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Supply chain disruption propagation: a systemic risk and normal accident theory perspective

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Abstract
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Keywords
supply chain risk management, disruption management, supply chain disruption propagation, systemic risk, case study

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Supply Chain Disruption Propagation: A Systemic Risk and Normal Accident Theory Perspective

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ABSTRACT

When a disruption occurs in a firm, its effects are often felt throughout the supply chain. As supply chains expand globally and companies pursue velocity and efficiency, the probability of disruptions propagating throughout a chain grows. In this paper, we employ a qualitative, grounded theory case study approach to help understand what drives supply chain disruption propagation and to provide theoretical insights into this emerging area. For a more complete perspective, we study three interconnected tiers in seven unique supply chains. Each supply chain triad consists of (1) a focal firm (a manufacturer), (2) a supplier to the focal firm and (3) a customer of the focal firm allowing us to gain perspective from three levels in multiple supply chains. Three aggregate dimensions are defined which help explain the propagation of supply chain disruptions: the nature of the disruption, structure and dependence, and managerial decision making. Within these dimensions, six themes are identified giving an increased level of granularity into disruption propagation: correlation of risk, compounding effects, cyclical linkages, counterparty risk, herding, and misaligned incentives. Organizations should consider these themes and their interactions to effectively deal with supply chain disruptions.

Keywords: Supply Chain Risk Management, Disruption Management, Supply Chain Disruption Propagation, Systemic Risk, Case Study

1. Introduction

Disruptions are a reality in today's complex and dynamic supply chains (Manuj and Mentzer 2008), and considerable research has been invested in understanding, predicting, preventing, and managing disruptions (Ivanov et al. 2016). A supply chain disruption is an unexpected event that stops or slows the normal flow of material (Craighead et al. 2007) with potentially negative consequences to supply chain members (Chopra and Sodhi 2004; Blackhurst et al. 2011). The spread or propagation of the supply chain disruption influences the magnitude of the outcome. Supply chain disruptions may propagate through an entire system with serious or even devastating results (Craighead et al. 2007; Blackhurst et al. 2008, Ivanov et al. 2014). We define supply chain disruption propagation as the spread of the disruption effects beyond the initial disruption location. Other terminology for supply chain disruption propagation in the academic literature include risk diffusion (Basole and Bellamy 2014), cascading failures (Hearnshaw and Wilson 2013) and the Ripple Effect (Ivanov et al. 2014a; 2014b; Solokov et al. 2016).

It is important to understand this phenomenon because as the disruptions spreads, the negative impact may increase in severity. Even a very small initial disruption may propagate throughout the supply chain (Blackhurst et al. 2011), growing in magnitude. This propagation of disruptions can affect performance including profit loss and in extreme cases can influence the survivability of the supply chain (Ghadge et al. 2011). Significant research has transpired to understand how organizations and supply chains may increase their resilience in the face of these disruptions (Bhamra et al. 2011).

While it is true that supply chain disruptions are inevitable, successful firms seek to understand and minimize disruptions and maintain effective supply chain operations. The ability to address supply chain disruptions requires an understanding of the factors that affect the propagation of the disruption in the supply chain. Managers who understand these factors are better prepared to contain disruptions and prevent them from spreading through the supply chain (Chopra and Sodhi 2014). Sawik (2017) developed a portfolio approach to manage supply disruptions through the selection of primary and recovery suppliers and orders from a firm's perspective. However, even when the initial disruption is isolated to a single firm, the disruption may propagate through the system creating loss for more than one supply chain member. Thus, one failure in the supply chain may lead to other entities failing and may even result in an entire supply chain shutting down (Jüttner and Maklan 2011). While it may be possible to manage disruptions affecting a firm by dispersing purchases across different suppliers (Gupta et al. 2015; He et al. 2016), that management practice may actually increase the propagation of the disruption at an aggregated level. Therefore, disruptions must be contained before they can affect a larger portion of the supply chain (Chopra and Sodhi 2004; Blackhurst et al. 2011; Marley et al. 2014).

A better understanding of disruption propagation is necessary to manage supply chain disruptions (Wu et al. 2007; Blackhurst et al. 2011). For a recent review of literature on supply chain disruptions and recovery see Ivanov et al. (2017). Research has investigated how to optimize supply chain coordination (Sawik 2014) with promising results, but a single disruption can propagate with devastating effects, and little is known about the propagation phenomenon from a systemic perspective (Ghadge et al. 2011; Ivanov et al. 2014a; 2014b). Because supply chains are inherently complex, understanding risks of disruptions is truly a multi-criteria problem requiring multiple solution approaches (Ho et al. 2010), and has been of increasing interest in the research community. For example, Sawik (2016) developed mixed integer programs to investigate the impact of supply disruptions and their propagation in a three-echelon supply chain. This research also helps to fill this gap. Specifically, we examine the factors that affect supply chain disruption propagation. We take a qualitative case study approach (Glaser and Strauss 1967; Strauss and Corbin 1998) and use a grounded theory method. We collected data on seven supply chains to inform our understanding of what drives the propagation of supply chain disruptions. In order to provide a robust supply chain perspective, each of the seven entities that we studied includes three tiers of unique firms. We focus on understanding how disruptions propagate throughout multiple tiers in the supply chain.

2. Theoretical Development

Two theoretical areas proved to be most helpful in addressing our research question. First, the *systemic risk literature* in the finance area provides interesting parallels and insights because of the inter-connectedness of different levels or layers of financial systems, which is analogous to the integrated nature of supply chains. Similarly, *normal accident theory* serves as a useful lens because it addresses the wide spread impacts of single defects in tightly coupled systems.

2.1 *Systemic Risk*

The concept of contagion or propagation is prominent in the systemic risk literature (Elsinger et al. 2006; Kambhu et al. 2007; Schwarcz 2008; Kane 2010), and it explains how a small shock can wreak havoc in a system. Systemic risk describes how a failure can manifest in a banking system creating a chain reaction, which leads to the failure of the entire system (Furfine 2003; Kaufman and Scott 2003; Nier et al. 2007; Schwarcz 2008; Acharya et al. 2010; Ray 2010). The Great Depression was the catalyst that began the theoretical development of systemic risk. Economist John Maynard Keynes observed that the shift in the economy from one state to another due to an initial shock followed by a series of contagion was an integral component of systemic risk (Keynes 2006). Since that time, systemic risk has mainly applied to finance and economics, but given the complexity of many systems beyond economics, such as climate, biology, and power systems, a more general theoretical development has emerged (Kambhu et al. 2007). Systemic risk is of utmost importance for maintaining the stability of a network and calls for methods to measure and manage risk (Martínez-Jaramillo et al. 2010). Therefore, in this paper we view supply chains disruptions through a systemic risk lens.

2.2 *Normal Accident Theory*

We supplement systemic risk theory with normal accident theory (NAT). NAT has not been widely employed in the supply chain disruption literature but can help to understand supply chain disruptions and their propagation (Speier et al. 2011). NAT is based on complex and tightly coupled systems (Perrow 1981; 1984; 1994; 1999), and is complementary to systemic risk in helping us to understand disruption prorogation. Due to the nature of the system, accidents are inevitable or even normal, and catastrophic failures are ordinary defects that run out of control (Perrow 1994). Hence, we see ties to supply chain disruption propagation. Tight coupling between supply chain firms is a form of dependence (Wolf 2001), and because of the interactive complexity of the system, failures will occur in unexpected ways (Marley et al. 2014). Accidents stem from the interaction of this dependence (tight coupling) and the complexity of the system (Wolf 2001). A failure in one part of the system will spread and disrupt the flow of other parts of the system (Perrow 1999). In fact, a small failure can cascade into increasingly larger failures (Perrow 1999). Skilton and Robinson (2009) draw upon NAT to investigate traceability in a supply chain and note that NAT demonstrates the structure of a system can create barriers to detection, comprehension and correction of variation in the system. The structure and complexity of the system can impede detection and correction of failures, while tight coupling may intensify the spread of the failure (Perrow 1999).

These two theoretical bases provide a lens through which we can look into why supply chain disruptions propagate. This understanding is of particular importance in recent years as supply chain trends such as lean, JIT and other efficiency-focused activities expose supply chains to increased risk and potential disruption spread. These trends can increase the coupling and interdependence of firms within supply chains.

3. Research Methods

This study employs a qualitative case study methodology to study supply chain disruption propagation (Glaser and Strauss 1967; Corbin and Strauss 1990; Clark et al. 2010; Gioia et al. 2013). The purpose of qualitative case studies is to investigate specific "real world" phenomena using contextual data collected by interviewing actors who are directly involved (Barratt et al. 2011). Qualitative research is particularly useful for emerging areas of study where the research questions explore the how and why of a particular phenomenon (Benbasat et al. 1987) and has been used successfully in many fields of study including supply chain risk (Blackhurst et al. 2011; Craighead et al. 2007).

Data for this study comes from interviews with supply chain managers in three tiers of the supply chain and follows guidelines outlined by Eisenhardt (1989), Yin (1994) and Strauss and Corbin (1998). Our study uses the theoretical lens of systemic risk and normal accident theory to gain deeper insights into the data by allowing these theories to help guide the data collection and analysis (Locke 1996; Strauss and Corbin 1998). The results of this study will contribute to our knowledge of supply chain management and help managers minimize the impacts of disruptions and their propagation in the supply chain.

3.1 *Research Procedures*

We targeted large and mid-sized manufacturing firms in a variety of industries in order to collect data in such a way to allow theoretical sampling to allow us to explore the concept of supply chain disruption propagation (Strauss and Corbin 1998; Locke and Golden-Biddle 1997; Langley 1999; O'Reilly et al. 2012). Firms were chosen based on the following criteria: (1) they were all part of well-established global supply chains; (2) they had acknowledged supply chain disruptions with their partner firms also selected for this study; and (3) they represented different product and customer characteristics. In using these criteria, we sought to increase the diversity of the supply chains we explored. In addition, to gain a true supply chain perspective, each of the seven cases we selected agreed to provide information from three tiers of their supply chain, moving our understanding of disruption propagation beyond a dyad (Ghadge et al. 2012). We continued to collect and analyze our data until we had reached theoretical saturation with no substantial insights gained from additional interviews (Strauss and Corbin 1998; Locke and Golden-Biddle 1997). Our data set is unique because we have seven three-tiered supply chains with representation from three different tiers in each supply chain. This allows us to obtain multiple views into the propagation of a unique disruption within each supply chain. Each of our triad of firms consists of 1) a focal firm, 2) a supplier to the focal firm, and 3) a customer of the focal firm, thus allowing us to gain perspective from three tiers or locations in each supply chain.

The procedure for identifying and obtaining prospective respondents was as follows. We first contacted the focal firm to request their participation in the study. As a requirement of participation, each focal firm was responsible for providing us contact information and permission to interview two of their key supply chain partners (1) with whom they work closely; (2) upon whom they are dependent; and (3) with whom they had experienced a supply chain disruption that propagated through the three tiers. We required both a key supplier and a key customer fitting the above criteria from each focal firm. Only those focal firms that were able to give us access to supply chain decision makers in the three-tier supply chain participated in this study. The seven three-tiered supply chains resulted in 21 unique interviews with separate firms. Of the seven focal firms, four were Fortune 500 companies. The others were either private or publicly traded companies with a minimum of 2500 employees and 2012 revenue of at least $2B. Table 1 provides a summary of the participants. The selected supply chains span a variety of industries including window and door manufacturing, office furniture, appliances, industrial supplies, medical supplies, chemicals, and food. All respondents managed functions in the supply chain as reflected by job titles such as Logistics Manager and Operations Manager, or they oversaw the supply chain with titles such as Supply Chain Manager, Vice President for Supply Chain, or Owner.

INSERT TABLE 1 HERE

3.2 Data sources

In this study, the primary method of data collection was through interviews of key managers from multiple nodes in the supply chain. Interviews were conducted by teams of researchers with one researcher conducting the interview questions and one to two additional researchers recording observations. There was a minimum of two researchers participating in each interview. Individual interviews lasted between 45 and 90 minutes, and each was recorded, and transcribed for data analysis. After each interview, the researchers immediately discussed the interview observations (Strauss and Corbin 1998; Langley 1999). We coded and analyzed the data as data collection proceeded to ensure that we achieved both theoretical sampling and theoretical saturation (Glaser and Strauss 1967; Corbin and Strauss 1990). The interview protocol is included in the Appendix. Data collection continued until the point of theoretical saturation (Glaser and Strauss 1967; Corbin and Strauss 1990). This point occurred when the researchers agreed that no new knowledge was gained from additional interviews and concepts were being regularly repeated.

Our secondary data collection included supporting printed material from the participating companies such as protocols, guidelines, and internal processes. These additional materials from the participants allowed triangulation, thereby improving our understanding of the phenomena and increasing the reliability of our study (Strauss and Corbin 1998; Langley 1999). Triangulation is effective in dealing with potential discrepancies in the data through the analysis of multiple forms of data focusing on the same issue or phenomenon (Gibbert et al. 2008; Blackhurst et al. 2011). Examples of forms of data used to augment the semi-structured interviews in this research include supplier handbooks, excel-based supply chain risk management tools, supply chain disruption management protocols, and presentations related to supply chain disruptions shared by the key informants.

3.3 Data analysis

We used Atlas.ti software to facilitate the grounded theory analysis process during this study. The grounded theory approach taken in this research calls for *a priori* theory to guide the data collection and analysis (Lock 1996; Strauss and Corbin 1998). Qualitative research results in massive amounts of data that require detailed and voluminous coding, searching, and interpreting by the researchers. The data were analyzed in accordance with rigorous qualitative methods involving an iterative process with constant comparison between emergent themes in the data and existing theory (Glaser and Strauss 1967; Strauss and Corbin 1998; Clark et al. 2010; Gioia et al. 2013). We follow the Gioia method of presenting the results of our grounded theory data analysis. The Gioia method was developed to combat the common criticism that the description of most qualitative studies that claim to be grounded theory do not adequately justify their results (Gioia et al. 2013.) Initially, first-order or open coding is used to describe the data and summarize it. Open coding separates data into "concepts and categories" (Smit 2002; Strauss and Corbin 1998; O'Reilly et al. 2012). Our goal in this stage was to examine the data to identify factors influencing supply chain disruption propagation as guided by relevant literature (Alvesson and Kärreman 2007; O'Reilly et al. 2012). Subsequently, second-order or pattern coding is employed to reduce the data by grouping similar codes and descriptions (Glaser and Strauss 1967; Corbin and Strauss 1990; Nag et al. 2007). Pattern coding looks at the relationship between the codes (Smit 2002; Gioia et al. 2013) and how categories cross cut and link (Glaser and Strauss 1967; Corbin and Strauss 1990; Langley 1999). We note that this analysis is described as occurring at two levels – the actual words from the interview and the conceptualization of the data into major themes by the researchers.

Finally, third-order analysis consolidates the second-order themes into logical groupings called aggregate dimensions (Clark et al. 2010; Gioia et al. 2013). In this stage, we refined the codes identified in the data to theoretical concepts (Corbin and Strauss 1990). These theoretical concepts allow us to articulate the main understandings from the study. To ensure the rigor of our analysis all coding of the data was performed by two trained researchers and then two additional researchers reviewed the coding. Throughout the coding process, inter-coder agreement was above 80%, and the Fleiss' kappa was above 65%, indicating good agreement (Fleiss 1981). Any discrepancies were discussed and resolved by all of the researchers through consensus (Holsti 1969; Dibbern et al. 2008).

4. Results

Next, we describe the emergent data structure and inductive theoretical model developed through the application of the methods described in Section 3 in the context of relevant prior theory (Glaser and Strauss 1967; Corbin and Strauss 1990). Figure 1 illustrates the data structure that emerged through our analysis of the data and informed by previous research. This structure is based upon the recommendation and layout of Clark et al. (2010) and Corley and Gioia (2011). First order concepts (on the left hand side of Figure 1) represent the key insights on the propagation of supply chain disruptions gleaned from data analysis. Next, these concepts are organized into a higher level of abstraction (Gioia et al. 1994; Clark et al. 2010), which is depicted as second order themes (in the middle of Figure 1). In our analysis, six second order themes emerged: cyclical linkages, counterparty risk, correlation of risks, compounding effects, herding, and misaligned incentives. Finally, the second order themes are arranged into aggregate dimensions (on the right hand side of Figure 1), which represent the major themes that emerged during data analysis. We have three aggregate dimensions to help explain the propagation of supply chain disruptions: (1)

the nature of the disruption, (2) supply chain structure and dependence, and (3) managerial decision making related to the supply chain disruption.

INSERT FIGURE 1 HERE

While these themes are distinct, they do interact with each other to some degree. In this section, we discuss each of the second order themes and related aggregate dimensions in a descriptive manner including some poignant quotes from our interviews. A discussion of the interrelationships between the themes is presented in the subsequent sections.

4.1 *Nature of the Disruption*

The first aggregate dimension found in the data was related to the actual disruption. This dimension sets the landscape for disruption propagation. Disruptions will happen with varying duration and impact. The disruption itself has characteristics that would increase the severity of the disruption propagation in the supply chain. The two themes that emerged within this aggregate dimension were the correlation of risks and compounding effects of the disruption as it spreads.

4.1.1 Correlation of risks

Considering the nature of the disruption itself, the systemic risk literature discusses the concept of correlation of risk events (Elsinger et al. 2006; Schwarcz 2008; Deloitte and Touche LLP 2010) where risks can never truly be considered in isolation. Interestingly, small errors or failure may interact in unexpected ways and cascade into a larger failure (Perrow 1999). The nature of the disruption needs to be better understood as a foundational element of managing disruption propagation.

Risks are interrelated in cases where one risk or even a risk mitigation strategy can cause another risk (Chopra and Sodhi 2004; Ackermann et al. 2007). Supply chain decision makers need to understand these connections and associations in order to be effective. Disruptions rarely happen in isolation. A weather phenomenon may cause damage to a manufacturing facility that can influence order fulfillment. Companies mitigating the risk may move to another supplier and cause unanticipated bottlenecking. Unexpected increases of alternate shipping also affect logistics. In fact, the weather phenomenon may also cause delays in shipping by a direct effect on transportation. Traditional risk registers ignore the most significant aspects of risk – the fact that risks are connected and inter-related to each other, and these correlations are often not obvious to decision makers (Ackermann et al. 2007). Yang et al. (2017) proposed modeling global supply chains as a Physical Internet because traditional supply chain network have been hierarchical and constrained to dedicated assets and budgets. Their approach is promising, but is based on a presupposition that products can simply flow in the same way as IP packets flow on the Internet, and that is often impossible and dangerous.

The Chemical manufacturer describes an example of correlation of risks as follows:

> *"Ocean carriers have started this new process called slow steaming for sustainability and cost reasons because they use less fuel. So, the transit times in ocean transport are increasing, and we need to incorporate that into our inventory management models, and it's becoming more and more complex to do so. One of our products we manufacture can't be shipped on the same vessel with class one explosives, and we never know at any moment if there is going to be class one explosives on the ship."*

This firm noted the flammable nature of their product limits transportation options. To deal with these risks they count on transportation providers to help them move product from an overseas location, but the providers have risk with the cost of fuel and sustainability pressures that leads to an increase in shipping time. In addition, the transportation provider may choose to remove the product from a vessel (without notice) if they determine that the flammable nature of the product presents too much risk to other cargo. Meanwhile there are pressures to decrease inventory levels and concern to meet global demand. In this example, different risks for the same product at different points in the supply chain exacerbate each other.

The Food supplier described actions made by stores to drive promotions and actions by customers in multiple streams create an “inefficient signal for our supply chain, so wrong product, wrong place drives issues in manufacturing” which affects scheduling and then poor lead times. In this example, a strategy to drive sales in order to reduce the risk of inaccurate forecast demand had unintended consequences:

> *“I think our biggest risk is unknown variations and customer demand…various aspects that drive that risk are unannounced customer promotions, buyer changes, and competitive actions by customers.”*

Thus, we know that correlation of risks will increase supply chain disruption propagation.

4.1.2 Compounding Effects

A key issue in understanding supply chain disruptions relates to how a disruption may grow as it spreads through the supply chain. We note that the impact of disruptions has not been well studied on a supply chain level (Blackhurst et al. 2005) but rather at isolated or limited points in the supply chain. There are parallels to the phenomenon of the Bullwhip Effect where changes in demand can propagate through the supply chain, distorting in magnitude as the change passes from tier to tier (Lee et al. 1997). Not only may the disruption contaminate other areas of the supply chain, but also the impact may grow in size and severity as it moves through the supply chain. One of the major contributors to compounding effects is found in the decision making of supply chain stakeholders. These contributing themes will be discussed in greater detail later, but we would like to illustrate their effect here. A disruption’s size and severity can grow when individual supply chain members take self-preservation or even opportunistic measures to reduce the risk to which they are exposed. A company may store up inventory to weather the storm, but in doing so spread the disruption to competitors and partners. Additionally, as multiple stakeholders in a supply chain, or even entirely separate supply chains, all react to a disruption the aggregated movement of members can increase the disruption's magnitude.

Firms discussed the need to stop the propagation of a disruption and to prevent it from compounding. The Windows supplier described a "spiral" where one problem would cause another:

> *"When you have a supply disruption you can start to see your sales trail off because you don't have enough inventory. So, you can end up with this downward spiral where you don't have enough inventory to actually achieve all the sales that you could. So, you end up able to buy less inventory because your sales are down, and then you order less, so then you sell less."*

The Windows supplier acknowledged while it is desirable to prevent disruptions, they still occur, and one of the jobs of the supply chain manager is to keep those disruptions from propagating downstream to the customer.

Because a large failure can occur from a seemingly small disruption (Perrow, 1999), firms must recognize that disruptions of all sizes pose risk to their supply chain. Disruptions need to be identified and contained early before the compounding effects make the disruption worse. A good analogy is the spread of a disease through a population. It can start with just a few cases of a mild form of the disease affecting a small percentage of the population. If the contagion is not stopped, the disease spreads and it can become pandemic. This is supported by Singhal and Singhal (2012) who cite a Washington Post article (Heal and Kunreuther, 2010) calling for firms to understand interconnectedness and how a disruption in an obscure branch of the supply chain could bring the entire system to its knees. In other words, compounding effects will increase supply chain disruption propagation.

4.2 *Structure and Dependence*

The structure of the supply chain and the dependencies of the entities within the supply chain will affect supply chain disruption propagation. Supply chains with high levels of dependence (tight coupling) are more prone to disruptions occurring and spreading (Perrow, 1999; Speier et al., 2011). Firms must consider the interdependence and connectedness of their supply chain when supply chain disruptions occur (Bhamra et al., 2011). NAT provides the position that in complex and tightly coupled systems failures will quickly spread and go beyond the control of the system (Perrow, 1999). Because of the structure of the supply chain, disruptions can quickly escalate out of control (Speier et al., 2011).

Analysis revealed that the structure of the supply chain and the relationships between entities played a role in how disruptions spread in the supply chain. Two factors emerged in this aggregate dimension – the presence of cyclical linkages and the existence of counterparty risk.

4.2.1 Cyclical linkages

In the systemic risk literature, a cyclical linkage can be seen where a problem in node A can lead to a problem in node B where it propagates onto node C. Node C may, in turn, have a feedback effect on node A (Eisenberg and Noe 2001), increasing the risk of self-sustaining disasters (Ackermann et al. 2007). Another interesting representation of cyclical linkages can be found in Thompson's (1967) reciprocal interdependence in workflow analysis. In a reciprocal interdependence scenario, the output from task one is used in task two. The output in task two is then used in task one. In our study, we observe how these cyclical structures serve to allow a disruption to continue to cycle though the network by looking at how the network is structured. Often firms do not even realize that the cyclical linkages exist. A number of factors may cause cyclical linkages. First, supply chain members may have multiple roles. For example, in our data we had instances of a supplier to a focal firm also being a customer to the same focal firm. Since the multiple nodes in the supply chain can actually be the same company, it is easy to see how a feedback effect can manifest. Similar to companies functioning in multiple roles within a supply chain, it is often the case that supply chains containing many tiers and nodes will have organizations functioning in different capacities at multiple tier levels among different partners. For example, a direct supplier to a company may also supply other direct suppliers, making them a tier two supplier in the same supply chain they function as a tier one. The supplier of the Chemical supply chain discussed cyclical linkages when he described his supply chain.

> *"Many of the people that we sell to, we also buy raw materials from. For example, let's use [Product Name] as an example. We sell it to the automotive coating industry, but we're also in the automotive coating industry in a different division, and a different piece of [Customer's] derivatives is the raw materials' supplier."*

The supplier in the Chemical supply chain described how this structure of having a supplier for one of his products also be the customer for another product can create issues where a problem on the supply side can influence the customer side through the circular links. The Appliance firm echoed this idea saying that some of their tier one suppliers are also in their tier two suppliers. They described walking a "tight rope" with how much information to share with these types of suppliers to prevent cyclical linkage disruptions, while being aware that the tier two suppliers were also tier one for the firm's competitors. This is consistent with the literature (Lau et al. 2002; Kleindorfer and Saad 2005; Wakolbinger and Cruz 2011) and is an example of a risk being both cyclical and counterparty risk.

Cyclical linkages also should be better understood as a factor influencing supply chain disruption propagation. However, these linkages may often be difficult to see. Supply chain managers should take note, step back and look at the supply chain as a whole because cyclical linkages will increase supply chain disruption propagation.

4.2.2 Counterparty risk

A valuable insight in the financial systemic risk literature is the concept of counterparty risk. Acharya and Engle (2009) give the following example: "a party to a financial contract may sign a second, similar contract with someone else -- increasing the risk that it may be unable to meet its obligations on the first contract. So the actual risk on one deal depends on what other deals are being done." Counterparty risk emerged as a factor from our data analysis that increases supply chain disruption propagation. Counterparty risk occurs when one link in the supply chain is affected by other links. Often these linkages are hidden or not obvious. For example, counterparty risk can occur when a supplier to a focal firm may be a supplier to a main competitor (Dubois et al. 2004). This is emphasized by Basole and Bellamy (2014, page 777) who state "risks originating in seemingly unrelated and distant parts of the entire network can quickly propagate, disrupting and potentially crippling the entire network".

Supply chains are highly interconnected (Skipper and Hanna 2009), and no single firm can see all the interconnections through which it can be affected. For example, the Appliances firm described a situation where their product used a specific color in their electronics that is also used in certain televisions, and when the television market demand increased, the specific supply required for their product was no longer available. The television market was not a competing market to the Appliance firm. Firms that focus on first tier suppliers may not recognize risk rippling through deeper parts of the supply chain that may eventually hit the firm by surprise (Tang et al. 2009). The Door and Window Manufacturer noted the following counterparty risk that affected their supply chain.

> *"We sourced from a company who is foreign owned. It is very secretive. They told us up front they supply a different industry, and there has been a down turn because the industry has hit a little bit of a hiatus lately. They told us 'hey we have bigger fish to fry when that industry comes back, so don't think that we are going to do this for you forever.'"*

Simply stated, risks borne by partners or suppliers, seen or unseen, are born by the focal firm. The focal firm may directly share the risk, or it may manifest in a different form. If a supplier faces financial difficulties and cannot meet its orders, the focal firm also faces risk in the form of not receiving necessary supplies to make product and meet its own demand. The crux of counterparty risk falls on locus of control. If an organization does not have control over the necessary components of its supply chain, which is most often the case, it is susceptible to any manner of disruption through its supply chain partners. Finally, counter party risk may be created unwittingly because of information hiding. There are several reasons companies would hide information from their partners: maintaining company image, not wanting to cause concern, not wanting to give reason to go with a competitor, etc. Unfortunately, this information hiding may cause partners to make wrong decisions because they do not see all the connections between entities in the supply chain. These wrong decisions then cause additional problems furthering the disruption.

The concept of counter party risk can be understood with the following quote. To add an additional level of protection, we were asked to keep the industry and firm unspecified. The firm discussed the concept of counterparty risk and how it would help to understand the structure of the supply chain and how different parties in the supply chain were connected as well as how much they relied on each other.

> *"Optimally, you would want to be able to segment your inventory availability based on the 'degree of reliance' or some other definition of your customers. We don't have that capability today, and therefore, our response is to carry more safety stock to accommodate the demand volatility."*

In order to mitigate counterparty risk, the firm carried more safety stock. However, more safety stock also exposes the firm to different risks.

Understanding how the structure of the supply chain impacts disruption propagation may also have interesting implications on how to effectively allocate resources. For example, it has been argued that resources should be located where the supply chain is the weakest (Melnyk et al., 2010). There is no one size fits all approach to supply chain risk management, and the mitigation strategies need to be chosen to most effectively address the risk of disruption (Chopra and Sodhi, 2004). However, simply increasing inventory levels, alternate sourcing, or contingency strategies are not always ideal and may even increase supply chain risk (Tomlin, 2006; Kull and Closs, 2008). Many supply chain strategies or best practices neglect to consider the impact of supply chain risk (Craighead et al., 2007). In addition, the ability of a firm to withstand a disruption not only depends on its own internal operations and decisions but on the decisions of supply chain members (Hua et al., 2011) because of the interdependence of the firms in the supply chain. Interdependence is intrinsic in supply chains, and connectivity in a supply chain is the degree of interdependence between nodes (Pettit et al., 2010). The concept of counterparty risk is particularly challenging as it entails a firm or a supply chain unknowingly exposed to risk due to relationships their partners have with other parties. Because of confidentiality requirements, obtaining information about a partner's relationships with others is often not possible. Moreover, when firms do not look beyond their first or second tier, often due to supply chain complexity, they may not see potential issues inherent in the unseen relationships.

4.3 *Managerial Decision Making*

Finally, the decisions that supply chain managers make in the face of a disruption can increase propagation. The themes in this aggregate dimension include herding behavior within managerial decisions and the impact of misaligned incentives on decision making.

4.3.1 Herding

Herding behavior will increase supply chain disruption propagation. Herding occurs when firms behave in the same way they see other firms behaving even when their own independent analysis would suggest some alternative course of action (Banerjee 1992). There is an aspect of not wanting to be left behind, so once a firm determines an appropriate course of action, often because that course is what everybody else is doing, they move. Another influence on herding behavior is pressure from supply chain partners, specifically if the partner is larger. When a risk is perceived, a larger supply chain partner may try to mitigate the risk by forcing their suppliers to absorb it. Reactionary decisions frequently make things worse. Consider when the Hynix memory maker in China had a fire, and it was expected that prices for computer memory would rise. Computer manufacturers and parts suppliers quickly bought up as much inventory as possible to lock in better prices, but in doing so, actually drove up the prices and created a shortage (Patrizio 2013).

An example of herding behavior is when competing customers react to each other's sales and cause supply shortages. The focal firm of the Food supply chain described this saying,

> *"Last Thanksgiving [Customer 1] decided that they wanted to 'own' the boxed potato market for Thanksgiving. So, not only did they pull product a week earlier, unknown to anyone within [Focal firm], they decided to triple their ordered volume by lowering the price point on their own from $1.99 to $1.20 to $0.88. So, pulling demand forward in time, tripling volume, obviously we weren't prepared, and that created a chain event with [Customer 2] and other competitors."*

Another example of herding was discussed with the Manufacturing firm's competitors observing and copying actions that exacerbated a disruption:

> *"During a rail strike in 2007 we were short of rail cars for storage of our product. Because of the slowdown of delivering cars to our plant; the plant was getting starved. Of course, we then went out and leased 100 more cars to send to our plant which only added to the*

> *congestion on the RR lines which slowed it down even more. Our competitors saw what we were doing and they also bought more cars and that just made it worse."*

We often see herding behavior at the consumer facing level. Gas stations, for example, will often adjust prices based on other local stations' prices. This same type of behavior occurs upstream, and not only in pricing, but in other behaviors such as buying up scarce materials for additional safety stock.

4.3.2 Misaligned incentives

Incentives in supply chain performance have been discussed by van Veen-Dirks and Verdaasdonk (2009) where local control potentially hinders overall supply chain performance. Incentives influence behavior, and a failure to align supply chain metrics can result in local optimization to the detriment of the system as a whole (Cohen et al. 2007). When incentives are implemented that are focused solely at the organizational level, then it stands to reason actions will be directed there. The Appliance firm mentioned this:

> *"if we have a parts availability problem, and I have to fly in parts from China, I'm going to have a mega impact in my transportation budget. My manufacturing guy is going to look like he's doing a great job because he's keeping the plant running, but we realize that there is a cost in another area."*

This firm described how different supply chain decision makers have different perspectives. Some have a broader supply chain view while others are "myopic" and make decision that will benefit them at the expense of other parts of the supply chain. A similar example was described by the Chemical manufacturer:

> *"In our production planning department, our planners get in a lot less trouble for having too much inventory than running out of inventory. So, we tend to reinforce some lessons by the culture in the company."*

This firm talked about the tension between running lean and making sure the customers' demand was met. Sales would push on production to make sure there was more than enough inventory to meet demand, and the company consequently carried too much inventory. None of our interviewees indicated any incentives that went beyond their organization into the supply chain. In fact, most interviewees intimated that they would not be rewarded and may be penalized if they spent resources on overall supply chain improvement. Also, little reward is given for proactive behavior unless it could be directly tied to savings or efficiency. More often it was the case that the actions taken after a disruption occurred were the basis for reward over the actions taken to avoid a disruption. This is intuitive albeit unfortunate. Firefighters are regarded as heroes when they perform their reactive duty, but fire safety professionals are perceived as a nuisance. To our knowledge, there has not been research investigating incentives for behaviors and decisions related to supply chain wide risk management.

The Chemical manufacturer specifically discussed senior management in his firm focusing on supply chain wide measures but not tying these measures to how managers are evaluated. We also found it very interesting that none of the supply chains we studied has created a system to measure and incentivize success at all three tiers. In fact, there was a lack of consistency through each supply chain on incentives. The Industrial Supplies manufacturer mentioned how misaligned incentives led to arguments with the different functional areas even in her firm:

> *"I report to the supply chain organization, and I also report to the 'Industrial Supplies' division, and their metrics sometimes compete."*

The Industrial Supplies manufacturer described the challenges of hitting plant productivity metrics which compete with overall supply chain metrics of reducing inventory and allocating it to certain locations.

In the systemic risk literature, there is a mistaken assumption in banking system analysis that if individual banks are safe, the entire system is safe (Elsinger et al., 2006). Herding behavior is difficult to see without a high-level view of one's own supply chain combined with a similar view of the supply chain competitors. Misaligned incentives may also be difficult to see without this high-level view of the supply chain and an understanding of the interdependence amongst firms and functions. In addition, supply chain managers are often near-sighted, given the nature of the visibility provided by the information systems they use. In fact, the majority of our interviewees revealed that their visibility of the supply chain did not extend beyond one tier up and one tier down. Supply chain managers are encouraged to understand how incentives affect decisions and how risk mitigation strategies need to be carefully considered and coordinated throughout the supply chain. If everyone reacts the same way to a disruption at multiple points in the supply chain (i.e., herding), the disruption will spread.

5. Managerial Implications of Interconnected Aggregate Dimensions

It can be observed from the preceding discussion and literature review the factors involved in the propagation of disruptions within the supply chain. For the companies in our study, the nature of the disruption event is the overarching context within which to consider the subsequent impact on the organizations involved. However, the nature of the disruption itself does not dictate the final level of propagation for a particular supply chain. Within this context, there are additional important factors that determine the severity of propagation. Specifically, the structure of the supply chain itself with heavy emphasis on how strongly each organization is dependent on the others. Secondly, the human response to the risk event will have a critical impact. The managerial decision-making processes within the supply chain will influence the disruption propagation pattern.

5.1 *Interaction of dimensions*

The level of propagation that occurs after a disruption is influenced by some combination of the six factors identified that are contained in the three aggregate dimensions. Figure 2 shows the inter-connectedness of the three dimensions. Each dimension interacts with the other two, and it is critical not to ignore these interactions as they will cause ripple effects downstream (Ivanov 2017a). Containment of supply chain disruption propagation is dependent on the nature of the disruption, the supply chain structure, and managerial decisions. Therefore, it is very important for firms to recognize that their risk management plans must account for not only all the risks that can be easily recognized but also the correlated risks. Similarly, firms must consider the complexities of their supply chain structure where one firm may serve multiple roles in a single chain and may increase dependencies in an unknown pattern. Finally, the decisions made in response to a disruption will have a measurable impact on the propagation of the disruption effects. Often, responses to disruption events are made quickly and without consideration of their impact on other nodes in the supply chain. These types of responses could be caused by management teams who are incentivized to optimize outcomes within their own firm rather than across their supply chains.

While supply chain risk management is an active research area, our understanding of the systemic causes a disruption to propagate through a supply chain is limited (Wu et al. 2007; Ghadge et al. 2012; Sodhi et al. 2012). Because the causes of disruption propagation are not always simple, the controls which must be considered by organizations to effectively reduce disruption propagation may be equally complex. For example, information hiding mentioned in counter party risk can cause supply chain firms to mistakenly, through lack of correct information, make choices that drive cyclical linkages and make a disruption worse. Interestingly, researchers have begun exploring more complicated systemic disruptions using optimization and simulation to simulate ripple effects (Ivanov 2017b).

5.2 *Need for systemic awareness in disruption monitoring*

Disruption propagation may be halted through supply chain wide monitoring (Craighead et al. 2007; Deane et al. 2009). When a disruption is detected, supply chain managers have a wide variety of ways in which they may respond, and it is important that they are able to intelligently and appropriately choose a response (Chopra and Sodhi 2004). Addressing the disruption incorrectly could serve only to magnify the negative effects. Moreover, without accurate information, the likelihood of misdiagnosing the problem or its consequences is high, and that can lead to even greater problems (Kane 2010). A "risk spiral" occurs when a lack of confidence leads to actions that may not be the right response (Christopher and Lee 2004). Firms should link risk assessment and quantification with risk management options (Kleindorfer and Saad 2005) and understand that, ideally, risks and rewards should be equally distributed amongst members in the supply chain. This should be reflected in metrics and incentives in the supply chain (Narayanan and Raman 2004). Our study adds to this by tying incentives misalignment to the dynamic aspect of risk management, i.e., how a supply chain disruption will propagate in a supply chain due to these misaligned incentives.

5.3 *Tradeoff between efficiency and increased systemic risk*

Our study also highlights the need for companies to balance the efficiencies gained from greater integration and connectivity with the increased potential for disruption propagation that also results. Systemic risk theory and NAT help to highlight these issues. While firms tend to recognize that the effects of disruptions at the firm level are transmitted both upstream and downstream in the supply chain, they may neglect to consider the impact of supply chain design decisions on disruption propagation. For instance, as individual firms consider initiatives such as leaning out the supply base or moving to fewer suppliers, they need to recognize that systemic supply chain risk may be increased by placing too much dependence on fewer supply chain partners.

It was interesting to note how firms truly reacted when facing disruptions as told though their examples and experiences. In our data collection, we asked how each firm dealt with a disruption event. We expected examples of natural disasters, fires, strikes, etc. While there were some examples of disastrous types of disruptions, more often the examples given were unanticipated demand, rush orders, shortage in supply, company buyouts, delivery coordination, and sourcing constraints. There were also examples of flooding, labor, strikes, and socio-political disruptions. The common response to how these disruptions were addressed was increased safety-stock, dual or multi-sourcing, and better forecasting. It became increasingly evident that while most, if not all, nodes in each supply chain would say coordination is important, when push came to shove, each node primarily looked out for itself. Some of the ways in which organizations would address disruptions were to ride the disruption event out and then make changes to avoid the same kind of disruption in the future. For example, if a firm found itself in a bad situation based on single sourcing, it determined never to single source again. Another firm described a disruption caused by unanticipated global demand. This firm's response to the disruption was to prioritize which customers would get what amount (an allocation process), and then they simply delivered product against those fixed allocation amounts until the problem went away. In addition, they prioritized engineering resources to expedite new equipment to aid in meeting demand. These types of responses were common, illustrating behaviors that were myopic, and could exacerbate disruptions beyond the single firm. Therefore, it is important to note that supply chain risks may not occur in isolation, and the co-occurrence of the risks have systemic effects on the supply chain that may mask or exacerbate each other. This idea is not new. In fact, significant research has looked into disaster tolerance and disaster recovery from a technical perspective (Nguyen et al. 2016), particularly when striving for business continuity (Nijaz 2014). However, supply chains have not been considered in the same way as technical-cultural systems, but there is value in convergence of each discipline.

5.4 *A need for systemic risk management tools*

Researchers and practitioners alike are seeking ways to better understand the types of risk supply chains are facing and methods to avoid or at least mitigate these risks. For example, risk registers are one option when risks are enumerated while another common tool is a probability vs. severity matrix (e.g. Norrman and Jansson 2004) when risks are evaluated based on the probability of occurrence and severity of impact. However, these tools do not account for risks propagating through the supply chain (Blackhurst et al. 2005) nor do they account for the interaction between risks (Ackermann et al. 2007). Such tools fail to provide a holistic understanding of how the event may propagate and compound. It is a static tool, applied to a dynamic problem, where the analysis is only appropriate for one location in the supply chain at a single point in time. Managers should develop a richer understanding of the types of diagnostic tools and information employees need in order to select appropriate counter measures, and these decision aids need to be able to identify and assess system wide disruption impact.

6. Limitations and Future Work

This research is not without limitations. As is common in qualitative research projects, findings are heavily dependent upon researchers' interpretation and biases (Clark et al. 2010). Second, the information presented by those we interviewed is not exhaustive and may be biased by factors outside of our control, such as impression management or workplace frustration. Third, despite attempting to make our findings more broadly representative through the selection of seven distinct supply chains, we recognize we could not make it definitively generalizable. Specifically, we have focused on the manufacturing sector in selecting the focal firms in which to gather data. This limits the generalizability of our findings to the manufacturing sector and neglects the service sector. Although many of the factors influencing disruption propagation are possibly similar for service supply chains, we cannot claim to show that in our results. However, irrespective of these limitations, we believe our research provides relevant theoretical and managerial findings.

More research is needed to determine additional factors that influence disruption propagation. These might include supply chain level factors like complexity, geographic scope, firm position within the supply chain, the degree of inter-firm integration, and other supply chain design features. For example, we believe it would be interesting to model a supply network using graph theory, reconfigure the network by removing edges or nodes, and then measure the robustness of the network when a disruption occurs. It would also be interesting to simulate a disruption as it can propagate both up-stream and down-stream in a supply network. They should also include firm level factors such as supply chain risk management, orientation of the firm, and internal integration of supply chain processes. The themes influencing supply chain disruption propagation identified in this research should be investigated further. In addition, greater interest should be given to multi-objective criteria for mitigating risks of disruption to show the importance of viewing disruption factors from a bigger picture perspective and to not over simplify the problem. Finally, we recommend in depth case studies of firms that have a high level of awareness and demonstrated success in managing inter-firm risk. The identification of best practices in this arena will be a valuable contribution to management practice and supply chain risk management research

7. Conclusion

This paper offers insights into the understudied causes of supply chain disruption propagation. Some of the insights are not novel and have been investigated in previous research. However, the presence and implications of the co-occurrence of any and all of the systemic risks is noteworthy and worth further study. The motivation to pursue this question is to better understand the mechanisms and conditions driving supply chain disruption propagation. This systemic perspective has been lacking both in research and in practice. As supply chains continue to grow globally, this lack of understanding and internal focus will prove disastrous. To address this, we took a grounded theory approach with seven distinct supply chains. Our research reveals that while some factors, such as the nature of the disruption, may be beyond the control of supply chain decision makers, it is important to consider them in conjunction with the structure and dependence of the supply chain and the managerial decision making aspects of risk mitigation and addressing of disruptions. Specifically, organizations within a supply chain can reduce disruption propagation by taking a systemic risk perspective first by recognizing the interrelated themes presented in this research that contribute to disruption propagation, and then by addressing the themes, not in isolation, but in combination. It is imperative to take a holistic approach.

Appendix: Interview protocol

1. Please provide your title and years of experience in supply chain management.
2. Please provide a brief description of your supply chain design. (Locations of suppliers and facilities; general flow of information and material flow).
3. What is the biggest source of risk in your supply chain?
4. What do you do to mitigate your biggest source of risk in your supply chain?
5. Where does your supply chain risk come from? What factors drive risk in your supply chain?
6. How does the size and complexity of your supply chain affect the propagation of supply chain risk and your ability to manage supply chain risk?
7. How do you decide how to deal with or handle a disruption event? Please give an example.
8. How do your targets or incentives affect your decisions related to supply chain disruptions?
9. Describe the relationship with your suppliers.
10. How much influence do you have in the internal processes of your suppliers and/or them with yours?
11. Describe the relationship with your customers.
12. How much influence do you have in the internal processes of your customers and/or them with yours?
13. How does information sharing and coordination in your supply chain affect your ability to handle a disruption? Please give an example.

Table 1: Supply Chain Firm Summary Information

Supply Chain	Tier	Informant's Title	Years of SC experience	Focal Firm profile
Door and Windows Mfg.	Supplier	Senior Account Manager	22	U.S.-based manufacturer of windows, patio doors, entry doors and storm doors.
	Focal Firm	Plant Manager	7	
	Customer	Operations Manager	Not reported	
Office Furniture	Supplier	President	Not reported	U.S.-based manufacturer of workplace furniture. Multiple manufacturing facilities throughout the U.S.
	Focal Firm	Procurement Manager	19	
	Customer	Owner	26	
Appliances	Supplier	Director of Global Accounts	20	U.S.-based company manufacturer of appliances across all major categories.
	Focal Firm	Vice President of Supply Chain	15	
	Customer	Director of Demand Planning	20	
Industrial Supplies	Supplier	Supply Chain Manager	23	U.S.-based company manufacturer of industrial supplies including tapes, abrasives, and adhesives.
	Focal Firm	Supply Chain Manager	9	
	Customer	Distribution Manager	16	
Medical Supplies	Supplier	Supply Chain Manager	35	U.S.-based company manufacturer of medical devices and supplies.
	Focal Firm	Supply Chain Director	20	
	Customer	Plant Manager	30	
Chemicals	Supplier	Supply Chain Manager	38	Canadian-based manufacturer of plastics and chemicals. Firm has U.S.-based manufacturing locations.
	Focal Firm	Director of Logistics and Operations	26	
	Customer	Commodity Manager	22	
Food	Supplier	Materials Manager	20	U.S.-based company manufacturer of food products.
	Focal Firm	Logistics and Operations Manager	12	
	Customer	Logistics and Operations Manager	30	

Figure 1: Data Structure

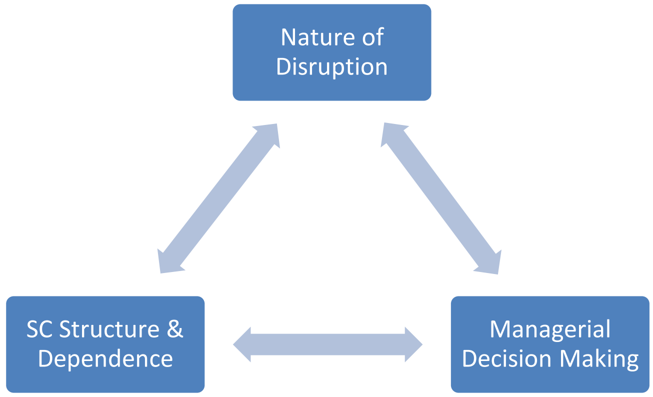

Figure 2: Relationship of Aggregate Dimensions

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