

Managing Supply Chain Disruptions

By Asoo J. Vakharia and Arda Yenipazarli

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Abstract

Given the substantive negative financial, marketing, and operations-related consequences of supply chain disruptions, it is not surprising that most organizations are expending significant efforts to develop effective disruption management strategies. Further, the focus on low-cost (and lean) supply chains to control costs has also resulted in magnifying the impact of even a small disruption at any stage of the chain. Thus supply chain managers are constantly evaluating and trading-off the low costs of a lean supply chain with the benefits of a highly responsive (and potentially higher cost) supply chain. In this monograph, the authors provide a comprehensive review of the current research and practice related to managing supply chain disruptions. In essence, the focus is to structure and describe these extant contributions with a view to identify directions for future research.

Dedication

Dedicated to my son Rohan Vakharia whose passion for learning and desire for excellence was an inspiration to all those who knew him.

1

Introduction

Consider the following recent occurrence:

The recent (January 2009) recall of peanut butter made by Peanut Corp. of America underscores the inherent difficulties large food companies have in monitoring their supply chains. Though analysts say product recalls have only a measured financial impact on food makers in the short term, greater costs are inherited in the long term as consumers question the safety of their products. According to Pat Conroy, national consumer products leader at Deloitte LLP, “the soft costs are with respect to [product] brand, which is ever more important as consumers have the ability to differentiate [between] products more than they used to.” Although companies with large product portfolios, like Kellogg and General Mills, are less likely to suffer from the financial impact of product recalls as they are generally viewed as safe and trustworthy by the wider public, consumers are becoming less tolerant of food recalls, and are taking greater

initiative to ensure that the products they purchase are indeed safe. Conroy recommends that companies put more effort into policing not only direct suppliers, but also those in their suppliers' supply chains, and educating consumers about the methods they use to ensure product safety.¹

This example is one of many that highlights the fact that there are substantial short- and longer-term effects stemming from supply chain disruptions. In addition, several recent observations/developments have also led to an increased focus on supply chain disruption management. First, supply chain managers are starting to recognize that business continuity planning mechanisms are not enough to mitigate the impact of supply chain disruptions on their operations as documented by responses to disasters such as the terrorist attacks on 9-11, the devastation of New Orleans after hurricane Katrina, and the tsunami in Thailand and India. Second, there are several studies which document that disruptions in the supply chain can lead to a substantive negative financial impact on firm and industry performance. Third, the potential negative regulatory and consumer ramifications of supply disruptions of consumer goods, such as toys and food products, are leading firms to recognize the significant non-financial impact of disruptions in supply channels. Fourth, the move toward a lean supply chain to obtain supply chain efficiencies has resulted in a loss of "slack" capacity and more interdependent links within the chain. Thus, it is likely that even a small "glitch" at one stage in the chain could result in a significantly larger effect downstream and/or upstream much like the bullwhip effect. Finally, the emergence of globalization as a competitive strategy has also led to an increase in the types of risks inherent in supply chains which span multiple countries.

From a supply chain perspective, disruptions can lead to severe consequences. For example, Hendricks and Singhal [18, 19, 20] report that companies experiencing disruptions in the supply chain can typically expect declines in sales growth, stock returns, and company value. On a

¹<http://www.smartmoney.com/news/on/?story=ON-20090120-000599-1451&print=1>.

global level, there are also reports of Australian firms which face similar consequences due to disruptions in the supply chain²; MG Rover in the UK which was forced to suspend plant operations due to parts shortages and soon thereafter the company ceased to exist. Other examples of major disruptions in the last decade include:

- In 2001, the attack on the World Trade Center led to significant regulatory changes in the process by which goods could be shipped in and out of the United States. In the short run, retail companies such as JC Penney, which relied on shipping products on a “just-in-time” basis, experienced significant short-term lost sales due to product unavailability.³
- In 2002, the longshoremen strike at the LA docks significantly impacted the availability of retail products which were manufactured in the Far East and sold in the United States.⁴
- In 2004, a flu vaccine manufacturer in the UK encountered contamination in its processes and this led to a shortage of the flu vaccines available to consumers in the 2004–2005 flu season.⁵
- In 2007, the recall of Mattel toys (primarily toy cars) manufactured in China due to the toxic contents of the paint resulted in significant lost sales for the company.⁶

From an individual firm or company perspective, disruptions due to natural causes (such as earthquakes, floods, hurricanes, and tsunamis) are not an entirely new phenomenon. In fact, “Business Continuity Planning” (BCP) has its foundations in the effective management of the consequences of disruptions due to natural causes. For example, companies that operate customer service call-centers in Jacksonville, Florida recognize that hurricanes can completely disrupt their operations.

² www.gartner.com/press_release/asset_148797_11.html.

³ A presentation made at the Center for Retailing Education and Research, University of Florida by Jim LaBounty, VP of Supply Chain Management, JC Penney, October 12, 2006.

⁴ <http://scm.ncsu.edu/public/risk/risk7.html>.

⁵ <http://www.logisticstoday.com/displayStory.asp?S=1&sNO=7792&MLC=SC..>

⁶ <http://www.theferrari.com/blog1/?cat5>.

Hence, their continuity plans include at a minimum: (a) a technology (hardware and software) backup at alternative locations; and (b) plans to physically move their employees to the alternative locations. In more recent years, BCP has expanded to focus on other types of supply chain risks (i.e., those which are not always a consequence of natural causes). Perhaps the single most critical factor driving this is the fact in the increasing dependence on suppliers has led to supply chains to become more and more lean and in these settings the impact of disruptions is more significant. As with any organization wide initiative, key elements and principles for implementing BCP are top management commitment, processes to ensure continuity of responses, risk assessment mechanisms, and speed and responsiveness indicators/measures. Zsidsin [53] also presents case study evidence of how a firm managed the impact of disruptions stemming from hurricanes Katrina and Rita. This firm used liquid hydrogen as a key energy source for manufacturing its products and due to this natural disaster faced a severe quantity shortage. A combination of risk assessments, business interruption plans, and inventory management policies enabled the firm to reallocate existing stocks of liquid hydrogen from its R&D facilities to its manufacturing plants, and simultaneously develop alternative energy sources for continuing its R&D activities.

A more proactive approach to managing disruptions is the risk management framework adopted by Ericsson to manage supply chain disruptions after the company's operations were significantly impacted by a fire at a supplier facility in Albuquerque (Norrman and Jansson [30]). The focus adopted by the company was to minimize the risk exposure in the supply chain on the basis of a process with feedback loops between the sub-processes. In essence, a four-stage process was adopted: Risk identification — mapping of the upstream supply chain to identify critical aspects, sources of risk, and the likelihood of their occurrence; Risk assessment — analyze each risk source to obtain a perspective on how to avoid business interruptions due to the risk; Risk treatment — development of alternative risk mitigation strategies with corresponding costs and their potential to address specific risks; and Risk monitoring — focuses on analyzing the process by which specific risks and developing standardized templates to handle similar risks.

In addition to this four-stage analysis, the company also evaluates the adoption of each risk management strategy by trading-off the costs of a strategy versus the potential benefits of reduced business recovery time.

The recent trends and developments within supply chains, such as increased use of outsourcing of manufacturing and R&D to suppliers, reduction of supplier base, reduced inventory and lead time buffers, shorter product life cycles, have created long, lean, and interconnected chains of companies which are vulnerable to disruptions and their potentially devastating ripple effects. Further, the integrated nature of these supply chains indicates that it is not possible to manage disruption risks by focusing on a single stage. Instead disruption strategies should be developed and implemented such that they mitigate risks across the entire chain. Industry efforts to combat disruptions have been to either adapt traditional thinking (a la BCP) or formulate company-specific strategies (à la Ericsson) as discussed above.

In this monograph we categorize and review the substantive research contributions relating to managing SC disruptions. Since our primary focus is on formulating directions for future research, we do not offer a comprehensive review but instead focus on significant research and practical findings which enable us to do so. The remainder of this monograph is organized as follows. In the next section, we review the general area of SC disruptions and examine classifications of disruptions which can be used to provide insights into the disruption management process. In Section 3, we review the literature in the emerging field of disruption risk management which attempts to identify specific risks associated with SC disruptions. This is followed, in Section 4, by a review of conceptual/empirical research with a focus on providing general insights into how one or more organizations have managed the risk associated with disruptions. Given that designing robust SC networks are a key feature of managing disruption risk, we review the relevant research in this domain in Section 5. A detailed analysis of prior research targeted at managing specific risks (e.g., product, supply, operations/process, and transportation risks) is presented in Section 6, and finally, directions for future research are discussed in Section 7.

2

Supply Chain (SC) Disruptions

An SC disruption can be defined as any occurrence which has negative consequences for regular SC operations and hence, causes some degree of “confusion/disorder” within the SC. The primary focus of this section is to provide an overview of alternative classifications of different SC disruptions which might enable the development of more specific disruption management strategies.

At a very broad level, one potential classification of disruptions is to categorize them as being caused by either *acts of nature* (e.g., flooding, earthquakes, and hurricanes) or by *acts of humans* (e.g., political instability, terrorism, and quality problems). Although such a classification would identify the underlying cause of disruptions, it is more useful to further classify them based on their mean and variance of occurrence frequency. For example, standardized mechanisms and strategies to react to disruptions which are more frequent and highly predictable (i.e., higher mean/lower variance) would be appropriate while evolutionary and customized processes would need to be designed for dealing with disruptions which are less frequent and more unpredictable (lower mean/higher variance).

Another categorization of disruptions would be to focus on the supply chain *life cycle*. Analogous to the commonly accepted product/process life cycle and the notion of a different focus supply chain for each product [12], every supply chain also follows an evolutionary cycle where initially the focus might be on creating a chain to deliver high-quality, customized offerings so as to satisfy diverse customer demands. At this stage decisions related to product development, product introduction, and quality would obviously be the most relevant and thus disruptions in these processes would be of primary concern. Managerially, this points to ensuring that not only are decision processes organized efficiently, but also that mechanisms to protect linkages between multiple firms primarily involved in these interdependent activities are designed. For example, pharmaceutical firms which typically face long research and development times typically organize and or subcontract their R&D activities in lower cost regions but also make investments in technology infrastructures so that disruptions (if they occur) are identified quickly. Obviously as the supply chain evolves to offering a smaller set of standardized offerings to segmented markets, a leaner and more efficient chain is desirable since the competition is primarily cost based. In such a setting, maintaining continuous product flows between sourcing, operations, and distribution and decisions to operate each of these links efficiently is more of a priority for the supply chain manager. In practice, consumer goods manufacturers who operate these types of chains are driven by lean strategies which seek to provide efficiencies in sourcing, operations, and distribution. In addition, several of the organizations in this industry group (such as Proctor & Gamble) also make significant investments in enterprise systems such as SAP to facilitate not only coordination between these key processes but also to enable a quick response to disruptions.

A third classification is based on the type of disruptions. If we adopt the flow and process perspective, a supply chain can be viewed as a series of nodes (representing transformation processes) with connecting arcs (representing flows of information, products, and/or service offerings). Examining each of nodes/arcs, a supply chain will in all likelihood encounter disruptions caused by changes in quantity (e.g., shipments of key cell-phone components for Ericsson impacted due to a fire at a

supplier plant [30]), lead time (shipments into retail stores delayed due to the LA longshoremen dock strike¹), quality (Mattel toy shortage due to toxic paint used by an offshore supplier²), and technology (a compromise of the Speakeasy Network of Seattle which resulted in significant financial losses for the online credit card payment company PayPal³).⁴ The usefulness of this categorization is that it can provide direction on managing the risk of each type of disruption. For example, quantity disruption risk can be mitigated by developing backup suppliers; by using multiple transportation routes, lead time disruption risk can be better managed; quality disruptions can be better controlled through explicit and detailed communications of product designs; and technology disruptions require a focus on developing/implementing secure network management tools.

These alternative classifications of disruptions provide guidelines on the likelihood of the occurrence of different types of disruptions based on the stage of the supply chain life cycle and the key related processes. For example, if the supply chain life cycle is in the start-up/growth phase, quantity, lead time, and/or technology disruptions are likely to occur with lower probability as compared to when the supply chain life cycle is in the maturity phase. The rationale for such an argument stems from observations that significantly higher levels of materials flows, longer lead times, and tightly integrated IT systems are more characteristic of a supply chain in the mature phase as compared to smaller material flows and shorter lead times, and loosely coupled IT systems in a supply chain in the start-up/growth phase. It follows that quantity, lead time, and technology disruptions are more likely to occur in the former setting as compared to the latter. A quality disruption, on the other hand, is more likely to occur when the supply chain is in the start-up/growth stage as compared to a supply chain in

¹ <http://scm.ncsu.edu/public/risk/risk7.html>.

² <http://www.theferrarigroup.com/blog1/?cat5>.

³ http://www.seattlepi.com/local/39579_hacker20.shtml.

⁴ Some or all of these aspects are interrelated. For example, a change in lead time which would focus on the flow of materials between two nodes would obviously have an impact of the quantity being received by a downstream node. However, given the flow and process focus, we are more interested in tracing the underlying type of disruption and hence, treat these as separate dimensions.

the mature phase since in the former setting, product and/or service designs are modified more frequently as compared to the latter setting where standardized offerings are the norm.

A final managerial perspective on SC disruptions would be to focus on the organizational impact. Thus, disruptions could have a strategic, tactical, and/or operational impact on SC processes. For example, a disruption caused by product recalls (e.g., Mattel toys) would require a revision of sourcing, operations, distributions/logistics, and communication strategies, while a disruption in the transportation network (e.g., the LA dock strike) would probably require more of a tactical response in terms of a revision of the product allocation decisions within the supply chain distribution network. Further, shorter-term disruptions in terms of labor markets, downtimes, and/or emergency customer requests would require an operational response for one or more nodes in the supply chain.

In sum, SC disruptions can be categorized based on cause, SC life cycle, type, and managerial decisions. Using such categorizations, two of the specific examples of disruptions described in the introduction section could be classified as follows:

- Peanut butter recall
 - Cause: “acts of humans;”
 - SC life cycle stage: mature;
 - Type: product quantity; and
 - Decision Focus: sourcing, operations, and distribution strategies.
- Flu Vaccine shortage
 - Cause: “acts of humans;”
 - SC life cycle stage: introduction/growth;
 - Type: product quality; and
 - Decision Focus: operations redesign.

Obviously the usefulness of these classifications is that all of them provide some managerial insights into the cause, type, and stage of SC.

However, classifying disruptions in this manner does not lend itself to making better SC design decisions and thus, there is a need to approach the process of SC disruption from a more structured perspective. A commonly used framework in this context is that of Risk Management and this is described in the next section.

3

Disruption Risk Management

The seemingly relentless pressure of globalization has produced a paradigm shift in supply chains, where companies now seek to locate manufacturing based on low operating costs and also the outsourcing of their non-core activities to concentrate on areas with opportunities to build better competitive advantages. Further, the proliferation of technology has resulted in time compression since information flow is almost instantaneous. Since the current SC is in all likelihood long, lean, and integrated, it is vulnerable to significantly more disruption risks. This appears to be the primary motivation for managing SC risks by focusing on prevention, control, and impact management.

The effective management of SC disruptions can be carried out through a core product, process, and location focus along the entire supply chain. Subsequently, the types of events/risks that can disrupt each of these aspects can be identified and this would enable the development of decision processes for managing them. From a control perspective, it is necessary to recognize potential SC risks and implement technology and processes to prevent the likelihood of their occurrence. Following generally accepted practices, a firm might require all its suppliers not only to prevent the occurrence of a fire by reducing the

flammable materials in the process, but also to install sprinkler systems to safeguard against the negative implications of a fire. In terms of impact management, it is key to recognize that a quick response can help to alleviate negative effects. In this context, BCP is obviously of significant importance and in addition, financial losses can also be managed more effectively by covering losses of key fixed and working assets through insurance mechanisms.

One approach to structuring the SC disruption risk management process is that proposed by Sheffi [35] who recommends that it consists of four inter-related steps: creating awareness, prevention, response management, and consequence management. Given that there is sufficient awareness of disruption risks in the current setting, there is now a move toward creating the resilient enterprise to manage these risks [36] [37]. An alternative perspective is that since disruption risks for each setting might not readily be visible, a multi-step approach to identify these risks is as follows: obtaining senior management understanding and approval; identifying key processes and characterizing facilities, assets and human populations that are likely to be affected by disruptions; undertaking traditional risk assessments for each of these processes; and reporting, periodic auditing, management and legal reviews of implementation plans, and on-going results.¹ Once this process is complete, then an effective SC disruption risk management strategy should focus on designing an agile, adaptable, and aligned supply chain [26] which can respond quickly to sudden changes in supply or demand by dynamic adjustments in the supply chain network, and in addition, establish incentives for supply chain partners to improve performance of the entire chain. Successful strategies which have been used to achieve these objectives include providing all SC partners with equal access to forecasts, sales data, and plans; maintaining an inventory of inexpensive, non-bulky product components to prevent manufacturing delays; monitoring changes in new and developing markets; modularizing production to achieve product mix flexibility; SC specialization by product families; and redefining partnership terms with to share risks, costs,

¹<http://knowledge.wharton.upenn.edu/article.cfm?articleid=1548>.

and rewards across all SC firms [26]. From a distribution and logistics perspective, SC risks can also be better managed by segmenting products and product lines, and by looking at inventory hedging and redundant transportation options so as to provide a quick response to changing market conditions. Of course, the need to perform a cost — benefit analysis related to each of these strategies is also essential since it is well recognized that an SC cannot be protected against every risk. On the other hand, by following a structured risk management process, an SC manager can not only realize a competitive edge, but also minimize costs associated with disruptions.

Christopher and Lee [9] note that the current marketplace is characterized by turbulence and uncertainty, and it tends to increase due to volatile demands in almost every industrial sector, short product and technology life cycles, and globally dispersed network partners. At the same time the vulnerability of supply chains to disturbance or disruption has increased. It is not only the effect of external events such as strikes or terrorist attacks, but also the impact of changes in business strategy. Many companies have experienced a change in their supply chain risk profile as a result of changes in their business models, such as the adaption of lean practices, the move to outsourcing and a general tendency to reduce the size of the supplier base. The major thesis explored in this paper is that tangible and intangible disruption risks in the supply chain occur due to a lack of confidence and this could lead to chaotic effects. In order to increase confidence in the SC, an enhanced visibility and control mechanism needs to be implemented. However, given the fact that the end-to-end SC pipeline is typically very long, maintaining visibility across the entire SC is quite a difficult task. To deal with this issue, the authors point to the usefulness of the newly emerging field of supply chain event management. The idea behind event management is that partners in a supply chain collaborate to identify the critical nodes and links through which material flows across the network. At these nodes and links, control limits are agreed within which fluctuations in levels of activities are acceptable. Enabling adequate control levers to be accessible to the partners allows prompt actions to be taken when information reveals such needs. Both visibility and control are critical for restoring supply chain confidence.

Without visibility and control, it is common that the supply chain is plagued with buffer inventories and excessive capacity. The lack of confidence also makes it difficult to be responsive customers, to react to changes in market conditions, and to be competitive in providing customer service.

Kleindorfer and Saad [23] investigate the effects of alternative SC design options on the efficiency and robustness of the supply chain subject to various sources of disruption. A conceptual framework that reflects the effective integration of the joint activities of risk assessment and risk mitigation, and provides strategic directions, actions, and necessary conditions that help advance cost-effective mitigation practices is proposed. The framework is based on the following premises: in order to manage risk, the nature of the underlying hazard giving rise to this risk should be identified; the risk has to be quantified through a disciplined risk assessment process; to effectively manage risk, the approach used must fit the characteristics and needs of the decision environment; and appropriate management policies and actions need to be integrated with on-going risk assessment and coordination among supply chain partners. Based on this framework, three main tasks that have to be practiced continuously and concurrently as the foundation of disruption risk management are specifying sources of risk and vulnerabilities, assessment, and mitigation, denoted as SAM. This conceptual framework and related task implementation steps are supported by empirical evidence from the U.S. Chemical Industry. Based on the analysis and empirical evidence presented in the paper, two key dimensions emerge as fundamental in guiding management practice of disruption risk in supply chains. The first dimension consists of strategies and actions aiming at reducing the frequency and severity of risks faced at both the firm level and across the supply chain. The second element focuses on increasing the capacity of supply chain participants to absorb more risk, without serious negative impacts, or major operational disruptions. It is argued that disruption risks which belong to the low probability, high consequence domain of outcomes cannot be managed in the traditional manner based on measuring outcomes and translating these into process improvements. Rather the approach must be in the spirit of very high-quality process management, in which the process itself is

continually audited to assure a proper balance between risks and benefits of mitigation. In addition, as indicated by chemical industry study, many disruption risks involve a broader class of stakeholders including public sector regulators, employees, and external stakeholders.

The lack of disruption management strategies has been highlighted in recent years when examining the impact of terrorist attacks, natural disasters, and regional power outages. Hale and Moberg [17] argue that while SC disruptions caused by external events can have a significant financial and operational impact on firms not properly prepared, it is also critical that firms become more proactive in their disaster planning and work at developing the coping and recovery skills that will be required to maintain supply chain continuity during future, inevitable times of crisis. One critical component of disaster management planning in supply chains is the storage of emergency supplies, equipment, and vital documents. That is to say, firms should store critical documents, emergency supplies and equipment, satellite phones, medical equipment, water, clean-up supplies, portable lights, inventory and equipment records, and generators in a safe and secure location. However, storing a set of these items at every distribution center, manufacturing facility, transportation hub, and office within in the supply chain can be cost prohibitive. Besides, gaining access to these items during an emergency may be prevented in some instances because of the nature of some external events that could destroy the emergency supplies stored at the facilities directly affected by the disaster. Given the cost and risk constraints, the goal of this paper is to provide a site selection model for emergency resources that can be utilized by logistics managers and supply chain continuity teams to determine the appropriate number and locations of storage areas for critical emergency equipment and supplies. Projecting costs for disaster planning and response scenarios and working to make these costs more efficient is a critical aspect of effective disaster planning to ensure that available resources matched the requirements of the disaster plan. The proposed model uses five-stage disaster management process for supply chains as the framework of a decision process for secure site locations. The decision process combines recommendations from FEMA's Disaster Management Guide

with a set covering location model to help establish a network of secure site locations.

Faisal, Banwet and Shankar [11] focus on the fact that globalization has created small and medium enterprises (SMEs) which face intense pressure due to international competition. These SMEs are now facing new dimensions of uncertainties and risks in their supply chains that stem from the emergence of new markets and commercial opportunities. The risks in the supply chains can be mitigated if SMEs can understand the variables having impact on risk management in the supply chains. For that reason, managers in small- and medium-sized organizations now need to be equipped to identify, analyze, and manage risks and crises from a more diverse range of sources and contexts and this involves an understanding as to how various enablers of risk mitigation interact with each other. The purpose of this paper is to present an approach to effective supply chain risk mitigation by understanding the dynamics between various enablers that help mitigate risk in supply chain. In this framework, using interpretive structural modeling (ISM), the research presents a hierarchy-based model and the mutual relationships among the enablers of risk mitigation. Enablers of risk mitigation are categorized into 11 variables (such as trust among supply chain partners, collaborative relationships among supply chain members, information sharing in the supply chain and knowledge about risks) depending upon their driving power and dependence. These enablers play a key role to counter risks in a supply chain. The linkage variables including strategic risk planning, corporate social responsibility, and aligning incentives and revenue sharing policies are influenced by lower level variables and in turn impact other variables in the model. The final cluster includes variables like continual risk assessment, agility, risk sharing, and information security. Using the ISM model, strategic aspects such as trust, collaborative relationships, information sharing are shown to be more critical. For risk mitigation purposes, a process for continual monitoring of SC risks is also proposed. The key finding is that there exists a group of enablers having a high driving power and low dependence requiring maximum attention and of strategic importance while another group consists of those variables

which have high dependence and are resultant actions. This classification provides a useful tool to supply chain managers to differentiate between independent and dependent effects and their interdependence in managing the SC disruption risk management process.

Tang and Tomlin [41] observe that firms strive to improve their financial performance by implementing various supply chain initiatives that are intended to increase revenue, reduce cost, and reduce assets. For example, increased product variety, more frequent new product introductions, supply base reduction, just-in-time inventory systems, vendor managed inventory, outsourced manufacturing, information technology, and logistics are just a few of the options which are explored by firms. Although effective in a stable environment, the feasibility of gains due to such initiatives is questionable as the number of supply chain partners increases, and supply chains become longer and more complex. It is noted that firms regularly face at least six major types of SC risks: supply risks, process risks, demand risks, intellectual property risks, behavioral risks, and political/social risks. This paper focuses on three of these six types of risks that are inherent to all supply chains, namely supply, process, and demand risks and for each risk type, two common measures are proposed for quantification purposes: likelihood of the occurrence of an undesirable event and the negative implications of the event. Some undesirable events associated with supply, process, and demand risks include increase in supply cost, decrease in supply capability, and discrepancy between forecast and actual demand. The mechanisms to reduce the likelihood of the occurrence of certain undesirable events are based on the risk avoidance concept and some TQM principles. To reduce the negative implications of certain undesirable events associated with supply, process, and demand risks, the firm needs to focus on mechanisms which can result in an SC which is aligned, adaptable, and agile [26].

Manuj and Mentzer [27] argue that global supply chains need to find a balance between productivity and profitability to effectively move goods and materials between nations in a timely and seamless manner. The process for global supply chain risk management and mitigation includes five interdependent steps: risk identification; risk assessment and evaluation; selection of appropriate risk management strategies;

implementation of these strategies; and finally mitigation of supply chain risks. Such a framework for global supply chain risk management provides three main benefits. This step-by-step approach forces the decisions to move out of typical intuitive thinking and preset mental

Table 3.1. Research on Disruption Risk Management.

Reference	Contribution/Focus
Sheffi (2002) [35]	A hierarchical four-step disruption risk management process is proposed which is as follows. Create awareness → Prevention → Response Management → Consequence Management.
Christopher and Lee (2004) [9]	Low level of confidence in an SC leads to chaotic problems stemming from disruptions. Alleviate such problems by improving visibility in an SC. Proposed approach for improving visibility is event management through which critical SC links/nodes should be collaboratively identified.
Kleindorfer and Saad (2005) [23]	Categorization of risks as those stemming from a supply and demand mismatch and those stemming from disruptions. Proposed framework (with experiential evidence from the chemical industry) for risk management is as follows. Identify underlying hazard which leads to a risk → Quantify the risk → Develop a risk management process (in line with the current decision making environment) → Coordinate process implementation with organizational priorities and SC partners.
Hale and Moberg (2005) [17]	Management of critical supplies (documents and other facilitating goods) when SC disruptions occur. Idea is to identify “safer” locations for storage of these critical supplies. Uses a set-covering model coupled with FEMA disaster management guidelines to identify secure cite locations for storing critical supplies.
Faisal et al. (2006) [11]	Identifies enablers which can alleviate SC risks for small- and medium-sized firms. Using interpretive structural modeling, key enablers for risk reduction are as follows: strategic aspects such trust in the SC, collaborative relationships, and information flow.
Manuj and Mentzer (2008) [27]	Process for global supply chain risk management and mitigation includes five interdependent steps. Risk identification ↔ risk assessment and evaluation ↔ selection of appropriate risk management strategies ↔ implementation of these strategies ↔ mitigation of supply chain risks. Benefits of this framework are: (a) encourages a programmatic thought process for disruption management; (b) defines risks and then uses risk profiles to generate appropriate risk management strategies; and (c) it evaluates risks based on context rather than a “cookie” cutter approach.
Tang and Tomlin (2008) [41]	Focus is on supply, process, and demand risks in an SC. Proposes that causes of these risks be quantified using two measures: likelihood of the occurrence, and level of negative implications. Recommends that TQM concepts and risk avoidance be used to manage these risks.

models. It provides an understanding of the constituents of risk, creates a risk profile, and uses the risk profile to generate a set of appropriate strategies in the context of global supply chain. In addition, the approach uses a mix of multiple risk assessment tools that consider both the qualitative and quantitative dimensions of risk. Finally, the framework explicitly recognizes the presence of the dynamic environments in which global supply chains operate. Hence, as environments and organizations change, this framework can be used as a guideline to continually update risk management strategies.

The major contributions of each of these research studies are summarized in Table 3.1. In general, this review indicates that after establishing a risk-cause linkage, SC disruption risks can be addressed by focusing on prevention, control, and impact management of SC disruption risks. Given the fact that the recommendations are general (such as creating a flexible SC; enhancing the capacity of SC partners to weather the consequences of these risks; and also identifying key SC players who should be tasked with managing the risks), this leads us to provide a more detailed analysis of the research literature in the next three sections of this monograph. To start with, in the next section, we discuss conceptual/empirical research which describes how SC disruption risks have been prevented/controlled/managed in industry settings.

4

Conceptual/Empirical Research

The primary focus of this section is to examine the perceptions of supply chain managers regarding SC disruption risks and also how such risks should be managed. Obviously all the research reviewed in this section is empirically driven and hence, general guidelines for managing SC risks within each setting are provided.

Peck [32] reports findings of a cross-sector empirical study of the sources and drivers of supply chain vulnerability to provide insight by which to improve the resilience of the supply chain networks in the UK. The core of the research is an in-depth exploratory case study of SC for manufacturing and assembly of high-performance military aircraft. Results of the case study are validated through in-depth interviews with managers representing other critical sectors of the UK economy. The context for the procurement and production of military aircraft represents an extreme risk environment with national security as well as commercial sensitivities, characterized by extreme levels of technological, financial, product safety, and political risk. The major finding of this paper is that there is a remarkable absence of any widespread understanding of the scope of and dynamic nature of the SC vulnerability problem. The methodology employed is to examine this problem

from multiple perspectives and at four discrete levels of analysis as follows:

- Level 1: value stream/product or process. At this level, supply chain vulnerability is examined from the prevailing process engineering-based supply chain management perspective. It is a view that is in keeping with lean manufacturing and demand-driven logistics concepts. The emphasis is on the efficient, value based, design, and management of processes relating to workflows and their accompanying information. The availability of credible and reliable information is, of course, central to this process management perspective.
- Level 2: assets and infrastructure dependencies. The focus at this level is on required assets and infrastructure so as to deliver the goods and provide information flows. The resilience of the network is assessed in terms of the implications of the loss of links, nodes, and other essential operating assets. The choice of transport mode automatically determines immediate transportation asset-related risks such as shortages of heavy goods vehicle drivers in the UK.
- Level 3: organizations and inter-organizational networks. This level views supply chains as inter-organizational networks. It moves supply chain vulnerability up to the level of corporate risk management, business strategy, and microeconomics.
- Level 4: the environment. The fourth and final level is the wider macroeconomic and natural environment within which organizations do business, assets and infrastructure are positioned and value streams flow. Factors for consideration are the political, economic, social, and technological elements of the operating environment as well as geological, meteorological, and pathological factors.

The key findings are that a resilient network involves much more than the design and management of robust supply chain processes. Supply chains are inter-organizational networks, embedded within an environment characterized by many uncontrollable forces, and so managerial

control is limited and complex. Besides, supply chain vulnerability and resilience is wider in scope than integrated supply chain management, business continuity planning, commercial corporate risk management or an amalgamation of all of these disciplines. Further, given that political and public policy dimensions, it would seem that slack in the system, whether in the form of inventory, capacity, capability, and even time, and constant awareness and vigilance are needed if supply chains are to become and remain truly resilient.

Blackhurst et al. [4] note that supply networks are inherently vulnerable to disruptions and the failure of any network segment causes the whole network to fail. In addition, three inter-related trends and characteristics of current supply chain practices (increased global sourcing, integrated responsiveness, and low inventory/higher agility focus) increase the potential negative impact of a disruption. The focus of this research is to understand three critical aspects (disruption discovery, disruption recovery, and SC redesign) relative to the analysis and mitigation of the detrimental impact of supply chain disruptions in a global environment. Using a cross-sectional empirical study, the authors attempt to understand the current industrial focus on disruption management strategies. The key findings are that: (a) to facilitate the discovery process, the organization needs to focus on enhancing visibility across the SC, build adequate slack capacity (supply, operations, channel, and transportation) into the SC, and also develop rigorous predictive tools to more accurately forecast certain types of disruptions; (b) to quicken the recovery process, there should be real-time response and damage control systems in place; and (c) to enable SC redesign, tools for understanding design trade-offs and models for SC redesign should be readily available.

Over the last decade, increased competitive pressure and crises and catastrophes (such as 9-11 and hurricane Katrina) have revealed the vulnerability in SCs in all industries. It is also recognized that there are costs associated with SC risk management and hence, firms need to have information of probability of occurrence of SC disruptions and their potential impact on performance. Wagner and Bode [48] report the results of an empirically derived operationalization of supply chain risk sources and analyze the risk associated with these sources. In

generic terms, SC risk is defined as the deviation from the expected value of a certain performance measure, resulting in undesirable consequences for the focal firm and is thus equated with the damage or loss resulting from a supply chain disruption. The specific hypotheses tested are that supply chain performance declines with: (a) higher demand side risk; (b) higher supply risk; (c) higher regulatory, legal, and bureaucratic risks; and (d) higher risks associated with catastrophes. Using multiple item measurements of each construct and a sample of 760 top-level logistics and supply chain management executives of German firms, the results indicate that supply chain risks only partially explain the variance in supply chain performance and there is no significant relationship between regulatory, legal and bureaucratic risks, infrastructure risks, and catastrophic risks and supply chain performance. On the other hand, the findings support the hypothesis that there are negative associations between supply- and demand-side risks and supply chain performance and these risk sources are relevant contextual variables in strategic supply chain decisions.

The major contributions of each of these studies are summarized in Table 4.1. The usefulness of this research efforts is that industry case

Table 4.1. Conceptual/Empirical Research — A Summary.

Reference	Contribution/Focus
Peck (2005) [32]	Exploratory case study of one SC for a firm manufacturing military aircraft in the UK. Focus on the SC vulnerability problem at four levels: product/process; assets/infrastructure; organization/inter-organization network; and environment. Finds are that resiliency in a network requires a focus on building slack at all levels.
Blackhurst et al. (2005) [4]	Empirically examine issues related to disruption discovery, disruption recovery, and SC redesign. Key findings are that increased SC visibility, building in more slack capacity, designing real-time response and damage control systems, and availability of tools/models for SC design enhances the ability of firms to deal with disruptions.
Wagner and Bode (2008) [48]	Analyzes sources of SC risks and how these impact SC performance. Using a cross-sectional empirical study of a large number of German firms, he finds that higher supply and demand side risks negatively impact SC performance. On the other hand, there is no significant impact of regulatory and catastrophic risks on SC performance.

studies and empirical evidence points to the fact that visibility, slack capacity, real-time damage control systems, and SC redesign tools are all key for preventing, managing, and recovering from disruptions; and supply and demand risks are explicitly related to SC performance. In the next section, our focus now turns to reviewing prior research on how robust SCs can be designed to mitigate the impact of potential future disruptions.

5

Robust SC Design Research

The research reviewed in this section primarily focuses on how SC networks should be designed to mitigate potential future risks stemming from disruptions. In certain cases, the risks considered are quite general (i.e., a disruption at any node in the SC network), while in other cases, the risks relate to specific occurrences (such as supplier performance in terms of delivering the required quantities of a product/component).

Vidal and Goetschalckx [47] start by noting that although SCs are global, there is no generally accepted method by managers and researchers for designing a global SC. At the international level, exchange rates, duties, transfer prices, taxes, cash flow, information flow, trade barriers, and government regulations constitute complicating factors in GLS modeling along with traditional engineering factors such as cost, capacity, and timeliness. More specifically for the firm operating the SC, factors critical in configuring a global SC include labor costs, transportation costs, infrastructure, proximity to markets, trade and investment patterns, cash flow considerations, taxes and duties, and possibility of joint ventures. However, the uncertainty inherent in all these aspects have made it difficult to formulate a

comprehensive global SC optimization approach. On the other hand, the author makes a strong case for applying mathematical programming (MP) techniques, especially mixed integer programming (MIP) models and their solution algorithms which can yield interesting insights into the design of global SC. To start with, the implementation of the configurations generated by the optimization models and the management of supply chain provide feedback to allow further refinements of the models, and conducting multiple sensitivity runs allows managers to analyze the effect of uncertainties on the system. In this context, fine-tuning is a fundamental issue, since relatively small variations in some parameters can produce important differences in logistics cost. Another key aspect is to focus on the model-building process which requires analysts to identify the most significant factors to include in the model. For example, factors critical in configuring a global supply chain system include labor costs, transportation costs, infrastructure, proximity to markets, trade and investment patterns, cash flow considerations, taxes and duties, and possibility of joint ventures. Relating to these aspects, the need for reliable and accurate supporting data is a critical dimension. Finally, since uncertainty due to disruption risks is inherent in a global SC, the model should be developed so that it can provide insights into global SC structures which are more capable of handling these risks.

An example of reliability constraints which can be incorporated into mathematical formulations according to [47] are as follows. In order to respond to the variability in supplier performance, companies use safety lead time and safety stocks of raw materials, especially for materials whose shortage may have a significant effect on the production process. Even when a safety lead time for a supplier has been established, shipments may be tardy and thus, one way to consider supplier reliability is to use historical data to estimate the probability that a supplier will send timely and accurate shipments. If suppliers are independent of one another, the following constraint could be enforced:

$$\prod_{i \in SC(p)} \prod_{r \in R(i) \cap R(p) \cap RC} PR_{ir}^{V_{ijr}} \geq PROB_{jp}, \quad j \in M, p \in P(j) \cap PCR, \quad (5.1)$$

where

- M = set of manufacturing plants;
- $P(j)$ = set of finished products that can be produced in manufacturing plant $j \in M$;
- PCR = set of finished products that need at least one critical raw material;
- $R(i)$ = set of raw materials that can be supplied by supplier $i \in S$;
- $R(p)$ = set of raw materials used by product p ;
- RC = set of critical raw materials;
- S = set of suppliers;
- $SC(p)$ = set of suppliers that can supply at least one critical raw material; to make product $p \in PCR$;
- PR_{ir} = probability of supplier $i \in S$ for shipping critical raw material $r \in R(i)$ on time;
- $PROB_{jp}$ = target probability to achieve at plant $j \in M$ for having critical raw materials to make product $p \in P(j) \cap PCR$ on time; and
- $V_{ijr} = 1$, if supplier $i \in S$ ships critical raw material $r \in R(i)$ to plant $j \in M$; 0 otherwise.

The above constraints ensure that the probability of being on time of all suppliers shipping critical raw materials to each plant and for each product using at least one critical raw material is at least specified target value. In order to facilitate tractability, a suggested linearization of these constraints is as follows:

$$\sum_{i \in SC(p)} \sum_{r \in R(i) \cap R(p) \cap RC} v_{ijr} \log(PR_{ir}) \geq \log(PROB_{jp}), \quad j \in M, \quad p \in P(j) \cap PCR. \quad (5.2)$$

Gaonkar and Vishwanadhan [14] examine the impact of product exceptions (stemming from supplier quantity shortages) on SC performance. SC networks are subject to risks stemming from focused factories and centralized distribution (which reduces operations flexibility), increasing uses of outsourcing (which force a focus on more partners), reduction of the supplier base (loss in sourcing flexibility), and volatility of demand. In this context, management of exceptions due to disruptions due to changes in quality, quantity, lead time (operations and

logistics), natural disasters, and terrorist incidents is critical. In general, exception management requires monitoring of the global supply chain process for exceptions, evaluating their consequences in terms of production and shipments and suggesting actions to the stakeholders to minimize the total cost of disruption. There are two approaches to manage exceptions: preventive and interceptive. The preventive route to exception management seeks to reduce the likelihood of occurrence of an exception through the design of a robust chain. The interceptive approach on the other hand attempts to contain the loss by active intervention once the exception occurs. In both cases it is necessary to identify the exceptions that can occur in the chain, estimate the probabilities of their occurrence, map out the chain of immediate and delayed consequential events that propagate through the chain and quantify their impact. This paper addresses exception management at the strategic level through the preventive selection of supply chain partners that mitigate risk in the network. Initially, all the critical undesirable events that can occur at various stakeholders and their interfaces are identified and how each of them propagates through the supply chain is mapped out. In this way, critical exceptions for all SC partners are identified and the impact of these exceptions on suppliers is assessed. A mixed integer programming model for partner selection that minimizes the overall impact on the supply shortfall resulting from supplier non-conformance is proposed. The model is an adaptation of the credit risk minimization model employed in financial portfolio management. Given the expected probabilities for various exception scenarios and the supply shortfalls under each of these scenarios the objective for the manufacturer is to choose a set of suppliers that minimize the expected shortfall during the operation of the supply chain. A brief overview of this model is as follows.

Indices

- $i \in I$: Supplier index.
- $k \in K$: Scenario (state) index. K is the set of all supply scenarios (states), which is obtained as a mix of all combinations of supplier non-performance events for all the suppliers in the set I .

Parameters

- p_k : per unit penalty cost associated with scenario k .
- K : Quantity required by the manufacturer.
- x_i : Quantity supplied by supplier i .
- R_i : Relation cost of including supplier i into the supply chain.
- C_i : Capacity of supplier i .

Variables

- F_i : 0 if supplier i is not selected and 1, if selected.
- y_k : Shortfall in total supply to manufacturer in scenario k .

Based on this, the model is as follows:

$$\text{Minimize } Z = \sum_{k=1}^K p_k y_k + \sum_{i=1}^I R_i F_i \quad (5.3)$$

subject to:

$$K - \sum_{i=1}^I x_i = y_k \quad \forall k \in K \quad (5.4)$$

$$x_i = F_i \times C_i \quad \forall i \in I. \quad (5.5)$$

The objective of the model is to choose suppliers such that the expected shortfall in supply, in the face of supplier disruptions, is minimized. The first constraint determines the supply shortfall for each possible supply scenario while the second constraint enforces the quantity/supplier capacity relationship.

Bundshcuh et al. [6] propose models for robust and reliable SC design with long-term contracting. Their basic premise is that while reliable SCs are less likely to be disrupted, robust SCs would be able to perform well even when supply channels are disrupted. A brief overview of their base model is as follows. Given a set of possible suppliers, the task is to design an inbound supply chain for a manufacturer, leveraging reliability, robustness, and cost. Let N be the set of all suppliers, which for ease of notation includes the single manufacturer. N is partitioned in k stages, S_i , $i \in \{1, \dots, k\}$. A stage consists of all possible suppliers for a specific product, required as a component for the manufactured

product on the succeeding stage. The supply chain design problem is represented as a network where the nodes correspond to the N suppliers. Let $n \in N$ represent the final manufacturer node, which by definition is on stage S_k and an arc $e = (u, v)$ corresponds to a feasible supply channel from supplier u to customer v . A is the set of all arcs and let I_v/O_v denote all incoming/outgoing arcs of node v . Component manufacturers, which consist of nodes on intermediate stages S_i , $i \in \{2, \dots, k-1\}$, are simultaneously suppliers and customers. Thus, a node $u \in S_i, i \in \{1, \dots, k-1\}$ is connected to the nodes on the succeeding stage S_{i+1} . By definition, $O_n = \emptyset$ and $I_v = \emptyset$ for all $v \in S_1$.

The base model is a deterministic mixed integer programming model. It has two types of decision variables. For every arc $e \in A$, the binary variable Y_e is 1 if this link is used in the supply chain and 0 if it is inactive. The continuous variable X_e represents the amount of units flowing along arc e . A flow $X_e > 0$ can only be assigned to an arc if it is active, i.e., $Y_e = 1$. With every arch $e \in A$, a unit cost for production cp_e , a unit cost for transportation ct_e , and fixed costs for an open supply channel f_e are associated. The objective function of the base model is to minimize the total production, transportation, and fixed costs, given by:

$$\sum_{e \in A} [(cp_e + ct_e)X_e + f_e Y_e]. \quad (5.6)$$

For every $v \in \bigcup_{i=2}^k S_i$ let α_v be the bill-of-materials parameter that expresses how many input units are required for the production of one output unit. The sum of the incoming material flows to the final manufacturer node must equal the aggregated demand D , multiplied by the bill-of-materials parameter, which is expressed as $\sum_{e \in I_n} X_e = \alpha_n D$. Nodes on intermediate stages S_i , $i \in 2, \dots, k-1$ are technically transshipment nodes for which the total flow into this node has to equal the total flow out. The supply inputs to these nodes are transformed into component flows to the next stage, considering the bill-of-materials relationship. The following flow balancing constraints:

$$\sum_{e \in I_v} X_e = \alpha_v \sum_{e \in O_v} X_e \forall v \in \bigcup_{i=2}^{k-1} S_i \quad (5.7)$$

guarantee that there are no additional sources than those on the first stage and no additional sinks except the end manufacturer node. Each supplier v has a production capacity limit m_v that must not be exceeded:

$$\sum_{v \in O_v} X_e \leq m_v \forall v \in N/\{n\}. \quad (5.8)$$

With every arc e , a minimum flow q_e is associated. This represents minimum order quantities demanded by the suppliers and prevents unreasonably low flows.

$$q_e Y_e \leq X_e \forall e \in A. \quad (5.9)$$

The following constraints guarantee that flows can only be assigned to active arcs:

$$X_e \leq M Y_e \forall e \in A. \quad (5.10)$$

In these inequalities, M is an auxiliary parameter representing a large enough number. As is obvious, in this formulation, the major focus is of an inbound SC. This based model is modified to embed aspects of reliability and robustness within the traditional model. Reliability is captured through constraints that enforce a minimum desired reliability level while robustness aspects are captured through several features: (a) restricting the maximum amount that can be sourced from a supplier to force multiple supplier selection; and (b) maintaining a contingency (safety) stock at each stage. The combined reliability and robustness model incorporates the individual aspects of each feature and also an aggregate service level feature for the entire SC. Through extensive numerical experiments, the authors are able to document trade-offs between several alternative SC design structures. For example, as compared to the base model, the combined model identifies SC designs which are more reliable and robust. However, the increased reliability and robustness of these SC networks is only achievable at significantly larger costs as compared to the base model. For specific numerical parameters, the authors also show that high levels of reliability/robustness are correlated to steep cost increases.

Kouvelis and Su [24] start by formulating a comprehensive mathematical programming model for designing a new global SC network. Their approach focuses on two facility levels (plants and distribution centers) operated by a single firm. Using a finite planning horizon, they formulate a model which integrates market demands, prices (selling and transfer), variable production costs, tax rates, interest rates, plan capacities, discount rates, fixed costs, and investments costs. Their objective is to maximize the net present value of the firm profits subject to the typical constraints related to meeting demand and not exceeding capacity. One unique feature incorporated is that of a loan ceiling constraint within each country. Their key findings based on two case study applications of their models are that transportation costs, demands variability, and correlations, all play a role in defining the optimal robust SC design. A detailed formulation of their comprehensive model is provided in the Appendix. This initial formulation is then modified to account for SC risks by incorporating a macro-economic perspective (i.e., risks stem from exchange rates and/or inflation) where a robust SC design is considered feasible, provided it meets a specified percentage deviation from the model solution which does not incorporate the risk. An example formulation in this context is as follows. Consider the following variant of the uncapacitated plant location problem with a profit maximization objective. In the absence of uncertainty, the problem can be formulated as:

$$\text{Maximize } Z = \sum_i \sum_j (P_j - c_{ij})X_{ij} - \sum_i F_i Y_i \quad (5.11)$$

subject to:

$$0 \leq X_{ij} \leq Y_i D_j \quad \forall i, j \quad (5.12)$$

$$Y_i \in \{0, 1\} \quad \forall i \quad (5.13)$$

$$\sum_i X_{ij} \leq D_j \quad \forall j, \quad (5.14)$$

where

- P_j = the market price for output in market j ;
- X_{ij} = the quantity shipped from plant i to market j ;

c_{ij} = the unit cost of supplying market j from plant i ;
 D_j = the target demand in the j -th market;
 Y_i = a zero-one variable to indicate whether plant i is open; and
 F_i = the fixed cost of opening the i -th plant.

Using the mean — variance approach in the form of $Z = E(R) - \lambda Var(R)$, one way to incorporate risk aversion in facility location decisions in the absence of the capacity constraints is as follows:

$$\begin{aligned}
 \text{Maximize } Z = E \left[\sum_i \sum_j (P_j - c_{ij}) X_{ij} - \sum_i F_i Y_i \right] \\
 - \lambda Var \left[\sum_i \sum_j (P_j - c_{ij}) X_{ij} - \sum_i F_i Y_i \right] \quad (5.15)
 \end{aligned}$$

subject to the same constraints above.

A comprehensive review of models for robust SC network design is that of Snyder and Daskin [38] and Snyder et al. [39]. Both these contributions provide key insights not only in the context of currently available mathematical programming based approaches for robust SC network design but also in terms of how to implement these approaches to optimize a number of alternative disruption risk measurements. To start with, robust SC network models are classified as those which focus on designing a new network or “fortify” an existing network. By focusing on two classes of models: facility location and network design which can be used either context, they also describe how alternative risk assessment measures can be embedded in each approach. A brief overview of the model in [39] is as follows. Let S be a set of scenarios, each of which specifies the failure state of all facilities in J . Let A_s be the set of facilities that fails in scenario s . Define $a_{js} = 1$ if facility j fails in scenario s and 0 otherwise and assume that scenario s occurs with probability q_s . These scenarios may have been identified a priori by managers as likely possibilities that are worth planning against. Alternatively, they may represent all possible combinations of facility failures. For example, if each facility j fails with probability p_j and

failures are independent, then scenario q_s can be determined as follows:

$$q_s = \prod_{j \in A_s} p_j \prod_{j \in J/A_s} (1 - p_j). \quad (5.16)$$

To model the emergency facility, it is required that $a_{us} = 0$ for all s , or equivalently $q_s = 0$ if $a_{us} = 1$, where u denotes a dummy emergency facility. The scenario probability q_s is interpreted as the long-run fraction of time that the precise set of facilities A_s is disrupted. Put another way, the fraction of time in which facility j is disrupted is given by $p_j = \sum_{s \in S: j \in A_s} q_s$.

The base model is developed with the objective of minimizing the expected cost and the scenario-based formulation of the reliability fixed charge location problem (RFLP1) is as follows:

$$\text{Minimize } Z = \sum_{j \in J} f_j X_j + \sum_{s \in S} \sum_{i \in I} \sum_{j \in J} q_s h_i d_{ij} Y_{ijs} \quad (5.17)$$

subject to:

$$\sum_{j \in J} Y_{ijs} = 1 \quad \forall i \in I, \quad s \in S \quad (5.18)$$

$$Y_{ijs} \leq (1 - a_{js}) X_j \quad \forall i \in I, \quad j \in J, \quad s \in S \quad (5.19)$$

$$X_j \in \{0, 1\} \quad \forall j \in J \quad (5.20)$$

$$Y_{ijs} \geq 0 \quad \forall i \in I, \quad j \in J, \quad s \in S, \quad (5.21)$$

where

- f_j : annual fixed cost of operating facility j ;
- h_i : annual demand for customer i ;
- d_{ij} : per unit transportation cost to customer i from facility j ; and
- X_j : is 1 if we open a facility j , and 0 otherwise.

The objective function minimizes the fixed cost plus the expected transportation cost across all scenarios. The first set of constraints requires each customer to be assigned to some facility in every scenario while the second set prohibits a customer from being assigned to a facility

that has not been opened, or to a facility that has failed in a given scenario. The third and fourth sets enforce the technological constraints on the decision variables.

The base model formulation above assumes that facilities have infinite capacity or that they can serve any number of demands. In many cases, this might not be true. Define k_{js} to be the capacity of a facility at candidate site j in scenario s . This notation and the following formulation allow a facility to incur impaired capacity in a scenario without completely failing. Let the capacity of the dummy facility u be $k_{us} = \infty$ for all scenarios s , indicating that this facility can accommodate all demands if necessary in each scenario. With this notation, replace the second constraint by its more traditional version

$$Y_{ijs} \leq X_j \forall i \in I, j \in J, s \in S \quad (5.22)$$

and add the following capacity constraint, where the demand placed on a facility's capacity is measured in terms of the demand units h_i

$$\sum_{i \in I} h_i Y_{ijs} \leq k_{js} X_j \forall j \in J, s \in S \quad (5.23)$$

An alternative formulation of the RFLP in which the random disruptions are modeled implicitly is as follows. This formulation requires the assumption that the facilities are divided into two sets; the facilities in the first set never fail, while all of the facilities in the second set fail independently with the same probability q . The first set is called non-failable (NF) while the second set is called failable (F). Since the emergency facility never fails, note that $u \in NF$ and that F and NF constitute a partition of J . In this implicit formulation, assignments are made based on levels and not scenarios. In particular, an assignment of customer i to facility j is said to be a level- r assignment if there are r open, failable facilities that are closer to i than j is. If $r = 0$, then j is i 's primary facility — the facility that serves it under normal circumstances — while if $r > 0$, j is a backup facility. A given customer must be assigned to some facility at every level- r from 0 to the number of open facilities, unless it is assigned to some non-failable facility at level $s < r$. Define $Y_{ijr} = 1$ if customer i is assigned to facility j as level- r

assignment.

$$\begin{aligned} \text{Minimize } Z = & \sum_{j \in J} f_j X_j + \sum_{i \in I} \sum_{r=0}^{|J|-1} h_i d_{ij} \left[\sum_{j \in NF} q^r Y_{ijr} \right. \\ & \left. + \sum_{j \in F} q^r (1 - q) Y_{ijr} \right] \end{aligned} \quad (5.24)$$

subject to:

$$\sum_{j \in J} Y_{ijr} + \sum_{j \in NF} \sum_{s=0}^{r-1} Y_{ijs} = 1 \quad \forall i \in I, r = 0, \dots, |J| - 1, \quad (5.25)$$

$$Y_{ijr} \leq X_j \quad \forall i \in I, j \in J, r = 0, \dots, |J| - 1, \quad (5.26)$$

Table 5.1. Research on Robust SC Design.

Reference	Contribution/Focus
Vidal and Goetschalckx (2000) [47]	There is a lack of models for designing global SC. Identifies key parameters of interest to integrate in a model for global SC design. Notes that issues related to data integrity, measuring, and integrating risk measures in the models, and the potential to generate alternative SC designs to handle different disruption risks are key in developing these models.
Gaonkar and Vishwanadham (2003) [14]	How does an SC handle product exceptions? An exception is any disruption caused by quality defects, quantity shortages and/or lead time increases, natural disasters, and/or terrorist incidents. Proposes a mixed integer programming model for partner/supplier selection which minimizes shortfalls due to disruptions. Usefulness of the model is that it can be used to identify partners/suppliers selected in order to minimize expected shortfalls.
Bundschuh et al. (2003) [6]	Propose models for robust and reliable SC design. Models integrate aspects of reliability, robustness, and aggregate service levels for SC networks. Numerical experiments identify trade-offs between alternative SC designs.
Kouvelis and Su (2005) [24]	Formulate a comprehensive multi-country, multi-plant, multi-market finite horizon mathematical programming model for SC design. Propose an adaptation of the model to handle macro-economic risks such that a solution will be well within a prespecified limit. On applying the model to two example applications, they find that the key parameters driving the global SC design are transportation costs, and demand variability.
Snyder et al. (2006) [39]	Provide an overview of available design models which can be used to identify robust SC designs. Identify alternative measures of risk and how these can be incorporated in these models to generate multiple SC structures. Through numerical examples, they should how a firm can use these models to generate designs that are more robust in handling disruptions.

$$\sum_{r=0}^{|J|-1} Y_{ijr} \leq 1 \quad \forall i \in I, j \in J, \quad (5.27)$$

$$X_j \in \{0,1\} \quad \forall j \in J, \quad (5.28)$$

$$Y_{ijr} \geq 0 \quad \forall i \in I, j \in J, r = 0, \dots, |J| - 1. \quad (5.29)$$

The key contributions of this work are that the authors provide tractable formulations to identify robust SC designs; using illustrative examples, they also reinforce the fact that using a priori consideration of risk measurements, alternative SC structures which are disruption “proof” can be identified; and provide explicit operationalizations of alternative risk measures to capture the impact of disruptions.

Table 5.1 summarizes this literature on robust SC network design. Although, several models to design robust SC have been developed, the problem of identifying SC disruption risks, and also defining and measuring them is obviously in its infancy. Further, the approaches reviewed in this section focus more on strategic/tactical issues related to design of the SC network. Given that there is also a stream of work which analyzes specific SC disruptions and the corresponding response mechanisms, in the next section we review these research contributions.

6

Research on Specific Disruption Risks

In order to organize the substantial volume of literature related to specific SC disruption risks, the contributions are categorized as those focusing on managing disruption risks due to: product-related uncertainties; supply uncertainties; operations/process uncertainties; and transportation network uncertainties. Finally, we also review some additional research contributions which do not fit into any one of these categories.

6.1 Product Uncertainties

Lee [25] starts by recognizing that developments in technology present significant opportunities for cost reduction and service improvements in an SC since they provide the ability to reduce response times, connect supply chain segments in real time, and align SC strategies to deal with product demand and supply uncertainties. Based on this, the “right” SC strategy depends upon the specific needs of targeted customers, and demand and supply characteristics of corresponding products. For that reason, it is necessary to understand the sources of underlying uncertainties of products before setting up a supply chain strategy. The proposed approach to characterize a product is the “uncertainty

framework”, which specifies the two key uncertainties faced by the products, namely demand and supply uncertainties. Demand uncertainty is about the predictability of the demand for the product. Functional products have long product life cycles and low product variety, while innovative products have short selling season and high product variety. Therefore, functional products and innovative products tend to have low and high demand uncertainties, respectively. Supply uncertainty revolves around the supply side of the product and can be divided into two processes: stable and evolving. In a stable supply process, the underlying technology is mature, highly automated and manufacturing complexity tends to be low or manageable. On the other hand, in an evolving supply process, the underlying technology is under early development, requires a lot of fine-tuning and is vulnerable to breakdowns and uncertain yields. On the basis of this uncertainty framework, it is hypothesized that supply chain performance can be improved through a reduction in both demand and supply uncertainty. Information sharing, tight coordination, and synchronized planning across the supply chain play a crucial role in controlling supply chain efficiency through a reduction in demand uncertainty. In order to reduce supply uncertainty, free exchanges of information from product development stage up to end-of-life phases of the product life cycle, and early design collaboration are highly effective tools.

Tomlin and Wang [46] start by observing that resource flexibility strategies offer demand pooling and contribution margin benefits that are advantageous in the presence of demand uncertainty, while dual sourcing networks offer diversification benefits that are advantageous in the presence of unreliable resource investments. Current research appears to have examined the impact of each of these strategies in isolation, i.e., the mix flexibility literature has assumed perfectly reliable supply; and the dual sourcing literature has focused on single product analysis. This paper bridges the mix flexibility and dual sourcing literatures by studying unreliable supply chains that produce multiple products on the basis of four canonical network structures: single-source dedicated (SD), single-source flexible (SF), dual-source dedicated (DD), and dual-source flexible (DF). In this model, product demands are uncertain at the time of resource investment, and the

products can differ in their contribution margins. Besides, resource investments can fail, and the firm may choose to invest in multiple resources for a given product to mitigate such failures. The general model which can be used to identify each of the supply networks (SD, SF, DD, and DF) as instances is developed as follows. There are N products $n = 1, \dots, N$ and the marginal contribution margin for product n is p_n (where $p_1 \geq p_2 \geq \dots \geq p_N$). Let $\mathbf{p} = (p_1, \dots, p_N)$ and all vectors are assumed to be column vectors, and denotes the transpose operator. The firm can invest in nonnegative levels (K_j) of J different resources labeled $j = 1, \dots, J$. Let \mathbf{T} be the $N \times J$ technology matrix with $t_{nj} = 1$, indicating that resource j can produce product n . Demand $\tilde{\mathbf{X}} = (\tilde{X}_1, \dots, \tilde{X}_N)$ is uncertain, with a joint density $f_X(x_1, \dots, c_N)$ at the time of the investment decision. The demand-correlation matrix is denoted \mathbf{p}_x with element \mathbf{p}_{mn} being the correlation coefficient for products m and n . The marginal density for \tilde{X}_n is $f_{X_n}(x_n)$ and the cumulative distribution function is $F_{X_n}[x_n]$. Realizations of demand are denoted $x = (x_1, \dots, x_N)$. Resource investments are unreliable and the realized level \tilde{K}'_j for resource j is stochastically proportional to the invested level K_j , i.e., $\tilde{K}'_j = \tilde{Y}_j K_j$. In particular, a Bernoulli yield model is assumed in which $\tilde{Y}_j = 1$ with probability θ_j and $\tilde{Y}_j = 0$ with probability $1 - \theta_j$ where θ_j is the reliability of resource j (the \tilde{Y}_j are assumed to be independent). Let $\tilde{Y} = (\tilde{Y}_1, \dots, \tilde{Y}_J)$ and let a realization be denoted by $\mathbf{y} = (y_1, \dots, y_J)$.

The firm's investment problem can be formulated as a two-stage stochastic program. In the second stage, after demands and investments have been realized, the firm allocates production to maximize the contribution by solving:

$$r(\mathbf{K}, \mathbf{x}, \mathbf{y}) = \max_{s_n, q_{nj} \geq 0} \mathbf{p}'\mathbf{s} \quad (6.1)$$

$$\text{subject to } s_n \leq x_n \quad n = 1, \dots, N, \quad (6.2)$$

$$s_n \leq \sum_{j=1}^J t_{nj} q_{nj} \quad n = 1, \dots, N \quad (6.3)$$

$$\sum_{n=1}^N q_{nj} \leq y_j K_j \quad j = 1, \dots, J, \quad (6.4)$$

$$(6.5)$$

where q_{nj} denotes the production of product n by resource j , $\mathbf{s} = (s_1, \dots, s_N)$ denotes the sales of products $1, \dots, N$. The first constraint ensures that sales do not exceed realized demand; the second constraint ensures that sales do not exceed production; and the last constraint ensures that resource usage does not exceed the realized level. Let w_0 be the firm's initial wealth and let $\tilde{W}(\mathbf{K})$ be the random gain or loss achieved by investment \mathbf{K} . The firm's realized profit on investment \mathbf{K} is given by $w(\mathbf{K}) = -\mathbf{c}(\mathbf{y})'\mathbf{K} + r(\mathbf{K}, \mathbf{x}, \mathbf{y})$. The firm's random terminal wealth is then $w_0 + \tilde{W}(\mathbf{K})$. In the first stage, before demands and yields are realized, the firm chooses a nonnegative investment vector $\mathbf{K} = (K_1, \dots, K_J)$ to maximize some objective function $V(\mathbf{K})$ where $V(\mathbf{K})$ depends on the firm's terminal wealth. Three different types of firms: a risk-neutral firm, a loss-averse firm, and a firm concerned about downside risk, each represented by a distinct form of the objective function and corresponding decisions are analyzed.

The key insights stemming from the analysis are as follows. In comparing SD and SF networks, the critical roles of risk tolerance and resource reliabilities in the relative attractiveness of the two networks are identified. The prevailing intuition; an SF-type network is strictly preferred to an SD-type network when the dedicated resources are costlier than the flexible resource, is refined in this paper, and it is proved to be valid if either the resource investments are perfectly reliable or the firm is risk neutral. However, this intuition can be wrong if both of these conditions fail to hold, because there is a resource aggregation disadvantage to the flexible strategy that can dominate the demand pooling and contribution margin benefits of the flexible strategy when resource investments are unreliable and the firm is risk averse. Regarding the DD and DF networks, analytical results are provided for the influence of prices, marginal costs, and reliabilities on the optimal expected profit and resource levels for both networks. Contrary to DD networks, optimal dedicated resource levels in the DF networks are dependent on resources that are dedicated to other products. Based on a comprehensive numerical study (to investigate how the attributes of three key supply chain element: product portfolio, resources, and the firm, influence the attractiveness of various supply chain structures that differ in their levels of mix flexibility and diversification),

additional results are that appropriate levels of diversification and flexibility are very sensitive to the resource costs and reliabilities, the firm's downside risk tolerance, the number of products, the product demand correlations, and the spread in product contribution margins.

In a later paper, Tomlin [43] analyzes disruption management strategies for short life-cycle products. This paper investigates supply-side and demand-side disruption management tactics in the context of a firm that sells multiple products with short life cycles and long lead times. The relevant operational tactics for firms operating in such an environment are demand switching, contingent sourcing, and supplier diversification. Under demand switching, the firm provides incentives for a customer to purchase a different product when her/his preferred product is unavailable; contingent sourcing is where the firm turns to a backup supplier in the event of a failure at its normal supplier; and supplier diversification refers to a firm routinely sourcing from multiple suppliers. In designing a disruption management strategy, a firm may employ any combination of these three options and the choice is a function of the nature of the suppliers, the products, and the firm. Related to this point, supplier reliability, correlation between supplier failures, proportion of order cost charged in the event of failure, contribution margins, demand uncertainties, demand correlation, substitutability, and decision maker's risk aversion can be listed as potential drivers of a firm's disruption management strategy. The most effective strategy presumably depends on supplier reliability and cost characteristics, while the decision maker's risk tolerance also has some bearing on the firm's strategy. In this framework, the paper considers a firm that sells two products in a single season, and all sourcing and switching quantity decisions are made with the objective of maximizing expected utility. Therefore, both supply- and demand-side operational tactics are considered in the context of a two-product newsvendor model. There are two models formulated: for a risk-neutral buyer and a risk-averse buyer. Each of these models in the context of a single product is as follows. For the risk-neutral buyer, the expected profit $\pi_A(Q)$ as a function of the order size Q is given by:

$$\pi_A(Q) = -c(\lambda + [1 - \lambda]\gamma)Q + \gamma p E_X[\min\{X, Q\}], \quad (6.6)$$

where p is the marginal contribution margin for product, X is uncertain demand, γ is the overall probability of a supplier succeeding, c is the marginal total cost, and λ is the marginal committed cost. A refers to “acceptance” because this strategy accepts the disruption risk. Let Q_A^* and π_A^* denote the firm’s optimal order quantity and resulting expected profit. Then:

$$Q_A^* = F^{-1} \left(1 - \frac{c(\lambda + [1 - \lambda]\gamma)}{p\gamma} \right); \text{ and} \quad (6.7)$$

$$\pi_A^* = \gamma p \int_0^{Q_A^*} x f(x) dx. \quad (6.8)$$

The author then considers single sourcing with a contingent supplier (CONT). In CONT, the firm can place an order with a contingent supplier after it realizes the success or failure of the original order but before demand uncertainty is realized. Let z denote the realized inventory in epoch 2, i.e., the time at which the contingent order must be placed. In epoch 2, the firm chooses an order quantity $K(z)$ to maximize its expected future profit, which is given by $\pi_2(K) = pE_X[\min\{X, K + z\}] - c_e K$. This is a straightforward newsvendor problem and the optimal contingent order is given by $K^*(z) = \max\{K_{RN}^C - z, 0\}$, where $K_{RN}^C = F^{-1}(1 - \frac{c_e}{p})$ is the (risk neutral) contingent newsvendor quantity. Let $\pi_2^*(z)$ denote the optimal epoch-2 expected profit as a function of the realized inventory z . Then, $\pi_2^* = p \int_0^{K_{RN}^C} x f(x) dx + c_e z$ if $z < K_{RN}^C$, and $\pi_2^* = pE_X[\{X, z\}]$ otherwise. Then the optimal epoch-1 order quantity can be determined and the firm’s expected profit $\pi_X(Q)$ as a function of the order size Q is given by:

$$\pi_C(Q) = -c(\lambda + [1 - \lambda]\gamma)Q + (1 - \gamma)\pi_2^*(0) + \gamma\pi_2^*(Q). \quad (6.9)$$

For the risk-averse case, the firm’s expected utility $U_A(Q)$ as a function of the order size Q is given by:

$$U_A(Q) = (1 - \gamma)u(-\lambda cQ) + \gamma E_X[u(-cQ + p \min\{X, Q\})], \quad (6.10)$$

where for a given risk aversion coefficient $K \geq 1$, $u(W) = KW$ when $W < 0$ and $u(W) = W$ when $W > 0$.

An analysis of the models provides the following key results. For typical supplier reliabilities there is limited value for a risk-neutral decision maker in implementing a disruption management strategy since

the focus for such a decision maker is on maximizing expected profits without any explicit consideration of the variability inherent in supplier reliabilities. On the other hand, for firms with risk-averse decision makers, the implementation of some form of disruption-management strategy has substantial value even if reliabilities are high. Besides, for these firms demand switching tactic is less valuable than one for firms with risk-neutral decision makers. This is because although demand switching is effective at managing demand risk, it is not as effective as dual sourcing and contingent sourcing at mitigating supply-related losses. Contingent sourcing is preferred over dual sourcing, and dual sourcing is preferred over demand switching when risk aversion is increased even if the demand risk is high and supply risk is low. Lastly, a two-tactic strategy provides almost the same benefit as a three-tactic strategy for most reasonable supply and demand risk combinations.

6.2 Supply Uncertainties

In examining research addressing how supply uncertainties stemming from disruptions can be analyzed within an SC, it is important to note that a stream of literature on random yields in manufacturing is also of relevance. Essentially, this literature examines how to manage stages of a manufacturing process subject to random yield. It is obvious that quantity disruptions from a supplier create uncertain yields for the buyer in an SC. Rather than provide a review of the complete stream of literature on random yields, the reader is referred to Yano and Lee [52]. In the context of supplier quantity disruptions, there is also an existing stream of research addressing the supplier sourcing problem. The similarity in that stream of research is that it examines how supplier sourcing strategies can be used to dampen the effects of uncertainties in quantities which might be received from a supplier. Again we refer the reader to Elmaghraby [10] and Minner [29] who provide excellent and comprehensive summaries of prior literature in this area.

There are some key studies in supplier yield management which do have a bearing on how to manage supply disruptions. Gallego and Moon [13] address the supplier yield problem in a newsvendor framework.

Specifically, they consider minimizing the upper bound on cost in a setting with known mean and variance of demand, but the demand distribution is unknown. The base case analysis is extended to consider the situation where the buying firm pays for all units ordered from a single source with binomial yield. They show that this extension results in higher purchase quantities and costs as compared to the base case. Bassok and Akella [2] introduce the Combined Component and Production Problem (CCOPP). The problem is to select ordering and production levels of a critical component and its parent finished good for a single period with uncertainty in both demand for the finished good and component supply. Similarly, Gurnani et al. [16] decide ordering and production levels for a two-component assembly system facing random final product demand and random yield from two suppliers, each providing a distinct component. The basic results from these latter two papers is that diversification is a preferred sourcing strategy for handling the problem of uncertain yields. In more recent studies, Burke et al. [7] use the newsvendor framework to analyze the supplier sourcing problem under random supplier yields and uncertain demand. They show that regardless of the supplier yield distribution, it is generally optimal to source from a single supplier when supplier yields are identical. On the other hand, under distinct supplier cost and yield structures, a multiple sourcing strategy is the preferred choice.

One moderating aspect to these general results in the context of supply disruption management relates to order quantities which should be allocated to multiple suppliers. Chopra et al. [8] examine the choice of sourcing from either a reliable, more expensive supplier, or an unreliable, less expensive supplier, or a combination of both. Consider a single period problem where the buyer faces a fixed demand D over the coming period. The buyer has two supply options: one cheaper but prone to disruption and recurrent supply risk (referred to as the first supplier) and the other perfectly reliable and responsive but more expensive (referred to as the reliable supplier). The first supplier may have supply disrupted with probability P , in which case the buyer receives a supply of 0. If there is no disruption (with probability $1 - P$), the amount delivered is a symmetric random variable, X , with density function $f(X)$ having a mean of S (the quantity ordered) and standard

deviation σ_X . In this model, supply may exceed the order quantity and such a situation may arise in a context where yields are random (such as the flu vaccine or semiconductors) and the contracts are on production starts. Such an assumption simplifies the analysis and allows us to draw useful managerial insights. Each unsold unit at the end of the period is charged an overage cost of C_o and each unit of unmet demand is charged a shortage cost of C_u and it restricts attention to the case where $C_u > C_o$.

The reliable supplier has no disruption or recurrent supply uncertainty, that is, the supplier is able to deliver exactly the quantity ordered. Responsiveness of the reliable supplier allows the manager to place her order after observing the response of the first supplier and yet receive supply in time to meet demand. This reliability and responsiveness, however, comes at a price. The reliable supplier charges a premium and requires the manager to reserve I units (at a unit cost of h per unit) at the beginning of the period before knowing the outcome of supply from the first supplier. Once the outcome from the first supplier is known, the manager can order any quantity up to the I units reserved at an exercise price of e per unit. It is assumed that $e + h < C_u$, so that the manager would choose to use the reliable supplier in certain situations; and similarly it is also assumed that $h < C_o$ to allow the manager to have the option of reserving capacity from the reliable supplier in the absence of disruption. Finally, it is assumed that the total cost from the reliable supplier $e + h$ exceeds the cost of overstocking C_o of purchases from the cheaper supplier, that is, $e + h > C_o$. In this setting, the manager's goal is to minimize total expected costs.

To understand the manager's actions when uncertainties are bundled, the authors first analyze the case where the delivery quantity from the first supplier only has recurrent uncertainty (no disruption) represented by a random supply w with cumulative distribution function $G(w)$ with a mean S (the quantity ordered) and standard deviation σ_w . In the absence of disruption, the expected costs from the perfectly reliable supplier are given by

$$E(TC_{reliable}) = hI + e \int_0^D \min(I, D - w) dG(w). \quad (6.11)$$

The expected over- and understocking are all attributed to the first supplier and are given by

$$\begin{aligned}
 E(TC_{\text{over+under}}) &= C_u \int_0^{D-I} (D - I - w) dG(w) \\
 &\quad + C_o \int_D^\infty (w - D) dG(w). \quad (6.12)
 \end{aligned}$$

The next step is to evaluate the manager's actions if she decouples the two uncertainties when making her decision. The total cost in this case can again be broken up into two parts: one from contracting with the reliable supplier and one from purchasing from the first supplier. Observe that it is never optimal to reserve more than D units with the reliable supplier, that is, $D \geq I$. The expected cost for the reliable supplier consists of three components: the cost of reserving quantity I , the cost of purchasing I units and understocking by $D - I$ units in case of a disruption, and the cost of purchasing the minimum of the reserved quantity I and the shortage $D - x$ in case the supply x is less than the demand D . The expected cost for the reliable supplier is given by:

$$\begin{aligned}
 E(TC_{\text{reliable}}) &= hI + P(eI + C_u(D - I)) \\
 &\quad + (1 - P)e \int_0^D \min(I, D - x) dF(x). \quad (6.13)
 \end{aligned}$$

The expected over- and under-stocking costs (when supply arrives but leads to cover or understocking) is given by

$$\begin{aligned}
 E(TC_{\text{over+under}}) &= (1 - P)(C_u \int_0^{D-1} (D - I - x) dF(x) \\
 &\quad + C_o \int_D^\infty (x - D) dF(x)). \quad (6.14)
 \end{aligned}$$

The key results stemming from the analysis are that the choice of suppliers is moderated by whether the supply risk stems from recurrent or disruption risks. For example, if supply risk growth stems from a recurrent uncertainty, then choosing to source more from the unreliable supplier is a preferred strategy, while if supply risk growth stems from increases in disruption probability, then the choice should be source of a

larger quantity from the reliable source. This finding indicates that the insights stemming from examining the sourcing decisions under supplier uncertainty need to be moderated when they are generalized for handling supply disruption risks. The authors also note the importance of not bundling the two sources of supply uncertainty (yield variability versus disruption) since each of them has distinct impacts on the risk mitigation strategy.

Given that most of this prior work has focused on quantity disruptions (i.e., uncertainty in supply quantities), there is a limited stream of research focusing on sourcing under lead time uncertainty. For example, Kelle and Silver [22] investigate a continuous review inventory policy replenishment system for suppliers with stochastic delivery lead times, and find that order-splitting among multiple sources reduces safety stock without increasing stockout probability. Ramasesh et al. [33] also analyze a reorder point inventory model with stochastic supply lead time, and find that in the presence of low ordering costs and highly variable lead-times, dual sourcing can be cost preferable. The general results for both these studies are that uncertainties in lead times are best handled through a multiple sourcing strategy. Given that transportation network disruptions could also create such uncertain lead times, these results obviously indicate that multiple sourcing is a viable tool to manage such disruptions.

In the context of managing supply uncertainties for managing disruptions, Tomlin [42] analyzes three supply-side tactics available to a firm, namely sourcing mitigation, inventory mitigation, and contingent rerouting. A single product setting in which a firm can source from either unreliable and/or reliable but a more expensive supplier is studied in this paper. Suppliers are under capacity constraints, however, the reliable supplier may possess volume flexibility and so it can temporarily adjust its capacity. In this line, two critical dimensions of volume flexibility, namely the magnitude of the capacity increase and the time required for the extra capacity to become available, are captured by the model. The purpose is mainly to provide insights into the factors that influence a firm's optimal disruption management strategy. Supplier reliability (percentage uptime) and the nature of the disruptions (frequent but short or rare but long) along with firm characteristics such

as risk tolerance are found to be the key determinants of the optimal strategy though their impact varies based on the frequency and level at which mitigation and contingency costs are incurred. For a given percentage uptime, sourcing mitigation is increasingly favored over inventory mitigation as disruptions become less frequent but longer since in the latter case significant quantities of inventory need to be carried for extended periods without a disruption. Partial sourcing from the reliable supplier and carrying inventory can also be optimal if the unreliable supplier has finite capacity or if the firm is risk averse. It is also noted that supplier characteristics including capacity and flexibility are effective in moderating the choice of an optimal disruption management strategy. If the reliable supplier has no flexibility and the unreliable supplier has infinite capacity, a risk-neutral firm pursues either mitigation by carrying inventory strategy, mitigation by single sourcing from the reliable supplier strategy or passive acceptance. Volume flexibility can also substantially benefit a firm through an enabling contingent rerouting strategy which reduces the firm's costs.

The importance of default risk management has been reinforced due to supply disruptions that stem from natural disasters, production failures, and firm-specific manufacturing failures. Babich et al. [1] address the effect of supplier competition that affects equilibrium wholesale prices in a market where the retailer is considering diversification as a strategy to reduce the supply chain risk. On the basis of a simple one-period model of a supply chain with one retailer and multiple risky suppliers, this paper addresses supplier selection, pricing, and ordering policies among firms. In the setting, suppliers compete with each other for the retailer's business, and they are collectively Stackelberg leaders in a game with the retailer. When there is more than one supplier in an environment with uncertain supply but deterministic demand, the default risk may be hedged by retailer through splitting orders. The modeling framework is as follows. The payments from the retailer to the suppliers are made at date 0. Let K_i be the wholesale price charged by supplier $i = 1, \dots, N$. One could think that at date 0 the suppliers bid for the retailer's business by quoting their unit wholesale prices. Based on those quotes, the retailer decides how to divide the business among suppliers. Let δ_i be a binary random variable denoting the number of

defaults of supplier i during the production period. The default and demand random variables are independent and the per unit retail sales price, s , is predetermined. One can think of s as the expected present value of the future random price $S(T)$ where $S(T)$ is independent from other random variables in the model (i.e., $s = e^{-r}E[S(T)]$). The problem of the retailer that can place orders with N suppliers is:

$$\sup_{z_1 \geq 0, \dots, z_N \geq 0} \left(sE \left\{ \min \left[D, \sum_{i=1}^N (1 - \delta_i) z_i \right] \right\} - \sum_{i=1}^N K_i z_i \right). \quad (6.15)$$

The objective function is bounded, continuous, decreasing for large z_i , and concave. Therefore, problem has a unique solution. Denote by $z_i(K_1, \dots, K_N)$ the retailer's order quantity to supplier i . The suppliers compete with each other for the retailer's business and solve the following optimization problems:

$$\sup_{K_i \geq 0} (K - i - c_i) z_i(K_1, \dots, K_N), i = 1, 2, \dots, N. \quad (6.16)$$

An analysis of the problem offers the following insights. In a competitive environment where the wholesale prices are determined endogenously by suppliers, default correlation has a crucial impact on the trade-offs faced by the retailer. On the one hand, decreases in default correlations lead to decreases in competition between suppliers and hence the equilibrium wholesale prices charged by the suppliers increase. On the other hand, the retailer may minimize disruption risks and when there are two suppliers, the benefits of price competition effects outweigh the diversification benefits. With more than two suppliers, it is possible for the retailer to benefit from low wholesale prices and diversification simultaneously. For instance, if two suppliers have highly correlated default processes while the default process of the third supplier is negatively correlated with the other two, then the firms that are highly co-dependent charge low wholesale prices to compete away their profits and the retailer may use the third supplier to hedge against disruption risk. The overall direction of the results stays same, when models with multiple risky suppliers in a competitive environment where both supply and demand are random are considered. Related to those points, it seems that positive default correlation benefits the retailer, but a negative default correlation benefits the suppliers and

the channel as a whole. This relation contradicts the initial intuition about the advantages of diversification. The economic consequences of the results indicate that once suppliers are chosen, they can increase their benefits through reducing their correlation by selling to different customers, using different production technologies, procuring from different raw materials sources and reducing exposures to common catastrophic events.

In general, dual sourcing and inventory investment are two prevalent supply chain risk mitigation strategies. Inventory investment mitigates future supply risk, since the firm orders more than its current period needs and will have additional units on hand in case of low yields in future while dual sourcing mitigates the current period's supply risk, because the firm places orders with two suppliers and the probability of both suppliers having low yields is smaller than that of a single supplier having a low yield. Since firms do not always have perfect information on supply distributions and must make diversification and inventory decisions based on such imperfect knowledge, learning can be used to refine their information over time. In this context, Tomlin [44] introduces and analyzes a Bayesian model of supply learning, i.e., reliability-forecast updating, and investigates how supply learning influences both sourcing and inventory strategies in dual sourcing and single-sourcing models, respectively. The model defined in this paper focuses on a Bernoulli yield model, where each supplier is unreliable in the sense that an order placed with a supplier may succeed or fail, but also considers general yield distributions. A risk-neutral firm that can source from two suppliers over a finite-horizon with discrete periods is analyzed. Define the probability of success as given by θ^i and refer to θ^i as the reliability of supplier i (constant over time). c^i is the cost per unit ordered and q^i is the cost per unit delivered. Demand not filled in a period is lost, with a lost sales cost of π per unit. With no uncertainty about supplier reliability, that is, the firm knows supplier 2's reliability θ^2 , the finite-horizon problem can be decomposed into T identical single-period problems. Since demand in each period is drawn from a stationary, continuous distribution with support on the interval $[x_{min}, x_{max})$, and the density function is denoted by $f(x)$, let $\widehat{C}(\mathbf{q}; \theta^1, \theta^2)$ denote the single-period expected cost as a function of the

order vector $\mathbf{q} = (q^1, q^2)$. Then,

$$\begin{aligned}\widehat{C}(\mathbf{q}; \theta^1, \theta^2) &= (c^1 + \theta^1 g^1)q^1 + (c^2 + \theta^2 g^2)q^2 + \theta^1 \theta^2 L(q^1 + q^2) \\ &\quad + \theta^1(1 - \theta^2)L(q^1) + (1 - \theta^1)\theta^2 L(q^2) \\ &\quad + (1 - \theta^1)(1 - \theta^2)\pi\mu_X,\end{aligned}$$

where

$$L(q) = \pi \int_q^{x_{\max}} (x - q)f(x)dx - v \int_{x_{\min}}^q (q - x)f(x)dx \quad (6.17)$$

and μ_X is the expected demand.

When there is uncertainty about supplier reliability, it is assumed that the firm knows supplier 1's reliability with certainty, but it only has a forecast of supplier 2's reliability. The firm's forecast is represented by a probability density $h(\theta^2)$ for supplier 2's reliability. In single-period case, the firm's problem is to minimize $E_{\theta^2}[\widehat{C}(\mathbf{q}; \theta^1, \theta^2)]$. $\widehat{C}(\mathbf{q}; \theta^1, \theta^2)$ is linear in θ^2 and so

$$E_{\theta^2}[\widehat{C}(\mathbf{q}; \theta^1, \theta^2)] = \widehat{C}(\mathbf{q}; \theta^1, \overline{\theta^2}), \quad (6.18)$$

where $\overline{\theta^2}$ is the expected value of the firm's forecast of supplier 2's reliability.

The major contribution of this research is that supply learning can have an important impact on the operating policy. Particularly, in the case of Bernoulli yields, an increase in the firm's about a supplier's reliability makes that supplier more attractive because of the potential gains from learning that the supplier has a higher reliability than initially thought. On the other hand, it is proven that for a given expected supplier reliability, i.e., the mean of the firm's forecast for the probability of successful delivery, an increase in the reliability forecast uncertainty (measured by the squared coefficient of variation) increases the attractiveness of a supplier, but it reduces the firm's desire to invest in inventory to protect against future supply failures.

On the basis of global sourcing, international trade regulations become an important driver of supply chain strategy in many industries. In particular, the textile, footwear, paper, chemicals, agriculture, and steel industries face significant levels of non-tariff barriers (NTBs)

such as safeguard controls, antidumping rules, countervailing duties, and voluntary export restraints. NTBs are designed to protect domestic industries, and they are typically targeted at low-cost countries (LCC) and emerging economies that have a distinct cost advantage in the protected industry. In this environment, when a firm places an order with a supplier, it is often difficult for the firm to predict the future availability and/or price of export permits. For that reason, firms need to consider the potential availability and price risks associated with NTBs while designing their supply chain. In this framework, Wang et al. [49] describe and analyze four observed supply chain strategies in industries subject to NTB risks: direct procurement (sourcing from a single supplier located in an LCC); split procurement (sourcing from two suppliers, one located in an LCC and the other located in a medium cost country or MCC); direct outward processing or D-OPA (a strategy by which the firm can through direct LCC involvement completely avoid the NTB), and indirect outward processing or I-OPA (a strategy by which the firm can through third-party mechanisms completely avoid the NTB). Given this setting, a newsvendor-type model to characterize the optimal procurement quantities within a single selling season is proposed. In this setting, the firm may source the finished product either domestically (DOM) or overseas (LCC and/or MCC). Sourcing from a supplier in an LCC is subject to NTB control for importing the product to DOM but sourcing from a supplier in an MCC is not. In order to eliminate the impact of exchange rate fluctuations, it is assumed that the firm's purchasing contract is negotiated in the domestic currency. Through a numerical analysis, managerial and policy level implications of the firm's preference among direct/split procurement and D-OPA strategies are explored. The results are that a stochastically larger NTB price hurts the direct/split procurement strategies as it increases the potential procurement cost and diminishes the postponement value. Besides, an increase in the variance of the NTB price may benefit direct/split procurement strategies. OPA strategies are more likely to be preferred when the NTB price is high but predictable. Considering the lead time advantages, because the value of postponement in the D-OPA strategy is directly linked to its lead time advantage, a

shorter DOM lead time increases the attractiveness of the D-OPA strategy relative to the rest strategies. A reduction in the DOM lead time is increasingly beneficial as demand uncertainty increases. Otherwise, an increase in market uncertainty actually hurts the D-OPA strategy. With respect to market size, an increase in the expected demand does not change the relative rankings of different strategies but an increase in the demand coefficient of variation (CV) does. With a sufficient lead time advantage (for domestic production), the D-OPA strategy dominates all other strategies and becomes increasingly attractive as the demand CV increases. From a policy perspective, it is found that careful attention should be paid to industry characteristics, such as aggregate demand and demand volatility, when setting the mandated domestic production fraction associated with the D-OPA strategy.

6.3 Operations/Process Uncertainties

In general, disruptions in operations/processes can be handled by building excess capacity and hence, achieving a desired level of process flexibility. This is a critical design consideration in multi-product supply chains facing uncertain demand. Building dedicated plants with sufficient capacity to cover the maximum possible demand is one of the approaches to deal with forecast uncertainty. However, it is expensive and the expected capacity utilization is mostly low. On the other hand, flexibility enables a production facility to process multiple products and so firms can allocate products to plants so as to meet realized demand most effectively. Graves and Tomlin [15] explore the benefits of process flexibility in general multistage supply chains so as to obtain insights into effective strategies for deployment in an SC. The modeling approach is as follows. There are K stages with J_k different plants at each stage k . Product — plant links (i, j) at stage k are represented by an arc set A_k . At stage k , plant j can process product i if and only if $(i, j) \in A_k$. $P^k(i)$ defines the set of plants of stage k that can process i , i.e., $j \in P^k(i)$ if and only if $(i, j) \in A_k$. Similarly, define the set of plants of stage k that can process one or more of the products in set M as $P^k(M) = \bigcap_{i \in M} P^k(i)$. To enable analytical tractability and simplify the presentation, assume that all products i , such that $(i, j) \in A_k$

require the same amount of plant j 's capacity per unit processed. Thus, the capacity of plant j of stage k , c_j^k is the number of product units that can be processed in the planning horizon.

To evaluate a flexibility configuration, define a single-period production — planning problem that minimizes the amount of demand that cannot be met by the supply chain. For a given demand realization, $\mathbf{d} = \{d_1, \dots, d_I\}$ and flexibility configuration, $\mathbf{A} = \{A_1, \dots, A_K\}$, the production planning problem is the following linear program, $\mathbf{P1}(\mathbf{d}, \mathbf{A})$:

$$sf(\mathbf{d}, \mathbf{A}) = \text{Min} \left\{ \sum_{i=1}^I s_i \right\} \quad (6.19)$$

subject to

$$\begin{aligned} \sum_{(i,j) \in A_k} x_{ij}^k + s_i &\geq d_i \quad i = 1, \dots, I, k = 1, \dots, K \\ \sum_{(i,j) \in A_k} x_{ij}^k &\leq c_j^k \quad j = 1, \dots, J_k, k = 1, \dots, K \\ x_{ij}^k, s_i &\geq 0, \end{aligned}$$

where $sf(\mathbf{d}, \mathbf{A})$ is the total shortfall, s_i is the shortfall for product i , x_{ij}^k is the amount of product i processed in plant j at stage k over the planning horizon. Obviously the focus is to determine a cost-effective flexibility configuration using a single-period production planning model which minimizes demand that cannot be met by the supply chain. Floating bottlenecks and stage-spanning bottlenecks, both of which reduce the effectiveness of a flexibility configuration, are considered in the analysis of the multistage operations process. While the floating bottleneck is a direct result of demand uncertainty and partial flexibility in an SC, the stage-spanning bottleneck can manifest itself even if demand is certain. Here, inefficiency is a measure of the supply chain performance and measures the impact of interaction within multiple stages. A general flexibility measure (GFM) is developed and applied to identify flexibility configurations with values of GFM greater than or equal to one which are shown to provide effective protection floating and stage-spanning bottlenecks. Lower values of GFM, on the other hand, result in inefficiencies. Finally, guidelines for designing flexibility

within an SC on the basis of chaining are proposed. In this framework, each stage of a supply chain with a moderate number of stages and products should create chains that encompass as many plants and products as possible, and simultaneously attempt to equalize the number of plant — product connections across the network and product to plant connections within each plant node in the network. A key finding is that for supply chains with more products or stages, flexibility can be increased by directly connecting products to more plants for a given chain configuration. In essence, the chaining policy is shown to be an effective flexibility hedge for multistage supply chains.

6.4 Transportation Uncertainties

Using the case of the UK, McKinnon [28] examines the impact of a road transportation disruption at a macro-economic level. Road transportation in the UK enjoys a near monopoly in the distribution of finished products at the lower levels of the supply chain, particularly in the delivery of retail supplies. The speed and flexibility of road transport has enabled companies to synchronize freight deliveries with their production and distribution operations. Many companies in UK have traded-off greater expenditure on express delivery for lower inventory, less warehouse space, and more responsive replenishment. By driving down inventory levels, however, these companies have made their operations mode dependent on rapid and reliable delivery by road. Buffer stocks have been sharply reduced and order lead times compressed, making the availability of products highly sensitive to even quite short delays in the transport system. Hence, even a temporary shut-down of the road freight system would sever the links between the various points in the supply chain at which inventory is held. Of course, the net effect of the withdrawal of trucks would partly depend on the extent to which consumers and companies could make four forms of substitution, termed as product substitution, modal substitution, vehicle substitution, and locational substitution. Regarding the product substitution, consumers could replace perishable foods with long-life products, or in the absence of newspapers, they would rely on television for news. However, the substitutability of drugs is limited, particularly life critical

varieties. In modal substitution, there would be very little scope for switching freight traffic between transport modes within the proposed time-scale. It would take weeks to investigate an alternative freight service due to the constraints on infrastructure, rolling stock, and operating procedures. For vehicle substitution, the opportunities for transferring freight to vans would also be very limited. It would have limited capacity to carry an additional burden of freight displaced from trucks. In locational substitution, the idea is to replace distant suppliers with local suppliers. The problem here is that there would be limited potential for switching to local supply and this would reverse the lengthening of supply chains. In this framework, this paper focuses on sectors with following characteristics: distribution is exclusively or predominantly by road; delivery by road is highly time-sensitive; limited inventory is held in the supply chain; order lead times are short; and they exert strong influence on the level of economic activity/quality of life. These sectors include grocery retailing, food services, fuel supply, healthcare, banking, postal services, parcels, beer, and waste disposal. In case of the withdrawal of road transport, there is little that individual companies can do to guard against such catastrophic failure. Standard risk mitigation measures, such as increasing safety stock, diversifying the supply base, and building redundancy into logical systems, are unlikely to afford much protection and yet significantly increase costs during periods of normal operation. This is because the complete failure of a national transport system is such a rare occurrence and it would be difficult to justify these additional costs. Responsibility for dealing with a crisis of this magnitude would primarily rest with government. Civil contingency plans, developed in partnership with the business community, are required to deal with such an emergency.

Wilson [51] studies the effect of a transportation disruptions impacting the flow of goods on supply chain performance through a system dynamics simulation. The uniqueness of transportation disruption is that only goods in transit are affected while all other operations of the supply chain are intact. Two simulation models are built, namely a traditional supply chain structure and a vendor managed inventory system (VMI), and the supply chain response is measured by number of unfilled customer orders, maximum and average inventory levels, and

maximum goods in transit. The supply chain in this research is modeled in continuous time and contains five sectors: the retailer, the warehouse, the tier 1 supplier, the tier 2 supplier, and the raw material supplier. In the traditional arrangement (aka the Beer Game with no information sharing), demand information flows upstream from the customer, and information flow between sectors is not identical. While the retailer receives customer demand information, other sectors only receive the order information of the downstream sector, and so upstream partners do not directly receive customer demand information. In the VMI structure, both tier 1 supplier and the retailer receive customer demand information, while tier 2 supplier and raw material supplier do not have access to customer demand information. In both traditional and VMI models, the transit times and processing times are identical so as to maintain comparability between the two systems. The transportation disruptions can occur at four different points in each arrangement and these are categorized as:

- Type 1: Between retailer and warehouse;
- Type 2: Between the warehouse and the tier 1 supplier;
- Type 3: Between the tier 1 supplier and the tier 2 supplier;
and
- Type 4: Between the tier 2 supplier and the raw material supplier.

The two different supply chain arrangements are simulated with 10 day disruptions at four different points corresponding to each disruption type, and the simulation is run for 600 days, with the disruption starting on day 200. Simulation results indicate that although a transportation disruption affects both the traditional and vendor managed supply chain, the impact when the VMI structure is used is much less pronounced. For both structures, Type 1 disruptions result in the greatest number of unfilled customer orders. On the other hand, a Type 2 disruption has the greatest ripple effect both downstream and upstream. For both structures, Type 3 disruptions causes the inventory levels for tier 2 supplier to temporarily rise by around 80%, while Type 4 temporarily increases the goods in transit by approximately 180%. On the basis of simulation results, the VMI structure seems to be superior to

the traditional supply chain structure, since it provides some protection against the effects of a Type 1 and a Type 2 disruption. Since the primary difference in the two structures is attributable to information sharing, risk mitigation strategies for transportation disruptions can probably be better managed by allowing a free flow of information within the entire SC.

6.5 Additional Research

Parlar and Berkin [31] study a one-period inventory problem under supply disruptions within the EOQ framework. Their major focus was to derive an expected cost function per unit time and then conduct a sensitivity analysis of key parameters when the supply disruptions are exponentially distributed. In a later note Berk and Arreola-Risa [3] observed that there were inconsistencies in the analytical derivation of the expected cost function. On reformulating the cost function, they repeated the sensitivity analysis and found that the optimal order quantity in this setting is: (a) nondecreasing in demand, holding cost, and ordering cost; (b) nondecreasing when the frequency of disruptions decreases; and (c) concave when the mean rate of disruptions increases. Weiss and Rosenthal [50] also focus on an inventory policy within an EOQ framework in the presence of either supply or demand disruptions. Assuming that information on the starting point of a disruption and its length is known a priori, structural results for an optimal EOQ type policy under non-stationary parameter settings are presented. Ross et al. [34] address the question as to what improvements in cost can be gained by using time-varying policies as compared to stationary policies. Using extensive numerical experiments, they compare policies under several cost, demand, and disruption parameters. They also investigate the robustness of time-dependent policies to estimation errors in the probabilities of disruptions. Their major finding is that non-stationary policies are an effective tool for balancing costs and robustness.

Tomlin and Snyder [45] examine how threat advisory systems (reflecting the potential for supply disruptions) impact a

periodic-review inventory system. In this setting they consider a firm sourcing from two suppliers: a reliable, higher-cost supplier and an unreliable, low-cost supplier. The optimal threat-level-dependent inventory levels are characterized and it is shown that using such a process, there are significant cost savings from a threat advisory system. Further, they also show that the presence of such a system and the disruption risk significantly impact the choice of the disruption management strategy. Snyder and Shen [40] explore the different impacts of supply and demand uncertainty in multi-echelon supply chains. They conjecture that the effects of each type of uncertainty (supply and demand) would be distinct and unique. Through simulation of a simple multi-echelon system, they show that different strategies (in terms of order frequency, inventory placement, and supply chain structure) are required to handle disruptions stemming from each type of uncertainty.

Hopp and Yin [21] analyze an arborescent supply chain subject to a random and extended failure of individual supply nodes. Assuming that these failures are likely to be infrequent (e.g., stemming from natural catastrophes), they develop an optimization model to balance costs of lost sales versus costs of inventory and capacity buffering. A unique insight is that under certain cost conditions, an optimal policy is such that at most one node in the chain requires an inventory or capacity protection. In addition, using a numerical analysis, they are also able to show that if the frequency or length of the failures increases upstream, the optimal inventory and/or capacity protection mechanisms also move upstream. A more recent paper by Bradley [5] examines the complexity of the probabilistic risk assessment process within SCs. In this case, complexity is a function of SC attributes and models used to perform a probabilistic risk assessment of disruptions. As would be expected, the applicability of analytical approaches for risk assessment is computationally complex. In addition, it is also found that simulation might also not be a viable tool in situations where SC disruptions lead to effects which are of a large magnitude. The paper concludes by noting that the Failure Modes and Effects Analysis methodology holds some promise for addressing the problem of probabilistic risk assessment of disruptions within SCs.

6.5.1 Summary

The research reviewed in this section can be summarized as follows:

- **Product Uncertainties:** Although not always stated, the focus of the research in this category addresses issues related to demand uncertainties stemming from disruptions. In addition, these uncertainties are obviously more prevalent in the current marketplace which is characterized by shorter life cycles and longer lead times. A general result based on this stream of work is that information sharing, coordination, and integration tools are all essential to manage uncertainties stemming from disruptions in demand. Prior research with this focus is summarized in Table 6A.
- **Supply Uncertainties:** In this area, there is a wealth of prior research on random yields and supplier sourcing strategies

Table 6A. Research on Product Uncertainty Risks.

Reference	Contribution/Focus
Lee (2002) [25]	Develops a framework that assist managers in developing the right supply chain strategy by focusing on demand and supply uncertainty for products.
Tomlin and Wang (2005) [46]	Bridge the mix flexibility and dual sourcing literatures by studying unreliable supply chains that produce multiple products on the basis of four canonical network structures; single-source dedicated (SD), single-source flexible (SF), dual-source dedicated (DD), and dual-source flexible (DF). Key insights are that: (a) SF networks dominate SD networks only when resource investments are perfectly reliable and the firm is risk neutral; (b) the effectiveness of diversification and flexibility as disruption risk mitigation strategies is moderated by costs, reliabilities, downside risk tolerance, product demand correlations, number of products, and spread in product contribution margins.
Tomlin (2008) [43]	Analyzes disruption management strategies for short life-cycle products. Investigates supply-side and demand-side disruption management tactics in the context of a firm that sells multiple products with short life cycles and long lead times. Key findings are that: (a) if the firm is risk neutral, disruption management is of little value; (b) demand switching is of less value as compared to dual and/or contingent sourcing strategies for a risk-averse firm; and (c) ordering of strategies in terms of effectiveness of dealing with disruptions is: contingent sourcing; dual sourcing; and demand switching.

which can be extended to identify effective disruption strategies. However, one key aspect of disruptions, i.e., whether they are recurring or one time, is critical in identifying the relevant supply disruption management strategies. A second issue worth noting is that most of the research has been driven by assuming that uncertainties stem primarily from quantity disruptions. Hence, most managerial strategies which are proposed focus on hedging risk (by choosing multiple suppliers) and/or by maintaining larger (safety) stocks. Prior research with this focus is summarized in Table 6B.

Table 6B. Research on Supply Uncertainty Risks.

Reference	Contribution/Focus
Kelle and Silver (1990) [22]	Investigate a continuous review inventory policy replenishment system for suppliers with stochastic delivery lead times, and find that order splitting among multiple sources reduces safety stock without increasing stockout probability.
Bassok and Akella (1991) [2]	Introduce the Combined Component and Production Problem (CCOPP) to select ordering and production levels of a critical component and its parent finished good for a single period with uncertainty in both demand for the finished good and component supply. In this setting, diversification is a preferred sourcing strategy when supplier yield is uncertain.
Gallego and Moon (1993) [13]	Address the supplier yield problem in a newsvendor framework. Consider minimizing the upper bound on cost in a setting with known mean and variance of demand, but the demand distribution is unknown. Show that if a buying firm pays for all units ordered, costs, and quantities ordered increase.
Gurnani et al. (2000) [16]	Decide ordering and production levels for a two-component assembly system facing random final product demand and random yield from two suppliers, each providing a distinct component. A diversified sourcing strategy is preferred over a single-sourcing strategy.
Tomlin (2006) [42]	Analyzes three supply-side tactics available to a firm, namely sourcing mitigation, inventory mitigation, and contingent rerouting. Studies a single product setting in which a firm can source from either unreliable and/or reliable but a more expensive supplier. Key aspects investigated are supplier reliability and the nature of the disruption. Key insights are: (a) sourcing mitigation is preferred over inventory mitigation for given supplier reliability levels; and (b) partial sourcing combined with inventory buffering is optimal when suppliers are capacity constrained and/or firm is risk averse.

(Continued)

Table 6B. (Continued)

Reference	Contribution/Focus
Chopra et al. (2007) [8]	Examine the choice of sourcing from either a reliable, more expensive supplier or an unreliable, less expensive supplier or a combination of both. Supplier choice moderated by whether the supply risk stems from recurrent or infrequent actions. Important not to bundle risks stemming from yield variability with those stemming from infrequent occurrences since each of them have distinct impacts and hence, require different risk mitigation strategies.
Babich et al. (2007) [1]	Address the effect of supplier competition that affects equilibrium wholesale prices in a market where the retailer is considering diversification as a strategy to reduce supply chain risk. Focus is on the decisions related to supplier selection, pricing, and ordering policies. The correlation between supplier defaults tends to increase supplier competition and hence, wholesale prices are higher. A positive correlation of default risks benefits the retailer while negative correlation of default risk benefits the suppliers and the overall channel.
Tomlin (2008) [44]	Introduces and analyzes a Bayesian model of supply learning, i.e., reliability-forecast updating, and investigates how supply learning influences both sourcing and inventory strategies in dual sourcing and single-sourcing models, respectively. Insights are that: (a) supply learning has a significant impact on the optimal-operating policy; and (b) if delivery uncertainty increases but mean reliability is constant, then it is more likely that the firm will select and place a larger order with a supplier.
Wang et al. (2008) [49]	Describe and analyze four observed supply chain strategies in industries subject to NTB risks: direct procurement; split procurement; direct outward processing or D-OPA; and indirect outward processing or I-OPA. Propose a newsvendor type model to characterize the optimal procurement quantities within a single selling season. Key insights are that: (a) higher NTB prices results in a higher cost of the direct/split procurement policies; and (b) reducing lead time is effective to dampen the negative consequences of demand uncertainty.
Burke et al. (2009) [7]	Use the newsvendor framework to analyze the supplier sourcing problem under random supplier yields and uncertain demand. Key insights are that: (a) distribution of yields irrelevant in identifying an optimal sourcing strategy; (b) if the objective is cost minimization in a setting without supplier capacity constraints, then a single supplier sourcing strategy is optimal; and (c) multiple supplier sourcing strategies are optimal only when supplier costs are equal, supplier capacity constraints are binding, and/or diversification benefits are explicitly incorporated in the analysis.

- Operations/Process Uncertainties: The issue of chaining to link multiple stages is one of the major contributions of research in this area. Further, the development of a flexibility

Table 6C. Research on Process and Transportation Risks

Reference	Contribution/Focus
Graves and Tomlin (2003) [15]	Explore the benefits of process flexibility in general multistage supply chains so as to obtain insights into effective strategies for deployment in an SC. Focus is to identify an optimal process/supply chain configuration that minimizes demand not met. If the supply chain is more complex (i.e., handles more products or consists of a large number of stages), then specialization by product increases supply chain efficiency.
Mckinnon (2006) [28]	Examines the impact of a road transportation disruption at a macroeconomic level within an economy characterized by monopolist transportation carriers. Observes that impact of disruptions would be a function of product carried (i.e., whether consumers can identify substitutes), transportation mode flexibility (i.e., size of trucks), safety stock, and governmental preparations for dealing with a disruption.
Wilson (2007) [51]	Studies the effect of a transportation disruptions impacting the flow of goods on supply chain performance through a system dynamics simulation. Builds two simulation models, namely a traditional supply chain structure and a vendor managed inventory system (VMI), and measures the supply chain response by number of unfilled customer orders, maximum and average inventory levels, and maximum goods in transit. Through a simulation model, finds that disruptions between a retailer and warehouse result in the highest number of unfilled customer orders; and disruptions between the warehouse and suppliers tend to have a ripple (bullwhip?) effect in the entire supply chain. VMI seems to be effective at mitigating the impact of transportation disruptions.

measure (GFM) which can be used to quickly identify flexible SC networks is of course, invaluable. Prior research with this focus is summarized in Table 6C.

- **Transportation Uncertainties:** Developing and maintaining alternative transportation modes and routes is a key to alleviating transportation risks due to disruptions. Information sharing as a mechanism to alleviate the impact of disruptions in this setting is also critical. Prior research with this focus is summarized in Table 6C.
- **Additional Research:** The usefulness and benefits of non-stationary inventory mechanisms to buffer against disruption risks is established. Further, the monitoring of probabilities of risks is also quite important. However, difficulties associated with measuring such probabilities using established

Table 6D. Research on Other specific SC Risks.

Reference	Contribution/Focus
Parlar and Berkin (1991) [31]	Derive an expression for the expected cost per unit time (within an EOQ framework) when supply disruptions occur. A corrected analysis of the expected cost expression by Berk and Arreola-Risa [3] indicates that the optimal order quantity is nondecreasing when the frequency of disruptions decreases and is concave when the mean rate of disruptions increases.
Snyder and Shen (2006) [40]	Note that effects of each type of uncertainty (supply and demand) would be distinct and unique. Illustrate that in a simple multi-echelon system, different strategies (in terms of order frequency, inventory placement, and supply chain structure) are required to handle disruptions stemming from each type of uncertainty.
Hopp and Yin (2006) [21]	Develop an optimization model to balance costs of lost sales versus costs of inventory and capacity buffering for a supply chain subject to infrequent disruptions. Find that under certain cost conditions, an optimal policy is such that at most one node in the chain requires a inventory or capacity protection. Also show that if the frequency or length of the failures increases upstream, the optimal inventory and/or capacity protection mechanisms also move upstream.
Bradley (2008) [5]	Examines the complexity of the probabilistic risk assessment process within SCs. Finds that using simulation might not be viable in situations where SC disruptions lead to effects which are of a large magnitude. Suggests that Failure Modes and Effects Analysis methodology hold some promise for addressing this issue.
Ross et al. (2008) [34]	Address the question as to what improvements in cost can be gained by using time-varying policies as compared to stationary policies. Compare policies under several cost, demand, and disruption parameters. Find that non-stationary policies are effective to balance costs and robustness.
Tomlin and Snyder (2008) [45]	Examine how threat advisory systems impact a periodic-review inventory system, and consider a firm sourcing from two suppliers: a reliable, higher-cost supplier and an unreliable, low-cost supplier. The benefits of a threat-advisory system for shown to exist regardless of the sourcing strategy adopted by the firm.

tools is noted and hence, alternative measurement methods should be developed. Prior research with this focus is summarized in Table 6D.

In the next and final section of this monograph, we identify gaps which still exist in the current research and use this to outline directions for future research.

7

Directions for Future Research

In order to focus and direct future research efforts in this complex but critical area, it is reasonable to start with some industry evidence. A study by Accenture found that 73% of the executives interviewed had experienced a serious supply chain disruption in the past five years. As a result, the companies failed to meet customer expectations or their profits took a hit.¹ Another study by FM Global² reports that a survey of 600 financial executives indicates that supply chain risks were identified as having the greatest potential to disrupt their top revenue drivers. A third survey by McKinsey³ reports that more than 75% of the respondents indicate that the degree of supply chain risk faced by their organizations has increased in the last five years. There is no shortage of additional anecdotal evidence which points to the fact that disruptions result in significantly negative consequences and that the risks associated with these disruptions are projected to increase in the next

¹ http://www.accenture.com/Global/Consulting/Supply_Chain_Mgmt/R_and_I/Corporate_ResilienceRisk.htm.

² http://www.fmglobal.com/assets/pdf/P0667_Chainsupply.pdf.

³ McKinsey Quarterly, July 2008, Survey on global supply chains.

few years. Given this evidence, it is obvious that there is a significant need for future research on managing supply chain disruptions.

To start with, there is a need to re-examine the current categorizations of potential disruptions. In essence, the usefulness of current research which classifies disruptions as those caused by “acts of nature” versus “acts of humans” needs refinement. For example, additional dimensions which could guide managerial efforts in managing disruptions would be those related to whether the causes can be: (a) forecast accurately; and are (b) frequent or infrequent occurrences. The rationale for including these aspects is that if the causes of disruptions can be forecast with a high degree of certainty, then prevention and/or recovery strategies for managing their impact need to be in place. Further, if the causes of the disruptions occur frequently, it also points to the need for maintaining a disruption prevention and recovery team on a continual basis.

From an organizational impact perspective, it would also be useful to extend the current categorization of disruptions in terms of the level of impact (i.e., strategic, tactical, and/or operational) to the magnitude of impact. Since the development and implementation of disruptions strategies and mechanisms will almost always require up-front organizational effort, there is a need to trade-off the benefits resulting from these efforts versus the downside costs of letting disruptions occur. In this manner, firms can make effective decisions as to whether it is beneficial to implement strategies for managing all potential disruptions. Finally, it would also be useful to identify the link in the SC at which a specific disruption might occur. Rather than simply focus on the type of disruption (i.e., quantity, quality, lead time, and/or technology), the stage at which any of these types of disruptions occur would provide more insight into whether there would or would not be a “cascading” impact of the disruption. For example, a quantity disruption in the supply channel would obviously have a direct impact on the operations, distribution channel, and customer linkages but a quantity disruption in the distribution channel would directly impact only the customer link. Using such a type and linkage-based classification would help to identify the potential coverage of disruption management strategies as they are formulated.

In terms of managing the risks stemming from disruptions, it is often argued that firms tend to undervalue the element of risk as well as the complexity of risk.⁴ In addition, there is also the issue of whether risk management strategies should be tailored based on alternative classifications of potential SC disruptions in terms of their process (i.e., financial, political, social, and/or economic) impact. In addition, the increasing use of outsourcing and/or offshoring within current SC also indicates a need to focus on risks stemming from the coordination of multiple players in the SC. In this context, there are several critical needs which need to be addressed through additional research.

To start with, there is a need for research which focuses on addressing issues related to the nature on specific risks that are inherent in a contemporary SC. For example, if we focus our attention on financial risks with an SC, the disruptions experienced in current financial markets obviously are leading to previously unanticipated consequences ranging from unavailability of capital for financing capacity expansions, changing consumption preferences due to a drop in the value of retirement assets, and volatility in exchange rates. This leads us to note that disruptions in the financial marketplace would impact almost all the links in an SC and hence, would require a simultaneous coordinated risk management effort. Research endeavors which would be worthwhile to pursue in this domain would be to identify the nature of alternative SC risk; how each of these risks impact stages in the SC; what are appropriate measures to quantify these risks; alternative risk management procedures which would be useful for managing each risk; and finally, potential models for trading-off the benefits of pro-actively managing the risk versus the costs of doing so.

A second area which would be of interest is the process by which risks stemming from disruptions should be managed. In this case, prior research focusing on “best” practices has indicated that the key dimensions incorporated by firms are related to maintaining decision visibility across the entire SC, establishing communication/collaboration protocols, quantifying the nature of the risk, employee education, and transparency of the risk management process are of relevance. It follows that

⁴ www.marshriskconsulting.com/st/psev.c.228051_sc_228063_nr_303.htm.

there is a need to develop a generalizable structured risk management process and validate it through either empirical or case study-based research. As an extension, the process should also be formalized in terms of team management and provide guidelines on team composition which would be moderated by the type of risks which are to be addressed.

There also is a need for more rigorous conceptual/empirical studies which focus on establishing and empirically “testing” typologies of disruption management. Current work in this domain seems to be limited to exploratory studies which examine managerial perspectives on dealing with disruption. An extension of this current stream of work would be to draw upon the related literature on recovery and change management with a view to proposing an overall typology and developing related propositions stemming from such a typology. A follow-up research project could be on developing valid measures for measuring the key constructs related to the propositions and then using both industry specific and cross-sectional data in order to validate the typology and related propositions.

In the last few years, there have been a few rigorous studies which have addressed the issue of robust SC network design. In this context, the major focus seems to have been to propose mathematical programming models which integrate robustness parameters as either an objective or as a bounding constraint. It is not surprising that given the complexity of these formulations, “optimal” solutions for larger and more realistic problems are difficult to obtain. One obvious and promising avenue of future research in this arena would be to develop extensively tested heuristic methods which can provide “near-optimal” solutions for larger and more realistic problems in SC network design. A second promising avenue of future research in this area would be to develop dynamic robust SC network design approaches which can be used to investigate alternative SC structures which might be better able to handle disruption-related risks. In fact, given that firms anticipate that disruption risks are expected to increase significantly in the near future,⁵ it would be particularly useful to propose approaches which

⁵ http://multichannelmerchant.com/opsandfulfillment/preparing_supply_disruptions_0206/.

can dynamically adjust SC networks to respond to such risks. A third avenue for future research related to SC network design (in line with the early research on hierarchical production planning) would be to develop a set of inter-related SC network design models which can be used to address strategic, tactical, and operational SC disruption risks.

In managing specific disruptions, there are also several opportunities for future research. Since shorter product life cycles and longer lead times are characteristic of contemporary SC, analytical and empirical research which investigates the impact of demand and product mix uncertainties on an SC is obviously critical. For example, different disruption management strategies could be evaluated for identifying appropriate distribution channel configurations when disruptions cause substantial changes in either demand and/or mix of product offerings in one or more markets. Given that the most researched area is that related to managing quantity disruptions in the supply channel, the focus of future research efforts in this area should be on examining strategies for managing lead time variations. Integrating the issue of location and size of the supply base is also critical in this research domain since the advent of outsourcing and offshoring has an impact on lead times within the supply chain. The review of prior research on disruptions in operations nodes and transportation linkages between nodes indicates that these disruptions have been addressed by very few researchers. Thus, there are several opportunities for future research examining the impact of disruptions in these areas. For example, research which examines the ramifications of disruptions in capacity with a view to identifying strategies to mitigate and even prevent the impact of such disruptions would be extremely useful. Further, research which identifies and develops models for evaluating alternative transportation strategies to handle disruptions would also be useful.

Finally, using disruptions to jumpstart innovation in enterprises seems to be an emerging paradigm.⁶ The key idea is that one of the potential impacts of organizational change (in this case, changes stemming from disruptions) fosters the development of innovative processes for managing change. In this context, disruptions (especially if they

⁶ <http://hbswk.hbs.edu/item/5636.html>.

result in severe consequences) represent an obvious opportunity for proposing and also, “testing” innovative ideas since they force a re-evaluation of existing practices. More rigorous research which examines and attempts to structure such advantages in the context of disruptions would obviously be useful.

A

Appendix

The comprehensive global SC design model proposed by Kouvelis and Su [24] is as follows.

Indices

- i : subassembly index, $i = 1, \dots, I$
- n : country of operation index, $n = 1, \dots, N$
- k : country of locating a distribution center (DC) index, $k = 1, \dots, N$
- m : country of locating a plant index, $m = 1, \dots, N$
- q : subassembly plant index within a given country, $q = 1, \dots, I$
- j : country (market) index, $j = 1, \dots, J$
- t : time period, $t = 1, \dots, T$
- z : number of subassemblies produced at the same plant index,
 $z = 1, \dots, I$

Parameters

- V_{im} : unit variable production cost of subassembly i produced in
country m ,
- v_k : unit variable assembly cost at a DC in country k ,
- F_m : annual fixed cost of operating a subassembly plant in country
 m (base cost),

- f_m : annual fixed cost per square foot of operating a plant in country m (linear component),
 B_{zm} : annual fixed cost of producing the z -th subassembly in the same plant in country $m, z = 2, \dots, I$ (B_{zm} is increasing in z),
 U_k : annual fixed cost of operating a DC in country k (base cost),
 u_k : annual fixed cost of operating a DC in country k (linear component),
 K_{im} : maximum capacity (in units) of a production line for subassembly i in country m ,
 C_m : maximum capacity (in square feet) of a subassembly plant built in country m ,
 c_k : maximum capacity (in units) of a DC built in country k ,
 G_{im} : space requirement (in square feet) per unit of a production line for subassembly i in m ,
 E_{im} : investment cost for equipment to build a production line for subassembly i in m (base investment),
 e_{im} : investment cost per unit for equipment to build a production line for subassembly i in m (linear component),
 A_m : investment cost for land and building to build a subassembly plant in country m (base investment),
 a_m : investment cost per square foot for land and building to build a plant in country m (linear component),
 H_k : investment cost to build a DC in country k (base investment),
 h_k : investment cost per unit to build a DC in country k (linear component),
 S_{kj} : cost to ship one unit of the final product from a DC in country k to market j (shipment costs include any assessed trade tariffs and other duties),
 $\lambda_i S_{mk}$: cost to ship one unit of subassembly i from country m to country k (i.e., subassembly transportation cost is expressed as a fraction of the transportation cost of the final product, with λ_i the fraction for subassembly i),
 D_{jt} : demand of the final product in country j in period t ,
 r_n : per-period interest rate on the loan in country n ,

- $R(r_n, T)$: loan payment factor given interest rate r and planning horizon T ,
- $\rho_t(r_n, T)$: interest calculation factor for period t given interest rate r and planning horizon T ,
- τ_n : marginal corporate income tax rate in country n ,
- P_j : sales price of the final product (translated into dollars with real exchange rate) in country j ,
- p_{imk} : transfer price of subassembly i made in country m shipped to DC in country k ,
- d_{nt} : applicable depreciation rate in country n in period t (% per period),
- β_n : discount rate of after tax cash flows in country n ,
- l_n : maximum loan that country n can give to the firm.

Decision variables

- X_{imqkt} : units of subassembly i made in country m at plant q and assembled in country k during t ,
- x_{kjt} : units assembled at a DC in country k and sold in market j during t ,
- L_n : the loan that the company will take from the country n government for investment in n ,
- Z_{imq} : 1 if a production line for subassembly i is built in country m at plant q , and 0 otherwise,
- Y_{zmq} : 1 if a z -th subassembly is produced in country m at plant q , and 0 otherwise,
- y_k : 1 if a DC is operated in country k , and 0 otherwise,
- W_{imq} : size (in units) of production line i built in country m at plant q ,
- Q_{mq} : size (in square feet) of plant q in country m ,
- w_k : size (in units) of a DC operated in country k .

Revenue from units assembled and subassemblies produced in country n in period t :

$$\alpha_{nt} = \sum_{j=1}^J P_j x_{njt} + \sum_{i=1}^I \sum_{q=1}^I \sum_{k=1}^N p_{ink} X_{inqkt} \quad (\text{A.1})$$

Variable production costs and cost of goods sold in country n in period t :

$$\delta_{nt} = \sum_{j=1}^J v_n x_{njt} + \sum_{i=1}^I \sum_{m=1}^N \sum_{q=1}^I p_{imn} X_{imqnt} + \sum_{i=1}^I \sum_{q=1}^I \sum_{k=1}^K V_{in} X_{inqkt} \quad (\text{A.2})$$

Annual fixed costs of a DC and subassembly plants in country n :

$$\gamma_n = U_n y_n + u_n w_n + \sum_{q=1}^I \left(F_n Y_{1nq} + f_n Q_{nq} + \sum_{z=2}^I B_{zn} Y_{znq} \right) \quad (\text{A.3})$$

Transportation costs from facilities (plants and DCs) located in country n in period t :

$$\eta_{nt} = \sum_{j=1}^J S_{nj} x_{njt} + \sum_{i=1}^I \sum_{q=1}^I \sum_{k=1}^N \lambda_i S_{nk} X_{inqkt} \quad (\text{A.4})$$

Loan payment in country n in period t :

$$\varphi_{nt} = L_n R(r_n, T) \quad (\text{A.5})$$

Loan interest payment in country n in period t :

$$\varphi'_{nt} = L_n \rho_t(r_n, T) \quad (\text{A.6})$$

Investment cost in country n :

$$\begin{aligned} \xi_n = & H_n y_n + h_n w_n + \sum_{q=1}^I (A_n Y_{1nq} + a_n Q_{nq}) \\ & + \sum_{i=1}^I \sum_{q=1}^I (E_{in} Z_{inq} + e_{in} W_{inq}) \end{aligned} \quad (\text{A.7})$$

Depreciation expense in country n in period t :

$$\psi_{nt} = \xi_n d_{nt} \quad (\text{A.8})$$

Before-tax income in country n in period t :

$$\pi_{nt} = \alpha_{nt} - (\delta_{nt} + \gamma_n + \eta_{nt} + \varphi'_{nt} + \psi_{nt}) \quad (\text{A.9})$$

Corporate income tax paid in country n in period t :

$$\omega_{nt} = \pi_{nt}\tau_n \quad (\text{A.10})$$

Cash expenditures in fixed assets in year 0 that are not financed by external sources:

$$\mu = \sum_{n=1}^N (\xi_n - L_n) \quad (\text{A.11})$$

So the objective function which maximizes the net present value is:

$$\text{OBF} = \max \left[\sum_{n=1}^N \sum_{t=1}^T (\pi_{nt} + \varphi'_{nt} + \psi_{nt} - \varphi_{nt} - \omega_{nt}) / (1 + \beta_n)^t \right] - \mu \quad (\text{A.12})$$

Demand constraints:

$$\sum_{k=1}^N x_{kjt} \leq D_{jt}, \quad \forall j, t \quad (\text{A.13})$$

Subassembly Line Capacity:

$$\sum_{k=1}^N X_{imqkt} \leq W_{imq}, \quad \forall i, m, q, t \quad (\text{A.14})$$

$$W_{imq} \leq K_{im} Z_{imq}, \quad \forall i, m, q \quad (\text{A.15})$$

$$\sum_{q=1}^I Z_{imq} \leq 1, \quad \forall i, m \quad (\text{A.16})$$

$$\sum_{i=1}^I Z_{im(q+1)} \leq \sum_{i=1}^I Z_{imq}, \quad \forall m, q < I \text{ (for solution efficiency)} \quad (\text{A.17})$$

$$Z_{imq} = 0 \forall i, m, q > i \text{ (for solution efficiency)} \quad (\text{A.18})$$

Plant Capacity Constraints:

$$\sum_{i=1}^I G_{im} W_{imq} \leq Q_{mq} \forall m, q \quad (\text{A.19})$$

$$Q_{mq} \leq C_m Y_{1mq} \forall m, q \quad (\text{A.20})$$

$$Y_{1m(q+1)} \leq Y_{1mq} \forall m, q < I \text{ (for solution efficiency)} \quad (\text{A.21})$$

DC capacity constraints:

$$\sum_{j=1}^J x_{kjt} \leq \omega_k \forall k, t \quad (\text{A.22})$$

$$\omega_k \leq c_k y_k \forall n \quad (\text{A.23})$$

Conservation of Subassembly Flows:

$$\sum_{m=1}^N \sum_{q=1}^I X_{imqkt} = \sum_{j=1}^J x_{kjt, \forall i, k, t} \quad (\text{A.24})$$

Loan Ceilings:

$$L_n \leq l_n \forall n \quad (\text{A.25})$$

$$L_n \leq \xi_n, \forall n, \omega_k \leq c_k y_k, \forall n \quad (\text{A.26})$$

Nonnegative profit in each country in each period (assumption of convenience to avoid unnecessarily complicated tax calculations):

$$\pi_{nt} \geq 0, \forall n, t \quad (\text{A.27})$$

Count the number of different subassemblies produced at each plant:

$$\sum_{i=1}^I Z_{imq} = \sum_{i=1}^I Y_{zmq} \forall m, q \quad (\text{A.28})$$

$$Y_{(z+1)mq} \leq Y_{zmq} \forall x \neq I, m, q \quad (\text{A.29})$$

References

- [1] V. Babich, A. N. Burnetas, and P. H. Ritchken, “Competition and diversification effects in supply chains with supplier default risk,” *Manufacturing & Service Operations Management*, vol. 9, pp. 123–146, 2007.
- [2] Y. Bassok and R. Akella, “Ordering and production decisions with supply quality and demand uncertainty,” *Management Science*, vol. 37, pp. 1556–1574, 1991.
- [3] E. Berk and A. Arreola-Risa, “Note on ‘Future Supply Uncertainty in EOQ Models’,” *Naval Research Logistics*, vol. 41, no. 1, pp. 129–132, 1994.
- [4] J. Blackhurst, , C. W. Craighead, D. Elkins, and R. B. Handfield, “An empirically derived agenda of critical research issues for managing supply-chain disruptions,” *International Journal of Production Research*, vol. 43, pp. 4067–4081, 2005.
- [5] J. R. Bradley, “The complexity of assessing supply chain risk,” *Working Paper, College of William & Mary*, 2008.
- [6] B. Bundschuh, D. Klabjan, and D. L. Thurston, “Modeling robust and reliable supply chains,” *Optimization Online e-print; www.optimization-online.org*, 2003.
- [7] G. J. Burke, J. Carrillo, and A. J. Vakharia, “Sourcing decisions under stochastic supplier reliability and uncertain demand,” *Production & Operations Management*, vol. in press, 2009.
- [8] S. Chopra, G. Reinhardt, and U. Mohan, “The importance of decoupling recurrent and disruption risks in a supply chain,” *Naval Research Logistics*, vol. 54, pp. 544–555, 2007.

- [9] M. Christopher and H. L. Lee, "Mitigating supply chain risk through improved confidence," *International Journal of Physical Distribution & Logistics Management*, vol. 34, no. 5, pp. 388–396, 2004.
- [10] W. J. Elmaghraby, "Supplier contract competition and sourcing policies," *Manufacturing & Service Operations Management*, vol. 2, pp. 350–371, 2000.
- [11] M. N. Faisal, D. K. Banwet, and R. Shankar, "Supply chain risk mitigation: Modeling the enablers," *Business Process Management Journal*, vol. 12, no. 4, pp. 535–552, 2006.
- [12] M. A. Fisher, "What is the right supply chain for your product?," *Harvard Business Review*, vol. 75, no. 2, pp. 1–11, 1997.
- [13] G. Gallego and I. Moon, "The distribution free newsboy problem: Review and extensions," *Journal of the Operational Research Society*, vol. 8, pp. 825–835, 1993.
- [14] R. Gaonkar and N. Viswanadham, "Robust supply chain design: A strategic approach for exception handling," in *Proceedings of the 2003 IEEE International Conference on Robotics and Automation*, (Taipei, Taiwan), pp. 1762–1767, September 2003.
- [15] S. C. Graves and B. T. Tomlin, "Process flexibility in supply chains," *Management Science*, vol. 49, pp. 907–919, 2003.
- [16] H. Gurnani, R. Akella, and J. Lehoczky, "Supply management in assembly systems with random yield and random demand," *IIE Transactions*, vol. 32, pp. 701–714, 2000.
- [17] T. V. Hale and C. R. Moberg, "Improving supply chain disaster preparedness: A decision process for secure site location," *International Journal of Physical Distribution & Logistics Management*, vol. 35, no. 3, pp. 195–207, 2005.
- [18] K. B. Hendricks and V. R. Singhal, "The effect of supply chain glitches on shareholder wealth," *Journal of Operations Management*, vol. 21, pp. 501–522, 2003.
- [19] K. B. Hendricks and V. R. Singhal, "Association between supply chain glitches and operating performance," *Management Science*, vol. 51, pp. 695–711, 2005.
- [20] K. B. Hendricks and V. R. Singhal, "An empirical analysis of the effect of supply chain disruptions on long-run stock price performance and equity risk of the firm," *Production & Operations Management*, vol. 14, pp. 35–52, 2005.
- [21] W. J. Hopp and Z. Yin, "Protecting supply chain networks under catastrophic failures," *Working Paper, Northwestern University*, 2006.
- [22] P. Kelle and E. A. Silver, "Decreasing expected shortages through order splitting," *Engineering Costs & Production Economics*, vol. 19, pp. 351–357, 1990.
- [23] P. R. Kleindorfer and G. H. Saad, "Managing disruption risks in supply chains," *Production & Operations Management*, vol. 14, no. 1, pp. 53–68, 2005.
- [24] P. Kouvelis and P. Su, "The structure of global supply chains: The design and location of sourcing, production, and distribution facility networks for global markets," *Foundation and Trends in Technology, Information, and Operations Management*, vol. 1, no. 4, pp. 233–374, 2005.
- [25] H. L. Lee, "Aligning supply chain strategies with product uncertainties," *California Management Review*, vol. 44, p. 105, 2002.
- [26] H. L. Lee, "The triple a supply chain," *Harvard Business Review*, vol. 83, no. 10, pp. 1–11, 2004.

- [27] I. Manuj and J. T. Mentzer, "Global supply chain risk management strategies," *International Journal of Physical Distribution & Logistics Management*, vol. 38, no. 3, pp. 192–223, 2008.
- [28] A. McKinnon, "Life without trucks: The impact of a temporary disruption of road freight transport on a national economy," *Journal of Business Logistics*, vol. 27, no. 2, pp. 227–251, 2006.
- [29] S. Minner, "Multiple-supplier inventory models in supply chain management: A review," *International Journal of Production Economics*, vol. 81/82, pp. 265–279, 2003.
- [30] A. Norrman and U. Jansson, "Ericsson's proactive supply chain risk management approach after a serious sub-supplier accident," *International Journal of Physical Distribution & Logistics Management*, vol. 34, no. 5, pp. 434–456, 2004.
- [31] M. Parlar and D. Berkin, "Future supply uncertainty in EOQ models," *Naval Research Logistics*, vol. 38, no. 1, pp. 107–121, 1991.
- [32] H. Peck, "Drivers of supply chain vulnerability: An integrated framework," *International Journal of Physical Distribution & Logistics Management*, vol. 35, no. 4, pp. 210–232, 2005.
- [33] R. V. Ramasesh, J. K. Ord, J. C. Hayya, and A. Pan, "Sole versus dual sourcing in stochastic lead time (s,Q) inventory models," *Management Science*, vol. 37, pp. 428–443, 1991.
- [34] A. M. Ross, R. Rong, and L. V. Snyder, "Supply disruptions with time-dependent parameters," *Computers and OR*, vol. 35, no. 11, pp. 3504–3529, 2008.
- [35] Y. Sheffi, "Supply chain management under the threat of international terrorism," *International Journal of Logistics Management*, vol. 12, no. 1, pp. 1–11, 2002.
- [36] Y. Sheffi, *The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage*. Cambridge, MA: MIT Press, 2005.
- [37] Y. Sheffi and J. Rice, "A supply chain view of the resilient enterprise," *Sloan Management Review*, vol. 47, no. 1, pp. 41–48, 2005.
- [38] L. V. Snyder and M. S. Daskin, "Models for reliable supply chain network design," in *Reliability and Vulnerability in Critical Infrastructure: A Quantitative Geographic Perspective*, (A. T. Murray and T. H. Grubescic, eds.), New York, NY: Springer, 2006.
- [39] L. V. Snyder, M. P. Scaparra, M. S. Daskin, and R. L. Church, "Planning for disruptions in supply chain networks," in *Tutorials in Operations Research*, (M. P. Johnson, B. Norman, and N. Secomandi, eds.), Providence, RI: INFORMS, 2006.
- [40] L. V. Snyder and Z. J. M. Shen, "Supply and demand uncertainty in multi-echelon supply chains," *Working Paper, Lehigh University*, 2006.
- [41] C. Tang and B. Tomlin, "The power of flexibility for mitigating supply chain risks," *International Journal of Production Economics*, 2008.
- [42] B. Tomlin, "On the value of mitigation and contingency strategies for managing supply chain disruption risks," *Management Science*, vol. 52, pp. 639–657, 2006.
- [43] B. Tomlin, "Disruption-management strategies for short life-cycle products," *Working Paper, University of North Carolina*, 2008.

- [44] B. Tomlin, "The impact of supply learning when suppliers are unreliable," *Manufacturing & Service Operations Management*, *in press*, 2008.
- [45] B. Tomlin and L. V. Snyder, "On the value of a threat advisory system for managing supply chain disruptions," *Working Paper, University of North Carolina*, 2008.
- [46] B. Tomlin and Y. Wang, "On the value of mix flexibility and dual sourcing in unreliable newsvendor networks," *Manufacturing & Service Operations Management*, vol. 7, no. 1, pp. 37–57, 2005.
- [47] C. J. Vidal and M. Goetschalckx, "Modeling the effect of uncertainties on global logistics systems," *Journal of Business Logistics*, vol. 21, no. 1, pp. 95–120, 2000.
- [48] S. M. Wagner and C. Bode, "An empirical examination of supply chain performance along several dimensions of risk," *Journal of Business Logistics*, vol. 29, no. 1, pp. 307–325, 2008.
- [49] Y. Wang, W. Gilland, and B. Tomlin, "Regulatory trade risk and supply chain strategy," *Working Paper, University of North Carolina*, 2008.
- [50] H. J. Weiss and E. C. Rosenthal, "Optimal ordering policies when anticipating a disruption in supply or demand," *European Journal of Operational Research*, vol. 59, pp. 370–382, 1992.
- [51] M. C. Wilson, "The impact of transportation disruptions on supply chain performance," *Transportation Research*, vol. 43, pp. 295–320, 2007.
- [52] C. A. Yano and H. L. Lee, "Lot sizing with random yields: A review," *Operations Research*, vol. 43, pp. 311–334, 1995.
- [53] G. A. Zsidsin, "Business and supply chain continuity," *Critical Issues Report; www.capsresearch.org*, 2007.