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CONCEPTUAL NOTE

The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities

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ABSTRACT

Supply chain disruptions and the associated operational and financial risks represent the most pressing concern facing firms that compete in today's global marketplace. Extant research has not only confirmed the costly nature of supply chain disruptions but has also contributed relevant insights on such related issues as supply chain risks, vulnerability, resilience, and continuity. In this conceptual note, we focus on a relatively unexplored issue, asking and answering the question of how and why one supply chain disruption would be more severe than another. In doing so, we argue, de facto, that supply chain disruptions are unavoidable and, as a consequence, that all supply chains are inherently risky. Employing a multiple-method, multiple-source empirical research design, we derive novel insights, presented as six propositions that relate the severity of supply chain disruptions (i) to the three supply chain design characteristics of density, complexity, and node criticality and (ii) to the two supply chain mitigation capabilities of recovery and warning. These findings not only augment existing knowledge related to supply chain risk, vulnerability, resilience, and business continuity planning but also call into question the wisdom of pursuing such practices as supply base reduction, global sourcing, and sourcing from supply clusters.

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INTRODUCTION

Supply chain disruptions are unplanned and unanticipated events that disrupt the normal flow of goods and materials within a supply chain (Svensson, 2000; Hendricks & Singhal, 2003; Kleindorfer & Saad, 2005) and, as a consequence, expose firms within the supply chain to operational and financial risks (Stauffer, 2003). The 2002 longshoreman union strike at a U.S. West Coast port, for example, interrupted transshipments and deliveries to many U.S.-based firms, with port operations and schedules not returning to normal until 6 months after the strike had ended (Cavinato, 2004). Likewise, the lightning bolt that, in March 2000, struck a Philips semiconductor plant in Albuquerque, New Mexico, created a 10-minute blaze that contaminated millions of chips and subsequently delayed deliveries to its two largest customers—Finland's Nokia and Sweden's Ericsson (Latour, 2001).

The inconvenience to firms expecting to ship or to receive goods and materials is, however, not the entire story; disruptive events within a supply chain can also significantly and negatively impact the financial bottom line for affected entities in the supply chain. Publicly traded firms experiencing supply chain disruptions, for example, have reported negative stock market reactions to announcements of such disruptive events, with the magnitude of the decline in market capitalization being as large as 10% (Knight & Pretty, 1996; Hendricks & Singhal, 2003, 2005). As a matter of fact, Ericsson reported a $400 million loss because it did not receive chip deliveries from the Philips plant in a timely manner (Latour, 2001). Although the true costs of any supply chain disruption can be difficult to quantify precisely, at least one firm surveyed by Rice and Caniato (2003) estimated that the daily cost impact of a disruption in its supply network to be in the neighborhood of $50-$100 million.

Because a supply chain disruption can potentially be so harmful and costly, there has been, not surprisingly, a recent surge in interest and publications—from academics and practitioners alike—regarding supply chain disruptions and related issues. Table 1 provides an exemplary, as opposed to an exhaustive, listing of recent publications about supply chain disruptions. For example, besides classifying supply chain risks into different categories (two of which, namely disruptions and delays, are consistent with what we have defined as supply chain disruptions), Chopra and Sodhi (2004) also identified drivers of these different risk categories and discussed how risk mitigation strategies might reduce one type of risk but at the same time increase another type of risk. Kleindorfer and Saad (2005), another example, developed a conceptual framework subsuming 10 principles for managing risks of supply chain disruptions.

Extant research, therefore, has not only confirmed the costly nature of supply chain disruptions but has also contributed relevant insights pertaining to such related issues as supply chain risks (e.g., Chopra & Sodhi, 2004), vulnerability (e.g.,

Table 1: An exemplary review of literature related to supply chain disruptions.

Article Year	Authors	Research Focus
2000	Applequist, Pekny, & Reklaitis	Develops a metric for evaluating supply chain projects with significant risk. The measure quantifies a risk premium used to measure return and risk on an investment in comparison with other investments.
2001	Johnson	Enumerates lessons learned from managing supply chain risk in the toy industry. Risk mitigation techniques are presented in terms of managing demand and managing supply.
	Sheffi	Discusses supply chain investments and re-organization needed to prepare for terror attacks in terms of the challenges of dealing with the aftermath of a terror attack and managing supply chains with increased uncertainty.
2003	Mitroff & Alpasan	Presents recommendations for proactive preparation of intentional attacks.
	Rice & Caniato	Discusses the need for security and resilience in a supply chain and ideas to develop more secure and resilient supply chains.
	Zsidisin & Ellram	Considers the influences of inbound supply chain risk and techniques to deal with these risks based on the results of a survey.
2004	Cavinato	Focuses on logistics risk in a supply chain and discusses the broadening definition of risk.
	Chopra & Sodhi	Presents a high level categorization of supply chain risks and their drivers with recommendations to improve risk preparedness.
	Sinha, Whitman, & Malzhan	Develops a methodology to mitigate risk in an aerospace supply chain based on a five-step IDEF0 model.
	Zsidisin, Ellram, Carter, & Cavinato	Presents findings of an empirical study on how purchasing organizations assess risk.
	Hallikas, Karvonen, Pulkkinen, Virolainen, & Tuominen	Discusses a general risk management process for supplier networks.
2005	Kleindorfer & Saad	Develops a conceptual framework for managing supply chain disruption risk that includes the tasks of specification, assessment, and mitigation.
	Peck	Presents a framework for understanding supply chain vulnerability and a discussion of the drivers of vulnerability.
	Sheffi & Rice	Discusses the stages of a disruption and provides high-level recommendations for improving flexibility in the supply chain.
	Zsidisin, Melnyk, & Ragatz	Discusses the use of business continuity planning to manage purchasing and supply risk.
	Sodhi	Presents two risk measures (demand-at-risk and inventory-at-risk) and two linear programming models to be used together to manage demand and inventory risk in a consumer electronics supply chain.
2006	Tomlin	Develops a supply chain model to investigate mitigation and contingency strategies and recommends when to use them based on a firm with a single product and the option of two suppliers: one that is unreliable and the other that is reliable but more expensive.

Svensson, 2000), resilience (e.g., Sheffi & Rice, 2005), and business continuity planning (e.g., Zsidisin, Melnyk, & Ragatz, 2005). Yet one issue remains relatively unexplored—namely, how and why would one supply chain disruption be more severe than another? Formally, the *severity* of a supply chain disruption can be defined as the number of entities (or nodes) within a supply network whose ability to ship and/or receive goods and materials (i.e., outbound and inbound flow) has been hampered by an unplanned, unanticipated event. A more severe supply chain disruption would, therefore, have more far-reaching and financially devastating impact within a supply network than one that is relatively less severe.

By posing and seeking answers to this two-part research question, we argue, de facto, that supply chain disruptions are unavoidable and, as a consequence, that all supply chains are inherently risky. In this conceptual note, we intend, therefore, to derive informative insights that would sensitize firms to specific factors that either contribute to or conversely dampen the severity of a supply chain disruption. These factors could, in turn, be taken into consideration when firms make decisions as to whether or not to enact or implement specific operational and supply chain policies, practices, and initiatives. Policies, practices, and initiatives that would inherently bolster the presence of factors contributing to the severity of a supply chain disruption can be avoided, whereas those that would lessen supply chain disruption severity can be pursued.

Given this intent, we purposively engaged in an exploratory, three-phased empirical study involving multiple sources of data and multiple data collection methods. By using multiple sources and multiple methods, we intend to reduce the potential for single-source bias and for common-method bias (Crampton & Wagner, 1994; Doty & Glick, 1998). Moreover, to the extent that different data sources lead to convergent findings and conclusions, this approach would substantially enhance the credibility of the findings and conclusions and would make derivative pragmatic advice even more valid and useful.

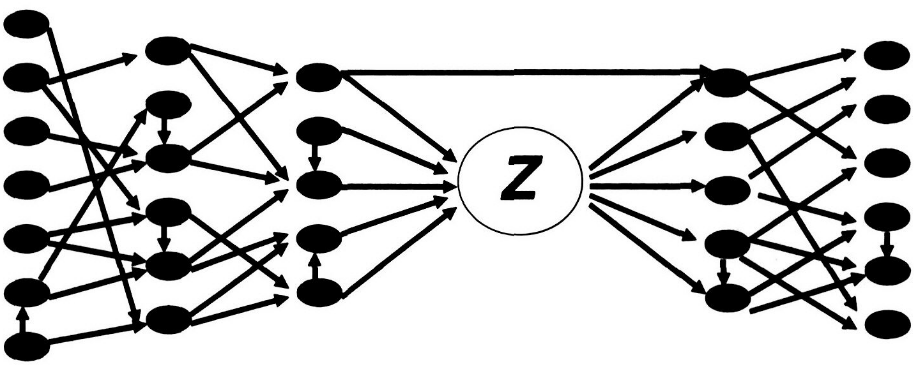
In the next section, we provide a brief introduction to what a supply chain is and how supply chains can be described. This provision would, in the worst case, correct for misconceptions and, in the best case, standardize the lexicon for describing supply chains and facilitate the latter presentation and discussion of the research findings.

SUPPLY CHAIN STRUCTURE

A supply chain (or, to be more accurate, supply network) comprises different entities that are connected by the physical flow of materials. These different entities, generically referred to as nodes in graph lexicon, are involved in the conversion, the logistics (i.e., warehousing, transportation, etc.), or the selling of materials (i.e., raw materials, work in progress, and finished goods), with the materials reaching final customers in some desired form and quantity. Relationships among nodes, in graph lexicon, are generally denoted by arcs and depicted as unidirectional or bidirectional arrows signaling the flow of materials.

A complete depiction of a supply chain would ideally identify all organizational entities (i.e., nodes) and all internode relationships (i.e., arcs) between some specified point of origin and the point of final consumption. While it is theoretically

Figure 1: A typical supply chain for manufacturer Z.



possible to make this identification without reference to any vantage point, it is more common that this be undertaken from the vantage point of a specific entity within the supply chain. Figure 1, for example, shows the supply chain from the perspective of a fictitious manufacturer, Z, and includes the various layers of suppliers that flow materials into and through Z and the various layers of distribution that flow materials away from Z toward the end customer. Together, this set of nodes and the associated pattern of arcs among these nodes for Z can be referred to as Z's supply chain design.

Because nodes and arcs are constitutional elements of supply chain design, supply chain designs can be usefully compared and contrasted by observing supply chain design characteristics that reflect differences in the numbers of nodes and/or in the patterns of arcs. Such a contrast and comparison could facilitate the identification and definition of structural and infrastructural differences across supply chains that, in turn, shed insights into why certain supply chain disruptions would be more damaging than others.

Moreover, because nodes depict organic entities (i.e., firms), they exhibit purposeful behavior via decisions and actions that they take. For example, Z may decide to replace a poorly performing supplier with another supplier. Likewise, Z could renege on its delivery promise to its immediate customers or increase its capacity by outsourcing some production to a contract manufacturer. In either example, the decisions and associated actions lead to either the maintenance of, or an alteration of, the nature of arcs leading into and/or emanating from particular nodes and, consequently, a restructuring of the essence of the supply chain itself.

DATA SOURCES, COLLECTION METHODS, AND ANALYSES

A three-phase empirical study involving different data sources and data collection methods was implemented, with the overarching aim being the identification and definition of the various factors that could contribute to or could dampen the severity of supply chain disruptions. In Phase One, we studied, in relatively great detail, the global supply chain of a U.S-based automobile manufacturer (Table 2). By focusing on a single firm and its supply chain, we sought depth of information pertaining to

Table 2: AUTO and its supply chain—data sources, data collection methods, and data content.

Supply Chain Entity	Data Source	Data Collection Methods	Data Content
AUTO (Original)	Key Informants	Semi-structured telephone and face-to-face interviews with: • VP of Worldwide Purchasing • Worldwide Purchasing Manager • Enterprise Risk Analyst • International Logistics Leader • Director of Supply Chain Planning • Supply Operations Manager • Purchasing Research Engineer Interviews generally lasted between 45 and 90 minutes per key informant.	• Characteristics that make a disruption severe; characteristics that amplify the potential for/impact of a disruption; disruption discovery and mitigation strategies; and barriers to, and enablers of, disruption recovery • Risk assessment, classification, and management • Management of supply chain disruptions
	Archival Records	Presentations by: • Supply Operations Manager • Two Purchasing Research Engineers • Enterprise Risk Analyst	• Global procurement process and strategy • Risk management program
First-Tier Supplier (South Korea)	Key Informant	Semi-structured telephone and face-to-face interviews with Account Manager for AUTO	• Characteristics that make a disruption severe; characteristics that amplify the potential for/impact of a disruption; disruption discovery and mitigation strategies; and barriers to, and enablers of, disruption recovery
	Archival Records	Presentation by Account Manager for AUTO	• Product flow from supplier to AUTO • Management of supply chain disruptions
First-Tier Supplier (China)	Key Informant	Semi-structured telephone and face-to-face interviews with Account Manager for AUTO	• Characteristics that make a disruption severe; characteristics that amplify the potential for/impact of a disruption; disruption discovery and mitigation strategies; and barriers to, and enablers of, disruption recovery
	Archival Records	Presentation by Account Manager for AUTO	• Product flow from supplier to AUTO • Management of supply chain disruptions
Distribution Center	Key Informant	Written responses to interview questions from International Receiving Manager	• Characteristics that make a disruption severe; characteristics that amplify the potential for/impact of a disruption; disruption discovery and mitigation strategies; and barriers to, and enablers of, disruption recovery

Note: The identity of AUTO is withheld to preserve confidentiality.

the two-part question motivating this conceptual note. In executing the case study and adhering to the guidelines suggested in Yin (1994) and Eisenhardt (1989), we conducted semi-structured interviews, either face to face or via telephone, with key informants from different firms positioned along the supply chain, guided by the questions listed in Appendix A. All interview data were subsequently transcribed, validated, and coded. Additionally, as part of triangulation, we also collected and coded supporting documents in the form of informant presentations.

In Phase Two, we conducted semi-structured telephone interviews with high-level executives of nine firms in different industry sectors occupying different positions along a supply chain (Table 3). The interview questions submitted to the nine executives were identical to those used in Phase One (Appendix A). By focusing on different industry sectors, we sought breadth of information pertaining to the two-part research question. Per Eisenhardt (1989), we engaged in theoretical sampling in order to identify and select firms with a diverse set of supply chain and product flow characteristics. The intent with using theoretical sampling was to maximize the opportunity to observe relatively more complete and more robust insights pertaining to supply chain disruptions, their severity, and the factors that relate to their severity.

In the final phase, Phase Three, we facilitated three focus groups utilizing the critical incident technique (Flanagan, 1954), a systematic procedure for capturing characteristics relative to the success and/or failure of a specific task (Ronan & Latham, 1974). With these focus groups, we sought refinement of the answers to the two-part research question provided by data from Phases One and Two (Morgan, 1997). Procedurally, we asked the members of each focus group to describe (i) a specific supply chain disruption they deemed their firm handled well and (ii) a second critical incident where they deemed the firm's response to be less than desirable (see Appendix B for details).

Data from the three phases were analyzed following the three-step process defined by Miles and Huberman (1994). In Step One, we performed first-level coding to summarize and describe the data; in Step Two, we performed pattern coding to group similar codes and descriptions for the purpose of data reduction; and in Step Three, we formalized and systematized findings into propositions that explained why one supply chain disruption might be more severe than another.

The results of the three-step data analyses generated two major sets of propositions. The first set of three propositions relates specific supply chain design characteristics to the severity of supply chain disruptions, and the second set of two propositions relates specific supply chain mitigation capabilities to the severity of supply chain disruptions. The sixth and final proposition relates the severity of supply chain disruptions to the interaction between the set of three supply chain design characteristics and the set of two mitigation capabilities.

SUPPLY CHAIN DESIGN CHARACTERISTICS AND SUPPLY CHAIN DISRUPTION SEVERITY

Supply Chain Density

Analyses of the various data sources revealed supply chain density as a contributing factor to how severe a supply chain disruption could be. *Supply chain density*

Table 3: Interview participants—executives and firm profiles.

Firm	Executive Title	Profile
PHARMA: Pharmaceutical Manufacturer	Director of Global Distribution	• Global pharmaceutical company employing more than 100,000 employees and in the business of manufacturing prescription medication, vaccines, and consumer health products • Primary manufacturing facilities in the United Kingdom, Singapore, and Ireland • Supply chain is heavily regulated by governmental agencies.
LOGPRO1: Logistics Provider 1	Chief Operating Officer	• Global logistics provider offering warehousing, distribution, freight forwarding, and supply chain management solutions employing more than 10,000 employees • More than 300 warehouse and office locations
LOGPRO2: Logistics Provider 2	Manager of Latin American Operations	• Global door-to-door logistics provider present in 214 countries • Services range from individual package shipments to 3PL solutions.
MILCON: Military Contractor	Marketing Manager	• Global IT design and engineering firm for governmental missions such as national defense with more than 7,000 employees • More than 100 offices worldwide • Note: Study participant served 20 years in the military and responses reflect this perspective
RETAIL1: Retailer 1	Senior Manager, Import Operations	• Large U.S.-based retailer of mass merchandise with more than 1,200 stores in the U.S. • Imports 24% of goods from more than 60 countries (with an expected increase to 36% within 12 months) • Heavy seasonality in demand
RETAIL2: Retailer 2	Chief Logistics Officer	• Discount retailer with more than 25,000 employees in the U.S. • More than 2,000 store in the U.S. • Imports 50% of goods from overseas (with 80% of imports from China)
RETAIL3: Retailer 3	Vice President, International SC	• Large U.S.-based retailer with more than 1,500 stores in the U.S. • Imports 10% of goods from over 35 countries (with more than 80% from the Asia basin)
NUPOWER: Nuclear Energy Provider	Chemical Manager	• Energy company (nuclear power based) with more than 24,000 megawatts of generation capacity serving over 2.8 million customers
AIRLINE: Commercial Airline	Director of Fuels Management	• U.S.-based airline serving over 170 cities with a fleet of more than 800 aircraft • On an average day, AIRLINE will fly more than 2,600 flights and handle more than 290,000 pieces of luggage. • On a yearly basis, transports more than 80 million customers per year

connotes the geographical spacing of nodes within a supply chain, with supply chain density being inversely related to geographical spacing. Accordingly, when nodes within a supply chain are clustered closely together, as may be measured by the average inter-node distance, the particular supply chain can be described as being dense (i.e., having a high level of supply chain density). Conversely, when nodes with a supply chain are loosely clustered together, the particular supply chain can be described as being less dense (i.e., having a low level of supply chain density).

Consider, for example, two supply chains—X and Y. For the sake of simplicity, let us assume that both supply chains reside within the same geographical area (e.g., North America) and, as such, within the same geographical size. If one were to measure the distance between all pairs of nodes, sum these distances, and then take an average, one would then obtain an average of the geographical spacing between nodes within a supply chain. Hence, if the average inter-node distance for X were smaller than that of Y, then one could describe X as denser (i.e., having a higher level of supply chain density) than Y.

Supply chain density, as defined here, can also be used as a descriptor of the number of dense areas within a supply chain. That is, when entities within a supply chain reside in close proximity to one another within a geographical region, that specific portion of the supply chain (i.e., that region) can be deemed to be densely populated. In contrast, the larger the geographical spacing among entities within a specific portion of the supply chain, the less dense that portion would be.

A useful analogy to this intra-supply chain notion of supply chain density would be to compare and contrast a large metropolitan city (e.g., Chicago, Illinois, USA) to a small farming town (e.g., Ames, Iowa, USA). Because more people live in Chicago relative to Ames, the former can be described as densely populated (i.e., having a high level of density) while the latter can be described as sparsely populated (i.e., having a low level of density). In this respect, if supply chain X were to have a larger number of dense areas than Y, then one can describe X as having higher supply chain density than Y.

Supply chain density and the severity of supply chain disruptions

The severity of a supply chain disruption within a supply chain appears to be positively related to supply chain density. The Enterprise Risk Research Program Manager at an automobile manufacturing firm we studied (henceforth referred to as AUTO), for example, explained that the firm is more concerned with regional disruptions that affect a cluster of suppliers than with a disruption affecting any specific supplier. Likewise, the executives at several retailing firms, RETAIL1, RETAIL2, and RETAIL3 (see Table 3 for brief firm profiles), expressed concerns about supply chain disruptions that occur within specific regions of the world from which they source. With RETAIL2, the concern revolved around purchased items from China and the volatility of trade with China, whereas, with RETAIL 3, the concern revolved around labor strikes that interrupt work and exports from Italy during the summers. Similarly, the executive at a pharmaceutical firm, PHARMA, mentioned how cargo shipments on flights into the United States from Singapore were interrupted as a result of the war in Iraq:

> When Iraq was invaded by the [USA] there was an issue with product coming out of Singapore mainly because the flights from Singapore ... flew over the Middle East. So Singapore Airlines has to fly a more southern route ... and couldn't carry as much cargo, so capacity was down ...

RETAIL1, as a matter of fact, said that it uses a color-coding scheme to track the risk profiles of the different regions from which it sources:

> We do risk assessments in all our markets. We publish a report internally that gives us a risk assessment based on a traffic signal between red, yellow, and green. In green everything is fine ...

That supply chain density and the severity of a supply chain disruption are positively related makes logical sense. For a supply chain that has a low density level, the probability of a disruptive event affecting many entities within such a supply chain (i.e., more severe) is likely to be lower than in the case of a dense supply chain adversely affected by the same disruptive event. Hence:

P1: An unplanned event that disrupts a dense supply chain would be more likely to be severe than the same supply chain disruption occurring within a relatively less dense supply chain.

By extension, a supply chain disruption that affects a dense portion of a supply chain is likely to negatively impact more nodes than one affecting a less dense portion of the same supply chain. Indeed, this very logic explains why a tornado ripping through the downtown of a major city (not likely, by the way) would have a larger number of casualties and more structural damage than one plowing through cornfields with nary a town in sight. Hence:

$P1_{Corollary}$: An unplanned event that disrupts one or more dense portions of a supply chain would be more likely to be severe than the same supply chain disruption affecting relatively less dense portions of the same supply chain.

Supply Chain Complexity

A second and related factor contributing to how severe a supply chain disruption might potentially be is *supply chain complexity.* We define the complexity of a supply chain, consistent with other scholars (e.g., Choi & Krause, 2006), to be the sum of two components—the total number of nodes (N_{nodes}) and the total number of forward ($N_{forward}$), backward ($N_{backward}$), and within-tier materials flows ($N_{within\text{-}tier}$) within a given supply chain. Whereas forward flows denote the movement of materials from an upstream node to a downstream node, backward flows denote a reversal of materials flow from a downstream node to an upstream node (e.g., returns), and within-tier flows denote passing of materials between nodes in the same tier. Accordingly, a more complex supply chain would have a larger number of nodes and flows than one that is relatively less complex.

Two insights are evident from this definition. First, each node that is added to a given supply chain requires, at a theoretical minimum, one forward flow and one potential backward flow (assuming a defect rate > 0). The theoretical maximum per unit of addition is, of course, limited to $(N_{nodes}) \times [(N_{nodes}) - 1]$. Hence, when a firm decides to switch from sole sourcing to dual sourcing a particular item, it automatically increases the complexity of the supply chain in which it is embedded. Second, supply chain complexity has direct impact on coordination costs because more nodes and accompanying flows require greater effort at coordination within the supply chain. Hence, managing one supplier should be relatively easier and lower in coordination costs than managing two suppliers for the same item being sourced.

Supply chain complexity, as defined, can describe entire supply chains and be used informatively to compare and contrast one supply chain to another. However, as with density, complexity can also be an intra-supply chain property to describe portions of a supply chain such that one part of a supply chain can be deemed to be more complex than another part. Hence, for an automobile assembler, the portion of the supply chain corresponding to motor engines, for example, would be considered to be greater in complexity than the portion of the supply chain responsible for a molded plastic part.

Supply chain complexity and the severity of supply chain disruptions

Supply chain complexity and the severity of a supply chain disruption also appear to be positively related. Informants from AUTO, as well as the executives at two third-party logistics providers, LOGPRO1 and LOGPRO2, and those from RETAIL1, RETAIL2, RETAIL3, and PHARMA, all discussed the increasing complexity of their respective supply chains, particularly given their global outsourcing initiatives, and how this complexity makes them more vulnerable to disruptive events. For example, RETAIL3, which sources 9% of its products from overseas with 86% from Asia, commented that its entire supply chain is more prone to disruptive events. LOGPRO2, likewise, stated bluntly that:

> Complexity is critical.... The complexity of the supply chain is a key factor in disruptions.

Because complexity is a reflection of the nodes and flows within a given supply chain and, therefore, interdependencies among these nodes, a supply chain disruption at any node can potentially propagate, with the effects of the initial disruption being passed from one node to another connected node and so on. It is precisely this reasoning that prompted the AIRLINE executive to explain why delays at one airport, if not managed properly, can translate into delays at other airports:

> ...The original final destination is the primary area that will be affected by the disruption. Secondary locations will be discussed among the key players in the department. For example, one airport may be the primary location; however, if we pull supply from another unaffected location, that airport could eventually suffer a disruption.

In this respect, because a less complex supply chain would have structurally fewer internode dependencies defined by the various types of materials flows, the likelihood of a supply chain disruption propagating and become severe is reduced. Hence:

P2: An unplanned event that disrupts a complex supply chain would be more likely to be severe than the same supply chain disruption occurring within a relatively less complex supply chain.

Consistent with this logic, a disruption that affects a more complex portion of a given supply chain would likely have more nodes and flows affected than the same disruption affecting a less complex part of a given supply chain. Consider, for example, comparing a traffic accident in the middle of a major four-lane intersection with a large number of automobiles traveling in both a north–south and an east–west direction to a traffic accident occurring on a side road that is not frequently used. The resultant traffic jam in the former scenario would likely be more severe than that in the latter scenario. Hence:

$P2_{Corollary}$: *An unplanned event that disrupts one or more complex portions of a supply chain would be more likely to be severe than the same supply chain disruption affecting relatively less complex portions of the supply chain.*

Node Criticality

A third factor underscored by the various data sources as contributing to a supply chain disruption's severity level is node criticality. *Node criticality* can be more formally defined as the importance of a node within a supply chain and, as with density, can be used to characterize each specific node within a supply chain or, alternatively, a property of the entire supply chain.

Each node within a supply chain, in theory, should play a value-adding role and, as such, is important by nature. Even then, some nodes may be deemed to be more important than others, simply because of what they do and/or what their relative contribution is to value. For example, a node responsible for a critical component (e.g., critical supplier) would itself be more important (and, hence, more critical) than a node that handles a noncritical component. Alternatively, a node responsible for integrating many equally valued parts into a large component (e.g., subsystems supplier) would be more critical than one that integrates fewer parts of equal value. Similarly, a node that distributes materials to many other nodes within the same chain (e.g., distribution center) would be more critical than one that simply distributes materials to a few other nodes. The importance of a node (i.e., node criticality) is, therefore, context specific and relative to other nodes within a supply chain.

Node criticality can be extended to characterize an entire supply chain in terms of the number of critical nodes within the supply chain. A supply chain X with n nodes being deemed critical would, therefore, be structurally different than a supply chain Y, all else being equal, with m critical nodes where $m < n$. Supply chain X, as such, can be described quite simply as having more critical nodes than supply chain Y.

Node criticality and the severity of supply chain disruptions

The severity of a supply chain disruption also appears to be positively related to node criticality. The focus group participants generally agreed that sole supplier situations (i.e., the sole supplier would be a critical node) tend to be more risky and can lead to more severe disruptions for the supply chain. One participant recalled the case of a firm that sole sourced a particular component from a supplier who, in turn, had sole sourced a component part to a second-tier supplier. When outflow from the second-tier supplier was disrupted, the first-tier supplier was unable to deliver and meet its obligations to the firm. The firm eventually went out of business.

Several executives also recalled severe supply chain disruptions that arose from a node that had many outgoing paths emanating from it. LOGPRO1, for example, spoke of firms that depended on materials flowing through the customs checkpoint at the West Coast port and how the longshoremen strike at this port seriously affected the various firms. This same disruptive event proved to be less severe for RETAIL2, because it avoided dependence on the West Coast seaport by routing goods through other ports of entry:

> We knew that ILWU [International Longshore and Warehouse Union] was running into some problems so we diverted our Chicago freight early on even though it was more expensive to bring [freight] to the East Coast...

Last but not least, a node responsible for a major component of a product would become a critical node, especially when it is unable to respond quickly and flexibly to demand requirements from downstream nodes. For example, a participant who worked for an outdoors turf care company said:

> [The supplier] in Slovakia was unable to support market flexibility requirements ... we needed to "flex up" production but due to capacity constraints, manufacturing inflexibility, and transportation time, the Slovakian supplier could not adequately support this ... request ... we lost production since the supplier could not "flex up" as much as we needed...

When this happens, the financial consequences can be quite dramatic; both LOGPRO2 and PHARMA, for example, recalled how shortage of high-value or high-profit-margin raw materials negatively impacted sales. For this reason, MILCON, a global information technology design and engineering firm that contracts with the military, actually assigns codes to indicate the criticality of certain supplied items to particular military missions.

Logically, an event that disrupts a critical node can be expected to have more serious consequences than the same disruptive event occurring at a noncritical node. Hence:

P3: An unplanned event disrupting one or more critical nodes of a supply chain would be more likely to be severe than the same supply chain disruption affecting less critical nodes of the supply chain.

By extension, because materials within a supply chain flow from node to node, any disruptive event affecting a supply chain with many critical nodes can also be expected to be more severe than if it were to affect another supply chain with few critical nodes. This is because the critical node affected by a disruptive event would, in turn, propagate the effects of the initial disruption downstream to another critical node and so on, cumulating serious consequences across the entire supply chain as a result. Hence:

$P3_{Corollary}$: An unplanned event disrupting a supply chain with many critical nodes would be more likely to be severe than the same supply chain disruption occurring within a supply chain with few critical nodes.

SUPPLY CHAIN MITIGATION CAPABILITIES AND SUPPLY CHAIN DISRUPTION SEVERITY

Besides supply chain design characteristics, analyses of data from the three complementary sources revealed three supply chain mitigation capabilities that appear to affect how severe a supply chain disruption would be. By *mitigation capabilities*, we refer to "the organizational routines or regular and predictable patterns of activity ... [and] sequence of coordinated actions" (Grant, 1991, p. 122) that, when bundled with rent-yielding resources, enhance the abilities of the supply chain (i) to recover expediently from a manifested disruption and (ii) to create awareness of a pending or realized disruption.

Recovery Capability

One mitigation capability for supply chain disruptions to which the different data sources consistently alluded to is *recovery capability* or the interactions of supply chain entities and the corresponding coordination of supply chain resources to return the supply chain to a normal and planned level of product flow. These purposive interactions and coordination of resources allow interventions to be designed and implemented to overcome the slowing or stoppage of planned product flow within the supply chain.

Consider, for example, a situation in which Product P flows from node A to node B and then, in altered form, onward to nodes Z_1, Z_2, and Z_3. For the sake of demonstration, assume that inventory of Product P is held to a minimum across the nodes and that a power disruption shuts down manufacturing at A, effectively blocking all flows emanating from it and slowing (or completely stopping) the flow of Product P into B and, in turn, affecting the flow onward to Z_1, Z_2, and Z_3. In this case, from the standpoint of B, if Product P could be designed so that it could easily be rerouted to bypass A or if another source for Product P—for example, $A_{\text{Alternative}}$—could be contracted to readily step in for A, then the need for Product P (quantity and timing) could still be met at B and ultimately at Z_1, Z_2, and Z_3. To the extent that these interventions (i.e., rerouting, substitute source, etc.) were anticipated initially even before occurrence of a supply chain disruption at A, then the recovery capability could be considered to be proactive in nature. Conversely, if these interventions were undertaken after a disruption had already occurred, then the recovery capability would be considered to be reactive in nature.

Recovery capability and the severity of supply chain disruptions

The severity of a disruption appears to be negatively related to the presence of recovery capability (proactive, reactive, or both) within the supply chain. Informants from AUTO, the nine executives interviewed in Phase Two, and many of the participants in the focus groups agreed that, as recovery capability increases within a supply chain, the quicker the supply chain returns to normalcy postdisruption and the less severe the disruption will likely be. Hence, to the extent that resources and processes can be deployed and coordinated prior to, or right after, a supply chain disruption, the lower the downtime experienced by the supply chain will be.

For example, LOGPRO2 discussed the importance of strategically-placed excess transportation capacity (i.e., physical capital resources) within the supply chain:

> We have jets sitting all over the world ... empty ... poised in airports, strategically placed time-wise to recover freight all over the world ....

AUTO similarly stressed the importance of having seasoned managers trained to follow specific guidelines and procedures in handling supply chain disruptions (i.e., human capital resources), while RETAIL3 discussed the benefits of being able to deploy a command center at or near the origin of a supply chain disruption (i.e., organizational capital resources), and PHARMA pinpointed the placement of buffer inventory throughout the supply chain. RETAIL1, in greater detail, said:

> ...Knowing that there was potentially a disruption on the U.S. side of our business, in every port we operated in, I went out and leased anywhere from 30–50 chassis in every port and stuck them back in the corner lot. I paid for these chassis whether I was using them or not and for a long time people thought I was nuts because we are paying the rental fee for the chassis and nothing was happening.... By having these chassis, when we had a problem, we got our stuff out of the stacks and popped them on a chassis and we were able to keep working while other folks were just dying on the vine.

Resources and their availability are, of course, necessary, but resources, in and of themselves, are not sufficient to respond to supply chain disruptions. Equally important is the coordination of these resources, through communication and cooperation among nodes, so that an optimal response plan can be triggered. AIRLINE, for instance, argued that the:

> ... primary barriers to an effective disruption recovery are lack of communication and non-cooperation among suppliers and customers. To enable an effective recovery program, all parties need to communicate and cooperate. In recent disruptions, conference calls have been set up. Members will include all parties affected by the disruption. Calls were set up every 4–6 hours or as needed. The information passes on to everyone at once. All parties know what the suppliers are doing to recover and what the customers are doing to survive.

While such coordination among the supply chain entities in deploying these resources can be difficult to achieve, the acquisition or the development of a recovery capability can be expected to contribute to lessening the severity of supply chain disruptions. To quote LOGPRO2:

> We fail every day all over the world ... thousands of packages—but we have the best contingency planning in the world, so nobody ... knows ...

In an ideal scenario, the recovery capability residing with a supply chain should be proactive in nature, as in the case of RETAIL3, which re-routed its materials flow to other seaports prior to the West Coast strike of 2002. Such a proactive recovery capability is often cultivated by putting in place planned actions with several options that are triggered by specific disruptions. For example, at the nuclear facility, NUCPOWER, potential disruptive events are completely enumerated and mapped out, and pre-planned actions and procedures are defined to allow for a quick response should a disruption occur.

Alternatively, and in a less ideal scenario, a supply chain might not have a proactive recovery capability but might instead have a reactive recovery capability—one that allows the mustering and coordination of supply chain resources to respond to a disruptive event after the fact. While a reactive recovery capability could be less effective than a proactive recovery capability in avoiding and curtailing the propagation of a supply chain disruption, it is certainly better than not having any recovery capability at all.

In conclusion, we can, therefore, offer the following proposition relating recovery capability to the severity of a supply chain disruption:

P4: An unplanned event that disrupts a supply chain with the capability to proactively and/or reactively respond quickly and effectively to correcting the disruptive event is less likely to be severe than the same supply chain disruption affecting a supply chain with little or no capability to recover.

Warning Capability

Besides a recovery capability, another mitigation capability for supply chain disruptions to which the different data sources consistently alluded is the warning capability embedded within the supply chain. A *warning capability* can be more formally defined as the interactions and coordination of supply chain resources to detect a pending or realized disruption and to subsequently disseminate pertinent information about the disruption to relevant entities within the supply chain.

To illustrate, consider again the example of Product P above. Suppose now that a power overload at time T shuts down manufacturing at A, effectively stopping flow of Product P from nodes A to B. This supply chain, given the supposition, could be deemed to possess a warning capability to the extent that the disruptive event is detected prior to T, immediately at T, or even at t days after T and, moreover, that pertinent information about the pending or realized disruption is subsequently shared, as instantaneously as possible, with B, and, perhaps, even with Z_1, Z_2, and Z_3. Logically, a warning capability that could detect a supply chain disruption and communicate information about it before its manifestation (i.e., at time $< T$) or as close to its manifestation time (i.e., at time $= T$) would be more desirable than one that could only detect a supply chain disruption and make subsequent communications t days after T (i.e., at time $= T + t$ days).

However, the latter situation, while less desirable, may not be too disconcerting as long as t (i.e., the time increment after a disruption at T has occurred and has been communicated) is less than the amount of time that would have been originally planned for A to ship Product P to B. Hence, prior to the power overload at T, suppose the expectation had been set for Product P to arrive at B from A at time $= T + 10$ days. In this case, as long as $t < 10$ days, then B would have the opportunity, or more specifically $10 - t$ days, to search for and implement alternatives (i.e., to recover). In fact, as long as A is able to recover and re-establish the flow soon after detection at t days beyond T but significantly before $T + 10$ days, the opportunity for B to recover would remain.

Warning capability and the severity of supply chain disruptions

The severity of a supply chain disruption, therefore, appears to be negatively related to the warning capability present in the supply chain. In essence, the quicker a supply chain disruption is detected and the quicker that pertinent information about it is communicated, the more time the supply chain would have to inoculate itself from the negative effects of the disruption and the less severe a supply chain disruption would likely be. Indeed, informants from AUTO, the nine executives interviewed in Phase Two, and many of the participants in the focus groups stressed the importance of developing and possessing a warning capability within the supply chain.

AUTO, for example, lamented the fact that it did not have a warning capability that allowed it visibility beyond first-tier suppliers, prompting one informant at AUTO to complain:

> We spend effort to resolve ... [problems with supplier's suppliers] ... but we do not know what is going on! The lack of information makes it worse [since there is] lack of visibility into our supplier's supplier and where our inventory really is.

The LOGPRO1 executive, likewise, agrees fundamentally with the importance of having a warning capability within the supply chain to draw attention quickly to nodes where potential and realized disruptions occur:

> ... as a company, we move a billion boxes a year.... what we are really looking at is 10s of 20s of 30s of billions discrete events which have to be managed and all are subject to weather and disruptions.... it's all about trying to develop systems that allow you to go from the shipper's order system to the final destination as seamlessly as possible and with enough information to do exception reporting [i.e., warning signals] because no one can manage by looking at all the data every day. When a shipping vessel gets to be more than a day late, when trains are more than 6–12 hours late, when trucks are more than 2–4 hours late ... you have warning signals that go off that say "OK, let's look at the freight, let's look at what we have on that train that is now 12 hours late, and let's see what we need to do with those customers"...

For RETAIL1, the warning capability could be as simple as weekly notification updates by email:

> In my group, we require every office that does business with us overseas to send us a weekly update—and it's just an email. There is nothing fancy about it. It is an email communication from every country and ... they tell us of any carrier problems they are having, any port issues including congestions, labor disruptions, security related things, vendor problems, new legislations and an update from a political standpoint. So [if] there is something that is beginning to break that we would not have heard about because it is too small, ... this is a vehicle to give us a heads up and we can broadcast that to our network ...

Hence, as one informant at AUTO stated in explaining why a warning capability in the supply chain is a critical requirement, "Bad news needs to travel fast!" When it does, workflow stoppage could then be potentially avoided as when AUTO was able to avert production slowdown at its facility simply because it had quick notification of a riot affecting a supplier. Indeed, RETAIL2 similarly argued that a warning capability would allow visibility to certain events that take time to become disruptive, citing as an example the 2002 West Coast port strike. The labor issues that resulted in the strike did not happen overnight and had been visible for months ahead of time. RETAIL1, in fact, realizing that the West Coast port was a critical node in its supply chain and how crippling a strike at this port would be, had put in place a continual monitoring of the situation. This allowed RETAIL1 to proactively divert shipments of goods coming into the U.S. through another port instead of through the port where the strike occurred.

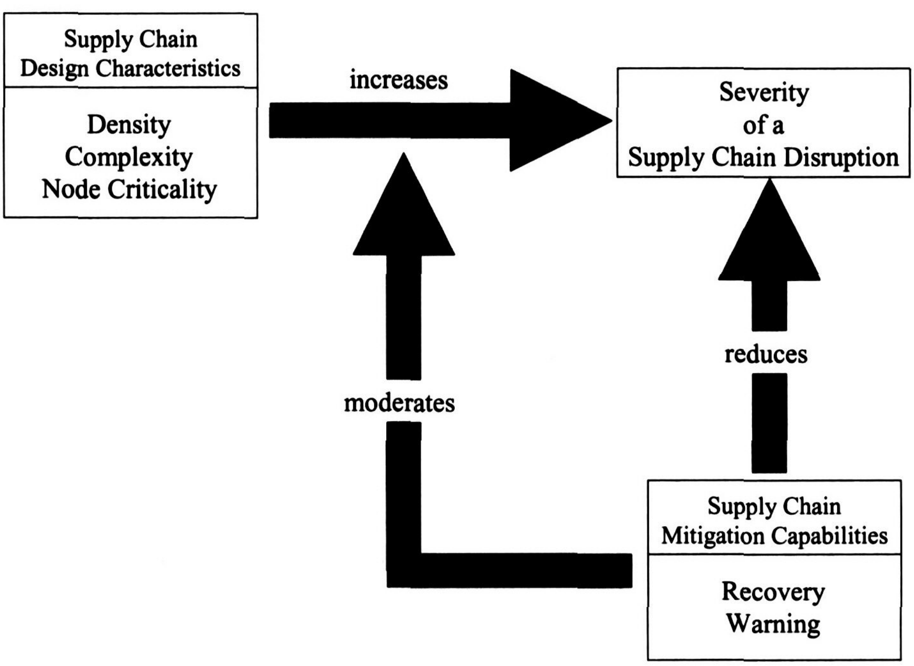
In conclusion, we can, therefore, offer the following proposition relating warning capability to the severity of a supply chain disruption:

P5: An unplanned event that disrupts a supply chain with the capability to quickly detect and disseminate pertinent information pertaining to the disruptive event is less likely to be severe than the same supply chain disruption affecting a supply chain with little or no capability to warn.

TOWARD A THEORETICAL SYNTHESIS

Figure 2 is a pictorial representation of the three propositions relating supply chain design characteristics and the two propositions relating supply chain mitigation capabilities to the severity of a supply chain disruption. In essence, supply chain density, complexity, and node criticality can be expected to be positively related to supply chain disruption severity (i.e., as the density, complexity, and node criticality

Figure 2: Theoretical synthesis.



of a supply chain increase, the potential severity of a supply chain disruption increases). Conversely, supply chain recovery and warning capabilities can be expected to be negatively related to supply chain disruption severity (i.e., as recovery and warning capabilities within a supply chain increase, the potential severity of a supply chain disruption reduces).

Moreover, as shown in Figure 2, supply chain mitigation capabilities and supply chain design characteristics, beyond their respective direct effects, can also interact in determining how severe a disruption would be within a supply chain. To be precise, we postulate that the supply chain mitigation capabilities of recovery and warning can moderate the impact that supply chain density, complexity, and node criticality have on supply chain disruption severity.

Consider, for example, a fire breaking out inside a plant that houses complicated, expensive, and difficult-to-replace manufacturing processes and equipment and that provides critical parts to many customers (i.e., the plant is a critical node). A fire that spreads quickly in such an environment would have the devastating effect of slowing or stopping flow of critical parts downstream. However, a fire alarm (i.e., warning capability) that detects a pile of rags smoldering when the fire is still in an infancy stage would be able to provide quick notification and to draw attention to this danger. Indeed, if such a fire detection system were tied to the sprinkler system (i.e., recovery capability), a sounded alarm could also activate the sprinkler system automatically and more immediately extinguish the fire before it grows into a difficult-to-control blaze. These warning and recovery capabilities would, therefore, play effective roles in preventing the fire from spreading quickly, destroying the plant, and disrupting flow of critical materials to the many customers downstream.

Hence, we can more formally articulate the interaction effects of supply chain mitigation capabilities and supply chain design characteristics on supply chain disruption severity as:

> *P6: An unplanned event disrupting a supply chain that is dense, complex, and with many critical nodes is less likely to be severe if the supply chain is embedded with the capability to quickly detect and disseminate pertinent information pertaining to the disruptive event and with the capability to proactively and/or reactively respond quickly and effectively to correct the disruptive event.*

DISCUSSION AND CONCLUSIONS

Firm survival in the modern business environment is no longer an issue of one firm competing against another firm but has, instead, become an issue of one supply chain competing against another supply chain (Fine, 1998). As such, that top executives at Global 1000 firms would consider supply chain disruptions and their associated operational and financial risks to be their single most pressing concern (Green, 2004) should not come as a surprise. Nor should the recent surge in academic and practitioner publications focusing on this concern be unexpected. Indeed, research on issues ranging from business continuity planning (e.g., Zsidisin, Melnyk, & Ragatz, 2005) to supply chain vulnerability (e.g., Svensson, 2000) to supply chain resilience (e.g., Sheffi & Rice, 2005) to supply chain risks (e.g., Chopra

& Sodhi, 2004) has not only confirmed the costliness of supply chain disruptions but has also contributed insights to this very concern. Despite the informative nature of this relevant literature base, our research has provided additional value to this body of knowledge and consequently to managerial decision making.

In this research, we adopted the perspective that all supply chains are inherently risky because all supply chains will experience, sooner or later, one or more unanticipated events that would disrupt normal flow of goods and materials. Consequently, we derived six propositions relating the severity of supply chain disruptions to the supply chain design characteristics of density, complexity, and node criticality and to the supply chain mitigation capabilities of recovery and warning. These six propositions augment extant knowledge as to what risk factors are present within a supply chain, how vulnerable a supply chain is to these risks, how resilient a supply chain is to some given risks, and what can be done to prevent or reduce the occurrences of severe supply chain disruptions. Further, the six propositions broaden the research agenda for supply chain disruptions to include the added content focus on what can be done to curtail the severity of supply chain disruptions when and if they do occur. Moreover, with the entire supply network as the unit of analysis, the six propositions represent a methodological departure from prior research on supply chain disruptions with the typical unit of analysis being specified as a firm or a function. As such, the research reported in this conceptual note essentially responds to the encouragement to consider the entire supply network the more appropriate unit of analysis for supply chain disruption research (Harland, Brenchley, & Walker, 2003) and for managers to move beyond individual firm and functional analyses to more systemic, holistic understanding of the network of nodes (Buhman, Kekre, & Singhal, 2005). Further, we believe that this network view has culminated in a solid basis for visual and spatial decision support tools, which could provide a visual tool for analysis and decision making (Mennecke, Crossland, & Killingsworth, 2000) relative to supply disruptions.

The six propositions offer enhanced guidance to help a firm systematically assess to what extent supply chain disruptions could be easily detected and dealt with by existing mitigation capabilities, what and where capability gaps exist within the supply chain, and what must be done by which supply chain entity to eliminate these capability gaps. In fact, when resources are scarce, the three supply chain design characteristics can serve to evaluate how these scarce resources should be rationed in efforts to develop, enhance, and/or locate warning and recovery capabilities within the supply chain.

The six propositions also offer guidance in evaluating specific supply chain decisions (e.g., switching suppliers or sole sourcing), not only in terms of their impact on the severity of supply chain disruptions but also in terms of what portions of a given supply chain would be exposed to the greatest risk as a result of such decisions. Indeed, the six propositions call into question the wisdom of adopting a number of publicly-proclaimed best practices in purchasing, including supply base reduction (e.g., Handfield & Nichols, 1999; Choi & Krause, 2006; Ogden, 2006), global sourcing (e.g., Trent & Monczka, 2003; Trent & Monczka, 2005), and sourcing from supply clusters (e.g., Wu, Yue, & Sim, 2006) without considering the impact of supply chain risk. The decision by a firm to pursue (i) supply base reduction increases node criticality; (ii) global sourcing increases complexity, and (iii) sourcing from supply clusters increases density, which, in turn, elevates the firm's exposure to severe supply chain disruptions. Therefore, while there is no dispute as to the efficiency gains possible from adhering to these best practices, the six propositions do raise serious concerns about the negative impact that these best practices might have on the severity of supply chain disruptions. On the other hand, by understanding the six propositions, managers can use this knowledge to lessen the exposure to severe disruptions even while employing these best practices. For example, a manager can avoid significant increases to node criticality even while fully employing a supplier reduction strategy. For example, if an item was sole sourced to a company that made the part at multiple nodes, the node criticality would not be higher (relatively speaking).

Moving forward, three potential research opportunities are noteworthy. A first and logical opportunity would be research seeking to test and validate the six propositions against other forms of data and research designs (e.g., large-scale studies utilizing the critical incident technique to systematically investigate differences between a supply chain disruption that is severe versus one that is not severe, simulation-based studies involving varying the levels of the three design characteristics and the two mitigation capabilities, and longitudinal field research tracking a supply chain disruption as it unfolds over time). To do so, the relevant constructs in the six propositions would have to operationally defined, which may, in turn, lead to an overall metric or profiling approach for quantifying supply chains. A second opportunity would be research investigating the nature of interactions among density, complexity, and node criticality and the extent to which these interactions, if any, increase or decrease the severity of supply chain disruptions. The aim of such research would be to go beyond main effects to determine whether or not, to what extent, how, and why the three supply design characteristics might compensate for one another relative to the severity of supply chain disruptions. Last but not least, a third opportunity would be research examining the dampening effects of specific forms of recovery capability (e.g., inventory buffering—how much and where within a supply chain) or warning capability (e.g., transportation planning systems, RFID) within a given supply chain design. Results from such research would prove useful in determining, within the supply chain, the type, level, and location of investments to allow for quick warning of and effective recovery from supply chain disruptions. [Received: August 2005. Accepted: January 2007.]

REFERENCES

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

Buhman, C., Kekre, S., & Singhal, J. (2005). Interdisciplinary and interorganizational research: Establishing the science of enterprise networks. *Production and Operations Management, 14*, 493–514.

Cavinato, J. L. (2004). Supply chain logistics risk. *International Journal of Physical Distribution & Logistics Management, 34*, 383–387.

Choi, T. Y., & Krause, D. R. (2006). The supply base and its complexity: Implications for transaction costs, risks, responsiveness, and innovation. *Journal of Operations Management, 24*, 637–652.

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

Crampton, S. M., & Wagner, J. A. (1994). Percept-percept inflation in microorganizational research: An investigation of prevalence and effect. *Journal of Applied Psychology, 79*, 67–76.

Doty, D. H., & Glick, W. H. (1998). Common methods bias: Does common methods variance really bias results? *Organizational Research Methods, 1*, 374–406.

Eisenhardt, K. (1989). Building theories from case study research. *Academy of Management Review, 14*, 532–550.

Fine, C. H. (1998). *Clockspeed: Winning industry control on the age of temporary advantage*. Reading, MA: Perseus Books.

Flanagan, J. (1954). The critical incident technique. *Psychological Bulletin, 51*, 327-359.

Grant, R. M. (1991). The resource-based theory of competitive advantage: Implications for strategy formulation. *California Management Review, 33*(3), 114–135.

Green, M. (2004). Loss/risk management notes: Survey: Executives rank fire, disruptions top threats. *Best's Review, 105*(5), 105.

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

Handfield, R., & Nichols, E. (1999). *Introduction to supply chain management*. Englewood Cliffs, NJ: Prentice Hall.

Harland, C., Brenchley, R., & Walker, H. (2003). Risk in supply networks. *Journal of Purchasing and Supply Management, 9*(2), 51–62.

Hendricks, K., & Singhal, V. (2003). The effect of supply chain glitches on shareholder wealth. *Journal of Operations Management, 21*, 501–522.

Hendricks, K., & Singhal, V. (2005). An empirical analysis of the effect of supply chain disruptions on long run stock price performance and equity risk of the firm. *Production and Operations Management, 14*(1), 35–52.

Johnson, M. E. (2001). Learning from toys: Lessons in managing supply chain risk from the toy industry. *California Management Review, 43*(3), 106–126.

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

Knight, R., & Pretty, D. (1996). The impact of catastrophes on shareholder value. In *The Oxford Executive Research Briefings*. Oxford, UK: Templeton College, University of Oxford.

Latour, A. (2001). Trial by fire: A blaze in Albuquerque sets off major crisis for cell-phone giants—Nokia handles supply shock with aplomb as Ericsson of Sweden gets burned—Was SISU the difference? *Wall Street Journal*, January 29, A1.

Mennecke, B., Crossland, M., & Killingsworth, B. (2000). Is a map more than a picture? The role of SDSS technology, subject characteristics, and problem complexity on map reading and problem solving. *MIS Quarterly, 24*, 601–629.

Miles, M., & Huberman, M. (1994). *Qualitative data analysis.* Thousand Oaks, CA: Sage.

Mitroff, I., & Alpasan, M. (2003). Preparing for evil. *Harvard Business Review, 81*(4), 109–115.

Morgan, D. L. (1997). *Focus groups as qualitative research.* Thousand Oaks, CA: Sage.

Ogden, J. (2006). Supply base reduction: An empirical study of critical success factors. *Journal of Supply Chain Management, 42*(4), 29–39.

Peck, H. (2005). Drivers of supply chain vulnerability: An integrated framework. *International Journal of Physical Distribution & Logistics Management, 35*, 210–232.

Rice, J., & Caniato, F. (2003). Building a secure and resilient supply chain. *Supply Chain Management Review, 7*(5), 22–30.

Ronan, W., & Latham, G. P. (1974). The reliability and validity of the critical incident technique: A closer look. *Studies in Personnel Psychology, 6*(1), 53–64.

Sheffi, Y. (2001). Supply chain management under the threat of international terrorism. *International Journal of Logistics Management, 12*(2), 1–11.

Sheffi, Y., & Rice, J. (2005). A supply chain view of the resilient enterprise. *MIT Sloan Management Review, 47*(1), 41–48.

Sinha, P., Whitman, L., & Malzahn, D. (2004). Methodology to mitigate supplier risk in an aerospace supply chain. *Supply Chain Management: An International Journal, 9*(2), 154–168.

Sodhi, M. (2005). Managing demand risk in tactical supply chain planning for a global consumer electronics company. *Production and Operations Management, 14*(1), 69–79.

Stauffer, D. (2003). Risk: The weak link in your supply chain. *Harvard Management Update, 8*(3), 3–5.

Svensson, G. (2000). A conceptual framework for the analysis of vulnerability in supply chains. *International Journal of Physical Distribution & Logistics Management, 30*, 731–749.

Tomlin, B. (2006). On the value of mitigation and contingency strategies for managing supply chain disruption risks. *Management Science, 52*, 639–657.

Trent, R., & Monczka, R. (2005). Understanding integrated global sourcing. *International MIT Sloan Management Review, 47*(1), 24–32.

Trent, R., & Monczka, R. (2003). Understanding integrated global sourcing. *International Journal of Physical Distribution & Logistics Management, 33*, 607–629.

Wu, L., Yue, X., & Sim, T. (2006). Supply clusters: A key to China's cost advantage. *Supply Chain Management Review, 10*(2), 46–51.

Yin, R. (1994). *Case study research: Design and methods.* Newbury Park, CA: Sage.

Zsidisin, G., Ellram, L., Carter, J., & Cavinato, J. (2004). An analysis of supply chain assessment techniques. *International Journal of Physical Distribution & Logistics Management, 34*, 397–413.

Zsidisin, G., & Ellram, L. (2003). An agency theory investigation of supply risk management. *Journal of Supply Chain Management, 39*(3), 15–29.

Zsidisin, G., Melnyk, S., & Ragatz, G. (2005). An institutional theory perspective of business continuity planning for purchasing and supply management. *International Journal of Production Research, 43*, 3401–3420.

APPENDIX A: FINAL INTERVIEW PROTOCOL

1. Please provide a brief description of your international supply chain design (location of overseas sources and general flow of information and material flow).
2. What supply chain/product characteristics amplify the potential for, or impact of, the disruptions?
3. What characteristics are common among severe disruptions?
4. How does a firm quickly discover the disruption and/or the event that will trigger the disruption? What are the key metrics available to detect early warning signals?
5. Given the discovery of the disruption/event, how does a firm efficiently assess what areas of the supply chain will be affected by the disruption?
6. In general, what are the alternative activities and mechanisms that may be employed to deal with disruptions?
7. What are the primary barriers to an effective disruption recovery? What are the technology, personnel, and decision-making processes enablers of an effective recovery program?
8. How can the supply chain be re-designed to minimize the potential for and impacts of disruptions?

APPENDIX B: FOCUS GROUP, CRITICAL INCIDENT QUESTIONS

Introduction (provided to participant)

Supply Chain Disruptions, defined as unplanned delays or stoppages of planned product flow, can be costly and result in significant supply chain delays. The increasingly global nature of today's supply chains has increased many organizations' exposure to the impact of disruptions.

We would ask that you answer the questions for both a disruption that was *well managed*, and for a disruption that had lots of *opportunity for improved management*. In other words, we are interested in both ends of the spectrum.

Well-managed disruption
Discussion Points:

1. Describe a recent severe global supply chain disruption your organization experienced.
2. What was the impact of the disruption?
3. How and when was the disruption discovered?
4. What did your organization do to mitigate or reduce the impact of the disruption and how did the discovery mechanism affect this?
5. What was the key approach for dealing with this severe supply chain disruption? How could this be better implemented and what are the barriers?

Opportunity for improvement disruption
Discussion Points:

6. Describe a recent severe global supply chain disruption your organization experienced.
7. What was the impact of the disruption?
8. How and when was the disruption discovered?
9. What did your organization do to mitigate or reduce the impact of the disruption and how did the discovery mechanism affect this?
10. What was the key approach for dealing with this severe supply chain disruption? How could this be better implemented and what are the barriers?

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