributor and two retail outlets	
Mentzer and Gomes (1991)	Extensively validated different SPM models in following ways: Compared simulation output with historical data from real system for by using Chi-square tests, Kolmogorov-Smirnov tests, Factor Analysis, Spectral Analysis, Simple Regression, and Theil's inequality coefficient. Warm-up and transient period: No effect beyond first month Stochastic Convergence: None for up to 5 years	An example illustration uses sample variance from pilot runs and a desired confidence interval width and precision	Example illustrations use: ANOVA Percentage increases in response variables	Two applications – one on JIT systems and one on manufacturer and distributor of automotive aftermarket- are discussed in the paper.
Gomes and Mentzer (1991)	SPM model had external validity (see Mentzer and Gomes 1991)	10 runs per cell determined as per 95% confidence interval Start-up transient period effected only first few weeks	ANCOVA for response variable profit; ANOVA for main effects of all other response variables Scheffe's method for multiple comparisons of cell means Fisher's Least Significant Difference method for pair-wise comparisons	ANCOVA is used because profit is significantly correlated to demand
Powers and Closs (1987)	Testing face validity by review groups Model stability and model sensitivity using ANOVA and sensitivity analysis	Not specified	Graphically Statistically using ANOVA	

STEP 1: FORMULATE PROBLEM

The first step is to formulate the problem. The second objective of this dissertation, as stated in Chapter I, is to build a theory of environment-strategy fit for risk management in the global supply chain. In light of this objective, and the hypotheses developed in Chapter II (see Table II-5), the research question driving the simulation process is the fourth research question identified in Chapter I: How does performance of global supply chains vary under different combinations of environmental conditions (i.e., supply and demand risks), and the strategy selected?

In this research, a simulated global supply chain with two suppliers, a manufacturer/distributor, and two customers is conceptualized (See Figure III-3). There is one supplier each in the US (S1) and China (S2). The manufacturer/distributor (M/D) and both customers (C1 and C2) are based in the US. The manufacturer/distributor is based in Memphis, Tennessee, the first customer (C1) in New York, New York, and the second customer (C2) in Miami, Florida. The manufacturer/distributor sells two products – Product A to C1 and Product B to C2. Product A is composed of two components – A-Component (AC) unique to Product A and Common-Component (CC) shared between Product A and Product B. Product B is composed of two components – B-Component (BC) unique to Product B and the Common-Component (CC). Both suppliers – S1 and S2 – can supply the two products (Product A and Product B) or the three product components (AC, BC, and CC).



Notes:

1. Both suppliers can supply product A (PA), product B (PB), component AC, component BC, and component CC.
2. C1 buys PA
3. C2 buys PB
4. PA = AC + CC
5. PB = BC + CC

FIGURE III-3 : SIMULATED SUPPLY CHAIN

The product chosen for this study was a printer. A printer has a medium value-weight and weight-bulk ratio, which is important because extreme product characteristics can limit the usefulness of findings. In addition, printers were chosen because imports share of domestic demand has grown steadily from 58.5% in 2001 to 78.1% in 2006.

STEP 2: SPECIFY PERFORMANCE CRITERIA AND SYSTEM PARAMETERS

Performance criteria include the dependent variables, and system parameters include the independent variables for a model.

System Parameters / Independent Variables

Risk events serve as the independent variables for this event-driven model. For supply and demand risks, a comprehensive list was provided in Table II-4 in Chapter II. However, due to time and resource constraints and to make sure that the results can be interpreted, there is a limit on the number of factors that can be included in a study. A short-listing of events most salient to global supply chains helps in maintaining the simplicity of the model without compromising the objectives of the research. Therefore, the risk events listed in Table II-4 in Chapter II were grouped into three categories based on how risk events are manifest, relevance of risk events to this research, and additional interviews conducted to collect data. These categories are: supply, demand, and disruption. For the supply category, events that do not differ significantly between domestic and global contexts (identified as Similar or S in Table II-4, Chapter II) were either not included in this research or not varied between domestic and global suppliers.

For the demand category, all supply chain customers are based in the US. Furthermore, it is assumed that the products have non-seasonal demands. Therefore, the risk events that are either global in nature or relate to a seasonal product were either not included in this research or not varied between low and high demand risks.

Disruption is a moderator in this research. As discussed in Chapter II, a supply disruption in the form of a port closure is modeled. Apart from the fact that port disruption was a major concern expressed by several supply chain managers, a port disruption is also relevant as it is an event that is global in nature. The main focus of this research is to understand the impact of risks in a "global" context. Since the manufacturer/distributor and the customers are based domestically, only disruption events that affect the global supplier or the inbound global supply are within the scope of this study. To model disruption for this research, a 45-day closure of the port of Los Angeles is operationalized.

Table III-2 provides a list of all independent variables, their definitions, values, and any additional information in the remarks column. Supply risk events are divided into: lead time variability, cost variability, and quality variability. Lead time variability is further divided into order processing time variability, and transportation lead time variability. Demand side risk is manifest by demand variability. The moderator is opertaionalized using a 45-day disruption at the US port. Please note that data sources for all independent variables are discussed in detail under the next step, i.e., Step 3.

TABLE III-2: INDEPENDENT VARIABLES

Risk Factors	Definition	Global (Low)	Global (High)	US*	Remarks
1. Supplier Order Processing Time Variability	Time from order placement to replenishment at the supplier facility	N(15, 1.5) days	N(15,3) days	N(10,1) days	Normal(Mean, SD)
2. Cost Variability	Sourcing cost variability due to changes in exchange rates, wage rates, shortage of goods, natural disasters, oil price increases, and any other unforeseen reasons				15% for low supply risk 45% for high supply risk T=Triangular
	Product A or Product B ($)	T (60,64.5, 69)	T (60, 73.5, 87)	80	T (Min, Mean, Max)
	Component AC or Component BC ($)	T (15, 16.125, 17.25)	T (15, 18.375, 21.75)	20	T (Min, Mean, Max)
	Component CC ($)	T (35, 37.625, 40.25)	T (35, 42.875, 50.75)	50	T (Min, Mean, Max)
3. Quality Variability/ Yield					
	Receipt of lower usable quantity due to losses, damages, and pilferage in-transit, communication errors, market capacity, war and terrorism, and natural disasters.	0.98	0.97	0.99	1% defects for domestic supplier 2% defects for low risk China supplier 3% defects for high risk China supplier

(Demand Risk Event)

Risk Factors	Definition	Manifest as	Low Risk	High Risk	Remarks
1. Variability of demand	Average variation in daily demand	Mean Standard Deviation	N (1000, 100)	N (1000,300)	Normal (Mean, Standard Deviation)

(Moderator)

Risk Factors	Definition	Manifest as	Remarks
1. Disruption	Closure of US port for 45 days	Closure of US port for 45 days on a randomly generated day between day 60 and day 600.	Only for 16 with-disruption scenarios

* US values remain constant throughout all scenarios

Performance Criteria / Dependent Variables

As discussed in Chapter II, the testing of hypotheses is based on total supply chain profit as it takes into account several other performance measures including total supply chain costs (inventory, transportation, and production costs), total supply chain revenues, and penalty costs associated with late deliveries. However, in addition to the total supply chain profit, several other measures are recorded including stock-outs, total inbound lead time, fill rates, delays to customers, and average inventory. The additional measures are recorded to help in interpretation of results.

The focus is not only on the measurement of means of total profit for different scenarios, but also on its distribution. In particular, it is important to look at distributions because a distribution may be skewed left or right or be leptokurtic (flatter than normal) and have "fat tails," or be exponential, Poisson, or any other distribution. The consequence of these characteristics is that extreme outcomes happen much more frequently than indicated in calculations using normal probability distributions, and "most likely" outcomes have a lower probability of occurrence than those calculated with normal distributions.

Table III-3 provides a list and definitions of dependent variables and the manner in which each variable is measured.

TABLE III-3: SUPPLY CHAIN PERFORMANCE CRITERIA
(Dependent Variables)

Performance Criteria	**Definition/Operationalization**	**Measured as**
Primary Criterion		
Total Supply Chain Profit	Difference between total revenues earned and total costs	Dollar value Distribution of dollar value
Other Criteria		
Total Supply Chain Cost	Sum total of costs incurred by the supply chain including transportation, inventory carrying, production, warehousing, and penalty costs	Dollar value Distribution of dollar value
Stock-outs	The inability to meet customer demand for a given quantity by due date because of non-availability of inbound components, products, or raw materials	Units Total penalty cost for late delivery
Total Inbound Lead Time	The sum of supplier lead time, transportation time, and port clearance time	Number of Days Distribution of number of days
Fill rates	Order fill rate: the number of orders filled complete and on time divided by total number of orders in a given time period. Unit fill rate: for a given order, unit fill rate is the number of units shipped divided by the total number of units ordered. Line fill rate: for a given order, line fill rate is the number of lines filled complete divided by the total number of lines in an order.	Percentages
Delays to customers	Orders delivered late and the length of delays	Length of delay Distribution of length of delay
Average Inventory	The average number of units on hand over a given period of time across the entire supply chain	Average number of units Dollar value of average inventory

Operationalization of Supply Chain Environments

Supply chain environments are comprised of supply and demand risks. The low supply risk environment was operationalized as low supplier order processing time variability, low cost variability, and low levels of quality defects. The high supply risk environment was operationalized as high supplier order processing time variability, high cost variability, and high levels of quality defects. The low demand risk environment was operationalized as low demand variability and the high demand risk environment was operationalized as high demand variability.

Operationalization of Supply Chain Risk Management Strategies

The assuming strategy was operationalized by using a single Chinese supplier. The hedging strategy was operationalized by using two suppliers, one each in the US and China.

The speculation strategy was operationalized by sourcing finished products from suppliers, i.e., the manufacturer/distributor buys Product A and Product B. The goods are held in finished form at the manufacturer/distributor, i.e., made-to-stock, and are shipped to customers per the demand. The postponement strategy was operationalized by sourcing components from the suppliers and assembling them at the manufacturer/distributor, i.e., the manufacturer/distributor buys parts AC, BC, and CC. The goods are assembled at the manufacturer/distributor, i.e., a made-to-order, and are shipped to customers per the demand.

STEP 3: DEVELOP AND VALIDATE MODEL CONCEPTUALLY

The third step deals with the development and validation of the conceptual model. The real-world system under investigation is abstracted by a conceptual model that includes mathematical and logical relationships concerning the components and structure of the system (Banks 1998). Forrester (1958) stated that to determine the behavior of a system by simulating the performance of its parts requires that one describe exactly, and in detail, the characteristics (relationships) which are to be included. The validity of the outcome of a system depends on what is included in the system description. It is important to construct a conceptual model so that the model can be verified prior to spending resources programming the model. The level of detail in the model depends upon the objectives, performance measures of interest, data availability, computer, time, and resource constraints, and the opinion of the users of the model.

To conceptually validate the model, subject matter experts were consulted and interviewed at every step. The primary review and consultation team consisted of four academics. Two are content experts and have experience with simulation modeling, one is a content expert, and one is a management scientist with experience using stochastic data for modeling. This team was consulted throughout the process. This research followed Banks' (1998) recommendation that modeling begin simply and complexity be added in steps until a model of acceptable detail and complexity has been developed. All changes made to the model because of additional literature explored, and data collected were reviewed by this team. When an acceptable level of detail and complexity was achieved as per this primary review team, two business practitioners separately reviewed the conceptual model.

The model flow for this study can be divided into the following six stages:

1. Demand generated at the customer location
2. Order received and processed at the manufacturer/distributor
3. Order placed on the supplier(s)
4. Order received at the supplier facility (order processing at suppliers)
5. Order shipped from supplier to the assembler/distributor
6. Order shipped from assembler/distributor to the customers

For each of these stages, the Table III-4 provides the sub-steps. For each sub-step cost and/or time, as applicable, are presented. For all independent variables, distribution and values, as identified earlier in Step 2, are incorporated. For every value used in the model, the last column provides either the source of data or rationale for using a value or states that the value is an assumed value.

The following discussion elaborates on each of the six stages of the conceptual model. Detailed information on each step is provided and all mathematical calculations are explained in the following paragraphs.

Stage 1: Demand generated at the customer location

The model is triggered by the generation of demand at the customer locations. Two activities take place during this stage: demand is generated, and demand is transmitted.

TABLE III-4: DETAILED MODEL FLOW

	Cost / Value	Time	Policy/Remarks	Operationalization (Independent Variables Only)		Data Source/ Rationale/Justification
				Distribution	**Values**	
Stage 1. Demand generated at the customer location						
a. Generation of demand	NA	NA	Generated Daily	Normal (N)	Low Risk ~N(1000,100) days High Risk ~N(1000,300) days	Average based on secondary data of a leading printer manufacturer SD validated in interviews and based on CV values by Mentzer and Gomes (1991)
b. Transmission of demand to manufacturer/ distributor	0	0	Transmitted instantaneously to manufacturer/ distributor Order due in 15 days			
Stage 2. Order received and processed at the manufacturer/ distributor						
a. Order processing costs and constraints						
Speculation	$10/unit	22.153 seconds /unit	Pick, pack Single work center (@130% daily capacity, i.e. 1300 units per day maximum; 1 shift/7 days a week/365 days an year			

TABLE III-4. Continued.

	Cost / Value	Time	Policy/Remarks	Operationalization (Independent Variables Only)		Data Source/ Rationale/Justification
				Distribution	Values	
Postponement	$20/unit	22.153 seconds /unit	Pick, assemble, pack, Assemble = $20Pick, pack, ship = $10Single work center (@130% daily capacity, i.e., 1300 units per day maximum;1 shift/7 days a week/365 days an year			Data from a major 3PL
b. Quality Variability	NA	NA	Quality checked for each product or component	Probability of an item being defective (binomial distribution)	Yield for strategies: Assuming Low Risk: 98% Assuming High Risk: 97% Hedging Low Risk: 98.5% Hedging High Risk: 98%	Assumed defect rates: US Supplier: 1% Low Risk China: 2% High Risk China: 3%
c. Inventory Value of products and components			Calculated on average purchase price of products and accounts for cost variability			
Assuming						
Component AC or Component BC	Low: $16.125 High: $18.375					Low: Mean for low risk China supplier High: Mean for high risk China supplier

TABLE III-4. Continued.

	Cost / Value	Time	Policy/Remarks	Operationalization (Independent Variables Only)		Data Source/ Rationale/Justification
				Distribution	Values	
Component CC	Low: $37.625 High: $42.875					Same as above
Product A or Product B	Low: $64.5 High: $73.5					Same as above
Hedging						
Component AC or Component BC	Low: $18.0625 High: $19.1875					Low: Average of the US supplier and Mean of low risk China supplier High: Average of the US supplier and Mean of high risk China supplier
Component CC	Low: $43.8125 High: $46.4375					Same as above
Product A or Product B	Low: $72.25 High: $76.75					Same as above
a. Order split	0	0	Assuming: All orders allocated to Chinese supplier Hedging: Every order has a 50-50 chance each of allocation to the US or Chinese supplier			

TABLE III-4. Continued.

	Cost / Value	Time	Policy/Remarks	Operationalization (Independent Variables Only)		Data Source/ Rationale/Justification
				Distribution	Values	
Stage 3: Order placed on the supplier(s)						
b. ROP-Q Values			Inventory levels checked every half hour When inventory levels falls below ROP level, an order for Q units is placed.			
ROP	NA	NA	Please see detailed explanation in the accompanying detailed model process explanation			
Q	NA	NA	Same as above			
c. Variability of purchase cost						
For US Supplier						
Product A	$80	NA				Fix US price; (US price-China price)/US price = 25%
Product B	$80	NA				
Component AC	$20	NA				
Component BC	$20	NA				
Component CC	$50	NA				
For Chinese supplier	Please see Indepen-dent Variables columns below		Triangular (T) distributions based on 15% and 45% changes in costs for low and high risk Chinese supplier respectively.			

TABLE III-4. Continued.

	Cost / Value	Time	Policy/Remarks	Operationalization (Independent Variables Only)		Data Source/ Rationale/Justification
				Distribution	**Values**	
Product A		NA		Triangular ($)	Low T(60,64.5, 69) High T(60, 73.5, 87)	15% is the cumulative effect of continuing trend of wage rate and currency exchange rate changes High of 45% chosen in consultation with the expert team
Product B		NA		Triangular ($)	Low T(60,64.5, 69) High T(60, 73.5, 87)	Same as above
Component AC		NA		Triangular ($)	Low T(15, 16.125, 17.25) High T(15, 18.375, 21.75)	Same as above
Component BC		NA		Triangular ($)	Low T(15, 16.125, 17.25) High T(15, 18.375, 21.75)	Same as above
Component CC		NA		Triangular ($)	Low T(35, 37.625, 40.25) High T(35, 42.875, 50.75)	Same as above
Stage 4: Order received at the supplier facility (order processing at suppliers)						
a. Orders fulfillment priority			Orders filled FIFO Supplier has no capacity constraints			FIFO validated in interviews (including backorder FIFO)

TABLE III-4. Continued.

	Cost / Value	Time	Policy/Remarks	Operationalization (Independent Variables Only)		Data Source/ Rationale/Justification
				Distribution	**Values**	
b. Order processing time	0	Please see Indepen-dent Variables column	Complete order shipped together	Normal (N) days	Domestic ~N(10,1) Days China Low Risk ~N(15,1.5) Days China High Risk ~N(15,4.5) Days	Gomes and Mentzer (1991)0.1 CV for low and 0.3 for high variability in inbound supply.
Stage 5: Order shipped from supplier to assembler/distributor						
a. Chinese supplier						
Ship complete order to HK Port (China supplier only)	0	1 day	Transportation cost included in per container charge from China port to US port			
At Hong Kong Port (China supplier only)	0	Please see Indepen-dent Variables column	Port costs included in per container charge from China port to US port	Triangular (T) days	T(4,5,6) Days	Data from interviews
HK Port to LA Port (China supplier only)	$3000 per container	Please see Indepen-dent Variables column	$3000/container includes the cost from China supplier through LA port including all taxes, charges, and other duties	Triangular (T) Days	T(13, 15, 20) Days	Report by Drewery Shipping Consultants Limited (Damas 2006)
At LA Port	0	Please see Indepen-dent Variables column	Port costs cost included in per container charge from China port to US port	Triangular (T) Days	T(3, 4, 5) Days	Data from interviews

TABLE III-4. Continued.

	Cost / Value	Time	Policy/Remarks	Operationalization (Independent Variables Only)		Data Source/ Rationale/Justification
				Distribution	**Values**	
From LA Port to Manufacturer/ Distributor	$3000 per TL	Please see Indepen-dent Variables column.		Triangular (T) Days	T(4,5,6) Days	Cost quote from trucking agency; times validated in interviews.
b. US supplier						
From Supplier to Manufacturer/ Distributor	$3000 per TL	Please see Indepen-dent Variables column		Triangular (T) Days	T(4,5,6) Days	Cost quote from trucking agency; times validated in interviews
Stage 6: Order shipped from Assembler/Distributor to the Customers						
a. Shipment to customers						
On-time orders	$10/unit	3 days	LTL transportation			
Late orders	$35/unit	3 days	$35 is penalty cost for each unit delivered late to the customer.			Penalty cost validated in interviews
b. Transit time		3 days				Data from interviews
c. Selling price	$150/ unit					Calculated based on secondary data on gross margins for a major printer manufacturer.

a. Generation of Demand

Demand is generated daily at both customer sites, C1 and C2. The average demand is distributed normally with a mean 1000 units per day per customer. The average demand for each customer is derived from secondary data of a major printer manufacturer company.

The standard deviation is set to 100 units for low demand risk scenario and 300 units for high demand risk scenario. This sets the coefficient of variation to 0.1 for low demand risk scenarios and to 0.3 for high demand risk scenarios. These coefficients of variation have been used in past research (Mentzer and Gomes 1991) to operationalize low and high demand risk scenarios. These values were also validated during conceptual validation with practitioners.

b. Transmission of demand to manufacturer/distributor

Demand generated at customers is transmitted instantaneously to the manufacturer/distributor. There is no cost for order transmission. The order is due in 15 days. Units arriving later than 15 days incur a penalty of $35/unit. This is approximately 25% of the selling price and was validated in qualitative interviews.

Stage 2: Order received and processed at the manufacturer/distributor

Orders placed by customers are received instantaneously at the manufacturer/distributor. The order processing begins immediately. The processing at manufacturer/distributor takes place 8 hours a day, 7 days a week, and 365 days a year. Order processing includes picking products, packing, and shipping goods in case of speculation scenarios. Order processing includes picking components, assembling, packing and shipping goods in case of postponement scenarios. Three main activities that take place during this stage are described below.

a. Order processing costs and constraints

For the speculation scenario, goods are picked from stock and shipped out to the customer. Order processing capacity is set to 130% of average daily demand. Not more than 1300 units of products of each type can be processed on any given day. Goods are shipped to customers every day. The cost of picking and packing either product A or product B is $10/unit and the cost of shipping either product A or product B is $10/unit.

For the postponement scenario, goods are assembled to order. The order processing capacity is set to 130% of daily demand. Not more than 1300 units of products of each type can be processed on any given day. Assembled, finished goods are shipped to the customers every day. The cost of assembling either product A or product B is $20/unit per unit and the cost of shipping either product A or product B is $10/unit.

b. Quality variability

Depending upon the supplier, i.e., Chinese or domestic, the number of usable units received varies. These are accounted for in the order processing stage. As mentioned earlier, quality variability is an independent supply risk variable in this model. Quality variability is operationalized using variable yields from different suppliers. For the domestic supplier, every unit has a 1% chance of being defective, i.e., the yield is 99% or 0.99. For the low risk Chinese supplier, every unit has a 2% chance of being defective, i.e., yield is 98% or 0.98. For the high risk Chinese supplier, every unit has a 3% chance of being defective, i.e., yield is 97% or 0.97. Therefore, for assuming scenarios, yield is set to 0.98 in low risk scenarios and 0.97 in high risk scenarios. As explained earlier, on average given the 50-50 chance of assignment of orders to one of the two suppliers, orders are split equally between the two suppliers in the hedging scenario. Therefore, average of the yields for the two suppliers is used for the hedging scenarios. For the hedging scenario, yield is set to 0.985 (average of 0.99 and 0.98) for the low risk scenarios and yield is set to 0.98 (average of 0.99 and 0.97) for the high risk scenarios.

c. Inventory value of products and components

The inventory value of products and components is assessed at average purchase cost and accounts for the changing cost variability under different scenarios. For example, for the low supply risk assuming scenarios, inventory for component AC is valued at $16.125, i.e., the average value, and not at $15 which is the base or lowest cost. Inventory is valued at 17% which is the average cost of carrying inventory per the 17th Annual State of Logistics Report (Wislon 2006). Inventory values of products and components are presented in Table III-4.

Stage 3: Order placed on the supplier(s)

As the orders are processed, inventory levels for finished products A and B in the speculation scenario and for component parts AC, BC, and CC in the postponement scenario are checked every half hour. Replenishment orders are placed based on Reorder Point (ROP) policy. Whenever the inventory level for a given product or component goes below the ROP, a replenishment order for a fixed quantity, Q, is placed with the supplier. Three main activities that take place during this stage are: assignment of orders to supplier, calculation of ROP and Q values, and calculation of purchase price.

a. Order Split

For the speculation scenario, all orders are assigned to the single Chinese supplier. For the hedging scenario, each replenishment order has an equal probability, i.e. 0.5, of being assigned to either the Chinese or the domestic supplier.

b. ROP-Q values

The value for ROP is calculated using the following formula (Mentzer and Krishnan 1985):

$ROP = \mu_{DDLT} + z\,\sigma_{DDLT}$

where,

μ_{DDLT} = average demand during lead time

$z = 1.00$ for an 84% in-stock probability

σ_{DDLT}= standard deviation of demand during lead time

The above formula is a standard business practice. The calculated value of ROP is rounded to the nearest integer that is a multiple of 500. This is done to avoid awkward numbers to minimize errors in keying in the data. It also provides simple 500-unit intervals when calculating expected costs of stock-outs as explained in the following paragraph. A validation check suggested that a difference of 250 units in reorder point, which is 0.5% of the smallest ROP value (46500), does not affect the model.

The value of Q is calculated using a procedure described in Coyle, Bardi and Langley Jr. (2003). First, the average and standard deviation of demand during lead time (DDLT) is calculated. Next, the probability of DDLT being greater than ROP level is calculated in increments of 500 units. The incremental probability between two levels of DDLT is multiplied by the difference of DDLT and ROP to calculate the number of stock-outs for each level. The total stock-outs for each level are then added to find the expected number of stock-outs for a given ROP. The expected value of stock-outs is used to calculate the value of Q using the following formula (Coyle, Bardi and Langley Jr. 2003):

$Q= \sqrt{(2R(A+G)/IC)}$

where,

R= Annual demand

A=Order cost per order

G=Stock-out cost per cycle

I=Inventory carrying cost

C=Cost of product or component

Finally, the calculated value of Q is rounded to the nearest integer that is a multiple of a container-load quantity for a given product or component. The number of units that fit in a 40-feet container is: 4880 units of component AC or BC, 1330 units of component CC, or 1200 units of finished product per container. The example in Table III-5 demonstrates the process for calculating Q for a low supply risk- low demand risk hedging -postponement scenario for component CC.

Table III-5 demonstrates the process of calculating ROP and Q values. The process is divided into four steps. First the mean and standard deviations of lead times are calculated. Then the value of ROP is calculated. Next, DDLT and standard deviation of DDLT are calculated to estimate the number of stock-outs per cycle. Finally, based on the cost of stock-outs, the value of Q is calculated.

TABLE III-5: AN EXAMPLE OF ORDER QUANTITY (Q) CALCULATION

a. Calculating mean and standard deviation of lead times

Lead Time for US Supplier	Min	Mode	Max	Mean	Variance	SD
Order processing time at US supplier				10	1.00	1
Domestic Supplier to M/D	4	5	6	5	0.17	
Total Lead Time for US Supplier				**15**	**1.17**	
Lead Time for Chinese Supplier						
Order processing time at Chinese supplier				15	2.25	1.5
China supplier to China Port	1	1	1	1	0.00	
At China Port	3	4	5	4	0.17	
China to US	13	15	20	16	2.17	
At US Port	2	3	4	3	0.17	
Port/Domestic Supplier to M/D	4	5	6	5	0.17	
Total Lead Time for Chinese Supplier				**44**	**4.92**	
Average/Pooled				**29.5**	**3.04**	

b. Calculating ROP

Demand – mean	2000
SD of Demand	140
LT- mean	29.5
LT- variance	3.04
sd of DDLT	3570
DDLT	59000
Inventory Carrying Cost	0.17
ROP (84%)	62570
ROP (rounded to nearest 500)	**62500**

TABLE III-5. Continued.

c. Calculating expected stock-outs

Demand during lead time (DDLT)	**Probability of DDLT**	**Marginal probability of DDLT**	**Expected stock-out (units)**
62,500	0.83655403		0.00000000
63,000	0.86873890	0.03218487	-16.09243689
63,500	0.89625653	0.02751763	-27.51763036
64,000	0.91932746	0.02307093	-34.60639839
64,500	0.93829514	0.01896768	-37.93535350
65,000	0.95358692	0.01529178	-38.22944764
65,500	0.96567610	0.01208918	-36.26753318
66,000	0.97504806	0.00937196	-32.80185627
66,500	0.98217263	0.00712457	-28.49829271
67,000	0.98748370	0.00531107	-23.89982342
67,500	0.99136610	0.00388240	-19.41200320
68,000	0.99414910	0.00278300	-15.30650532
68,500	0.99610534	0.00195624	-11.73741450
69,000	0.99745375	0.00134842	-8.76470291
69,500	0.99836518	0.00091143	-6.37998037
70,000	0.99896929	0.00060411	-4.53079927
70,500	0.99936193	0.00039265	-3.14116382
71,000	0.99961219	0.00025025	-2.12716580
71,500	0.99976859	0.00015641	-1.40767210
72,000	0.99986445	0.00009586	-0.91065510
72,500	0.99992206	0.00005761	-0.57609802
73,000	0.99995601	0.00003395	-0.35648927
73,500	0.99997563	0.00001962	-0.21582679
74,000	0.99998675	0.00001112	-0.12786765
74,500	0.99999293	0.00000618	-0.07414621
75,000	0.99999630	0.00000337	-0.04208790
75,500	0.99999810	0.00000180	-0.02338971
76,000	0.99999904	0.00000094	-0.01272752
76,500	0.99999953	0.00000048	-0.00678207
Total units			**-351.0022499**

TABLE III-5. Continued.

d. Calculating Q

Cost of Component CC	42.5
Annual Demand	730000
Order Cost	5
Cost of stock-out	35
# of stock-outs (see above)	352
Expected stock-out cost per cycle	12320
Q (with stock-out cost)	49905.8
Q (rounded to nearest container-load)	**50540**

Notes:
M/D = MANUFACTURER/DISTRIBUTOR
SD= Standard Deviation
DDLT=Demand During Lead Time
ROP = Reorder Point
ROQ = Reorder Quantity
LT=Lead Time

For the assuming scenario, calculation of ROP and Q values is based on the average and variability of lead times for the Chinese supplier, and average and variability of demand at the customers. For the hedging scenario, ROP is based on the average and variability of the Chinese supplier. This is because of the large variation between the lead times for the domestic and Chinese suppliers, basing the ROP calculation on either the US supplier or averages of the Chinese and US supplier leads to frequent stock-outs and unduly reduces the performance of a hedging strategy. Q is calculated based on the ROP and average of purchase cost from the US and Chinese suppliers.

Table III-6 presents ROP and Q values for all scenarios based on mean and standard deviation of lead time (order processing and transportation), and mean and standard deviation of demand.

c. Variability in purchase cost of products and components

The basic purchase price from the Chinese supplier is set to $60/unit for the product. Typically, the purchase cost of electronic products and components is around 20% to 30% cheaper in China. An interesting article by Engardio, Roberts and Bremner (2004) in the online edition of Business Week states that for electronic goods such as LCD TVs (data from 3Com) and networking equipment such as switches (data from SVA America), the price gap (expressed in percentage as price gap divided by the US price) is around 25% and 30% respectively. Following this article, and several discussions with practitioners, the purchase price from the US supplier is set to $80 because the resultant cost differential is 25% ((80-60)/80 =25%). This cost differential was also ratified as reasonable in additional qualitative interviews.

TABLE III-6: REORDER POINT-REORDER QUANTITY (ROP-Q) VALUES FOR ALL SCENARIOS

		Low Supply Low Demand Risks	**High Supply Low Demand Risks**	**Low Supply High Demand Risks**	**High Supply High Demand Risks**
Assuming					
A or B products	ROP	46500	49000	47000	49000
	Q	21600	39600	27600	40800
AC or BC Components	ROP	46500	49000	47000	49000
	Q	43920	78080	53680	82960
CC Component	ROP	92500	97500	93500	98000
	Q	59850	107730	61180	82960
Hedging					
A or B products	ROP	46500	49000	47000	49000
	Q	19200	31200	21600	32400
AC or BC Components	ROP	46500	49000	47000	49000
	Q	39040	63440	43920	63440
CC Component	ROP	92500	97500	93500	98000
	Q	50540	85120	54530	85120

Notes:

DDLT	Demand During Lead Time
s.d. of DDLT	Standard Deviation of Demand During Lead Time
Q	Based on carrying cost (17%), order cost ($5/order), and stock-out cost ($35/unit); rounded to nearest full container load
ROP	Based on in-stock probability of 84%; rounded to nearest 500

The cost of the components sourced from the Chinese supplier is set to $15 for components AC and BC, and $35 for the common component CC. Using a similar, approximately 25% cost differential, the component prices are set to $20 and $50 for the US supplier. Common component CC is approximately 80% of the value, weight, and volume of the products A and B. Unique components AC and BC are approximately 20% of the value, weight, and volume of products A and B respectively.

To operationalize the second aspect of supply risks, i.e., cost variability, the purchase cost of products and components from the Chinese supplier was set to a high of 15% for low risk scenarios and a high of 45% for high risk scenarios. The value of 15% was arrived at by extrapolating the current wage rate increase over the past six years and the gradual but continuous strengthening of Chinese currency (Yuan) over the past two years. The high value was based on trends in increase of prices of raw materials and components (such as iron ore, silicon wafers, and polysilicon) that go into electronic products, labor shortages that can potentially lead to further increases in labor costs, and oil price increases.

Using the purchase values of the product and component values discussed above as the minimum costs and higher limits (of 15% for low risk and of 45% for high risk), Table III-7 lists the minimum, mean, and maximum values for the products and three components.

TABLE III-7: PURCHASE COSTS FOR PRODUCTS AND COMPONENTS

Purchasing costs ($)	**Chinese Supplier ($)**	**Domestic Supplier ($)**
Products A and B	Low (60,64.5, 69) High (60, 73.5, 87)	80
Components AC and BC	Low (15, 16.125, 17.25) High (15, 18.375, 21.75)	20
Component CC	Low (35, 37.625, 40.25) High (35, 42.875, 50.75)	50

Stage 4: Order received at the supplier facility (order processing at suppliers)

Whenever the inventory level for a given product or component falls below the ROP level at the manufacturer/distributor, an order of Q units is placed with the supplier.

a. Order fulfillment priority

The orders at the supplier facility are processed using the First-In-First-Out (FIFO) priority. The supplier has no capacity constraints and fills all orders completely. There are no backorders at the supplier. Every order is filled complete and shipped together.

b. Order processing time

The order processing time at the domestic supplier is set to a normal distribution with a mean of 10 days and standard deviation of 1 day. The order processing time at the Chinese supplier is set to a normal distribution with a mean of 15 days and standard deviation of 1.5 days for low supply risk scenarios and standard deviation of 4.5 days for high supply risk scenario. This sets the coefficient of variation (CV) values to 0.1 and 0.3 for low and high risk scenarios respectively. These values for high and low CV have been used in past literature to operationalize low and high variability in inbound supply (Gomes and Mentzer 1991).

Stage 5: Order shipped from supplier to the assembler/distributor

Order shipped from the domestic supplier and the Chinese supplier follow different routes as described below.

a. Chinese supplier

After the Chinese supplier processes the order, the goods are sent to the Hong Kong port. At the Hong Kong port, goods are loaded onto a ship. The ship travels from the Hong Kong port to the US Los Angeles port. At the port, the goods are cleared through the customs and loaded onto a truck. Trucks transport the goods from the US port to the manufacturer/distributor.

b. Domestic supplier

After the domestic supplier processes an order, the goods are shipped to the manufacturer/distributor using trucks. The goods are shipped from the domestic supplier to manufacturer/distributor in full truck loads. The transportation times from the US and Chinese suppliers are presented in the Table III-4 above.

Stage 6: Order shipped from assembler/distributor to the customers

After the assembler/distributor processes the orders, goods are shipped to the customers.

a. Shipment to customers

Orders are shipped daily to customers. The transit time to customers is fixed at 3 days. The goods are shipped on a per unit basis with a charge of $10/unit. The transit times and cost figure are based on qualitative interviews and quotes from freight companies. Orders delivered late to customers are assessed a penalty cost of $35/unit. This is approximately 25% of the selling price and has been validated in qualitative interviews.

b. Transit time

The transit time from the manufacturer/distributor to the customers is 3 days.

c. Selling price

The selling price of the products is $150/unit. This is based on secondary data of a major printer manufacturer that states that typically the gross margins are around 32-35%. Average weighted gross margins with a selling price of $150/unit for all scenarios under average price (i.e., considering cost risk) work out to around 31%. A lower, 31%, gross margin was chosen as consumables like cartridges and toners have higher margins than printers.

STEP 4: COLLECT DATA

Going by the past studies and the objectives of this study, the data for this study came from the existing literature, secondary data sources, the qualitative study, and additional interviews with managers. For each of the values used in this model, the exact data source is identified in Table III-4 above.

STEP 5: DEVELOP AND VERIFY COMPUTER-BASED MODEL

Several programming languages and software packages have been utilized in the past to simulate distribution channels, and logistics and supply chain systems. These include MS Excel with add-ins, ARENA, SLAMSYSTEM, and Gauss 5.0. Interestingly, not all researchers have specified the simulation environment used. There is no proof in the literature reviewed of the superiority of any one package over the others. This research used a simulation package designed specifically to model supply chains called

Supply Chain Guru (SC Guru) developed by the Llamasoft Corporation (www.llamasoft.com). Supply Chain Guru is the commercially available supply chain analysis package that combines full mixed-integer/linear programming optimization and discrete event simulation.

Following the methods used by past studies described in Table III-1(B), and Fishman and Kiviat (1968), this study addressed the issue of model verification in several ways. First, services of two programmers who are expert in modeling supply chains using SC Guru were used. The first expert was called in to train the researcher in building the model using SC Guru and to help set up and verify the basic model structure of the supply chain and four risk management strategies. The second expert, a programmer involved in the development of the software was called in to verify multiple aspects of the program. For example, at one point, the second expert verified the yield (quality variability) function was working correctly. At another point, an attempt to verify the initial structure of the model revealed an issue with the transfer of products at the LA port. Moreover, continuous involvement of the experts minimized the possibility of programming errors (bugs).

Second, the output of parts of the model (sub-structures) was compared with manually calculated solutions to determine if they behaved acceptably. Typical validation during this process included verification of transportation times, queuing of shipments throughout the supply chain, and inventory policies. Following Gomes and Mentzer (1991), the uniformity and independence of the model's random number generators was inspected including purchase costs of components and products, demand for products A and B, order processing times at the supplies, transportation times and variability, and quality variability.

Third, the simulation results for short pilot runs of simple cases for the complete model were compared with manual calculations to test if the entire model (structure) behaved acceptably. This was done for all 32 scenarios in the experimental design. Typical validation for all scenarios included: inbound container load/truckload costs of transportation, average purchase costs for low and high risk scenarios, order processing and assembly costs at the manufacturer/distributor, picking and packing costs, and outbound cost/unit of transportation.

As a fourth way to verify model, this research followed Mentzer and Gomes (1991) who state that for their model, "All events were hand verified through each model segment – first with simple deterministic runs, followed by stochastic checks with increasing integration of activities." The model was built in stages where each sub-model was verified by replacing stochastic elements with deterministic elements and gradually integrating these sub-models into the main model.

STEP 6: VALIDATE MODEL

Following the methods used in past studies described in Table III-1 (C) and Law and Kelton (1982), this study addressed the issue of model validation in several ways. First, subject matter experts, including academic scholars and practitioners, were consulted in the conceptual development of model components and relationships between components. This step ensures that the correct problem is solved and the reality is adequately modeled (Law and Kelton 1982).

Second, a structured walk-through of the model and a review of the simulation results for reasonableness with a separate set of subject matter experts, including academic scholars and practitioners, were conducted. The results were consistent with how the subject matter experts perceive the system should operate. This reflects model face validity. Face validity was also confirmed using literature and review of supply chain simulation models in past research.

If there is an existing system, the simulation output can be compared with the output data collected from the actual system. This is called results validation. Fishman and Kiviat (1968) assert:

> "While validation is desirable, it is not always possible. Each investigator has the soul-searching responsibility of deciding how much importance to attach to his results. When no experience is available for comparison, an investigator is well advised to proceed in steps, first implementing results based on simple well-understood models and then using the results of this implementation to design more sophisticated models that yield stronger results. It is only thorough gradual development that a simulation can make any claim to approximate reality"

The above notion is also supported by Banks (1998) who suggests that modeling begin simply and complexity be added in steps until a model of acceptable detail and complexity has been developed. For this study, input-output transformation, i.e., comparing simulation data to real world data, was not possible for several reasons. First, complexity of real world supply chains is far greater than the one simulated in this research. Therefore, it is difficult to isolate the effect of the variables in the real data. Second, it is difficult to find a company willing to share complete data on all variables included in this research. Through several attempts to acquire real data from multiple companies, data that corresponds to different parts of the supply chain could be gathered.

However, data that spanned more than two levels of a supply chain for a given product could not be gathered. These partial datasets were used to extensively validate corresponding parts of the simulation model.

Finally, sensitivity analyses was performed on the programmed model to see which model factors have the greatest impact on the performance measures and, thus, have to be modeled carefully (Powers and Closs 1987). Details are provided in Article 1 (Chapter IV).

STEP 7: PERFORM SIMULATIONS

Combinations of high and low levels of risks were used to generate four possible combinations of demand and supply risk levels. All four risk management strategies were simulated separately for each of the four combinations of demand and supply risk levels. This meant four possible combinations of strategies, i.e. Assumption-Speculation, Assumption-Postponement, Hedging-Speculation, and Hedging-Postponement, were simulated for each combination of supply and demand risk levels, for a total of 16 scenarios. Each of these 16 scenarios was replicated with a 45-day LA port disruption. In total, 32 scenarios were simulated. These are presented in Table III-8 and correspond to Figures II-5 and II-6 presented earlier in Chapter II.

Sample size determination is an important issue to be addressed when running a simulation. As Beinstock (1994) suggests, given the computer software and simulation software currently available, increasing the number of replications is not difficult.

TABLE III-8: SIMULATION SCENARIOS

	Factor 1	Factor 2	Factor 3	Factor 4	Moderator
	Supply Risk	Demand Risk	Supply Strategy	Demand Strategy	Disruption
1	L	L	He	Po	No
2	L	L	He	Sp	No
3	L	L	As	Po	No
4	L	L	As	Sp	No
5	L	H	He	Po	No
6	L	H	He	Sp	No
7	L	H	As	Po	No
8	L	H	As	Sp	No
9	H	L	He	Po	No
10	H	L	He	Sp	No
11	H	L	As	Po	No
12	H	L	As	Sp	No
13	H	H	He	Po	No
14	H	H	He	Sp	No
15	H	H	As	Po	No
16	H	H	As	Sp	No
1d	L	L	He	Po	Yes
2d	L	L	He	Sp	Yes
3d	L	L	As	Po	Yes
4d	L	L	As	Sp	Yes
5d	L	H	He	Po	Yes
6d	L	H	He	Sp	Yes
7d	L	H	As	Po	Yes
8d	L	H	As	Sp	Yes
9d	H	L	He	Po	Yes
10d	H	L	He	Sp	Yes
11d	H	L	As	Po	Yes
12d	H	L	As	Sp	Yes
13d	H	H	He	Po	Yes
14d	H	H	He	Sp	Yes
15d	H	H	As	Po	Yes
16d	H	H	As	Sp	Yes

L= Low Risk
H=High Risk
He=Hedging Strategy
As=Assuming Strategy
Po=Postponement Strategy
Sp=Speculation Strategy

Increasing the number of runs reduces the standard deviation of the sampling distribution, and therefore, for a given level of confidence, the half-width of the confidence interval decreases. This results in an increase in the absolute precision of the estimate of the population of interest where absolute precision is defined as the actual half-width of a confidence interval (Law and Kelton 1982). However, increasing the number of replications until statistically significant results are obtained makes the external validity of the results obtained questionable.

An alternative to increasing absolute precision is, as Bienstock (1996, p. 45) states, "to let the number of replications be guided by a "practical" degree of precision, i.e., a reasonable degree of precision, given the magnitude of population mean(s) that is (are) being estimated." Bienstock further contends that conclusions drawn from results in this manner are more meaningful both in terms of research goals and practical problem solutions.

Law and Kelton (1982, p. 292) state, "one can think of the relative precision as the 'proportion' of μ (the population mean) by which $\overline{X}_{(n)}$ (the sample mean) differs from μ." Building on Law and Kelton, Bienstock (1996, p. 45-46) elaborates on the concept of relative precision. Desired relative precision ($0 < \gamma < 1$) is expressed as the percent difference the estimate of the population mean (i.e. the sample mean, $\overline{X}_{(n)}$) is from the population mean (μ). For example, if the degree of relative precision desired is 5 per cent (i.e. $\gamma = 0.05$) and α is defined as the probability of Type I error, the sequential procedure involves determination of the sample size that will produce an interval so that, it can be stated with 100 (1- α) percent confidence, the sample mean is not more than 5 per cent different from the population mean (μ).

The procedure described above based on Law and Kelton (1982) and Bienstock (1996) was used for sample size determination in this study. The procedure consisted of choosing an initial sample size (n_0) and a target value for the relative precision (γ). A series of pilot runs of the simulation model was conducted, replacing the sample size by n + 1 for each successive pilot run, until the desired relative precision was attained for all cells.

For this study, the sample size for 5% relative precision was 28 runs per cell. Relative precision values were calculated for 16 non-disruption scenarios and are presented in Table III-9. Relative precision values were not calculated for disruption scenarios. This was because a disruption leads to highly variable results between runs depending on the time of disruption, and it is unlikely that results will fall within a 5% precision level. Therefore, similar to non-disruption scenarios, a sample size of 28 runs each was used for disruption scenarios.

STEP 8: ANALYZE RESULTS

Model runs are used to estimate performance measures. For all scenarios simulated, decisions on tactical issues such as run length, warm-up period, manner of initialization, and the number of independent model replications were made.

The run length was set to two years, which was validated in interviews as a typical life frame of an off-shoring decision.

TABLE III-9: RELATIVE PRECISION VALUES

Without-Disruption Scenarios	Relative Precision Values
1	0.014
2	0.007
3	0.009
4	0.008
5	0.012
6	0.006
7	0.009
8	0.007
9	0.022
10	0.014
11	0.031
12	0.025
13	0.030
14	0.013
15	0.038
16	0.031

The warm-up period was set to 60 days. Multiple observations were made for each scenario and total cost and total revenues were observed for runs where data were collected at the following three points – beginning first month to end of twenty-four months, beginning of second month to end of twenty-five months, and beginning of third month to end of end of twenty-six month. All scenarios stabilized by the end of second month as reflected in the following observations: similar direction (negative or positive) of profit, stability in penalty costs of late deliveries, and stable order fill rates. Furthermore, efforts were made to minimize the effect of initial conditions on the model by setting up initial inventory levels at the manufacturer/distributor to the ROP levels.

Main analyses are based on Tukey's multiple comparison of cell means. In addition, methods used to analyze the results are:

1. Visual inspection of graphical outputs
2. Mean, lower and upper limits, standard deviation, and 5th and 95th percentile of dollar value of risks
3. Percentage changes in performance measures
4. ANOVA for response variable main effects

Results are analyzed and presented in detail in Article I (Chapter IV).

The first three chapters of this dissertation have provided the theoretical background and methodological approach of this research. The two papers that follow these chapters present the results and conclusions from this research.

CHAPTER IV : A COMPUTER SIMULATION BASED INVESTIGATION OF GLOBAL SUPPLY CHAIN RISK MANAGEMENT STRATEGIES

ABSTRACT

Several approaches have been suggested in existing literature to manage risks within organizations and in strategic alliances between organizations. However, there is limited guidance on managing risks in supply chains. In particular, selection of supply chain risk management strategies relative to global environmental conditions has been identified as a knowledge gap in past research. This paper addresses the gap by exploring four risk management strategies relative to different environments faced by global supply chains. Qualitative research and simulation modeling were adopted to build and test a model of environment-strategy fit in global supply chains. The results and findings add to both theoretical and practical understanding of the phenomenon.

INTRODUCTION

Any firm operating globally is part of multiple complex supply chains that require highly coordinated flows of goods, services, information, and cash within and across national boundaries (Mentzer 2001). Strategies for maximizing profits in a global environment include sourcing from locations that offer the lowest total procurement cost, manufacturing and assembling products in least cost countries, and marketing in high potential demand centers (AlHashim 1980). While these make the supply chain more efficient, they also make it riskier, due to heightened dependency on numerous links that are prone to breakdowns, disruptions, bankruptcies, and disasters (Chopra and Sodhi 2004).

To operate on a global basis, managers must address several concerns, including economic, political, logistical, competitive, cultural, and infrastructural challenges (Schmidt and Wilhelm 2000). Global supply chain managers must focus on risks to the various links in their supply chain (Souter 2000). Since companies in a supply chain are interdependent, individual risks in supply chains are often interconnected, and as a result, actions that mitigate one risk can end up exacerbating another (Chopra and Sodhi 2004).

Several researchers have attempted to define risk management in supply chains (Hauser 2003; Jüttner 2005; Jüttner, Peck and Christopher 2003; Norrman and Jansson 2004). For this paper, we adopt a definition by Manuj and Mentzer (2007b): Supply chain risk management is the identification of risks and consequent losses in the supply chain and implementation of appropriate strategies through a coordinated approach among supply chain members with the objective of reducing one or more of the following as related to supply chain outcomes – losses, probability, speed of event, speed of losses, the time for detection of the events, frequency, and exposure – that in turn lead to close matching of the actual cost savings and profitability targets with the desired ones.

Ghoshal (1987) recognized risk management as one of the goals of organizations operating globally. He stated that the strategic task of managing globally is to use three sources of competitive advantage – namely national differences, scale economies, and scope economies to optimize efficiency, risk, and learning in a world-wide business. Risk management as an important and critical issue in supply chains has also been addressed by several scholars recently (Blackhurst et al. 2005; Christopher and Lee 2004;

Jüttner, Peck and Christopher 2003; Kleindorfer and Saad 2005; Spekman and Davis 2004; Sykes 2006; Zsidisin et al. 2004).

Supply chain risk management is important as risk adjusted supply chain management can translate into improved financial performance and competitive advantage (Hauser 2003). Hendricks and Singhal (2005) investigated the effect of supply chain disruptions – many of them caused by the inability to better manage and control supply chain physical flows – and found that these disruptions could seriously depress the financial performance of a firm for three years or longer. The importance of the topic is also reflected in several special issues and tracks on risk management in academic journals and conferences. However, not many finance executives and risk managers feel that they are adequately prepared for disruptions to their business (Bradford 2003).

The process of supply chain risk management can be divided into five steps: risk identification, risk assessment and evaluation, selection of appropriate supply chain risk management strategies, implementation of supply chain risk management strategy(s), and mitigation of supply chain risks (Manuj and Mentzer 2007a). A review of the literature suggests, of these five steps, selection of supply chain risk management strategies is a topic that needs more and immediate attention. Several supply chain risk management strategies have been identified in existing literature. However, when to use a specific strategy is a question that has not been adequately addressed. Investigating supply chain risk management strategies in different global environments and industries is an important research direction (Jüttner, Peck and Christopher 2003). This paper attempts to address this gap by exploring risk management strategies in different supply chain environments.

The main objective of this paper is to investigate supply chain risk management strategies under different environmental conditions. Following Lee (2002), environmental conditions are defined in terms of supply and demand risks. Four supply chain risk management strategies, namely hedging, assuming, postponement, and speculation, are investigated in the context of global supply chain environments. The question driving this research is: How does performance of global supply chains vary under different combinations of environmental conditions and the strategy selected?

In addition to calling for more research on supply chain risk management, several academicians and practitioners have called for quantification of risks (Kleindorfer and Saad 2005) and mathematical modeling approaches such as simulation modeling to understand aspects of supply chain management (Min and Zhou 2002). Other disciplines, such as finance and insurance, have adopted much more rigorous mathematical and statistical techniques as compared to the logistics and supply chain disciplines (Sykes 2006). By understanding the variety and interconnectedness of supply chain risks, effective risk management strategies can be identified (Chopra and Sodhi 2004). Simulation modeling is an effective tool to model these interconnectivities and linkages (Chang and Makatsoris 2001; Mentzer and Cosmas 1979).

This paper makes three important contributions. First, theory based on extant literature and qualitative study is developed. A model of four supply chain risk management strategies (hedging, assuming, postponement, and speculation) is investigated relative to environmental conditions (low and high supply and demand risks). Second, a mathematical simulation modeling approach is applied and explained in detail, which contributes to the limited and often sketchy use of this methodology in supply chain and logistics journals. Third, the manuscript offers insights into the usefulness of the four supply chain risk management strategies under different environmental conditions.

METHODOLOGY

This research consisted of three successive phases: (1) literature review; (2) qualitative research; and (3) simulation. The literature review was an integrative investigation of the following disciplines: logistics, supply chain management, operations management, economics, international business, and strategy. The literature review revealed limited research on the topic. Therefore, qualitative research was undertaken to supplement the extant substantive base (Creswell 1998). The qualitative research was based on data from 14 in-depth qualitative interviews across 8 companies, and a focus group involving 7 senior executives of a global manufacturing firm. The qualitative study followed grounded theory methodology and rigorously adhered to the process suggested by Glaser (1998) and Glaser and Strauss (1967). Additional literature review was undertaken to explore new constructs discovered in the qualitative study and as a source of data to provide evidence for or against the emerging theory (Glaser 1978). The qualitative study and the literature were used to develop a comprehensive conceptual model of risk management strategies in global supply chains. To test part of this model, a simulation study was developed and executed. The simulation study followed an eight-step process suggested by Manuj, Bowers and Mentzer (2007). This process is discussed in detail in a later section titled “Simulation Model.” Additional interviews were conducted during the simulation model development to collect additional data and to validate the model.

MODEL AND PROPOSITIONS

Based on the preliminary literature review, qualitative research, and additional literature review undertaken after the qualitative study, a model of environment-strategy fit for global supply chain risk management was developed (See Figure IV-1). Due to the limitation of resources and time, and to keep the model simple but meaningful, this research focuses on selected constructs from the model presented in Figure IV-1. However, it is important to mention that the choice of constructs was based on the following criteria: importance awarded to a construct in the literature, importance awarded to a construct by the managers in the qualitative study, relevance of a construct to global supply chain risk management and the research objective, and availability of a sound theoretical base including the extant literature and the qualitative study for this research. Furthermore, an attempt was made to include factors that are external to the supply chain and beyond the direct control of supply chain managers.

The testing of hypotheses is based on total supply chain profit outcome, as it takes into account several other performance measures, including total supply chain costs (inventory, transportation, and production costs), total supply chain revenues, and penalty costs associated with late deliveries.

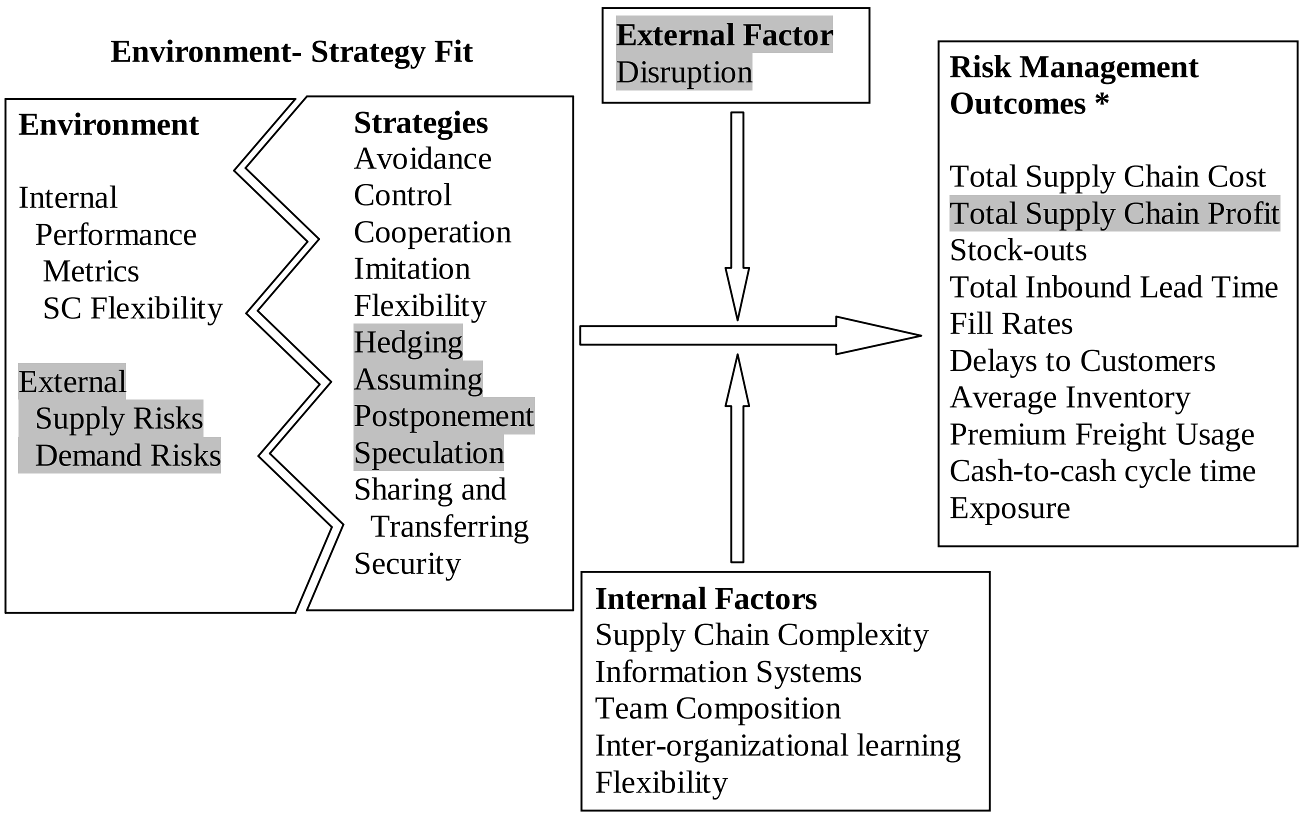


FIGURE IV-1：A CONCEPTUAL FRAMEWORK OF ENVIRONMENT-STRATEGY FIT FOR GLOBAL SUPPLY CHAIN RISK MANAGEMENT

However, in addition to the total supply chain profit, several other measures were recorded, including stock-outs, total inbound lead time, fill rates, delays to customers, and average inventory to help interpret results. The part of the model tested is shaded in grey in Figure IV-1.

Following Lee (2002), environments facing supply chains are defined in terms of the levels of supply and demand risks. "S_LD_L" denotes the presence of low supply and low demand risks, "S_LD_H" denotes the presence of low supply and high demand risks, "S_HD_L" denotes the presence of high supply and low demand risks, and "S_HD_H" denotes the presence of high supply and high demand risks.

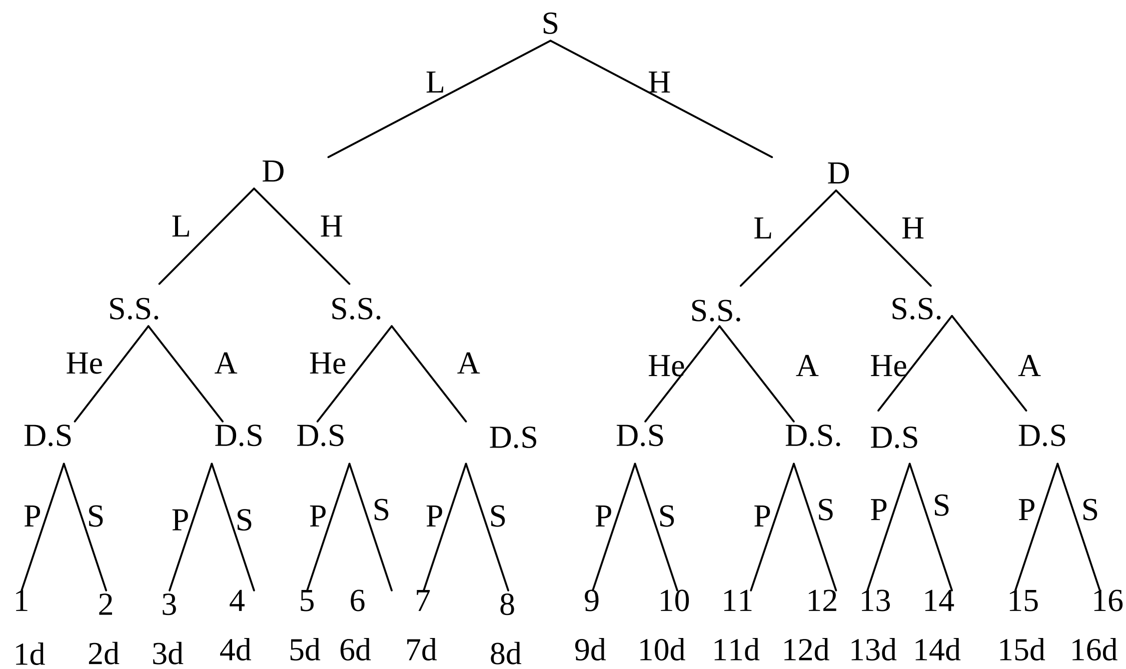
"Fit" is the underlying concept on which the models and hypotheses are developed. Venkatraman (1989) identifies six perspectives of fit – fit as moderation, mediation, matching, gestalts, profile deviation, and covariation. The concept of fit as matching is used because fit, in this research, is defined as the match between two related variables. Subsequently, the effect of fit on performance variables can be examined. This definition is most suitable for the major objective of this study, i.e., examining the effect of environment and strategy fit on supply chain outcomes. A resource's capacity to generate profits or to prevent losses depends, to a large extent, on the fit of a given strategy to the external environment (Amit and Schoemaker 1993; Porter 1991; Wernerfelt and Karnani 1987). Strategy, Structure, and Performance (SSP), a theory that deals with the concept of fit, is widely applied in strategy research and has been suggested as an appropriate theoretical basis to study supply chain phenomena (Defee and Stank 2005; Rodrigues, Stank and Lynch 2004; Stank, Davis and Fugate 2005).

SSP theory suggests that a firm's performance depends on the degree of fit between its strategy and the structural elements developed to support the strategy. Changing environmental factors such as customer requirements, competition, the state of the economy, and governmental regulations (Christensen and Montgomery 1981; Porter 1985) affect the appropriateness of this fit.

In sum, performance results from the degree of fit between strategy and structure taken within the context of internal and external environmental factors (Cavinato 1999; Chandler 1962). Therefore, if a risk management strategy selected by a supply chain fits its environment, then this supply chain will experience higher performance than a supply chain that adopts a strategy that is mismatched with the environment. As Kleindorfer and Saad (2005) suggest, *"to effectively manage risk, the approach must fit the characteristics and needs of the decision environment."*

Based on the concept of fit as matching, four sets of hypotheses are developed. First, hypotheses that specify the effect of one strategy at a time, called direct effect hypotheses, on performance outcomes are discussed. Second, hypotheses called interaction effect hypotheses that predict the outcome of a combination of strategies relative to different supply chain environments are presented. Third, hypotheses that are exploratory in nature are proposed for those combinations of strategies for which there is not enough theoretical background to predict the outcomes *a priori*. Finally, hypotheses called disruption hypotheses are presented that predict the outcome of a combination of strategies relative to different supply chain environments in the presence of a disruption.

Figure IV-2 shows the different paths that can be taken in terms of supply risks, demand risks, supply strategies, and demand strategies.



S: Supply; D: Demand; H: High Risks; L: Low Risks
SS: Supply Strategy; He: Hedging; A: Assuming
DS: Demand Strategy; P: Postponement; S: Speculation

Note: 1-16 represent net profit outcome for non-disruption scenarios.
1d-16d represent net profit outcome for disruption scenarios.

FIGURE IV-2: TREE AND BRANCH DIAGRAM FOR ALL POSSIBLE PATHS

As mentioned earlier, hypotheses' testing is based on total supply chain profit. The numbers 1 through 16 and 1d through 16d represent the total profit for each path for without-disruption and with-disruption scenarios, respectively. For example, 3 in Figure IV-2 is the total profit for a supply chain that faces low supply risks and low demand risks and adopts an assumption strategy on the supply side, and a postponement strategy on the demand side. Similarly, 3d is the total profit for a supply chain that faces low supply risks and low demand risks and adopts an assumption strategy on the supply side, and a postponement strategy on the demand side, but under disruption.

DIRECT EFFECT HYPOTHESES

Direct effect hypotheses specify the relative effect on outcomes of the fit of a supply (hedging or assuming) or a demand (postponement and speculation) strategy with the environment. In a supply-chain context, hedging is undertaken through a globally dispersed portfolio of suppliers and facilities such that a single event (like currency fluctuations or a natural disaster) will not affect all the entities at the same time and/or with the same magnitude (Bartmess and Cerny 1993; Carter and Vickery 1989). Hedging works as an option whose value depends on the direction and extent of change in events (Kogut and Kulatilaka 1994). However, not all supply chains benefit equally from hedging. Supply chains with low supply risks will not gain any substantial benefits because the transaction costs for those supply chains to find alternate sources of supply will be lower as compared to supply chains facing high supply uncertainty. In light of unstable manufacturing schedules or unreliable suppliers, hedging is an appropriate strategy to counter supply risks.

Assuming risks is the opposite of hedging risks. While hedging is a strategy designed to minimize exposure to risk, assuming is a strategy is designed to take on these risks. When the risks associated with a given option are considered acceptable, the effort is geared toward driving minimization of risks rather than spreading them through hedging. When the future is known with certainty, focusing resources yields more advantages, such as exploiting economies of scale, as compared to spreading the resources across multiple options (Wernerfelt and Karnani 1987). Assuming risks on the supply side in a global supply chain may take the form of sourcing from a single supplier or from a single geopolitical area, or depending on a single manufacturing plant for a particular product or line of products. However, such a strategy will not be effective when there are high risks such as those of quality, quantity, disruption, price, variability in performance, and opportunism (Berger, Gerstenfeld and Zeng 2004).

Therefore, for high supply risks, it is proposed that irrespective of the level of demand risks and strategy on the demand side:

> **H1: Supply chains facing high supply risks (S_HD_L and S_HD_H environments) that adopt a hedging strategy will show a higher profit than supply chains that adopt an assuming strategy.**

In other words, in Figure IV-2, 9, 10, 13, and 14 will be greater than 11, 12, 15 and 16, respectively.

For low supply risks, it is proposed that irrespective of the level of demand risks and strategy on the demand side:

> **H2: Supply chains facing low supply risks (S_LD_H and S_LD_L environments) that adopt an assuming strategy will show a higher profit than supply chains that adopt a hedging strategy.**

In Figure IV-2, 3, 4, 7, and 8 will be greater than 1, 2, 5, and 6 respectively.

Postponement entails delaying the actual commitment of resources to maintain flexibility and delay incurring costs (Bucklin 1965). There are two types of postponement – form and time. Form postponement includes labeling, packaging, assembly, and manufacturing. Time postponement refers to the movement of goods from manufacturing plants only after customer orders are received (Zinn and Bowersox 1988). The focus here is on form postponement. Due to the nature of and constraints on global transportation, the extent of time postponement is limited. The increasing use of mass customization, agile operations, and e-business strategies has caused a heightened interest in postponement to improve coordination between supply and demand (Appelqvist and Gubi 2005). However, there is a lack of empirical research supporting the cost-benefit trade-offs of postponement (Yang, Burns and Backhouse 2004).

The extent of form postponement depends on demand customization, component costs, product life cycle, product modularity (Chiou, Wu and Hsu 2002), and uncertainty (Perry 1991; Yang, Burns and Backhouse 2004). Potential benefits of postponement depend on the uncertainty projected in the operating environment (Perry 1991; Yang, Burns and Backhouse 2004). Therefore, it is argued that supply chains facing high demand uncertainty benefit more from form postponement.

Speculation (also called assumption or selective risk taking) is the opposite of postponement (Bucklin 1965). In speculation, decisions are made based on anticipated customer demand. The resources in the supply chain need to be directed to those specific products and customers that provide the firm with a competitive advantage (Perry 1991). In the interviews, speculation emerged as the most commonly used strategy to address uncertainty in the business environment. Among other strategies, speculation may involve maintaining inventory of finished products instead of component parts (Miller 1992). In speculating about cost-risk trade-offs, managers should typically be aware of the supply-demand and/or operating trade-offs associated with the options and choose to avoid certain options. Supply chains facing low demand uncertainty are better suited to achieve benefits of speculation.

Therefore, for high demand risks, it is proposed that irrespective of the level of risks and strategy on the supply side:

H3: Supply chains facing high demand risks (S_LD_H and S_HD_H environments) that adopt a postponement strategy will show a higher profit than supply chains adopting a speculation strategy.

In Figure IV-2, 5, 7, 13, and 15 will be greater than 6, 8, 14, and 16, respectively.

For low demand risks, it is proposed that irrespective of the level of risks and strategy on the supply side:

H4: Supply chains facing low demand risks (S_LD_L and S_HD_L environments) that adopt a speculation strategy will show a higher profit than supply chains that adopt a postponement strategy.

In Figure IV-2, 2, 4, 10, and 12 will be greater than 1, 3, 9, and 11 respectively.

INTERACTION EFFECT HYPOTHESES

So far, the hypotheses offered deal with a strategy that addresses one type of risk at a time. For example, hedging and assuming strategies deal with supply risks, and postponement and speculation strategies deal with demand risks. However, in reality, global supply chains face different levels of risks on the supply side and demand side. Applying the concept of fit again, a supply chain that adopts the strategy combination that fits both demand and supply risk conditions will perform better than a supply chain that adopts a mismatched strategy combination. Since, hedging is useful in case of high supply risks, assuming in case of low supply risks, postponement in case of high demand risks, and speculation in case of low demand risks, it is proposed that:

H5: Supply chains facing low supply risks and low demand risks ($S_L D_L$ environment) that adopt an assuming strategy on the supply side and a speculation strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.

In Figure IV-2, 4 will be greater than 1, 2, and 3

H6: Supply chains facing low supply risks and high demand risks ($S_L D_H$ environment) that adopt an assuming strategy on the supply side and a postponement strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.

In Figure IV-2, 7 will be greater than 5, 6, and 8.

H7: Supply chains facing high supply risks and low demand risks ($S_H D_L$ environment) that adopt a hedging strategy on the supply side and a speculation strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.

In Figure IV-2, 10 will be greater than 9, 11, and 12.

H8: Supply chains facing high supply risks and high demand risks ($S_H D_H$ environment) that adopt a hedging strategy on the supply side and a postponement strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.

In Figure IV-2, 13 will be greater than 14, 15, and 16.

EXPLORATORY HYPOTHESES

For each direct effect strategy above (H1 through H4) it is possible to identify the two environments under which that strategy works best. There is little guidance, however, on which among those two environments fits the selected strategy better. For example, if a firm has products with different supply and demand risks, and limited resources, then it has to make a decision on identifying those supply chain environments that stand to benefit most from adopting a particular strategy. For example, for H1, it is anticipated that supply chains facing $S_H D_L$ and $S_H D_H$ environments that adopt a hedging strategy perform better than a supply chain adopting a speculation strategy. However, we do not know enough to understand whether a supply chain facing a $S_H D_L$ environment or a $S_H D_H$ environment will gain more by adopting the hedging strategy.

Although we do not know much about other strategies, there is one study on postponement strategy. Lee (2002) suggests, based on empirical evidence from case studies of HP and IBM, that postponement for innovative products is most applicable with a reliable and stable supply base. Although the evidence is limited, it is proposed that in conditions of high demand risk:

> **H_E1: Supply chains facing low supply risks ($S_L D_H$ environment) will show a higher profit than supply chains facing high supply risks ($S_H D_H$ environment) from adopting a form postponement strategy.**

In Figure IV-2, 5 will be greater than 3, and 7 will be greater than 15.

The research by Lee (2002) also suggests that there is the possibility of differential performance for the other three strategies relative to a supply chain environment. Since there is not much guidance on the relative impact of the other three hypotheses, we assume the performance to be equal. Therefore, for hedging, assuming, and speculation strategies, it is proposed:

> **H_E2: Irrespective of the level of demand risks, all supply chains facing high supply risks ($S_H D_L$ and $S_H D_H$ environment) will show an equal profit from adopting a hedging strategy.**

In Figure IV-2, 9 will be equal to 13, and 10 will be equal to 14.

H_E3: Irrespective of the level of demand risks, supply chains facing low supply risks (S_LD_L and S_LD_H environments) will show an equal profit from adopting an assuming strategy.

In Figure IV-2, 3 will be equal to 7, and 4 will be equal to 8.

H_E4: Irrespective of the level of supply risks, supply chains facing low demand risks (S_LD_L and S_HD_L environments) will show an equal profit from adopting a speculation strategy.

In Figure IV-2, 2 will be equal to 10, and 4 will be equal to 12.

DISRUPTION HYPOTHESES

Disruptions manifest themselves in a variety of forms, including transportation delays, port closures, accidents, natural disasters, capacity shortages, quality problems, facility shut-downs, and terrorism (Blackhurst et al. 2005). Several disruption events were discussed by the participants in the qualitative study. A port closure was very salient to several practitioners who still remember the consequences of a port closure at the ports of Los Angeles and Long Beach in 2002 and expressed concern about future supply disruptions caused by congested ports or other factors such as terrorism or strikes. Therefore, in this study, the focus is on a supply disruption, namely port disruption. All types of disruptions are likely to negatively affect supply chain outcomes. Therefore it is proposed that:

H9: The total profit for a given combination of environment conditions and strategies under non-disruption condition will always be higher than total profit for the corresponding environmental conditions and strategies combination under disruption conditions.

For all scenarios, this translates into 16 sub-hypotheses: profit for path 1 > profit for path 1d, profit for path 2 > profit for path 2d, and so on.

Disruptions will have potentially less severe outcomes if there is some sort of buffer against a given disruption. As mentioned earlier, in this study we focus on a supply disruption. A buffer in the form of multiple suppliers, i.e., a hedging strategy, should lessen the impact of a supply disruption as compared to a single source arrangement, i.e., assuming strategy. Therefore, it is proposed that:

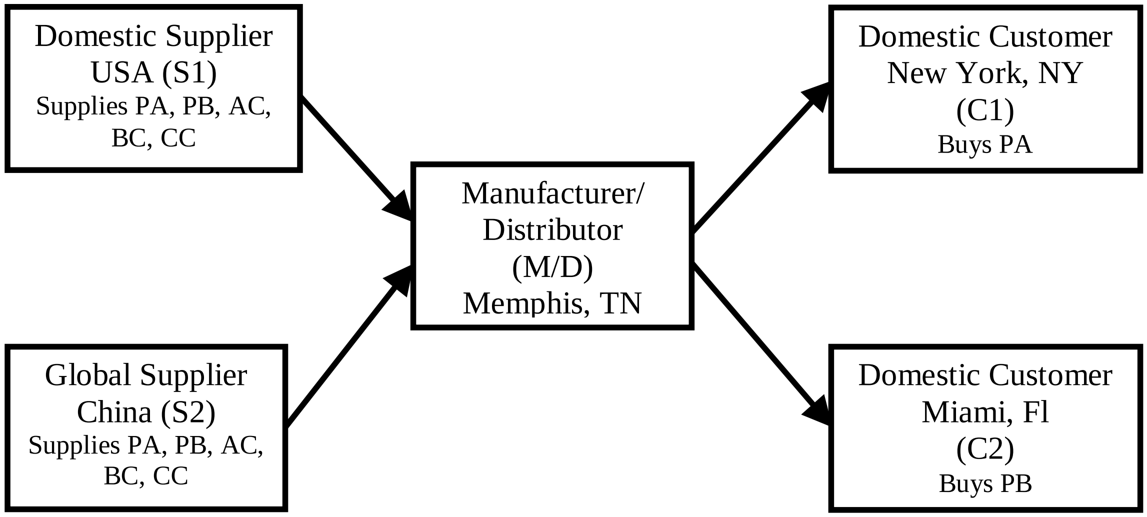
H10: For a supply disruption, hedging will always be better than assuming under corresponding environmental conditions and demand side strategy.

For all disruption scenarios, this translates into the following 8 sub-hypotheses:

i. Profit for path 1d > Profit for path 3d
j. Profit for path 2d > Profit for path 4d
k. Profit for path 5d > Profit for path 7d
l. Profit for path 6d > Profit for path 8d
m. Profit for path 9d > Profit for path 11d
n. Profit for path 10d > Profit for path 12d
o. Profit for path 13d > Profit for path 15d
p. Profit for path 14d>Profit for path 16d

SIMULATION MODEL

To test the model presented in Figure IV-1, a simulated global supply chain with two suppliers, a focal firm, and two customers is conceptualized (See Figure IV-3). There is one supplier each in the US and China. The manufacturer/distributor (M/D) and both customers (C1 and C2) are based in the US. M/D sells two products – Product A to C1 and Product B to C2.



Notes:

1. Both suppliers can supply product A (PA), product B (PB), component AC, component BC, and component CC.
2. C1 buys PA
3. C2 buys PB
4. PA = AC + CC
5. PB = BC + CC

FIGURE IV-3 : SIMULATED SUPPLY CHAIN

Product A is composed of two components – A-Component (AC) unique to Product A and Common-Component (CC) shared between Product A and Product B. Product B is composed of two components – B-Component (BC) unique to Product B and the Common-Component (CC). Both suppliers – S1 and S2 – can supply the two products (Product A and Product B) or the three product components (AC, BC, and CC). The product chosen for this study is a printer, which has a medium value-weight and weight-bulk ratio (important because extreme product characteristics can limit the usefulness of findings). In addition, according to a recent report, the imports share of domestic demand for printers has grown steadily from 58.5% in 2001 to 78.1% in 2006 (IBISWorld 2007).

Risk events serve as the independent variables for this event-driven model. For supply and demand risks, over 30 risk events such as oil price increases, currency fluctuations, supplier bankruptcy, and demand uncertainty were identified in the literature and the qualitative study. However, due to time and resource constraints, to keep the model simple without compromising the objectives and to make sure that the results can be interpreted, a short-listing of events most salient to global supply chains was undertaken. Risk events were grouped into three categories based on how risk events are manifested, namely supply, demand, and disruption. For the supply category, events that do not differ significantly between domestic and global contexts are either not included in this research or not varied between domestic and global suppliers. For the demand category, risk events that are either global in nature or relate to a seasonal product are either not included in this research or not varied between low and high demand risks. Disruption is modeled as a 45-day disruption at the port of Los Angeles.

In general, the data for this study came from the existing literature, secondary data sources, the qualitative study, and interviews with managers. Table IV-1 provides a list of all independent variables, their definitions, values, and any additional information in the remarks column. Supply risk events are divided into lead time variability, cost variability, and quality variability. Lead time variability is further divided into order processing time variability, and transportation lead time variability. Although there is variability in transportation times, they do not change between the low risk and high risk Chinese supplier. Therefore, transportation time is not an independent variable. Demand side risk is manifest by demand variability.

The low supply risk environment was operationalized as low supplier order processing time variability, low cost variability, and low levels of quality defects. The high supply risk environment was operationalized as high supplier order processing time variability, high cost variability, and high levels of quality defects. The low demand risk environment was operationalized as low demand variability and the high demand risk environment was operationalized as high demand variability. The assuming strategy was operationalized by using a single Chinese supplier. The hedging strategy was operationalized by using two suppliers, one each in the US and China. The speculation strategy was operationalized by sourcing finished products from suppliers. The postponement strategy was operationalized by sourcing components from the suppliers and assembling them at the focal firm.

TABLE IV-1: INDEPENDENT VARIABLES

Supply Risk Events

Risk Factors	Definition	Global (Low)	Global (High)	US*	Remarks
1. Supplier Order Processing Time Variability	Time from order placement to replenishment at the supplier facility	N (15, 1.5) days	N (15,3) days	N (10,1) days	Normal (Mean, SD)
2. Cost Variability	Variability in cost				
	Product A or Product B ($)	T (60,64.5, 69)	T (60, 73.5, 87)	80	15% for low supply risk 45% for high supply risk T=Triangular (Min, Mean, Max)
	Component AC or Component BC ($)	T (15, 16.125, 17.25)	T (15, 18.375, 21.75)	20	
	Component CC ($)	T (35, 37.625, 40.25)	T (35, 42.875, 50.75)	50	
3. Quality Variability/ Yield	Variability in usable products and components received from suppliers	0.98	0.97	0.99	1% defects for domestic supplier 2% defects for low risk China supplier 3% defects for high risk China supplier

Demand Risk Event

Risk Factor	Definition	Low Risk	High Risk	Remarks
Variability of demand	Average variation in daily demand	N (1000, 100)	N (1000,300)	Normal (Mean, Standard Deviation)

* US values remain constant throughout all scenarios

MODEL FLOW

The model is triggered by the generation of demand at customer locations. Demand is distributed normally with a mean of 1000 units per day per customer. Average demand for each customer is derived from secondary data of a major printer manufacturer company. The standard deviation is set to 100 units for the low demand risk scenario and 300 units for the high demand risk scenario. This sets the coefficient of variation to 0.1 for low demand risk and to 0.3 for high demand risk. These coefficients of variation have been used in past research (Mentzer and Gomes 1991).

The order is due in 15 days. Units arriving later than 15 days incur a penalty of $35/unit. This is approximately 25% of the selling price and has been validated in qualitative interviews. Demand generated at customers is transmitted instantaneously to the manufacturer/distributor at zero cost. The processing at M/D occurs 8 hours a day, 7 days a week, 365 days a year. For speculation, order processing includes picking products, packing, and shipping goods. For postponement, order processing includes picking components, assembling, packing, and shipping goods. Daily order processing capacity is set to 130% of daily demand. For either product, the cost of picking and packing is $10/unit, of assembling is $20/unit per unit, and of shipping is $10/unit.

Quality variability is operationalized using variable yields from different suppliers. For the domestic supplier, every unit has a 1% chance of being defective, i.e., the yield is 99%. In assuming scenarios, for the low risk Chinese supplier, yield is 98% and for the high risk Chinese supplier, yield is 97%. For the hedging scenario, yield is set to 98.5% (average of 99% and 98%) for the low risk scenarios and yield is set to 98% (average of 99% and 97%) for the high risk scenarios.

Inventory value of products and components is assessed at average purchase cost. Inventory is valued at 17%, which is the average cost of carrying inventory per the Annual State of Logistics Report (Wilson 2006). As orders are processed, inventory levels for finished products or component parts are checked every half hour. Whenever the inventory level for a given product or component goes below the reorder point, ROP, a replenishment order for a fixed quantity, Q, is placed with the supplier. For the speculation scenario, all orders are assigned to the single Chinese supplier. For the hedging scenario, each replenishment order has an equal probability (0.5) of being assigned to either the Chinese or the domestic supplier. The value for ROP is calculated using the following formula (Mentzer and Krishnan 1985) which is a standard business practice:

$$ROP = \mu_{DDLT} + z\ \sigma_{DDLT}$$

Where,
μ_{DDLT} = average demand during lead time
z = 1.00 for an 84% in-stock probability
σ_{DDLT}= standard deviation of demand during lead time

The value of Q is calculated using the following formula described in Coyle, Bardi and Langley (2003) that incorporates the expected cost of stock-outs. The calculated value of Q is rounded to the nearest integer that is a multiple of a container-load quantity for a given product or component.

$$Q= \sqrt{(2R(A+G)/IC)}$$

Where,
R= Annual demand
A=Order cost per order
G=Stock-out cost per cycle
I=Inventory carrying cost
C=Cost of product or component

For the assuming scenario, calculation of ROP and Q values is based on the average and variability of lead times for the Chinese supplier and of demand at the customers. For the hedging scenario also, ROP is based on the average and variability of the Chinese supplier. Because of the large variation between the lead times for the domestic and Chinese suppliers, basing the ROP calculation on either the US supplier or averages of the Chinese and US supplier leads to frequent stock-outs and unduly reduces the performance of a hedging strategy.

The product purchase price from the Chinese supplier is $60/unit. Typically, the purchase cost of electronic products and components is around 20% to 30% cheaper in China (Engardio, Roberts and Bremner 2004). Several discussions with practitioners confirmed this. The purchase price from the US supplier is $80 (i.e., the resultant cost differential is 25% ((80-60)/80 =25%)). The cost of the components sourced from the Chinese supplier is set to $15 for components AC and BC, and $35 for the common component CC. Using a similar cost differential (approximately 25%), component prices are $20 and $50 for the US supplier.

To operationalize the second aspect of supply risks, i.e., cost variability, the purchase cost of products and components from the Chinese supplier is set to a high of 15% for low risk scenarios and a high of 45% for high risk scenarios. The value of 15% was arrived at by extrapolating the current wage rate increase over the past six years and the gradual but continuous strengthening of Chinese currency (Yuan) over the past two years. The high value was based on trends in price increases of raw materials and components (such as iron ore, silicon wafers, and polysilicon) that go into electronic products, labor shortages that can potentially lead to further increases in labor costs, and oil price increases. Purchase costs are provided in Table IV-1.

Orders at the supplier facility are processed using the First-In-First-Out priority. The supplier has no capacity constraints and there are no backorders. Every order is filled complete. At the US supplier, the order processing time is set to a normal distribution with a mean of 10 days and standard deviation of 1 day. The order processing time at the Chinese supplier is set to a normal distribution with a mean of 15 days and standard deviation of 1.5 days for low supply risk scenarios and standard deviation of 4.5 days for high supply risk scenario. This sets the coefficient of variation (CV) values to 0.1 and 0.3 for low and high risk scenarios, respectively. These CV values have been used in past research (Mentzer and Gomes 1991). At the Chinese supplier, the goods are sent to the Hong Kong port using domestic transportation. At the Hong Kong port, goods are loaded onto a ship. The ship travels from the Hong Kong port to the US Los Angeles port. At the port, goods are cleared through the customs and loaded onto trucks, which transport the goods to the M/D. At the domestic supplier, the goods are shipped to the M/D using trucks in full truck loads. Transportation times used in this model are based on published secondary sources, interviews with managers, and quotes from trucking and freight forwarding companies.

From the M/D, orders are shipped daily to customers. Transit time to customers is fixed at 3 days. Goods are shipped on a per unit basis with a charge of $10/unit. Transit times and cost figures are based on interviews and quotes from freight companies.

The selling price of $150/unit is based on secondary data of a major printer manufacturer, which states that typical the gross margins are around 32-35%. Average weighted gross margins with a selling price of $150/unit for all scenarios under average price (i.e., considering purchase cost variability risk) work out to around 31%.

MODEL VERIFICATION AND MODEL VALIDATION

This research used a simulation package designed specifically to model supply chains called Supply Chain Guru (SC Guru) developed by the Llamasoft Corporation (www.llamasoft.com). SC Guru is the commercially available supply chain analysis package that combines optimization and discrete event simulation. Following methods used in past research (Mentzer and Gomes 1991; Shang, Li and Tadikamalla 2004); Fishman and Kiviat (1968) , this study addressed the issue of model verification in several ways. First, two programmers who are expert in modeling supply chains using SC Guru were used. The first expert trained the researcher in building the model using SC Guru and helped set up and verify the basic model structure of the supply chain and the four risk management strategies. The second expert, a programmer involved in the development of the software, verified multiple aspects of the program. The involvement of the experts also minimized the possibility of programming errors (bugs).

Second, output of parts of the model (sub-structures) was compared with manually calculated solutions to determine if they behaved acceptably. Aspects validated during this process included verification of transportation times, queuing of shipments throughout the supply chain, and inventory policies. Following Gomes and Mentzer (1991), the uniformity and independence of the model's random number generators was verified, including purchase costs of components and products, demand for products A and B, order processing times at the supplies, transportation times and variability, and quality variability.

Third, simulation results for short pilot runs of simple cases for the complete model were compared with manual calculations to test if the entire model (structure) behaved acceptably. Aspects validated for all scenarios included inbound container load/truckload costs of transportation, average purchase costs for low and high risk scenarios, order processing and assembly costs at the M/D, picking and packing costs, and outbound cost/unit of transportation.

As a fourth way to verify model, this research followed Mentzer and Gomes (1991) who state that for their model, *"All events were hand verified through each model segment – first with simple deterministic runs, followed by stochastic checks with increasing integration of activities."* The model was built in stages where each sub-model was verified by replacing stochastic elements with deterministic elements and gradually integrating these sub-models into the main model.

Following the methods used in past research (Bienstock and Mentzer 1999; Mentzer and Gomes 1991; Powers and Closs 1987; Shang, Li and Tadikamalla 2004); Law and Kelton (1982), this study addressed the issue of model validation in several ways. First, subject matter experts, including academic scholars and practitioners, were consulted in the conceptual development of model components and relationships between components. This step ensures that the correct problem is solved and reality is adequately modeled (Law and Kelton 1982).

Second, a structured walk-through of the model and a review of the simulation results for reasonableness with a separate set of subject matter experts, including academic scholars and practitioners, was conducted. Results were consistent with how the subject matter experts perceive the system should operate. This confirms model face validity. Face validity was also confirmed using literature and review of supply chain simulation models in past research.

For this study, input-output transformation, i.e., comparing simulation data to real world data, was not possible for several reasons. First, complexity of real world supply chains is far greater than the one simulated in this research. Therefore, it is difficult to isolate the effect of the variables in the real data. Second, it is difficult to find a company that is willing to share complete data on all variables included in this research. No data that spanned more than two levels of a supply chain for a given product could be gathered. These datasets were used to validate corresponding parts of the model. Finally, sensitivity analyses were performed on the model to see which model factors have the greatest impact on the performance measures and, thus, have to be modeled carefully (Powers and Closs 1987).

Combinations of high and low levels of risks were used to generate four possible combinations of demand and supply risk levels. All four risk management strategies were simulated separately for each of the four combinations of demand and supply risk levels. This totals to 2 x 2x 2 x2 =16 scenarios. All scenarios were repeated with a 45-day LA port disruption.

A procedure based on Law and Kelton (1982) and Bienstock (1996) was used for sample size determination. The procedure consisted of choosing an initial sample size (n_0) and a target value for the relative precision (γ). A series of pilot runs of the simulation model was conducted, replacing the sample size by n + 1 for each successive pilot run, until the desired relative precision was attained for all scenarios. For this study, the sample size determined using the technique discussed above at 5% relative precision was 28 runs per scenario. Relative precision values were calculated for 16 non-disruption scenarios. Relative precision values were not calculated for disruption scenarios because a disruption leads to highly variable results between runs depending on the time of disruption and it is unlikely that results will fall within a 5% precision level. Therefore, similar to non-disruption scenarios, a sample size of 28 runs each was used for disruption scenarios.

RESULTS

Net profit means for all non-disruption scenarios are provided in Table IV-2. Overall, Table IV-2 reveals that in all non-disruption scenarios, assuming-speculation shows the widest range of outcomes. This is because both assuming and speculation are risk taking strategies that seek to make use of low costs. If everything falls into place, i.e., the most favorable risk events happen, then the economies of purchase cost on the supply side as well as lack of assembly costs on the demand side lead to very low costs, and therefore, high profit. However, if unfavorable events, i.e., the undesirable extremes of risk events, occur, then there is no buffer on the supply side and no goods to sell on the demand side, which leads to high penalty costs and low revenues.

In the disruption scenarios, assuming-postponement has the widest range of outcomes. Hedging-speculation and hedging-postponement show a narrow range of outcomes because the effect of supply disruption is mitigated by the domestic supplier.

TABLE IV-2: MEAN NET PROFIT FOR ALL SCENARIOS

	SR	DR	SS	DS	Dis	Mean	Min	Max	Range
1	L	L	He	Po	No	50,840,238	46,466,384	54,069,936	7,603,552
2	L	L	He	Sp	No	65,202,222	62,094,720	70,009,248	7,914,528
3	L	L	As	Po	No	48,054,111	44,101,152	49,994,848	5,893,696
4	L	L	As	Sp	No	67,220,343	63,349,040	71,803,216	8,454,176
5	L	H	He	Po	No	48,513,789	45,734,208	51,691,536	5,957,328
6	L	H	He	Sp	No	65,532,359	62,746,976	68,042,896	5,295,920
7	L	H	As	Po	No	44,734,695	41,594,224	46,619,120	5,024,896
8	L	H	As	Sp	No	67,101,890	63,316,288	71,401,952	8,085,664
9	H	L	He	Po	No	30,802,842	25,204,864	36,231,424	11,026,560
10	H	L	He	Sp	No	51,519,762	47,350,192	56,542,624	9,192,432
11	H	L	As	Po	No	21,546,395	17,249,168	24,839,664	7,590,496
12	H	L	As	Sp	No	42,658,187	36,127,056	49,106,240	12,979,184
13	H	H	He	Po	No	29,285,917	22,917,360	33,948,048	11,030,688
14	H	H	He	Sp	No	51,884,733	48,145,744	56,423,920	8,278,176
15	H	H	As	Po	No	20,247,735	15,153,616	25,815,184	10,661,568
16	H	H	As	Sp	No	41,490,925	32,884,416	49,714,512	16,830,096
1d	L	L	He	Po	Yes	46,353,015	40,185,472	50,123,088	9,937,616
2d	L	L	He	Sp	Yes	63,994,919	60,844,528	67,239,264	6,394,736
3d	L	L	As	Po	Yes	37,817,641	33,584,288	48,144,896	14,560,608
4d	L	L	As	Sp	Yes	62,920,410	59,448,336	67,285,856	7,837,520
5d	L	H	He	Po	Yes	45,248,323	39,940,320	50,492,464	10,552,144
6d	L	H	He	Sp	Yes	63,748,942	59,197,840	67,450,432	8,252,592
7d	L	H	As	Po	Yes	36,775,135	28,752,624	43,091,456	14,338,832
8d	L	H	As	Sp	Yes	61,893,547	59,625,216	64,008,544	4,383,328
9d	H	L	He	Po	Yes	29,260,097	23,985,776	33,273,840	9,288,064
10d	H	L	He	Sp	Yes	49,470,853	41,316,672	55,261,632	13,944,960
11d	H	L	As	Po	Yes	18,525,630	8,455,872	30,324,272	21,868,400
12d	H	L	As	Sp	Yes	40,705,790	33,881,504	49,355,280	15,473,776
13d	H	H	He	Po	Yes	26,591,756	18,352,880	33,259,888	14,907,008
14d	H	H	He	Sp	Yes	50,281,122	43,728,544	55,949,408	12,220,864
15d	H	H	As	Po	Yes	18,901,424	7,723,568	24,194,496	16,470,928
16d	H	H	As	Sp	Yes	37,485,562	29,068,128	45,145,312	16,077,184

SR=Supply Risk; DR=Demand Risk; SS=Supply Strategy; DS=Demand Strategy; L=low; H=High; Dis=Disruption

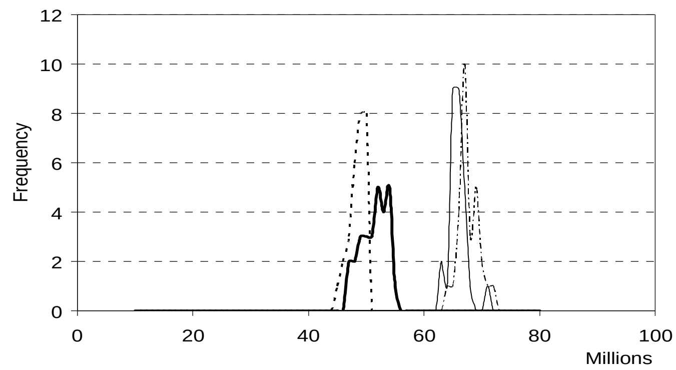
Assuming-postponement has a wider range over assuming-speculation because if disruption affects a shipment of either component AC or component BC, then the remaining goods can be sold and some profit can be made. On the other hand, if a disruption affects a shipment of common component CC, neither product A nor product B can be sold, resulting in very low profit. In assuming-speculation, if a shipment of either product A or product B is affected, the other product can be sold.

Figure IV-4 graphically presents outcomes of all four combinations of strategies under different supply and demand risk conditions. Three of the four charts show a combination of strategy that is distinctly superior to other strategies. Only for the low supply-high demand risk scenario, two strategies show similar performance. This confirms the underlying concept of "fit" that different combinations of strategies produce significantly different outcomes under similar environmental conditions.

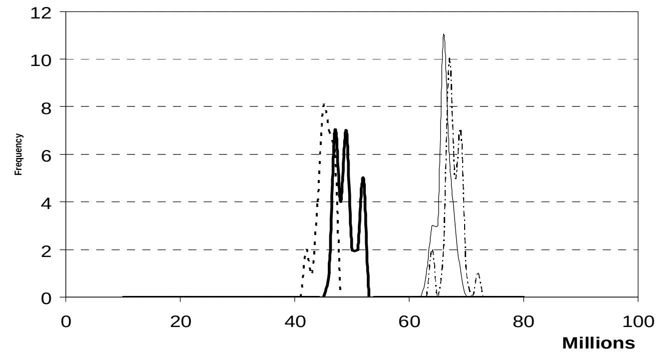
Hypotheses were tested with the General Linear Model in SPSS and Tukey's W procedure for multiple comparisons of means. Tukey's W procedure is used over several other methods of comparative testing of means, such as the commonly used Fisher's Least Significant Difference (LSD), because Tukey's method makes use of the Studentized range distribution that is more conservative, i.e., declares fewer significant differences. With LSD there is a high probability of declaring at least one pair of means significantly different when running multiple comparisons (Ott and Longnecker 2001). Tukey's procedure requires an equal sample size for all scenarios.

Two population means $\mu 1$ and $\mu 2$ are declared different if

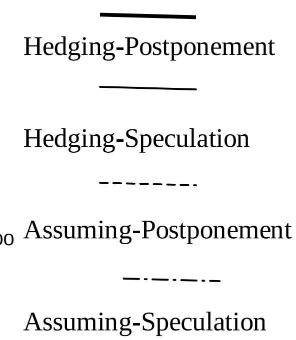
$|\mu 1=\mu 2| >= W$,



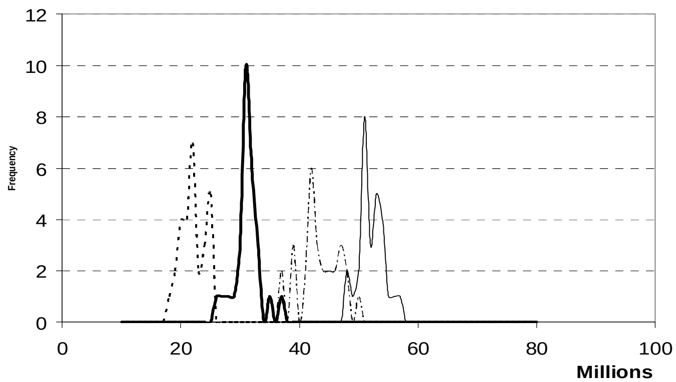
(a) Low Supply-Low Demand Scenarios



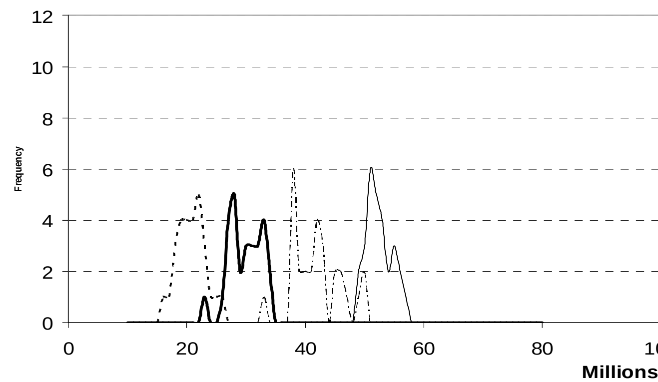
(b) Low Supply-High Demand Scenarios



Note: Graphs represent the distribution of values for all 28 runs.



(c) High Supply-Low Demand Scenarios



(d) High Supply-High Demand Scenarios

FIGURE IV-4 : DISTRIBUTION OF TOTAL PROFIT UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

Where,

$W = q_\alpha v\sqrt{(s^2w/n)}$
s^2w is the mean square within samples based on v degrees of freedom
$q_\alpha v\sqrt{(s^2w/n)}$ is the upper-tail critical value of the Studentized range for comparing t different populations
n is the number of observations in each sample
α is the level of significance, which is 0.05 for this study

The results are based on net profit, i.e., Total Revenue – Total Costs. Total costs include transportation, inventory, production (assembly), warehousing (picking and packing), penalty (late delivery), and purchase costs. Some results are additionally explained in terms of Return on Investment (ROI), i.e., net profit/total cost, when they are different from the net profit results.

Sensitivity analysis was also performed on several model parameters and independent variables. A summary of sensitivity analysis is presented in Table IV-3.

H1: Supply chains facing high supply risks (S_HD_L and S_HD_H environments) that adopt a hedging strategy will show higher profit than supply chains that adopt an assuming strategy.

9>11 Yes
10>12 Yes
13>15 Yes
14>16 Yes

H1 is supported (see Figure IV-5a). Hedging strategy is better than assuming strategy for supply chains facing high supply risks. In the face of both high or low demand risks, and high supply risks, hedging-postponement scenarios are better than assuming-postponement scenarios and hedging-speculation scenarios are better than assuming-speculation scenarios. In general, all assuming scenarios showed lower purchase costs compared to corresponding hedging scenarios. But this benefit was more than offset by lower transportation and lower penalty costs in the hedging scenarios.

TABLE IV-3: SUMMARY OF SENSITIVITY ANALYSIS

Hypothesis and Conclusion *	**Impact of**				
	Finding**	**Increase in Domestic Procurement Cost**	**Increase in Demand Variability**	**Decrease in Assembly Costs**	**Decrease in Penalty Costs**
		By 5% and 10%	From N(1000, 100) or N (1000, 300) to N(1000, 500)	From $20/unit to $10/unit	From $35/unit to $25/unit
H1: Supported	Hedging > Assuming for high supply risks	No change in finding	No change in finding	NU	No change in finding
H2: Partially Supported	Assuming ≤ Hedging for low supply risks	With 5% increase, assuming = hedging. With 10% increase, assuming > hedging.	NU	NU	Assuming is better than hedging.
H3: Not Supported	Postponement < Speculation for high demand risks	NU	No change in finding	Gap between postponement and speculation narrows.	Gap between postponement and speculation narrows significantly.
H4: Supported	Speculation > Postponement for low demand risks	NU	No change in finding	Gap between postponement and speculation narrows.	Gap between postponement and speculation narrows significantly.
H5: Partially Supported	Assuming-Speculation = Hedging-Speculation for low supply-low demand risks	NU	NU	NU	NU

TABLE IV-3: Continued.

Hypothesis and Conclusion *	Impact of				
	Finding**	**Increase in Domestic Procurement Cost**	**Increase in Demand Variability**	**Decrease in Assembly Costs**	**Decrease in Penalty Costs**
H6: Not Supported	Assuming Speculation = Hedging-Speculation for low supply-high demand risks	NU	NU	NU	NU
H7: Supported	Hedging-Speculation is the best fit for high supply-low demand risks	No change in finding	No change in finding	No change in finding	No change in finding
H8: Not Supported	Hedging-speculation> Hedging-postponement for high supply-high demand risks	No change in finding	No change in finding	Gap between hedging-postponement and hedging-speculation narrows.	Gap between hedging-postponement and hedging-speculation narrows significantly.

* Conclusion refers to whether a hypothesis was supported, partially supported, or not supported
** Finding refers to the actual final result based on statistical tests.
NU= Not Undertaken

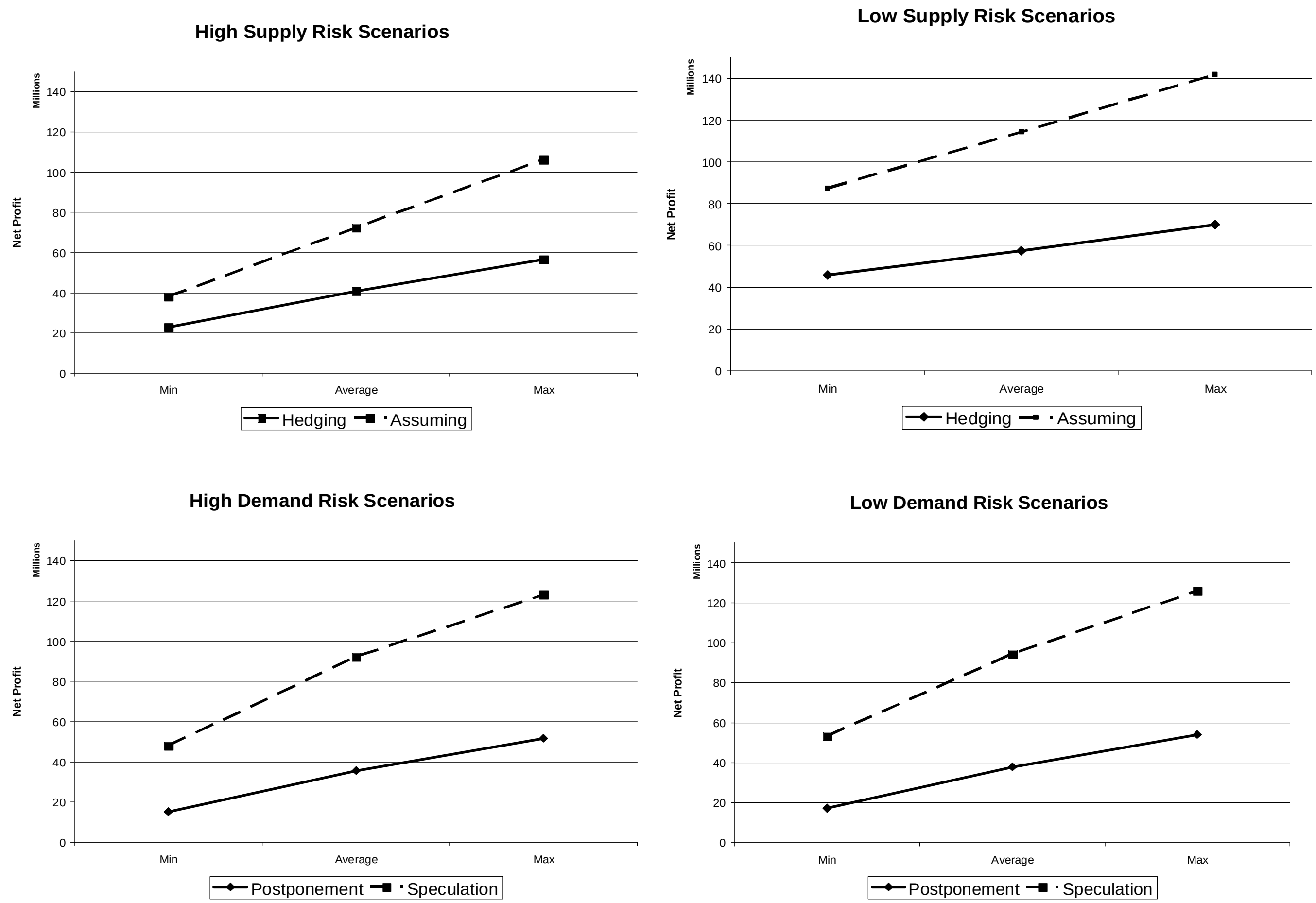


FIGURE IV-5 : TOTAL PROFIT UNDER DIFFERENT LEVELS OF SUPPLY AND DEMAND RISKS

This finding confirms the commonly held belief in practice and theory that it is beneficial to hedge risks by creating options when facing high risks. Further investigation of this result was undertaken by comparing scenarios 9 and 11 by: (a) increasing the domestic procurement costs by 5%, (b) increasing the domestic procurement cost by 10%, and (c) reducing the penalty cost per unit from $35 to $25. An increase in domestic procurement costs by either 5% or 10% did not change the superiority of hedging strategy over assuming strategy. However, as expected, it reduced the profit gap. On the other hand, while lower penalty costs also did not make hedging less desirable, the increase in profits was more for assuming scenarios than for hedging scenarios. This is because assuming scenarios incur higher penalty costs.

In sum, the use of hedging strategy under high supply risks is desirable and fairly robust to mild variations in the model parameters.

H2: Supply chains facing low supply risks (S_LD_H and S_LD_L environments) that adopt an assuming strategy will show higher profit than supply chains that adopt a hedging strategy.

3>1	No, 1>3
4>2	No, 4=2
7>5	No, 5>7
8>6	No, 8=6

H2 is not supported (see Figure IV-5b). Hedging strategy works as well as or better than assuming strategy in all cases of low supply risks. Hedging works as well as assuming works with speculation strategy on the demand side, i.e., 4=2 and 8=6. Hedging works better than assuming in case of low supply risks when the strategy on the demand side is postponement, i.e. 1>3 and 5>7. This is contrary to the hypothesis that assuming strategy fits better with low supply risk conditions. Penalty cost is the single biggest factor affecting the profitability.

In postponement scenarios, higher purchase costs and marginally higher inventory costs of hedging were offset, to a large extent, by penalty costs in an assuming strategy. This is because if there is a delay, and the common component is missing, neither Product A nor Product B can be sold. In the assuming-postponement scenario, the probability that a common component shipment faces any of the extremities of global risk events is 1/3. However, in the hedging-postponement scenario, since every order has an equal chance of being assigned to either supplier, the probability that the common-component faces any of the extremities is halved. In speculation scenarios, if there is a delay, whatever is available – Product A or Product B – can be sold to the customer and thus penalty costs can be minimized. Here, the lower purchase and high penalty costs balance each other such that profit is similar to that of a hedging scenario.

It is interesting to note that, in terms of ROI, 4>2 and 8>6, which provides some support for H2. For scenarios 4 and 2, and 8 and 6 the mean net profit of assuming strategy (4 or 8) is higher, though not significantly, than that of a hedging strategy (2 or 6 respectively). This higher profit combined with marginally lower costs in an assuming strategy leads to a significantly higher ROI (3%) for the assuming scenario. 4, 2, 8 and 6 represent scenarios with speculation strategy on the demand side. Therefore, assuming is a good option in light of low supply risks only when speculation strategy is used on the demand side. When postponement strategy is used on the demand side, then hedging is better even in case of low supply risks.

In terms of total profit distributions, it is interesting to note that scenario 4 has the highest range. Scenario 2 is next with a 6% lower range than scenario 4. Similarly, scenario 6 shows a significantly lower range than scenario 8. Although assuming-speculation is the best strategy, it also shows the widest possible range of outcomes. This is an interesting observation because, based on performance measures, a case can be made for either assuming or hedging. An important implication of this result is that performance measures must be chosen with great care as it affects the choice of strategy.

To further investigate these results, scenarios 1 and 3, and scenarios 5 and 7 were compared by: (a) increasing domestic procurement cost by 5%, (b) increasing domestic procurement cost by 10%, and (c) reducing penalty cost to $25 per unit from $35 per unit. It is interesting to note that a mere 5% increase in purchase cost marginally tips the scales in favor of an assuming strategy and a 10% increase makes assuming a significantly better strategy for all low supply risks. Reducing penalty cost by $10/unit again makes assuming a better strategy for all scenarios. Unlike in high supply risk scenarios, a hedging strategy is highly responsive to moderate changes in environment in low supply risk scenarios. Creating options for a hedging strategy is expensive and needs careful evaluation when implemented with low supply risk scenarios.

In sum, hedging is useful with postponement strategy. With speculation strategy, however, the use of either strategy is dependent on the performance measure used. Based on net profit, they are equal. Based on ROI, assuming is better. Overall, in scenarios where hedging is better, moderate changes in model parameters make assuming a better option under all combinations of low supply risks.

H3: Supply chains facing high demand risks (S_LD_H and S_HD_H environments) that adopt a postponement strategy will show higher profit than supply chains adopting a speculation strategy.

5>6	No, 5<6
7>8	No, 7<8
13>14	No, 13<14
15>16	No, 15<16

H3 is not supported (see Figure IV-5c). In all scenarios, speculation was better than postponement. Production cost, i.e., cost of assembling products in the US, was the biggest factor affecting the total costs. The next important factor was penalty costs. There was no significant difference in inventory costs. For example, between scenarios 5 and 6, the total revenues are not significantly different. Scenario 5 incurs a production (assembly) cost. In addition, the number of units delivered late is almost 18% higher for the postponement scenario (5), which directly increases the penalty costs and total costs. Similar observations comparing scenarios 7 and 8, 13 and 14, and 15 and 16 confirm that higher assembly and penalty costs make postponement unprofitable for all scenarios.

To ascertain the impact of assembly costs and demand variability on usefulness of a postponement strategy, further sensitivity analysis on scenarios 5 and 6 was undertaken with following variations: (a) lower assembly cost of $10 in place of $20, (b) higher demand variability with N (1000, 500) in place of N (1000, 300) without changing the ROP or Q values, (c) lower penalty cost per unit of $25 in place of $35, and (d) extended lead time to customers of 20 days in place of 15 days. As expected, the gap between net profit for postponement and speculation scenarios decreased significantly with decreasing assembly costs. Higher demand variability and lower penalty cost also narrowed the profit gap. However, the biggest impact came from increasing the lead time to customers. While scenario speculation 6 profit increased by only 7%, postponement scenario 5 gained 23%.

This leads to three interesting conclusions. First, a threshold level of demand variability should be present to justify the use of postponement strategy. Second, a conclusion already well known and accepted among practitioners, continuous lowering of processing costs domestically is required in addition to low-cost offshore procurement to reap optimum benefits of globalization. Off-shoring production to low cost countries without reducing costs domestically is not likely to lead to sustainable performance. Third, either reduction in assembly time or more time to serve customers is required to reap the benefits of a postponement strategy. In sum, speculation strategy is desirable under high demand risk conditions when the only demand risk is demand variability.

H4: Supply chains facing low demand risks (S_LD_L and S_HD_L environments) that adopt a speculation strategy will show higher profit than supply chains that adopt a postponement strategy.

2>1	Yes
4>3	Yes
10>9	Yes
12>11	Yes

H4 is supported (see Figure IV-5d). Speculation is better than postponement in the face of low supply risks. In the face of both high or low supply risks, and low demand risks, assuming-speculation scenarios are better than assuming-postponement scenarios and hedging-speculation scenarios are better than hedging-postponement scenarios. In general, all postponement scenarios incur assembly costs, and show higher penalty costs than assuming scenarios. This confirms the commonly held belief in practice and theory that it is beneficial to focus resources on fewer initiatives when risks are low.

Combined with the H3 result, it appears that demand risk level has no significant impact on selection of postponement or speculation strategy. This creates an opportunity for exploring the reasons. It is possible that two stock keeping units (SKUs) and two customers are not enough to represent the product and component diversity to reap the benefit of postponement. A minimum number of SKUs and components may be needed to justify investment in postponement strategy. It is also likely, as the sensitivity analysis for H3 suggests, that a threshold level of demand variability is required to justify the use of postponement strategy. As Yang, Burns and Backhouse (2004) note, postponement is a typical response to external uncertainty. However, while so much interest has been placed on how uncertainty is conceptualized, operationalized and measured, there is little agreement on which dimensions are the keys that affect the use of postponement strategy.

H5: Supply chains facing low supply risks and low demand risks (S_LD_L environment) that adopt an assuming strategy on the supply side and a speculation strategy on the demand side will show higher profit than other supply chains facing the same environment that adopt any other combination of strategies.

4> 1, 2, and 3 No, 4=2 and (4and 2)>1, 3

H5 is partially supported (See Figure IV-4a). Assuming-speculation (4) and hedging-speculation (2) are both equally good options for supply chains facing low supply-low demand risk conditions. Between scenarios 4 and 2, the high transportation and penalty costs of assuming strategy (4) are offset by higher purchase costs of the hedging strategy (2). In terms of ROI, 4>2, i.e., assuming-speculation is better than hedging-speculation. The mean net profit of an assuming strategy is higher, though not significantly, than that of a hedging strategy. This higher profit, combined with marginally lower costs in an assuming strategy, lead to a significantly higher ROI (3%)

for the assuming scenario. Based on ROI, it can be reasonably argued that in general assuming-speculation is the best fit for low supply-low demand risk scenarios.

As mentioned earlier under H2, it is interesting to note that scenario 4 shows the highest range. Therefore, although assuming-speculation is the best strategy, it also shows the widest range of outcomes. This implies that a strategy may have contradictory impacts on different performance measures and choice of performance measure affects the selection of strategy.

H6: Supply chains facing low supply risks and high demand risks ($S_L D_H$ environment) that adopt an assuming strategy on the supply side and a postponement strategy on the demand side will show higher profit than other supply chains facing the same environment that adopt any other combination of strategies.

7>5, 6, and 8 No, (8 = 6)>5> 7

H6 is not supported (see Figure IV-4b). Assuming-postponement (7) is not the best fit for a low-supply high-demand risk scenario. The best fit for a low supply-high demand risk scenario is assuming-speculation (8) or hedging-speculation (6). Although the net profit for both scenarios is the same, the factors driving the costs are different. Scenario 6 has higher purchase costs (because it is a hedging strategy) whereas scenario 8 has higher penalty costs because of higher late deliveries. However, going by ROI, assuming-speculation (8) is best.

This finding is similar to findings of H3 and H4 earlier that presence of high demand variability does not justify the use of a postponement strategy. A reasonable conclusion is that, based on net profit and ROI, assuming-speculation is the best fit for a low supply-high demand risk scenario.

H7: Supply chains facing high supply risks and low demand risks ($S_H D_L$ environment) that adopt a hedging strategy on the supply side and a speculation strategy on the demand side will show higher profit than other supply chains facing the same environment that adopt any other combination of strategies.

10>9, 11, 12 Yes

H7 is supported (Figure IV-4c). Hedging-speculation is the best combination for the high supply low-demand risk scenario. Comparing the best scenario, hedging-speculation (10), with the next best, assuming-speculation (12), it is interesting to note that late delivery penalty costs explain much of the difference. Although, scenario 12 has lower purchase costs and incurs no production costs, these benefits are more than offset by penalty costs and higher costs of global transportation for assuming scenarios.

Further investigation of this result compared scenarios 9, 10, 11 and 12 by: (a) increasing the domestic procurement costs by 5%, (b) increasing the domestic procurement cost by 10%, (c) reducing the penalty cost per unit from $35 to $25, and (d) by increasing demand variability to N(1000, 300) from N(1000, 100). All changes still reflected the superiority of hedging-assuming over all other combinations of strategies. Therefore, hedging-speculation is a good fit for the high supply risk – low demand risk environment and is robust to moderate environmental variations.

H8: Supply chains facing high supply risks and high demand risks ($S_H D_H$ environment) that adopt a hedging strategy on the supply side and a postponement strategy on the demand side will show higher profit than other supply chains facing the same environment that adopt any other combination of strategies.

13> 14, 15, and 16 No, 13>15 but 13<16<14

H8 is partially supported (Figure IV-4d). In the two postponement scenarios, hedging-postponement (13) works better than assuming-postponement (15). In the two speculation scenarios, hedging-speculation (14) works better than assuming-speculation (16). Both 13>15 and 14>16 support that hedging works better in high supply risk. Overall, hedging-speculation works best for high-supply high-demand risk scenario.

In light of the findings of H3 and H4 that demand variability does not justify the postponement strategy, a comparative sensitivity analysis of scenarios 13 and 14 was undertaken with following variations: (a) order due date of 20 days in place of 15 days, (b) lower assembly cost of $10 in place of $20, and (c) higher demand variability with N (1000, 500) in place of N (1000, 300) without changing the ROP or Q values. Under all scenarios, hedging-speculation (14) continued to be a better strategy than hedging-postponement. However, lower assembly costs and a longer order due date significantly narrowed the gap. This is interesting because while more time provided to fill customer orders made only a small contribution to the speculation scenario (14), it drastically improved the performance of the postponement scenario (13) by almost 100%. This is because of reduced penalties. This finding suggests that use of postponement strategy may need to be supplemented with shorter assembly times, lower assembly costs, or longer lead times to customers to deliver the flexibility benefits under high demand variability. As mentioned earlier, different operationalizations of demand risks with more products, components, and customers, as well as with interactions of the factors mentioned above are required to test the boundaries of this finding.

H_E1: Supply chains facing low supply risks (S_LD_H environment) will show higher profit than supply chains facing high supply risks (S_HD_H environment) from adopting a postponement strategy.

5>3 Yes
7>15 Yes

H_E1 is supported. Benefits of postponement are better achieved when supply risks are low. This is in line with the argument by Lee (2002).

H_E2: Irrespective of the level of demand risks, all supply chains facing high supply risks (S_HD_L and S_HD_H environment) will show equal profit from adopting a hedging strategy.

9=13 Yes
10=14 Yes

H_E2 is supported. Benefits of hedging are independent of demand side risks. This result holds when the only risk on the demand side is demand variability. Further sensitivity analysis on demand risks is required to provide more confidence in the result.

H_E3: Irrespective of the level of demand risks, supply chains facing low supply risks (S_LD_L and S_LD_H environments) will show equal profit from adopting an assuming strategy.

3=7 No; 3>7
4=8 Yes

H_E3 is partially supported. 3 is the low-supply low-demand risk assuming-postponement scenario, and 7 is the low-supply high-demand risk assuming-postponement scenario. Assuming works better when demand risks are low. 4 is the low-supply low-demand assuming-speculation scenario, and 8 is the low-supply high-demand assuming-speculation scenario. When employing a speculation strategy on the demand side, assuming works equally well with both low and high demand risks.

H_E4: Irrespective of the level of supply risks, supply chains facing low demand risks (S_LD_L and S_HD_L environments) will show equal profit from adopting a speculation strategy.

2=10; No; 2>10
4=12; No; 4>12

H_E4 is not supported. Scenario 2 is low-supply low-demand hedging-speculation, and 10 is high-supply low-demand hedging-speculation. 4 is the low-supply low-demand assuming-speculation scenario, and 12 is the high-supply low-demand assuming-speculation scenario. In both cases, speculation works better with low supply risks.

These exploratory hypotheses suggest an interesting conclusion. H_E1 and H_E4 indicate that the usefulness of demand strategy is dependent on supply risks, i.e., both postponement and speculation strategies work better with low supply risks. H_E2 and H_E3 suggest that while hedging is independent of demand risks, assuming works better with low demand risks when used with postponement strategy and is independent of demand risks when used with speculation strategy. Therefore, in all cases except one, usefulness of supply strategy is largely independent of demand side risks.

H9: The total profit for a given combination of environment conditions and strategies under non-disruption will always be higher than total profit for the corresponding environmental conditions and strategies combination under disruption.

For all non-disruption and disruption scenarios, this translates into the following 16 sub-hypotheses:

q.	Profit for path 1 > Profit for path 1d	Yes
r.	Profit for path 2 > Profit for path 2d	No, 2=2d
s.	Profit for path 3 > Profit for path 3d	Yes
t.	Profit for path 4 > Profit for path 4d	Yes
u.	Profit for path 5 > Profit for path 5d	Yes
v.	Profit for path 6 > Profit for path 6d	No, 6=6d
w.	Profit for path 7 > Profit for path 7d	Yes
x.	Profit for path 8 > Profit for path 8d	Yes
y.	Profit for path 9 > Profit for path 9d	No, 9=9d
z.	Profit for path 10 > Profit for path 10d	No, 10=10d
aa.	Profit for path 11 > Profit for path 11d	Yes
bb.	Profit for path 12 > Profit for path 12d	No, 12=12d
cc.	Profit for path 13 > Profit for path 13d	No, 13=13d
dd.	Profit for path 14 > Profit for path 14d	No, 14=14d
ee.	Profit for path 15 > Profit for path 15d	No, 15=15d

ff. Profit for path 16 > Profit for path 16d Yes

Only 8 out of 16 sub-hypotheses are supported, i.e., show significantly lower performance under the conditions of a disruption. Not surprisingly, all cases of assuming strategy, except two, show significant decline in performance under conditions of disruption. Assuming is a risk taking strategy that makes use of low cost and therefore results in high profit under normal conditions. However, if a supply disruption happens, there is no buffer and the total profit declines substantially owing primarily to high penalty costs and low revenues. All hedging scenarios, except two, do not show a significant decline in performance under conditions of disruption. This is because of the presence of a buffer in the form of a domestic supplier.

In general, hedging strategy is likely to provide better overall results under conditions of disruption. However, the use of hedging strategy does not guarantee that disruption can always be handled better by hedging as compared to assuming strategy. This is evident from the fact that two assuming scenarios did not show significant decline in performance and two hedging scenarios did.

H10: For a supply disruption, hedging will always be better than assuming under corresponding environmental conditions and demand side strategy.

For all disruption scenarios, this translates into the following 8 sub-hypotheses:

q. Profit for path 1d > Profit for path 3d Yes
r. Profit for path 2d > Profit for path 4d No, 2d=4d
s. Profit for path 5d > Profit for path 7d Yes
t. Profit for path 6d > Profit for path 8d No, 6d=8d
u. Profit for path 9d > Profit for path 11d Yes
v. Profit for path 10d > Profit for path 12d Yes
w. Profit for path 13d > Profit for path 15d Yes
x. Profit for path 14d>Profit for path 16d Yes

6 of out 8 sub-hypotheses are supported. The other two, b and d, are equal. Net profit under a hedging strategy is equal to net profit under an assuming strategy under the following conditions of disruption: (a) Low supply-low demand and postponement strategy on demand side (2d=4d), and (b) Low supply-high demand and speculation strategy on demand side (6d=8d)

When faced with low risks, the cost of a hedging strategy is not justified even by a disruption. The implication is that hedging is not always an answer to a potential disruption. This also points to an important distinction between supply chain risk management and risk mitigation strategies. Supply chain risk management is for recurrent risk events and risk mitigation for low-probability but high impact events. For example, a contingency second supplier combined with a low-cost assuming strategy may be a better option under the two conditions stated above. Although, some supply chain risk management strategies may double up as risk mitigation strategies, it is not necessarily true in all cases.

PRACTICAL AND THEORETICAL IMPLICATIONS

Similar to different types of hypotheses, inferences about supply and demand strategies in isolation, the interaction effects of strategies, and the behavior of environment-strategy fit under conditions of a supply disruption may be drawn. Hypothesis testing confirms that supply chains facing high supply risks benefit from adopting a hedging strategy, irrespective of the level of demand risks or demand strategy adopted. *Post hoc* sensitivity analysis confirmed that hedging-postponement scenarios are better than assuming-postponement scenarios and hedging-speculation scenarios are better than assuming-speculation scenarios even under mild variations of model parameters such as higher domestic purchase costs and lower penalties.

On the other hand, supply chains facing low supply risks do not necessarily gain from adopting an assuming strategy. When speculation strategy is used on the demand side, then, based on ROI, assuming turns out to be good strategy. However, based on net profit, hedging and assuming strategies work equally well. When postponement strategy is used on the demand side, hedging is better. However, sensitivity analysis revealed that hedging strategy is highly responsive to moderate changes in environment in low supply risk scenarios. An important implication of this result is managers need to look at the demand side strategy when choosing a hedging strategy over assuming strategy with low supply risks. Hedging is expensive and should be carefully evaluated for all low supply risk scenarios.

Combined results of H3 and H4 suggest that high demand variability does not justify the use of postponement. Sensitivity analysis suggests that use of a postponement strategy may need to be supplemented with shorter assembly times, lower assembly costs, or longer lead times to customers to deliver the flexibility benefits under high demand variability. Managers need to be aware that continuous lowering of processing costs domestically is required in addition to low-cost offshore procurement to reap the benefits of globalization. Off-shoring production to low cost countries without reducing domestic costs is not likely to lead to sustainable performance. Other ways to reap the benefits of postponement include reduction in assembly time or more time to serve customers.

The choice between postponement and speculation strategy provides empirical evidence for past conceptual research. Pagh and Cooper (1998) suggest that speculation is a good strategy when the product line is narrow. This provides partial support for the contention that two stock keeping units are not enough to represent the product and component diversity to reap the benefit of postponement. On the other hand, the finding that there are certain variables associated with demand and supply that may make postponement a good choice under very select condition provides empirical evidence for Fisher's (1997) matrix on matching products with supply chain types. Fisher suggests that demand uncertainty requires market responsiveness and for that, in addition to developing modular products conducive to postponement, supply chain managers need to reduce lead time to customers and deploy component buffers.

For combinations of strategies, as expected, hedging-speculation works best for high supply-low demand scenarios. None of the other combinations reveal such straightforward results. For low supply-low demand scenarios, both hedging-speculation and assuming-speculation are good profit strategies. However, assuming-speculation works better than hedging-speculation based on ROI. For the low supply-high demand scenario, both assuming-speculation and hedging-speculation work equally well. However, if we look at ROI, then assuming-speculation is better than hedging-speculation. For the high supply-high demand scenario, assuming-speculation works best. An important implication of this result is managers should be careful in selecting the performance measure, or preferably evaluate strategies on multiple performance measures, as choice of strategy is affected by choice of performance measures.

The exploratory hypotheses were aimed at understanding the interrelationship between demand risk and supply strategy and supply risk and demand strategy. H_E1 and H_E4 indicate the usefulness of demand strategy is dependent on supply risks, i.e., both postponement and speculation strategies work better with low supply risks. However, H_E2 and H_E3 suggest that the usefulness of supply strategy is largely independent of demand side risks. This again leads to the conclusion that demand variability by itself is not a significant risk. However, as revealed in the sensitivity analysis, several factors comprise demand risk and the interaction effect of these risks can modify the result.

Analysis of results of disruption hypotheses points to an important distinction between supply chain risk management and risk mitigation strategies. Although, in general, hedging strategy is likely to provide better overall results under conditions of disruption, the use of strategy does not guarantee that disruption can always be handled by a hedging strategy. It appears that when faced with low risks, the cost of a hedging strategy is not justified even by a disruption. Although some supply chain risk management strategies may double as risk mitigation strategies, it is not necessarily always true. A risk mitigation strategy or contingency planning may be required on top of a risk management strategy.

This paper has several theoretical implications. Although the literature identifies several strategies for managing supply chain risks, it falls short of identifying when to use each strategy. This paper addresses the gap by applying the concept of fit from the strategy literature to a supply chain context. A contribution to the body of knowledge of this research is the development of model of environment-strategy fit and exploration of the impact of this fit on supply chain performance.

A second theoretical implication is the moderating effect of disruption on the fit between environment and strategy. Although, both academics and practitioners alike have been concerned about the impact of disruption on increasingly fragmented and geographically disperse supply chains, little work has been done to quantitatively explain the nature of the impact of a disruption in supply chains. This research takes the first step in understanding the impact of a port closure on global supply chains.

This research also takes the much needed step to quantify several aspects of supply and demand risks and strategies in global supply chains. The rigorous use of simulation modeling and detailed description of all steps in the model building process is a contribution. Finally, several interesting conclusions presented earlier either substantiate the current knowledge or open several new directions for exploring the phenomenon of risk management in global supply chains. This also adds to the body of knowledge.

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

First, as the results indicate, there is not much effect of demand risks on the outcome of different combinations of supply chain risk management strategies. Further exploration is required of this interesting and counterintuitive finding that higher demand variability does not justify the use of a postponement strategy. Furthermore, preliminary sensitivity analyses also suggest that higher demand variability does not, in isolation, justify the use of a postponement strategy. However, lower penalty costs, lower assembly costs, and longer lead times to customers significantly improve the usefulness of a postponement strategy. It is likely that interactions between these factors may modify the results. Future research may focus on these interactions. Future research may also focus on the cost differences between purchasing products and purchasing components and assembling them and the point where postponement becomes desirable.

Second, although hedging and assuming show rather straightforward results as to when to use which strategy depending on environmental conditions and demand side strategy, further research should focus on the H2 finding that hedging strategy is very responsive to minor changes in model parameters such as a 5% increase in domestic procurement and lower penalty costs that made assuming a better option under all combinations of low supply risks. An interesting research direction would be to explore the difference in relative purchase costs that make hedging desirable or undesirable under conditions of low supply risks.

As mentioned earlier, the literature review and qualitative study revealed eleven strategies of which only four were tested in this strategy. Future research should focus on quantification and testing of the remaining seven strategies. One strategy, flexibility, is particularly interesting. A type of flexibility strategy commonly used in practice is expediting, i.e., having the flexibility of using an alternative faster mode of transportation when need arises because of circumstances such as disruptions or unexpected spike in demand. A potential research question is whether it is better to expedite and meet demand or incur a stock-out and save excess transportation costs.

This study used a 50-50 split between the domestic and global supplier. Every order had a 50% chance of being assigned either to the domestic or to the global supplier. Variation of this split can be studied, such as what if each order is split equally or what if every order is assigned alternately to two suppliers. Another interesting question to be explored in future research is the optimum split, such as 80-20 or 60-40, between two suppliers given different environmental conditions and strategies.

In the operationalization of the hedging strategy, similar ROP and Q levels were used for both domestic and global suppliers. ROP levels were based on the global supplier and Q was calculated according to ROP levels and average mean and pooled variation of the two suppliers. However, given the variable order processing and transportation times, an optimum solution could be much different. Using analytical and simulation methods, future research should focus on solving the problem of setting ROP and Q levels for multiple suppliers with different order processing and lead times.

Setting the value of Q for the models was also a challenging task. Inclusion and exclusion of stock-out costs made a large difference to the Q values. Furthermore, sensitivity analysis during model development revealed Q as one of the most important factors in the model that significantly affected model outcomes. A further investigation of setting the Q values and its impact on supply chain performance is warranted.

Finally, this study employed simulation methodology. According to McGrath and Brinberg (1983), all research methods possess limitations in terms of both external and internal validity. In their words, "*all methods are flawed, but different methods are flawed differently*" (p.116). A computer simulation model as the basis of an experimental design addresses the research goal of precision in control/measurement/manipulation of variables, and partially addresses the research goal of existential realism or realism of context, but does not address the research goal of ability to generalize to a population of interest (Bienstock 1994). McGrath and Brinberg suggest that the use of multiple methods is essential for statistical power as "*differently flawed methods shore up each others' vulnerabilities*" (p. 116). Therefore, future research should focus on testing the model through survey research that emphasizes representative sampling, and seeks to maximize population generalizability.

CHAPTER V : IMPROVING THE RIGOR OF DISCRETE-EVENT SIMULATION IN LOGISTICS AND SUPPLY CHAIN RESEARCH

ABSTRACT

Computer-based simulation has long been a tool for analysis of logistics and supply chain systems for reasons such as their size and complexity, their stochastic nature, level of detail necessary for investigation, and the inter-relationships between system components. A review of the literature reveals that much of the published simulation research in logistics and supply chain journals does not incorporate and/or report the measures taken to maintain the rigor of the study. Part of the reason may be that, unlike other methods used in logistics research such as structural equation modeling, there is no set standard for design, implementation, and evaluation of simulation research in logistics and supply chain management journals. This paper addresses this gap by providing an eight-step simulation methodology referred to as the Simulation Model Development Process (SMDP). The SMDP is illustrated using a simulation study to understand the impact of risks in global supply chains. The SMDP can be used by researchers to design and execute rigorous simulation research, by reviewers for academic journals to establish the level of rigor when reviewing simulation research, and by practitioners to answer logistics and supply chain system questions.

INTRODUCTION

Computer-based simulation has long been a tool for analysis of logistics and supply chain systems. The uncertainties and resulting variances in these systems are significant considerations (Bowersox and Closs 1989), and therefore, the capability of simulation to include stochastic situations makes it both a powerful research and decision-making tool. Computer-based discrete-event simulation enhances our understanding of logistics and supply chain systems by offering the flexibility to understand system behavior when cost parameters and policies are changed (Rosenfield, Copacino and Payne 1985) and by permitting time compression (Chang and Makatsoris 2001). Logistics and supply chain systems lend themselves to simulation because of the following characteristics of activities involved in these systems: networks of fixed facilities and connecting linkages, complex and stochastic linkages between components of a logistics system, and ability to generate data that are relatively quantifiable (Mentzer and Cosmas 1979). In sum, the size and complexity of logistics and supply chain systems, their stochastic nature, level of detail necessary for investigation, and the inter-relationships between system components make simulation modeling an appropriate modeling approach to investigate and understand such systems.

In addition to recognizing simulation modeling as a viable and appropriate means of studying complex logistics and supply chain problems, several scholars have made explicit calls for increased use of simulation modeling to study supply chains. Bowersox and Closs (1989) called for both refining existing simulation models and building new simulation tools to (i) identify and improve logistics system performance, and (ii) obtain better understanding of cost-service trade-offs. Allen and Emmelhainz (1984) contend that conventional managerial judgment may not always result in effective decision making, thereby making simulation-based research a worthy endeavor. More recently, Min and Zhou (2002) call for a resurgence of simulation models to evaluate dynamic decision rules for managing supply chains.

As a research method, mathematical modeling (including simulation) is the second most used method in the *Journal of Business Logistics* and the *International Journal of Physical Distribution & Logistics Management* and the third most used method in *Supply Chain Management: An International Journal* (Sachan and Datta 2005). Unfortunately, a review of the literature reveals that research in logistics and supply chain journals does not satisfactorily address and/or report the efforts taken to maintain the rigor of such simulation studies. Although there has been a general increase in rigor over the years, much more needs to be done to improve the overall quality of simulation research. Very few studies report in detail on rigor criteria and processes followed in designing simulation models. One of the major reasons is the lack of guidance on developing logistics and supply chain models to conduct rigorous simulation research (Keebler 2006).

Unlike other methods used in logistics research, such as structural equation modeling, there are no preset rigor criteria for publication of simulation studies in logistics and supply chain journals. For example, Arlbjørn and Halldorsson (2002) present their ideas on knowledge creation in the field of logistics by describing qualitative and quantitative empirical methods, but clearly specify that experimentoriented research such as modeling was outside the scope of their discussion. Keebler (2006) took a much needed first step in providing a prescriptive framework for rigor in logistics and supply chain models, dividing rigor into three stages: intellectual rigor during the problem formulation stage, computational rigor at the model design stage, and executional rigor during the model implementation stage. He provided several suggestions for improving the quality of logistics and supply chain models for each stage. However, a detailed and comprehensive discussion on rigor in discrete-event simulation studies is missing. There is no widely accepted standard, or even a minimum standard, for assessing the rigor of simulation studies in the areas of logistics and supply chain management.

To address this gap, the objective of this paper is to present an eight-step process, called the Simulation Model Development Process (SMDP), for the design, implementation, and evaluation of logistics and supply chain simulation models, and to identify rigor criteria for each step. It is expected that such prescriptive guidance will stimulate high quality simulation modeling research by providing researchers a much-needed framework for designing their studies. Furthermore, this paper should be useful for reviewers as it provides a framework and checklist to evaluate and identify rigorous studies, and thereby, increases the likelihood that only high quality simulation studies find their way into logistics and supply chain journals. For practitioners, it provides a checklist for assessment of the validity of available logistics and supply chain simulation models prior to their use in practical decision-making. For illustrative purposes, this paper also presents an application of the SMDP process using a simulation study of the impact of risks on the performance of global supply chains. This application can be used by researchers as a template for presenting their studies.

SIMULATION AS A RESEARCH STRATEGY

According to McGrath (1982), methodological research strategies fall into four generic classes (I, II, III, and IV in Figure V-1). These classes differ according to which one of three research goals (A, B, and C in Figure V-1) is maximized:

D. Maximum Generalizability, i.e., the ability to generalize to the population(s) of interest,
E. Maximum Precision/Control, i.e., precision in control/measurement/manipulation of variables,
F. Maximum Realism of Context, i.e., existential realism, or whether or not the research "(takes) place in settings that are existentially 'real' for the participants (or the objects of the system of interest)" (p.74).

Research goal A addresses one dimension of external validity, i.e., the ability to generalize to a population contingent on how much the chosen sample represents the population. Research goal B addresses the construct validity of a concept, as reflected in the convergent and discriminant validity of some particular set of operationalizations of the concept (McGrath and Brinberg 1983). Research goal C addresses a second dimension of external validity, i.e., that of realism, or whether or not the context of the research closely matches some real world counterpart (Lynch 1982).

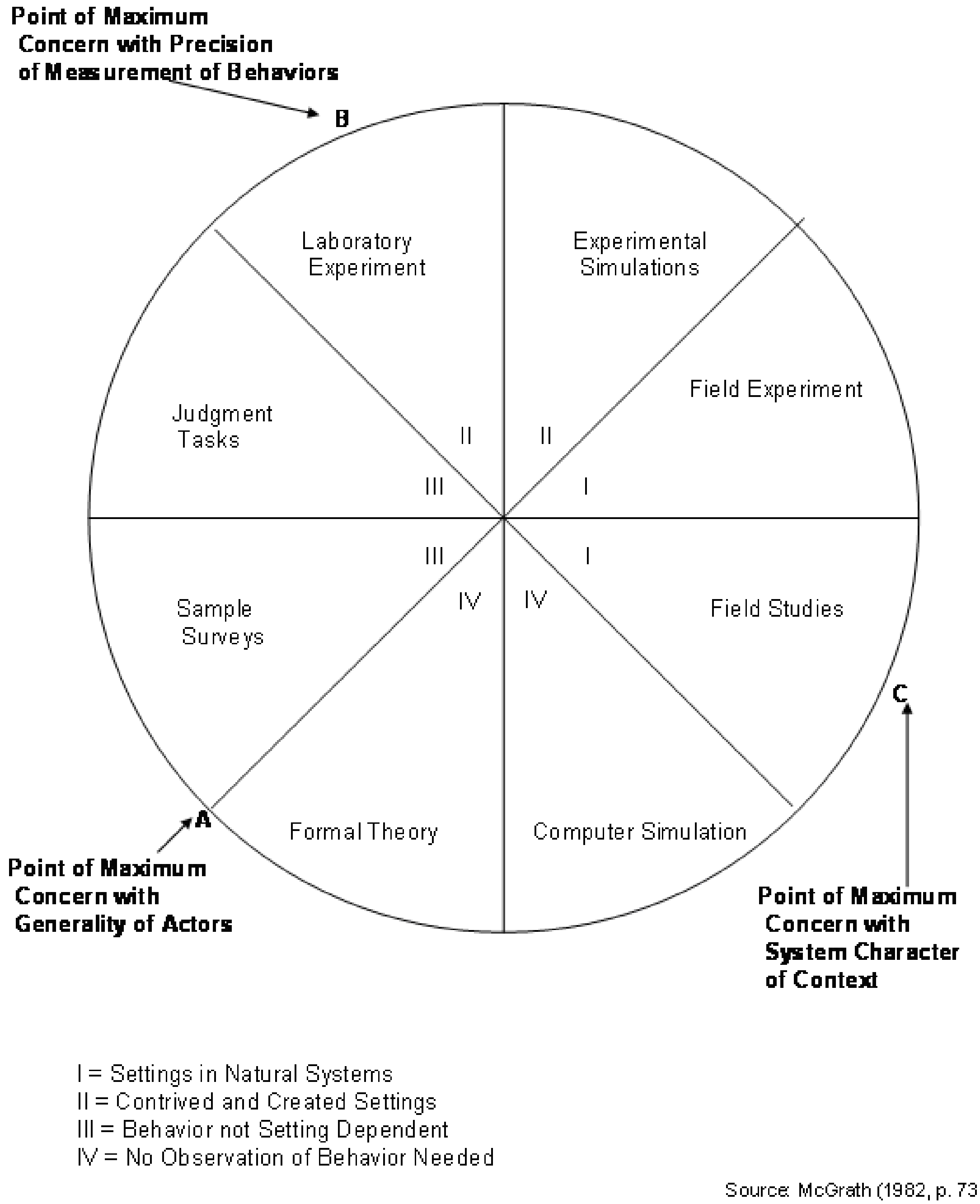


FIGURE V-1 : RESEARCH STRATEGIES

Source: McGrath (1982, p. 73)

A study that uses simulation addresses the realism of context goal (C). When a simulation model is used as a basis for experimental analysis, it offers high precision in manipulation of variables, and therefore, also addresses research goal B, but not research goal A (ability to generalize to a population of interest) (Bienstock 1994).

STRENGTHS OF SIMULATION METHODOLOGY

Simulation modeling is described as a mathematical depiction of a decision problem in significant detail, with problems solved for various alternatives and solutions compared for decision making, drawing insights, testing hypotheses, and making inferences (Keebler 2006). Computer-based simulation experimentation has four major strengths. First, for some processes, it is either too costly or impossible to obtain real world observations (Naylor et al. 1966). In terms of experimental design, the fact that "real life" controlled experimentation of logistics is extremely difficult makes experimental designs using computer simulation models an attractive alternative for understanding system behavior (Chang and Makatsoris 2001).

Second, even when "real life" experiments are possible, cost and organizational disruptions may not permit extensive revisions of the systems (Rosenfield, Copacino and Payne 1985). Through simulation, certain changes in a process or system, which would otherwise be impossible to accomplish, can be executed, and the effects of these changes on the system can be observed (Naylor et al.1966).

Third, simulation allows experimentation with complex interactions of a system or subsystem. As Shubik (1960, p.909) explains, "*(a) model is amenable to* *manipulation which would be too expensive or impractical to perform on the entity it portrays. The operation of a model can be studied, and from it, properties concerning the behavior of the actual system, or its subsystems can be inferred."* In particular, simulation models are useful when a limited number of alternatives are to be considered, and the objective is to understand the effects of change due to a single or a limited number of variables (Rosenfield, Copacino and Payne 1985).

Fourth, simulation facilitates the examination of dynamic processes or systems over time by allowing the compression of real time (Naylor et al. 1966). Simulation runs representing years can be accomplished in a matter of hours. This helps in drawing inferences about system behavior over a period of time and making timely decisions (Chang and Makatsoris 2001).

LIMITATIONS OF COMPUTER-BASED SIMULATION

As discussed earlier, no methodology is without limitations. Just as there are appropriate uses of simulation methodology, there are inappropriate uses as well. First, simulation should not be used when the goal is to generalize to a population of interest. Survey research is more appropriate in such cases. Second, simulation should not be used when an analytical solution is possible, or even preferable (Banks 1998). Simulation models do not provide optimal results, but rather are best for comparing a fixed number of alternatives (Law and Kelton 1982). Third, simulation results may be difficult to interpret as most simulation outputs are essentially random variables and are based on random inputs. It may, at times, be difficult to interpret whether an observation results from system interrelationships or randomness (Banks 1998).

A RIGOROUS SIMULATION MODEL DEVELOPMENT PROCESS

The main objective of this section is to outline a process for general use in the implementation of rigorous discrete-event simulation research. Examples of good research for each step are provided to demonstrate the process. In the next section, an application of the SMDP process is presented.

We draw from and build upon the works of Law and Kelton (1982) and Banks (1998) to suggest an eight-step discrete event simulation process for application specifically in logistics or supply chain research. The process is summarized in Figure V-2 and referred to as the Simulation Model Development Process (SMDP). The eight steps in SMDP lay out a process that can be implemented practically and represent a standard to which researchers may adhere in order to ensure academic rigor.

Logistics or supply chain systems can typically be modeled as multi-echelon, stochastic, event-driven models. A model is “stochastic” if it contains randomly generated variables, and is “multi-echelon” if it represents a number of consecutive levels in a supply chain. A dynamic event-driven model operates over time, allowing independent variables to act on performance measures. This is in contrast to a model that is static in time such as a plant location optimizer.

STEP 1: FORMULATE PROBLEM
State Model Objective Precisely
Involve Stakeholders and Experts in Problem Formulation

↓

STEP 2: SPECIFY INDEPENDENT AND DEPENDENT VARIABLES
Define Independent Variables
Define Dependent Variables

↓

STEP 3: DEVELOP AND VALIDATE CONCEPTUAL MODEL
Specify Assumptions, Algorithms, and Model Components
Perform a Structured Walk-Through with Experts

↓

STEP 4: COLLECT DATA
Define Data Requirements
Establish sources for Data Collection

↓

STEP 5: DEVELOP AND VERIFY COMPUTER-BASED MODEL
Develop a Detailed Flowchart
Choose Programming Environment
Involve an Independent Programmer
Cross-check Model Output Against Manual Calculations

↓

STEP 6: VALIDATE THE MODEL
Involve Subject Matter Experts
Perform a Structured Walk-Through
Check for Reasonableness of Results
Perform Results-Validation, If Possible
Perform Sensitivity Analysis

↓

STEP 7: PERFORM SIMULATIONS
Specify Sample Size, i.e., Number of Independent Replications
Specify Run Length and Warm-up Period
Perform Simulation Runs

↓

STEP 8: ANALYZE AND DOCUMENT RESULTS
Establish Appropriate Statistical Techniques
Document Results

FIGURE V-2 : SIMULATION MODEL DEVELOPMENT PROCESS (SMDP)
Developed based on Law and Kelton (1982), Banks (1998), Gomes (1988), and Bienstock (1994).

To a large extent, existing studies in logistics and supply chain journals report only a few of the eight steps in Figure V-2. Although there are instances of inadequate coverage for each of the steps, the most neglected (i.e., not reported or not sufficiently addressed) are Steps 3, 5, 6, and 7. The steps sufficiently addressed in the literature include Steps 2, 4, and 8. This paper explores all eight steps, with greater focus on those not sufficiently addressed in the existing literature.

To illustrate the SMDP and establish the level of rigor generally present in the literature, nine studies were chosen from those published in a wide variety of logistics, supply chain, and related journals. The first step in the selection process limited the pool of simulation studies to only those that dealt with simulating more than one echelon in logistics, supply chain, or distribution systems. Next, from this pool of studies, those that reported in detail on the steps taken during the model development process were chosen. These studies were included as they provide insights into the measures taken to maintain the rigor of the research at each step in the simulation model development process, thereby providing good examples of a rigorous process. Tables V-1 (A), (B), and (C) specify the manner in which each paper addressed each of the eight steps outlined in our proposed SMDP with the exception of Step 3. Step 3 is omitted from the table because only one study in our sample set (Appelqvist and Gubi 2005) provided documentation of this important step in model development.

TABLE V-1: SUMMARY OF PAST SIMULATION STUDIES

(Part A)

Author and Year	**Objective / Problem Formulation (Step 1)**	**Dependent Variable(s) (Step 2)**	**Independent Variable(s) (Step 2)**
Canbolat et al. (2005)	Estimating off-shoring risk for automotive components for an auto manufacturer (Ford)	Dollar value of risks, i.e., expected total costs after adjusting for risks	Around 40 risk factors can be specified in the model Delay, and duration of delay are key ones
Appelqvist and Gubi (2005)	Quantifying the benefits of postponement for a consumer electronics company as well as Supply Chain of Bang and Olefsun	Fill rate Total inventory	Demand Order-up-to levels for retail-outlet inventory Number of basic units Number of colored fronts
Shang, Li, and Tadikamalla (2004)	Identifying the best operating conditions for a supply chain to optimize performance	Total supply chain cost Service Levels	Extent of differentiation Extent of information sharing Capacity limit Reorder quantity Lead time Reliability of the suppliers Inventory holding costs Demand variability
Holland and Sodhi (2004)	Quantifying the effect of causes of Bullwhip Effect in a Supply Chain	Observed variance of manufacturer's order size Observed variance of retailer's order size	Demand autocorrelation Variance of forecast error Retailer's lead time Manufacturer's lead time Retailer's order batch size Manufacturer's order batch size Standard deviation of the deviation from the retailer's optimal order size Standard deviation of the deviation from the manufacturer's optimal order size
Bienstock and Mentzer (1999)	Investigating outsourcing decision for motor carrier transportation (applied to company H)	Mean total shipment cost	Structure (private/leased or for-hire carrier) Asset specificity Variation in loading, line-haul, and transportation times Volume and Frequency of shipments

TABLE V-1. Continued.
(Part A)

Author and Year	**Objective / Problem Formulation (Step 1)**	**Dependent Variable(s) (Step 2)**	**Independent Variable(s) (Step 2)**
Van der Vorst et al. (1998)	Improving performance in a real food supply chain	Inventory level at DC Inventory level at test outlet Product freshness at DC Product freshness at test outlet Total supply chain costs	5 improvement principles identified but the only ones discussed are: Delivery frequency Lead times
Mentzer and Gomes (1991)	Developing a strategic decision-support system called Strategic Planning Model which can be configured to simulate different logistics systems. Illustrated using one academic and one managerial application.	Depends on the system being simulated. (As an example, see Gomes and Mentzer (1991) below who used Strategic Planning Model (SPM) for their study)	Depends on the system being simulated.
Gomes and Mentzer (1991)	Understanding influence of JIT Systems on Distribution Channel Performance	Profit Order cycle time Standard deviation of order cycle time Percent customer orders filled	Materials management JIT (with or without) Physical distribution JIT (with or without) Materials management uncertainty Demand uncertainty
Powers and Closs (1987)	Understanding impact of trade incentives on a simulated grocery products distribution channel	Average distribution center inventory level Shipment size pattern Total number of shipments Customer service level Total financial performance	Response increase (% increase in sales during the incentive period) Demand uncertainty Payback (reduction in sales level from normal at the conclusion of the incentive) Incentive level

TABLE V-1. Continued.

(Part B)

Study (Author and Year)	**Sources of Data (Step 4)**	**Programming Environment (Step 5)**	**Model Verification (Step 5)**
Canbolat et al (2005)	Personal interviews or surveys (questionnaire) of company executives, and subject matter experts	MS Excel with @RISK add-in	Three case studies (one with Ford die cast component illustrated in this paper)
Appelqvist and Gubi (2005)(2005)	Historical data and made-up data Qualitative data from interviewing managers at the headquarters and retailers downstream	Not Specified	Not specified
Shang, Li and Tadikamalla (2004)(2004)	Bass (1969) Model for generating demand Existing research for inventory holding costs	ARENA	Verifying model architecture with literature and other researchers
Holland and Sodhi (2004)(2004)	Made-up data	Gauss 5.0	Not specified
Bienstock and Mentzer (1999)(1999)	Real companies Published sources such as books, and statistics from American Trucking Association	SLAMSYSTEM, a FORTRAN based simulation software	Mentions that model was verified but the process is not specified
Van Der Vorst et al. (1998)	Actual data from a producer, a distributor, and retailer outlets of chilled salads	Not specified	Not specified
Mentzer and Gomes (1991)	Depends on the system being simulated	Not specified	Testing random number generators using chi-square test Compare short pilot model runs to hand calculation Verify model segments separately Replace stochastic elements with deterministic Use simplified probability distributions Use simple test data input
Gomes and Mentzer (1991)	Real companies, and published sources such as books	Not specified	Verified as per Fishman and Kiviat (1968) Verification of uniformity and independence of model’s random number generators
Powers and Closs (1987)	Made-up data built on Simulated Product Sales Forecasting model	Not specified	Testing programming logic through statistical output

TABLE V-1. Continued.
(Part C)

Study (Author and Year)	**Validation (Step 6)**	**Sample Size and Sample Size Determination (Step 7)**	**Analysis Techniques (Step 8)**	**Other important details**
Canbolat et al (2005)	Validation using case studies	Not Specified	Ranking of failure modes Mean, lower and upper limits, standard deviation, and 5th and 95th percentile of dollar value of risks	
Appelqvist and Gubi (2005)	Using input-output transformation, i.e., comparing simulation data to real world data, on performance measures such as delivery times, delivery accuracy, and inventory levels. Structured walk-through with company management.	Five replications for each unique scenario Each replication consisted of a 100 day warm-up period and a 1,000 day steady-state run	Inspection of graphical outputs Percentage changes in performance measures	Same demand data sets used for all replications. This technique is known as correlated sampling and provides a high statistical confidence level.
Shang, Li, and Tadikamalla (2004)	Comparing simulation results with analytical models for simple known cases	1000 replications of the system for 20 months	Visual inspection of graphical output Taguchi (1986) method for parameter design Response surface methodology, i.e., fitting regression models to simulation output	
Holland and Sodhi (2004)	Not specified	186 time intervals (weeks) of which middle 152 weeks were used	Regression Analysis	
Bienstock and Mentzer (1999)	Testing face validity using literature, and review of distribution system simulation models Interviews with employees of company H Comparison of model output with actual company data	10 runs per cell determined as per Law and Kelton (1982) relative precision method	ANOVA	Tested for bias created by initial starting conditions

TABLE V-1. Continued.
(Part C)

Study (Author and Year)	Validation (Step 6)	Sample Size and Sample Size Determination (Step 7)	Analysis Techniques (Step 8)	Other important details
Van der Vorst (1998)	Implementation of one scenario to two retail outlets, and measurement against a control outlet as well as simulated results	Not specified	Percentage changes in performance measures (such as inventory levels and remaining product freshness) at distributor and two retail outlets	
Mentzer and Gomes (1991)	Extensively validated different SPM models in following ways: Compared simulation output with historical data from real system for by using Chi-square tests, Kolmogorov-Smirnov tests, Factor Analysis, Spectral Analysis, Simple Regression, and Theil's inequality coefficient. Warm-up and transient period: No effect beyond first month Stochastic Convergence: None for up to 5 years	An example illustration uses sample variance from pilot runs and a desired confidence interval width and precision	Example illustrations use: ANOVA Percentage increases in response variables	Two applications – one on JIT systems and one on manufacturer and distributor of automotive aftermarket- are discussed in the paper.
Gomes and Mentzer (1991)	SPM model had external validity (see Mentzer and Gomes 1991)	10 runs per cell determined as per 95% confidence interval Start-up transient period effected only first few weeks	ANCOVA for response variable profit; ANOVA for main effects of all other response variables Scheffe's method for multiple comparisons of cell means Fisher's Least Significant Difference method for pair-wise comparisons	ANCOVA is used because profit is significantly correlated to demand
Powers and Closs (1987)	Testing face validity by review groups Model stability and model sensitivity using ANOVA and sensitivity analysis	Not specified	Graphically Statistically using ANOVA	

STEP 1: FORMULATE PROBLEM

The first step is to formulate the problem and set the objectives. The purpose of problem formulation is to define overall objectives and specific questions to be answered with the simulation model. Lack of attention to this step is a leading cause of failure of models to perform satisfactorily (Keebler 2006). Ambiguous purpose can result in unnecessary or incorrect analysis, lost time, bad or ineffective decisions, and incorrect inferences (Dhebar 1993).

The problem may not initially be stated precisely or in quantitative terms. Often, an iterative process is necessary to facilitate problem formulation. Problem formulation should involve individuals who deal with the problem to make sure the correct and relevant problem is addressed. When the problem is clearly defined, performance measures of interest, scope of model, time frame, and resources required can be specified accurately and efficiently.

STEP 2: SPECIFY INDEPENDENT AND DEPENDENT VARIABLES

Once the problem has been formulated and the objective has been defined, independent and dependent variables must be specified. Dependent variables reflect the performance criteria and independent variables include the system parameters. In a simulation model, independent variables are manipulated and their effect on dependent variables is recorded and analyzed. Analyses of values of dependent variables provide answers to the problem formulated in Step 1.

The outcome of a model depends on what is included in the model. Therefore, the objective of the research and the specific questions to be answered using the simulation model should guide the selection of independent and dependent variables. Depending on the problem, all factors that influence the answers sought should be included, including technical, legal, managerial, economic, psychological, organizational, monetary, and historical factors (Forrester 1961). Model variables should correspond with those in the system being represented, and should be measured in the same units as real variables.

Several sources can be consulted to identify the variables of interest. Past research may be referenced to identify models similar to those being developed and the variables included in those studies. Similar to problem formulation, people who deal with the problem under consideration and/or subject matter experts should be consulted to ensure that all relevant and important variables are included and that chosen variables are expressed in correct units. For example, Canbolat et al. (2005) identify key stakeholders in sourcing decisions, namely, purchasing, supplier technical assistance, product development, material planning and logistics, manufacturing, and finance. Thereafter, they interviewed four executives and at least one subject matter expert (SME) in each of the six stakeholder groups. Using these interviews, they discovered almost forty risk factors (independent variables) and relationships among risk factors within the context of the stakeholders.

STEP 3: DEVELOP AND VALIDATE CONCEPTUAL MODEL

The modeler should ensure that the model develops in accordance with the problem statement. The real-world system under investigation is abstracted by a conceptual model that includes mathematical and logical relationships concerning the components and structure of the system (Banks 1998). Explicit statements of all assumptions are required. To determine the behavior of a system by simulating the performance of its parts requires that one describe exactly, and in detail, the characteristics (relationships) which are to be included (Forrester 1961). The validity of the outcome of a system depends on what is included in the system description. It is important to construct a conceptual model so that the model can be verified prior to investing resources in the development of a computer model.

A structured walk-through of the conceptual model before an audience – that may include analysts, computer-programmers, and SMEs – should be done (Law 2005). In this step, the problem structure and the accompanying model should be expressed in clear, jargon-free language that can be easily understood. There is little evidence in literature – both in the studies included in this research as well as those not included – of this important step of conceptual validation of the model. In fact, Law and McComas (2001) provide examples of instances when such a step was overlooked with disastrous consequences. Law (2005) emphasizes that conceptual validation increases validity and credibility of the simulation model. This step makes sure the objectives, performance measures, concepts, assumptions, algorithms, data summaries and any other aspect of interest of the model are correct and at an appropriate level of detail. This step also ensures that the correct problem is solved. Performing and documenting conceptual validation early in the model development process increases the credibility of the model with other researchers and acceptability with practitioners. This step is indispensable as decision-makers should understand and agree with the conceptual model.

Only one study in our sample set provided documentation of this important step in model development. Appelqvist and Gubi (2005) specified that their model was compared to actual supply chain performance and reviewed in a structured walk-through with company management. However, it is not clear when the walk-through was conducted. It appears that conceptual validation was done during the actual simulation model validation (i.e., step 6). In general, if researchers omit conceptual validation early in the model development process and attempt to validate the computer or computational model directly, it may be too late, too costly, or too time-consuming to fix errors and omissions in the computational model.

STEP 4: COLLECT DATA

"*Arguably, the most difficult aspect of simulation input modeling is gathering data of sufficient quantity, quality, and variety to perform a reasonable analysis*" (Vincent 1998, p 59). Data collection may follow or proceed concurrently with conceptual model development. Data requirements must first be established to specify model parameters, system layout, operating procedures, and probability distributions of variables of interest. Data collection efforts include company databases, interviews, surveys, books, and/or other published sources. Data may be generated using computers if the actual data may be reasonably approximated by such commonly used distributions as normal, Poisson, exponential, or several others.

Each independent variable can be manifested using one of three approaches (Banks 1998). First, the variable may be deterministic in nature. Second, an independent variable may be operationalized by fitting a probability distribution to the observed data. Third, a variable can be operationalized with an empirical distribution from observed data. For example, Appelqvist and Gubi (2005) first collected qualitative data by interviewing managers in a supply chain. Based on the interviews, previous work at the case company, and insights from literature, they developed three alternative delivery concepts and evaluated them using discrete-event simulation and data from company ERP systems.

Techniques such as Delphi and Failure Mode and Effects Analysis (FMEA) may also be employed to convert qualitative data into quantitative data and prioritize the elements that should go into the model. The Delphi method allows people to arrive at a consensus about an issue of interest. It consists of a series of repeated interrogations of individuals who are knowledgeable on the subject. After the initial interrogation of each individual, usually by means of questionnaires, each subsequent interrogation is accompanied by information about the preceding round of replies. Each participant is thus encouraged to reconsider and, if appropriate, change his or her previous reply in light of the replies of other members of the group. Delphi techniques have been applied in several logistics and supply chain management studies (e.g. Makukha and Gray 2004; Ogden et al. 2005; Robeson 1988). FMEA is often used in engineering design analysis to identify and rank the potential failure modes of a design or manufacturing process, and to determine its effect on other components of the product or processes in order to document and prioritize improvement actions (Sankar and Prabhu 2001).

Collecting data can be challenging as data may not be readily available in required formats or in an appropriate level of detail. Before incorporation into the model, data may need to be scanned, cleaned, and updated to account for discrepancies and/or missing data.

STEP 5: DEVELOP AND VERIFY COMPUTER-BASED MODEL

Verification is the determination of whether the computer implementation of the conceptual model is correct. This means examining the substructure outputs and determining whether they behave acceptably (Fishman and Kiviat 1968), as well as making sure the complete simulation model structure is executing as intended (Law and Kelton 1982). This is achieved by debugging the programming logic and code (Mentzer and Gomes 1991). Fishman and Kiviat (1967) identify two important benefits of verification: identification of unwanted system behavior, and determination as to whether an analytical or simple simulation substructure can be substituted for a complex one. Banks (1998) strongly advises that verification should be a continuous process rather than waiting until the entire model is coded.

Several programming languages and software packages exist to simulate logistics and supply chain systems, including MS Excel with add-ins, ARENA, SLAMSYSTEM, and Gauss 5.0. Interestingly, in simulation studies in the logistics and supply chain literature, not all researchers specified the simulation environment used. In our list of nine studies, only four state the simulation environment or programming platform used. In the literature reviewed, there is no evidence of preference for particular software, or a package that clearly outperforms others.

For verification, several methods can be employed. A detailed flowchart should be developed first. The model should be made as self-documenting as possible. The model should be run using a variety of input values. Results should then be checked to verify reasonable, expected, or known output values. Animation is also a useful tool in the verification process.

Based on methods used in the studies described in Table V-1, and Fishman and Kiviat (1968), the issue of model verification should be addressed in four ways. First, the code should be checked by at least one person other than the person who coded the model. Second, the output of parts of the model (sub-structures) should be compared with manually calculated solutions to determine acceptable behavior. Third, simulation results for short pilot runs of simple cases for the complete model should be compared with manual calculations to verify the entire model (structure) behaves acceptably. Fourth, all events should be verified manually through each model segment, first with simple deterministic runs, next by using simplified probability distributions followed by stochastic checks with increasing integration of activities (Mentzer and Gomes 1991).

Only one of the studies in our sample provided a good discussion of model verification. For example, Bienstock and Mentzer (1999) mention the model was verified but the process is not specified. Similarly, Powers and Closs (1987) mention that programming logic was tested through statistical output but fall short in explaining the process. Only Mentzer and Gomes (1991) provide a detailed discussion on model verification as well as validation, and identify additional statistical tests and analysis that can be used for further model verification. In summary, to maintain simulation research rigor, it is critical that details of the development and verification of the simulation model be documented to describe the programming environment, as well as the specifics of the model development and verification efforts.

STEP 6: VALIDATE MODEL

Model validation is the process of determining whether a simulation is an accurate representation of the system of interest (Law and Kelton 1982). All computer-based simulation models need to be validated or any decisions made with the model may be erroneous. A "valid" model can be used to make decisions similar to those that would be made if it were feasible and cost-effective to experiment with the system itself (Law 2005). However, a simulation model of a complex system can only be an approximation of the actual system, no matter how much time and money is spent on model building (Law and McComas 2001).

Based on the methods used in the studies described in Table V-1 and Law and Kelton (1982), the issue of validating the computer-based simulation model may be addressed in several ways, many of which are similar to those used to validate the conceptual model in Step 3 of the SMDP. First, subject matter experts, including academic scholars and practitioners, should be consulted in the conceptual development of model components and relationships between components. Law and Kelton (1982) suggest this step ensures that the correct problem is solved and reality is adequately modeled. Second, a structured walk-through of the computer-based model and a review of the simulation results for reasonableness with a separate set of subject matter experts, including academic scholars and practitioners, may be conducted. If the results are consistent with how the subject matter experts perceive the system should operate, the model is said to have face validity. Third, face validity may also be confirmed using the literature and review of supply chain simulation models in past research.

If there is an existing system, the computer-based simulation output can be compared with the output data collected from the actual system. This is called results validation. Fishman and Kiviat (1968) assert:

> *"While validation is desirable, it is not always possible. Each investigator has the soul-searching responsibility of deciding how much importance to attach to his results. When no experience is available for comparison, an investigator is well advised to proceed in steps, first implementing results based on simple well-understood models and then using the results of this implementation to design more sophisticated models that yield stronger results. It is only thorough gradual development that a simulation can make any claim to approximate reality"*

The above notion is also supported by Banks (1998) who suggests that modeling begin simply and complexity be added in steps until a model of acceptable detail and complexity has been developed. For any study, if required (and possible), input-output transformation, i.e., comparing simulation data to real world data by using spectral analysis of actual and simulated output may be undertaken to ascertain the validity of the model. Spectral analysis is a statistical technique that can be used to analyze a time series. The application of spectral analysis to a time series (actual or simulated) yields magnitude of deviations from the average levels of a given activity and the period or length of these deviations (Naylor, Wertz and Wonnacott 1969).

Finally, sensitivity analyses may be performed on the programmed model to see which model factors have the greatest impact on the performance measures, to test the stability of the model, and to test the sensitivity of the analysis to changes in assumptions (Powers and Closs 1987). Dhebar (1993) suggests that systematic sensitivity analysis serves at least three functions: to the extent that sensitivity can be examined only for known assumptions, it underscores the importance of an explicit recognition of the important assumptions; it improves the decision maker's understanding of the problem; and it is a useful way to identify and eliminate logical and methodological errors.

The issue of model validity was incorporated into almost all the studies reviewed, though the degree of importance awarded to the issue varies significantly between studies. Van der Vorst et al. (1998) measure their simulated output against actual implementation of a simulated scenario to two retail outlets and a control retail outlet. While this may not always be possible, this is a good example of results validation. Bienstock and Mentzer (1999), Mentzer and Gomes (1991), and Appelqvist and Gubi (2005) validated their models by comparing simulated output to the available company data.

STEP 7: PERFORM SIMULATIONS

For each system configuration of interest, decisions have to be made on run length, warm-up period, and the number of independent model replications. In simulation, the benefits of additional model replications, i.e., increased sample size, may be gained by (1) increasing the number of replications (simulation runs) for each experimental condition, (2) decreasing the length of a subinterval, i.e., reducing the time unit to provide more subintervals for the same length of run, and (3) increasing the length of the run to increase the number of subintervals (Mentzer and Gomes 1991; Bienstock 1994). In addition, the power of a statistical test to detect an effect increases with the number of replications (Mentzer and Gomes 1991). Each of the aforementioned practices may benefit the model but must be weighed against the cost in time and money to make additional runs.

Sample size determination, i.e., number of independent replications for each experimental condition, is an important issue to be addressed while running the simulation. Increasing the number of replications is not difficult (Beinstock 1994). Increasing the number of runs reduces the standard deviation of the sampling distribution, and therefore, for a given level of confidence, the half-width of the confidence interval decreases. This results in an increase in the absolute precision of the estimate of population of interest where absolute precision is defined as the actual half-width of a confidence interval (Law and Kelton 1982). However, increasing the number of replications until statistically significant results are obtained makes the external validity of the results questionable.

An alternative to increasing absolute precision is "to let the number of replications be guided by a 'practical' degree of precision, i.e., a reasonable degree of precision, given the magnitude of population mean(s) that is (are) being estimated" (Bienstock 1996, p.

45). A detailed discussion of this method with an example can be found in Bienstock (1996), who contends that conclusions drawn from results in this manner are more meaningful both in terms of research goals and practical problem solutions. However, this technique is appropriate for simulation modeling that employs successive independent replications of simulation runs; it is not appropriate for determination of achieved relative precision on subintervals of a single simulation run (Bienstock 1996). Also, this technique cannot be used in experimental designs that utilize variance reduction techniques.

Apart from Bienstock and Mentzer (1999), who adopt the relative precision method, no other study in our sample specifies the rationale for the selection of a given sample size. Of the sample set, 3 out 9 studies fail to even specify the sample size.

STEP 8: ANALYZE RESULTS

The studies in our sample set employ one or more of the following analysis techniques:

1. Visual inspection of graphical outputs,
2. Mean, lower and upper limits, standard deviation, and percentiles,
3. Percentage changes in performance measures,
4. Response surface methodology, i.e., fitting regression models to simulation output,
5. ANCOVA for main effects of response variables that are significantly correlated with input parameters,

6. ANOVA for main effects of response variables not significantly correlated with input parameters,
7. Scheffe's method for multiple comparisons of means of output measures for each experimental condition, and
8. Fisher's Least Significant Difference method for pair-wise comparisons of means of output measures for experimental conditions.

These are a subset of the techniques available to analyze simulation output. Modelers, reviewers, and practitioners should be aware of assumptions (e.g., normality or autocorrelation) that might affect the appropriateness of a given statistical technique for a given situation. The choice of analysis techniques will vary considerably depending on the distribution of input and output variables. Therefore, it is for the researcher to explain the choice. In this step, references from past research may be particularly useful.

AN EXAMPLE OF METHODOLOGICALLY RIGOROUS SIMULATION STUDY

The purpose of this section is to further elaborate on and illustrate the SMDP by using a simulation study designed to understand the impact of risks on global supply chains, presenting in detail how each step in the SMDP was executed to maintain a high degree of research rigor.

STEP 1: FORMULATE PROBLEM

This study consisted of three successive phases: an extensive literature review, a qualitative study, and a simulation study. The literature review was an integrative investigation of the logistics, supply chain management, operations management, economics, international business, and strategy literatures. Qualitative research was based on data from 14 in-depth qualitative interviews with senior supply chain executives across 8 companies. Apart from interviews, a focus group meeting involving 7 senior executives of a global manufacturing firm was conducted. Additional interviews were conducted during the simulation model development to collect data and validate the model. The objective of the first two phases of this research was to build a theory of environment-strategy fit for global supply chain risk management. The research question driving the simulation process was: How does performance of global supply chains vary under different combinations of environmental conditions and the strategy selected?

Based on the qualitative study, only the external supply chain environment comprising supply and demand risks were incorporated in this simulation model. Four types of environments were operationalized as combinations of high and low levels of supply and demand risks. Eleven strategies were identified during the first two phases, of which the following four were included in this research: assuming (or single-sourcing), hedging (or dual sourcing), speculation (or built to stock), and postponement (or built to order). The discussion of the remaining seven strategies is beyond the scope of this paper. However, it is important to mention that these four were selected because they were identified as important and came across as the ones most likely to be influenced by the supply chain managers.

Eight hypotheses were developed that hypothesize the impact of fit between environment and strategy selected on the performance of global supply chains. It is beyond the scope of this paper to elaborate on the development of the hypotheses, but they are presented in Table V-2.

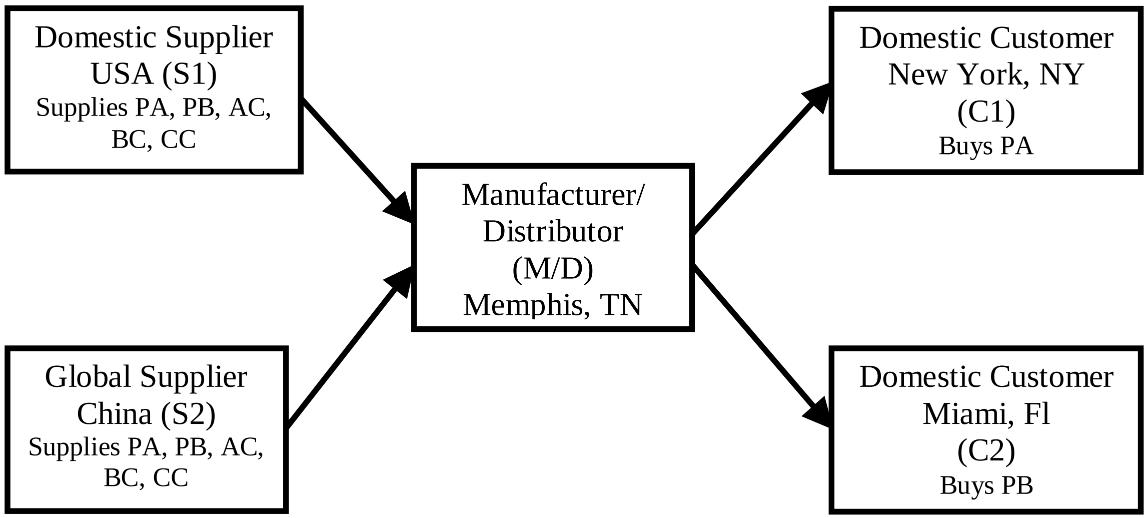
To test these hypotheses, a simulated global supply chain with two suppliers, a manufacturer/distributor, and two customers was conceptualized (see Figure V-3).

There is one supplier each in the US (S1) and China (S2). The manufacturer/distributor is based in Memphis, Tennessee, the first customer (C1) in New York, New York, and the second customer (C2) in Miami, Florida. The manufacturer/distributor sells two products – Product A to C1 and Product B to C2. Product A is composed of two components – A-Component (AC) unique to Product A and Common-Component (CC) shared between Product A and Product B. Product B is composed of two components – B-Component (BC) unique to Product B and Common-Component (CC) shared between Product A and Product B Both suppliers – S1 and S2 – can supply the two products (Product A and Product B) or the three product components (AC, BC, and CC).

The product chosen for this study was a printer. A printer has a medium value-weight and weight-bulk ratio, which is important because extreme product characteristics can limit the usefulness of findings. In addition, printers were chosen because imports share of domestic demand has grown steadily from 58.5% in 2001 to 77.2% in 2005.

TABLE V-2: LIST OF HYPOTHESES

H1	Supply chains facing high supply risks that adopt a hedging strategy will show a higher profit than supply chains that adopt an assuming strategy.
H2	Supply chains facing low supply risks that adopt an assuming strategy will show a higher profit than supply chains that adopt a hedging strategy.
H3	Supply chains facing high demand risks that adopt a postponement strategy will show higher a profit than supply chains adopting a speculation strategy.
H4	Supply chains facing low demand risks environments that adopt a speculation strategy will show a higher profit than supply chains that adopt a postponement strategy.
H5	Supply chains facing low supply risks and low demand risks that adopt an assuming strategy on the supply side and a speculation strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.
H6	Supply chains facing low supply risks and high demand risks that adopt an assuming strategy on the supply side and a postponement strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.
H7	Supply chains facing high supply risks and low demand risks that adopt a hedging strategy on the supply side and a speculation strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.
H8	Supply chains facing high supply risks and high demand risks that adopt a hedging strategy on the supply side and a postponement strategy on the demand side will show a higher profit than other supply chains facing the same environment that adopt any other combination of strategies.
H_E1	Supply chains facing low supply risks will show higher profit than supply chains facing high supply risks from adopting a form postponement strategy.
H_E2	Irrespective of the level of demand risks, all supply chains facing high supply risks will show an equal profit from adopting a hedging strategy.
H_E3	Irrespective of the level of demand risks, supply chains facing low supply risks will show equal profit from adopting an assuming strategy.
H_E4	Irrespective of the level of supply risks, supply chains facing low demand risks will show an equal profit from adopting a speculation strategy.
H9	The total profit for a given combination of environment conditions and strategies under without-disruption condition will always be higher than total profit for the corresponding environmental conditions and strategies combination under with-disruption conditions.
H10	Under the with-disruption condition, hedging will always be better than an assuming strategy under corresponding environmental conditions and demand side strategy.



Notes:

1. Both suppliers can supply product A (PA), product B (PB), component AC, component BC, and component CC.
2. C1 buys PA
3. C2 buys PB
4. PA = AC + CC
5. PB = BC + CC

FIGURE V-3 : SIMULATED SUPPLY CHAIN

STEP 2: SPECIFY PERFORMANCE CRITERIA AND SYSTEM PARAMETERS

Risk events serve as the independent variables for this event-driven model. For supply and demand risks, over 30 risk events were identified in the literature and the qualitative study. Some examples of risk events are oil price increases, currency fluctuations, supplier bankruptcy, and demand uncertainty. However, due to time and resource constraints and to make sure the results can be interpreted, there is a limit on the number of factors that can be included in a study. A short-listing of events based on specific questions to be answered and events most salient to global supply chains helped in maintaining the simplicity of the model without compromising on the objectives of the research.

Risk events were grouped into three categories (supply, demand, and disruption) based on how risk events are manifest, relevance of risk events to this research, qualitative study, and additional interviews conducted to collect data. For the supply category, events that do not differ significantly between domestic and global contexts were either not included in this research or not varied between domestic and global suppliers. For the demand category, all supply chain customers are based in the US. Furthermore, it is assumed that the products have non-seasonal demands. Therefore, risk events that are either global in nature or relate to a seasonal product were either not included in this research or not varied between low and high demand risks. For disruption, a supply disruption in the form of a port closure was modeled. Apart from the fact that port disruption was a major concern expressed by supply chain managers, a port disruption is also relevant as it is a global event.

Table V-3 provides a list of all independent variables, their definitions, values, and any additional information in the remarks column. Supply risk events are divided into lead time variability, cost variability, and quality variability. Lead time variability is further divided into order processing time variability, and transportation lead time variability. Although there is variability in transportation times, they do not change between the low risk and high risk Chinese suppliers. Therefore, transportation time is not an independent variable. Demand side risk is manifested by demand variability. A 45-day disruption at the US port is a moderator. Please note that data sources for all independent variables are discussed in detail under Step 3.

The values provided in Table V-3 were used to operationalize supply chain environments and strategies. The low supply risk environment was operationalized as low supplier order processing time variability, low cost variability, and low levels of quality defects. The high supply risk environment was operationalized as high supplier order processing time variability, high cost variability, and high levels of quality defects. The low demand risk environment was operationalized as low demand variability and the high demand risk environment was operationalized as high demand variability.

The assuming strategy was operationalized by using a single Chinese supplier. The hedging strategy was operationalized by using two suppliers, one each in the US and China.

TABLE V-3: INDEPENDENT VARIABLES

Supply Risk Events

Risk Factors	Definition	Global (Low)	Global (High)	US*	Remarks
1. Supplier Order Processing Time Variability	Time from order placement to replenishment at the supplier facility	N(15, 1.5) days	N(15, 4.5) days	N(10, 1) days	Normal(Mean, SD)
2. Cost Variability	Sourcing cost variability due to changes in exchange rates, wage rates, shortage of goods, natural disasters, oil price increases, and any other unforeseen reasons				15% for low supply risk 45% for high supply risk T=Triangular
	Product A or Product B ($)	T (60, 64.5, 69)	T (60, 73.5, 87)	80	T (Min, Mean, Max)
	Component AC or Component BC ($)	T (15, 16.125, 17.25)	T (15, 18.375, 21.75)	20	T (Min, Mean, Max)
	Component CC ($)	T (35, 37.625, 40.25)	T (35, 42.875, 50.75)	50	T (Min, Mean, Max)
3. Quality Variability/ Yield	Receipt of lower usable quantity due to losses, damages, and pilferage in-transit, communication errors, market capacity, war and terrorism, and natural disasters.	0.98	0.97	0.99	1% defects for domestic supplier 2% defects for low risk China supplier 3% defects for high risk China supplier

Demand Risk Event

Risk Factors	Definition	Manifest as	Low Risk	High Risk	Remarks
1. Variability of demand	Average variation in daily demand	Mean, Standard Deviation	N (1000, 100)	N (1000,300)	Normal (Mean, Standard Deviation)

Moderator

Risk Factors	Definition	Manifest as	Remarks
1. Disruption	Closure of US port for 45 days	Closure of US port for 45 days on a randomly generated day between day 60 and day 600.	Only for 16 with-disruption scenarios

* US values remain constant throughout all scenarios

Speculation was operationalized by sourcing finished products from suppliers, i.e., the manufacturer/distributor buys Product A and Product B. The goods are held in finished form at the manufacturer/distributor, i.e., made-to-stock, and are shipped to customers per demand. Postponement was operationalized by sourcing components from the suppliers and assembling them at the manufacturer/distributor, i.e., the manufacturer/distributor buys parts AC, BC, and CC. The goods are assembled at the manufacturer/distributor, i.e., a made-to-order policy, and are shipped to customers per demand.

Performance Criteria / Dependent Variables

Similar to independent variables, dependent variables were selected based on literature review, qualitative study, and the research objective. The testing of hypotheses is based on total supply chain profit as it takes into account several other performance measures including total supply chain costs (inventory, transportation, and production costs), total supply chain revenues, and penalty costs associated with late deliveries. However, in addition to the total supply chain profit, several other measures are recorded including stock-outs, total inbound lead time, fill rates, delays to customers, and average inventory. The additional measures are recorded to help in interpretation of results. The focus is not only on the measurement of means of total profit, but also on its distributions. In particular, it is important to look at distributions because a distribution may be skewed left or right or be leptokurtic (flatter than normal) and have "fat tails," or be exponential, Poisson, or any other distribution. The consequence of these characteristics is that extreme outcomes happen much more frequently than indicated in calculations using normal probability distributions, and "most likely" outcomes have a lower probability of occurrence than those calculated with normal distributions. Table V-4 provides a list and definitions of dependent variables and the manner in which each variable was measured.

STEP 3: DEVELOP AND VALIDATE MODEL CONCEPTUALLY

The third step deals with the development and validation of the conceptual model. To conceptually validate the model, subject matter experts were consulted and interviewed at every step. The primary review and consultation team consisted of four academics. Two were content experts and have experience with simulation modeling, one was a content expert, and one was a management scientist with experience using stochastic data for modeling. This research followed Banks' (1998) recommendation that modeling begin simply and complexity be added in steps until a model of acceptable detail and complexity has been developed. All changes made to the model because of additional literature explored, and data collected were reviewed by this team. When an acceptable level of detail and complexity was achieved as per this primary review team, two business practitioners separately reviewed the conceptual model.

The model flow for this study can be divided into the following six stages:

1. Demand generated at the customer location
2. Order received and processed at the manufacturer/distributor
3. Order placed on the supplier(s)
4. Order received at the supplier facility (order processing at suppliers)
5. Order shipped from supplier to the assembler/distributor
6. Order shipped from assembler/distributor to the customers

TABLE V-4: SUPPLY CHAIN PERFORMANCE CRITERIA
(Dependent Variables)

Performance Criteria	Definition/Operationalization	Measured as
Total Supply Chain Cost	Sum total of costs incurred by the supply chain including transportation, inventory carrying, production, warehousing, and penalty costs	Dollar value Distribution of dollar value
Total Supply Chain Profit	Difference between total revenues earned and total costs	Dollar value Distribution of dollar value
Stock-outs	The inability to meet customer demand for a given quantity by due date because of non-availability of inbound components, products, or raw materials	Units Total penalty cost for late delivery
Total Inbound Lead Time	The sum of supplier lead time, transportation time, and port clearance time	Number of Days Distribution of number of days
Fill rates	Order fill rate: the number of orders filled complete and on time divided by total number of orders in a given time period. Unit fill rate: for a given order, unit fill rate is the number of units shipped divided by the total number of units ordered. Line fill rate: for a given order, line fill rate is the number of lines filled complete divided by the total number of lines in an order.	Percentages
Delays to customers	Orders delivered late and the length of delays	Length of delay Distribution of length of delay
Average Inventory	The average number of units at hand over a given period of time across the entire supply chain	Average number of units Dollar value of average inventory

The following discussion elaborates on each of the six stages. Detailed information on each step is provided and all mathematical calculations are explained.

Stage 1: Demand generated at the customer location

The model is triggered by the generation of demand at the customer location. Demand is generated daily at both customer sites, C1 and C2. The demand is distributed normally with a mean of 1000 units per day per customer. The average demand for each customer is derived from secondary data of a major printer manufacturer company. The standard deviation is set to 100 units for the low demand risk scenario and 300 units for the high demand risk scenario. This sets the coefficient of variation to 0.1 for low demand risk scenarios and to 0.3 for high demand risk scenarios. These coefficients of variation have been used in past research (Mentzer and Gomes 1991) to operationalize low and high demand risk scenarios, and were validated during conceptual validation with practitioners. Demand generated at customers is transmitted instantaneously to the manufacturer/distributor. There is no cost for order transmission. The order is due in 15 days. Units arriving later than 15 days incur a penalty of $35/unit. This is approximately 25% of the selling price and was validated in qualitative interviews.

Stage 2: Order received and processed at the manufacturer/distributor

Orders placed by customers are received instantaneously at the manufacturer/distributor, and order processing begins immediately. Processing at the manufacturer/distributor takes place 8 hours a day, 7 days a week, 365 days a year. Order processing includes picking products, packing, and shipping goods in speculation scenarios. Order processing includes picking components, assembling, packing and shipping goods in postponement scenarios.

For the speculation scenario, goods are picked from stock and shipped to the customer. For the postponement scenario, goods are assembled to order. Order processing capacity is set to 130% of daily demand. Not more than 1300 units of products of each type can be processed on any given day. Goods are shipped to customers every day. The cost of picking and packing either product A or product B is $10/unit. The cost of assembling either product A or product B is $20/unit per unit. The cost of shipping either product A or product B is $10/unit.

Depending upon the supplier, i.e., Chinese or domestic, the number of usable units received varies. These are accounted for in the order processing stage. Quality variability, one of the independent variables, is operationalized using variable yields from different suppliers. For the domestic supplier, every unit has a 1% chance of being defective, i.e., the yield is 99%. For the low risk Chinese supplier, every unit has a 2% chance of being defective, i.e., yield is 98%. For the high risk Chinese supplier, every unit has a 3% chance of being defective, i.e., yield is 97%. Therefore, for assuming scenarios, yield is set to 0.98 in low risk scenarios and 0.97 in high risk scenarios. Orders are split equally between the two suppliers in the hedging scenario. Therefore, average of the yields for the two suppliers is used for the hedging scenarios. For the hedging scenario, yield is set to 0.985 (average of 0.99 and 0.98) for the low risk scenarios and yield is set to 0.98 (average of 0.99 and 0.97) for the high risk scenarios.

Inventory value of products and components is linked to the variability of purchase cost, which is discussed in detail under Stage 3, part c. The inventory value of products and components is assessed at average purchase cost and accounts for the changing cost variability under different scenarios. The value at which inventory cost is assessed is presented later in Table V-6 along with purchase cost. Inventory is valued at 17% which is the average cost of carrying inventory per the 17th Annual State of Logistics Report.

Stage 3: Order placed on the supplier(s)

As the orders are processed, inventory levels for finished products A and B in the speculation scenario and for component parts AC, BC, and CC in the postponement scenario are checked every half hour. Replenishment orders are placed based on Reorder Point (ROP) policy. Whenever the inventory level for a given product or component goes below the ROP, a replenishment order for a fixed quantity, Q, is placed with the supplier. For the speculation scenario, all orders are assigned to the single Chinese supplier. For the hedging scenario, each replenishment order has an equal probability, i.e. 0.5, of being assigned to either the Chinese or the domestic supplier. The value for ROP is calculated using the following formula (Mentzer and Krishnan 1985):

$$ROP = \mu_{DDLT} + z\ \sigma_{DDLT}$$

Where,
μ_{DDLT} = average demand during lead time
z = 1.00 for an 84% in-stock probability
σ_{DDLT}= standard deviation of demand during lead time

The above formula is a standard business practice. The calculated value of ROP is rounded to the nearest integer that is a multiple of 500.

To calculate the value of Q, first the average and standard deviation of demand during lead time (DDLT) is calculated. Next, the probability of DDLT being greater than ROP level is calculated in increments of 500 units. The incremental probability between two levels of DDLT is multiplied by the difference of DDLT and ROP to calculate the number of stock-outs for each level. The total stock-outs for each level are then added to find the expected number of stock-outs for a given ROP. The expected value of stock-outs is used to calculate the value of Q using the following formula (Coyle, Bardi and Langley Jr. 2003):

$$Q = \sqrt{(2R(A+G)/IC)}$$

Where,
R= Annual demand
A=Order cost per order
G=Stock-out cost per cycle
I=Inventory carrying cost
C=Cost of product or component

Finally the calculated value of Q is rounded to the nearest integer that is a multiple of a container-load quantity for a given product or component.

For the assuming scenario, calculation of ROP and Q values is based on the average and variability of lead times for the Chinese supplier, and average and variability of demand at the customers. For the hedging scenario, ROP is based on the average and variability of the Chinese supplier. This is because of the large variation between the lead times for the domestic and Chinese suppliers, basing the ROP calculation on either the US supplier or averages of the Chinese and US supplier leads to frequent stock-outs and unduly reduces the performance of a hedging strategy. Q is calculated based on the

ROP and average of purchase cost from the US and Chinese suppliers. Table V-5 presents ROP and Q values for all scenarios.

The basic purchase price from the Chinese supplier was set to \$60/unit for the product. Typically, the purchase cost of electronic products and components is around 20% to 30% cheaper in China (Engardio, Roberts and Bremner 2004). Following this article and several discussions with practitioners, the purchase price from the US supplier is set to \$80 because the resultant cost differential is 25% ((80-60)/80 =25%). This cost differential was also ratified as reasonable in additional qualitative interviews. The cost of the components sourced from the Chinese supplier was set to \$15 for components AC and BC, and \$35 for the common component CC. Using a similar, approximately 25% cost differential, the component prices were set to \$20 and \$50 for the US supplier. Common component CC is approximately 80% of the value, weight, and volume of products A and B. Unique components AC and BC are approximately 20% of the value, weight, and volume of products A and B respectively.

To operationalize the second aspect of supply risks, i.e., cost variability, the purchase cost of products and components from the Chinese supplier was set to a high of 15% for low risk scenarios and a high of 45% for high risk scenarios. The value of 15% was arrived at by extrapolating the current wage rate increase over the past six years and the gradual but continuous strengthening of the Chinese currency (Yuan) over the past two years. The high value was based on trends in price increases of raw materials and components (such as iron ore, silicon wafers, and polysilicon) that go onto electronic products, labor shortages that can potentially lead to further increases in labor costs, and oil price increases.

TABLE V-5: REORDER POINT-REORDER QUANTITY (ROP-Q) VALUES FOR ALL SCENARIOS

		Low Supply Low Demand Risks	High Supply Low Demand Risks	Low Supply High Demand Risks	High Supply High Demand Risks
Assuming					
A or B product	ROP	46500	49000	47000	49000
	Q	21600	39600	27600	40800
A or B component	ROP	46500	49000	47000	49000
	Q	43920	78080	53680	82960
C Component	ROP	92500	97500	93500	98000
	Q	59850	107730	61180	82960
Hedging					
A or B product	ROP	46500	49000	47000	49000
	Q	19200	31200	21600	32400
A or B Component	ROP	46500	49000	47000	49000
	Q	39040	63440	43920	63440
C Component	ROP	92500	97500	93500	98000
	Q	50540	85120	54530	85120

Notes:

DDLT	Demand During Lead Time
s.d. of DDLT	Standard Deviation of Demand During Lead Time
Q	Based on carrying cost (17%), order cost ($5/order), and stock-out cost ($35/unit); rounded to nearest full container load
ROP	Based on in-stock probability of 84%; rounded to nearest 500

Table V-6 lists the minimum, mean, and maximum values, and the inventory values for the two products and three components.

Stage 4: Order received at the supplier facility (order processing at suppliers)

Whenever the inventory level for a given product or component falls below the ROP level at the M/D, an order of Q units is placed with the supplier. The orders at the supplier facility are processed using the First-In-First-Out priority. The supplier has no capacity constraints, there are no backorders and every order is filled complete.

The order processing time at the domestic supplier is set to a normal distribution with a mean of 10 days and standard deviation of 1 day. The order processing time at the Chinese supplier is set to a normal distribution with a mean of 15 days and standard deviation of 1.5 days and 4.5 days respectively for low and high supply risk scenarios. This sets the coefficient of variation (CV) values to 0.1 and 0.3 for low and high risk scenarios respectively. These values of CV have been used in past literature to operationalize low and high variability in inbound supply (Gomes and Mentzer 1991).

Stage 5: Order shipped from supplier to the assembler/distributor

After the Chinese supplier processes the order, the goods are sent to the Hong Kong port using domestic transportation. At the Hong Kong port, goods are loaded onto a ship. The ship travels from the Hong Kong port to the US Los Angeles port. At the port, the goods are cleared through customs and loaded onto a truck. Trucks transport the goods from the US port to the manufacturer/distributor.

TABLE V-6: PURCHASE COSTS AND INVENTORY VALUES FOR PRODUCTS AND COMPONENTS

Product/ Component	Chinese Supplier ($) *	US Supplier ($)	Inventory Value – Assuming ($)	Inventory Value - Hedging ($)
Product A and Product B	Low: T(60,64.5, 69) High: T(60, 73.5, 87)	80	Low: 64.5 High: 73.5	Low (64.5+80)/2=72.25 High (73.5+80)/2=76.75
Component AC and Component BC	Low: T(15, 16.125, 17.25) High: T(15, 18.375, 21.75)	20	Low: 16.125 High: 18.375	Low (16.125+20)/2=18.0625 High (18.375+20)/2=19.1875
Component CC	Low: T(35, 37.625, 40.25) High: T(35, 42.875, 50.75)	50	Low: 37.635 High: 42.875	Low (37.625+50)/2=43.8125 High (42.875+50)/2=46.4375

*Triangular (Min, Mean, Max)

After the domestic supplier processes an order, goods are shipped to the manufacturer/distributor using trucks. The goods are shipped from the domestic supplier to manufacturer/distributor in full truck loads. The transportation times from the US and Chinese suppliers are presented in the Table V-7.

Stage 6: Order shipped from assembler/distributor to the customers

After the assembler/distributor processes the orders, goods are shipped daily to customers. The transit time to customers is fixed at 3 days. The goods are shipped with a charge of $10/unit. The transit times and cost figures are based on qualitative interviews and quotes from freight companies. Orders delivered late to customers are assessed a penalty cost of $35/unit. This is approximately 25% of the selling price and has been validated in qualitative interviews. The selling price of the products is $150/unit. This is based on secondary data of a major printer manufacturer that states that typically the gross margins are around 32-35%. Average weighted gross margins with a selling price of $150/unit for all scenarios under average price (i.e., considering cost risk) work out to around 31%. A lower, 31%, gross margin was chosen as consumables like cartridges and toners have higher margins than printers.

STEP 4: COLLECT DATA

Going by the past studies and the objectives of this study, the data for this study came from the existing literature, secondary data sources, the qualitative study, and additional interviews with managers.

TABLE V-7: TRANSPORTATION TIMES

	Cost / Value	Policy/Remarks	Values (Time) Triangular (Mix, Mean, Max)	Data Source
a. Chinese supplier				
Ship complete order to HK Port	0	Transportation cost included in per container charge from China port to US port		
At Hong Kong Port	0	Port costs included in per container charge from China port to US port	T(4,5,6) Days	Data from interviews
HK Port to Los Angeles Port	$3000 per container	$3000/container includes the cost from China supplier through the Los Angeles port including all taxes, charges, and other duties	T(13, 15, 20) Days	Report by Drewery Shipping Consultants Limited (Damas 2006)
At Los Angeles Port	0	Port costs cost included in per container charge from China port to US port	T(3, 4, 5) Days	Data from interviews
From Los Angeles Port to Manufacturer/ Distributor	$3000 per Truck-Load		T(4,5,6) Days	Cost quote from trucking agency; times validated in interviews.
b. US supplier				
From Supplier to Manufacturer/ Distributor	$3000 per TL		T(4,5,6) Days	Cost quote from trucking agency; times validated in interviews

STEP 5: DEVELOP AND VERIFY COMPUTER-BASED MODEL

As discussed under Step 5 of SMDP, there is no proof in the literature reviewed of the superiority of any one package. This research used a simulation package designed specifically to model supply chains called Supply Chain Guru (SC Guru) developed by the Llamasoft Corporation (www.llamasoft.com), that combines full mixed-integer/linear programming optimization and discrete event simulation.

Following the methods used by past studies described in Table V-1(B), and Fishman and Kiviat (1968), this study addressed the issue of model verification in several ways. First, two programmers who are expert in modeling supply chains using SC Guru were used. The first expert was called in to train the researcher in building the model using SC Guru and to help set up and verify the basic model structure of the supply chain and four risk management strategies. The second expert, a programmer involved in the development of the software was called in to verify multiple aspects of the program. For example, at one point, the second expert verified the yield (quality variability) function was working correctly. At another point, an attempt to verify the initial structure of the model revealed an issue with the transfer of products at the Los Angeles port. Moreover, continuous involvement of the experts minimized the possibility of programming errors (bugs).

Second, the output of parts of the model (sub-structures) was compared with manually calculated solutions to determine if they behaved acceptably. Typical validation during this process included verification of transportation times, queuing of shipments throughout the supply chain, and inventory policies. Following Gomes and Mentzer (1991), the uniformity and independence of the model's random number generators was inspected including purchase costs of components and products, demand for products A and B, order processing times at the suppliers, transportation times and variability, and quality variability.

Third, the simulation results for short pilot runs of simple cases for the complete model were compared with manual calculations to test if the entire model (structure) behaved acceptably. This was done for all 32 scenarios in the experimental design. Typical validation for all scenarios included inbound container load/truckload costs of transportation, average purchase costs for low and high risk scenarios, order processing and assembly costs at the manufacturer/distributor, picking and packing costs, and outbound cost/unit of transportation.

As a fourth way to verify model, this research followed Mentzer and Gomes (1991) who state that for their model, "All events were hand verified through each model segment – first with simple deterministic runs, followed by stochastic checks with increasing integration of activities." The model was built in stages where each sub-model was verified by replacing stochastic elements with deterministic elements and gradually integrating these sub-models into the main model.

STEP 6: VALIDATE MODEL

Following the methods used in past studies described in Table V-1 (C) and Law and Kelton (1982), this study addressed the issue of model validation in several ways. First, subject matter experts, including academic scholars and practitioners, were consulted in the conceptual development of model components and relationships between components. This step ensures that the correct problem is solved and reality is adequately modeled (Law and Kelton 1982).

Second, a structured walk-through of the model and a review of the simulation results for reasonableness with a separate set of subject matter experts, including academic scholars and practitioners, were conducted. The results were consistent with how the subject matter experts perceived the system should operate. This reflects model face validity. Face validity was also confirmed using literature and review of supply chain simulation models in past research.

For this study, input-output transformation, i.e., comparing simulation data to real world data, was not possible for several reasons. First, complexity of real world supply chains is far greater than the one simulated in this research. Therefore, it is difficult to isolate the effect of the variables in the real data. Second, it is difficult to find a company willing to share complete data on all variables included in this research. Through several attempts to acquire real data from multiple companies, data that corresponds to different parts of the supply chain could be gathered. However, data that spanned more than two levels of a supply chain for a given product could not be gathered. These partial datasets were used to extensively validate corresponding parts of the simulation model.

Finally, sensitivity analyses was performed on the programmed model to see which model factors have the greatest impact on the performance measures and, thus, have to be modeled carefully (Powers and Closs 1987).

STEP 7: PERFORM SIMULATIONS

Combinations of high and low levels of risks were used to generate four possible combinations of demand and supply risk levels. All four risk management strategies were simulated separately for each of the four combinations of demand and supply risk levels. This meant four possible combinations of strategies, i.e. Assumption-Speculation, Assumption-Postponement, Hedging-Speculation, and Hedging-Postponement, were simulated for each combination of supply and demand risk levels, for a total of 16 scenarios. Each of these 16 scenarios was replicated with a 45-day Los Angeles port disruption. In total, 32 scenarios were simulated. Table V-8 lists all 32 scenarios.

The procedure described earlier based on Law and Kelton (1982) and Bienstock (1996) was used for sample size determination in this study. For this study, the sample size for 5% relative precision is 28 runs per cell. Relative precision values were not calculated for disruption scenarios. This was because a disruption leads to highly variable results between runs depending on the time of disruption and it is unlikely that results will fall within a 5% precision level. Therefore, similar to non-disruption scenarios, for disruption scenarios, a sample size of 28 runs each was used.

STEP 8: ANALYZE RESULTS

Model runs are used to estimate performance measures. For all scenarios simulated, decisions on tactical issues such as run length, warm-up period, manner of initialization, and the number of independent model replications were made. The run length was set to two years, which was validated in interviews as a typical life frame of an off-shoring decision.

TABLE V-8: SIMULATION SCENARIOS

	Factor 1	Factor 2	Factor 3	Factor 4	Moderator
	Supply Risk	Demand Risk	Supply Strategy	Demand Strategy	Disruption
1	L	L	He	Po	No
2	L	L	He	Sp	No
3	L	L	As	Po	No
4	L	L	As	Sp	No
5	L	H	He	Po	No
6	L	H	He	Sp	No
7	L	H	As	Po	No
8	L	H	As	Sp	No
9	H	L	He	Po	No
10	H	L	He	Sp	No
11	H	L	As	Po	No
12	H	L	As	Sp	No
13	H	H	He	Po	No
14	H	H	He	Sp	No
15	H	H	As	Po	No
16	H	H	As	Sp	No
1d	L	L	He	Po	Yes
2d	L	L	He	Sp	Yes
3d	L	L	As	Po	Yes
4d	L	L	As	Sp	Yes
5d	L	H	He	Po	Yes
6d	L	H	He	Sp	Yes
7d	L	H	As	Po	Yes
8d	L	H	As	Sp	Yes
9d	H	L	He	Po	Yes
10d	H	L	He	Sp	Yes
11d	H	L	As	Po	Yes
12d	H	L	As	Sp	Yes
13d	H	H	He	Po	Yes
14d	H	H	He	Sp	Yes
15d	H	H	As	Po	Yes
16d	H	H	As	Sp	Yes

L= Low Risk
H=High Risk
He=Hedging Strategy
As=Assuming Strategy
Po=Postponement Strategy
Sp=Speculation Strategy

The warm-up period was set to 60 days. Multiple observations were made for each scenario and total cost and total revenues were observed for runs where data were collected at the following three points: beginning first month to end of twenty-four months, beginning of second month to end of twenty-five months, and beginning of third month to end of end of twenty-six months. All scenarios stabilized by the end of second month, reflected in the following observations: similar direction (negative or positive) of profit, stability in penalty costs of late deliveries, and stable order fill rates. Furthermore, efforts were made to minimize the effect of initial conditions on the model by setting up initial inventory level at the manufacturer/distributor to the ROP levels.

Elaboration of the results is beyond the scope of this paper, but it is important to mention that main analyses are based on Tukey's multiple comparison of cell means. In addition, methods used to analyze the results included visual inspection of graphical outputs; mean, lower and upper limits, standard deviation, and 5^{th} and 95^{th} percentile of dollar value of risks; percentage changes in performance measures; and ANOVA for response variable main effects.

IMPLICATIONS

This paper presented an eight-step methodology, called the Simulation Model Development Process (SMDP) for logistics and supply chain models, to establish the rigor of simulation studies. A detailed discussion of each step, along with examples drawn from simulation studies reported in leading logistics journals, were presented. The SMDP process was provided using a simulation modeling study as an illustration of the level of detail that should be provided in any such study. This has several implications for future discrete event simulation research for researchers, reviewers, and practitioners.

First, a review of simulation research reveals that there are very few studies that report all eight steps in-depth. Thus, there is no set standard for evaluation of simulation studies in logistics and supply chain journals. To this end, Figure V-2 provides a practical framework and checklist to establish the rigor of simulation research. To summarize the discussion on the SMDP, Table V-9 is presented below for easy reference for both reviewers and researchers. Table V-9 provides a practical framework and checklist to establish the rigor of simulation research. It provides insights into the basic standards that must be followed for any rigorous simulation research. It is incumbent on modelers to follow the process in Figure V-2 and provide sufficient answers to the questions in Table V-9 to convince the reader that the resultant models and conclusions are rigorous (i.e., trustworthy), or provide specific rationale for non-inclusion of any criteria if not applicable to a particular study. Reviewers (in deciding whether specific modeling research should be published) and practitioners (in deciding whether to trust the results of such research and apply it to real logistics and supply chain situations) must make judgment calls on whether each criterion has been satisfactorily addressed.

In the future, apart from addressing the eight steps in SMDP, researchers should also focus on some important aspects of the presentation of the study. First, the literature review reveals that often the assumptions are not explicitly stated and it is left to the reader to infer them. Such assumptions as probability distributions of variables or safety stock policies can have significant implications on the applicability and limitations of simulation results. Thus, it is critical that all assumptions be clearly stated.

TABLE V-9: EVALUATING THE RIGOR OF A COMPUTER-BASED SIMULATION RESEARCH

Step	**Questions to answer (at a minimum)**
Problem Formulation	What is the objective of the study? Is the problem stated and formulated clearly? Who was involved in problem formulation, particularly for real-life case studies?
Choice of dependent and independent variables	Are all relevant variables included? Are variables clearly defined? Who was involved in choice of variables? Is there evidence from prior literature on importance of variables? If no evidence from prior research, what is the rationale for the choice of variables?
Validation of Conceptual Model	Are important assumptions, algorithms, and model components described? Was anyone else other than the authors consulted for conceptual validation? Was a structured walk-through performed? Who served as the audience for walk-through?
Data Collection	What data are required to specify model parameters, system layout, operating procedures, and distribution of variables of interest? Where are the sources of data? Rationale for computer-generated data, if any?
Verification of Computer Model	What programming environment was used? Were the model sub-components and the complete model checked with manually calculated data? Was the computer model checked by at least one person other than the person who coded the model? Was the output of parts of the model (sub-structures) compared with manually calculated solutions?
Model Validation	Were experts other than authors consulted? Is there evidence of input-output transformation? Was a structured walk-through of the computer-based model performed? Was a review of the simulation results for reasonableness conducted? Is there evidence from literature of model design?
Performing Simulations	What sample size, run length, and warm-up period were used? Is the rationale for sample size, run length, and warm-up period stated?
Analysis Techniques	Which statistical techniques were used? Are the analysis techniques statistically appropriate?

Second, the discussion of model limitations is usually missing or incomplete. A thorough discussion of limitations not only minimizes misguidance but also opens doors for future research that may attempt to relax assumptions or extend the model to reduce limitations. Third, as mentioned earlier, there is a variety of simulation tools available to modelers. A brief discussion on the choice of a tool or a package, and its advantages and disadvantages should also be included to assist other researchers in making an informed choice about simulation packages. The result of such increased rigor in simulation modeling can only lead to increased confidence and application of the resultant stream of modeling research in logistics and supply chain management.

Finally, a rigorous simulation study based upon the SMDP framework (such as illustrated here) provides data sources and rationale for inclusion or exclusion of variables and parameters. This raises the level of confidence in the findings of a study as well as informs the reader of the extent of applicability of the results.

In sum, the SMDP can be used by researchers to design and execute rigorous simulation research, by reviewers for academic journals to establish the level of rigor of simulation research, and by practitioners to answer logistics and supply chain system questions. The illustration can be used as a template for what should be specified in a paper to enhance the contribution of a study for both readers interested in results and readers who gain from methodological insights.

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APPENDIX

APPENDIX: INTERVIEW PROTOCOL / GUIDE

Opening

- Introductions of interviewer and interview participant
- Overview of purpose of the study
- Confidentiality assurance
- Permission to audiotape

Demographic Data

- Title of interview participants
- Job history
- Organizational Structure
- Background on organization, industry

Lines of Inquiry

- What are elements of risk?
- What is a risk management process?
    - Steps in process
- Tools and techniques
- Strategies for risk management
- Risk Mitigation / Contingency planning
- Facilitators / Impediments in the process

Additional Unplanned/Floating Prompts

- Describe.
- Tell me more about that.
- Explain that in more detail.
- Give me examples or tell me about a related incident.
- How does that work?
- Tell me about a time when that did not happen.

VITA

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Her primary research interests are in the areas of risk and complexity management in global supply chains. Ila has presented at Council of Supply Chain Management Professionals and Decision Sciences Institute conferences and has published in Journal of Business Logistics. She has also co-authored a chapter in a book titled "Handbook of Global Supply Chain Management."

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