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Keep Your Friends Close? Supply Chain Design and Disruption Risk

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ABSTRACT

In this article, we evaluate the relationship between supply chain design decisions and supply chain disruption risk. We explore two supply chain design strategies: (i) the dispersion of supply chain partners to reduce supply chain disruption risk versus (ii) the co-location of supply chain partners to reduce supply chain disruption risk. In addition, we assess supply chain disruption risk from three perspectives: the inbound material flow from the supplier (supply side), the internal production processes (internal), and the outbound material flow to the customer (customer side) as a disruption can occur at any of these locations. We measure disruption risk in terms of stoppages in flows, reductions in flow, close calls (disruptions that were prevented at the last minute), disruption duration (time until normal operation flow was restored), and the spread of disruptions all the way through the supply chain. We use seemingly unrelated regression (SUR) to analyze our data, finding that lead times, especially supply side lead times, are significantly associated with higher levels of supply chain disruption risk. We find co-location with suppliers appears to have beneficial effects to the reduction of disruption duration, and, overall supply side factors have a higher impact when it comes to supply chain disruption risk than comparable customer side factors. [Submitted: October 16, 2012. Revised: November 24, 2013. Accepted: December 10, 2013.]

Subject Areas: Supply Chain Design, Supply Chain Disruption Survey Research, and Supply Chain Risk Management.

> Behold the fool saith, “Put not all thine eggs in the one basket”—which is but a manner of *saying, “Scatter your money and your attention”; but the wise man saith “Put all your eggs in the one basket and watch that basket.” (from* Puddn’head Wilson *by Mark Twain).*

INTRODUCTION

A hedging approach or essentially a "don't put all your eggs in one basket" approach to supply chain disruption risk mitigation is a well-established strategy in supply chain literature (Manuj & Mentzer, 2008). One example is the geographic distribution of supply chain partners so that a single disruptive event "does not affect all the entities at the same time and/or with the same magnitude" (Manuj & Mentzer, 2008). This has also been described as "dispersion" by Pettit, Fiksel, and Croxton (2010), who outline the benefits of the distribution of assets in the supply chain. However beneficial it may be, the dispersion of supply chain partners has left supply chains with longer lead times, which, in themselves increase supply chain disruption risk by introducing higher forecast errors, transportation delays, and shorter recovery times (Chopra & Sodhi, 2004; Christopher & Peck, 2004; Hendricks & Singhal, 2005).

However, as Mark Twain's quote points out, the alternative strategy bundles all one's investments in one place. For example, Alcácer (2006) studied agglomeration benefits in contrast with competition costs in terms of the activity and function of the firm to better understand co-location patterns. In supply chain terms, this phenomenon can be seen in the creation of supplier parks or clusters (Reichart & Holweg, 2008). A cluster is created when a group of suppliers co-locate into one central location. Like dispersion, though, co-locating of supply chain partners in a supply chain has also been linked to higher levels of disruption risk exposure. This spatial density of supply chain entities has been termed as risky because one localized disruption might affect a large portion of the co-located supply chain entities. Alcácer (2006, p. 1470) calls for more research to understand "which mechanisms make co-location more or less important . . . and under what circumstances one mechanism is more appropriate than another." This serves as one of the motivations of our study. Therefore, we investigate co-location decisions in the context (or circumstance) of better understanding and controlling supply chain disruption risk.

These are two valid supply chain design strategies, each associated with mitigating specific types supply chain disruption risk. Therefore, one may view these supply chain design decisions as a careful balancing act of the trade-offs of co-location or dispersion as each supply chain design strategy has benefits and drawback related to managing disruption risk in the supply chain. We seek to better understand the trade-offs of clustering or co-locating supply chain entities in contrast with dispersion of supply chain entities (in terms of the impact of co-location decisions) as well as the impact of long lead times on supply chain disruption risk. As such, this article empirically investigates the relationship of supply chain design (in terms of co-location vs. dispersion location decisions) and the susceptibility of supply chains to disruptions. Specifically, is co-location with supply chain partners associated with an increase or decrease of disruption risk exposure and what is the relation of increased lead times with supply chain disruption risk? Therefore, we seek to empirically examine which design strategy is associated with increased/decreased supply chain disruption risk and address the trade-offs in the literature related to supply chain design.

This article represents several contributions to the literature related to supply chain disruption risk and the factors associated with this risk. We investigate supply chain disruption risk as it relates to differing supply chain design strategies: (i) the dispersion of supply chain partners and its relation to supply chain disruption risk and (ii) the co-location of supply chain partners and its relation to supply chain disruption risk. To study these two questions, we examine whether co-location on the supply side of the supply chain are associated with more supply chain disruptions than similar strategic location decisions further downstream on the customer side. In other words, in which ways does the dispersion of supply chain partners or does the co-location of supply chain partners relate to supply chain disruption risk? In addition, we assess supply chain disruption risk from three perspectives: the inbound material flow from the supplier (supply side), the internal production processes (internal), and the outbound material flow to the customer (customer side) as a disruption can occur at any of these locations. We also consider the possible influence of independent variables related to disruption risk by decomposing disruption risk with more granularity than done in prior research into the following five factors: stoppages, reductions, close calls, duration, and spread as dimensions of supply chain disruption risk. The decomposition allows for a better interpretation of these discrete measurement items. Finally, we examine the type of disruption and the impact of supply chain lead time.

LITERATURE REVIEW

Interest in the topic of managing disruptions in a supply chain context has been increasing in recent years (Kleindorfer & Saad, 2005; Wagner & Bode, 2008; Braunscheidel & Suresh, 2009) because of the wide recognition that all supply chains are susceptible to a diverse set of disruption risks (Knemeyer, Zinn, & Eroglu, 2009) and disruptions in a supply chain can have both immediate and long-term effects (Blackhurst, Dunn, & Craighead, 2011). The design of today's supply chains, which may be characterized as being long, complex, and global in nature, leads to vulnerability and supply chain disruption risk. In fact, a single supply chain disruption can cause the collapse of the entire supply chain (Kern, Moser, Hartmann, & Moder, 2012). This growing research area has covered such topic areas as drivers of supply chain disruption risk (Chopra & Sodhi, 2004), supply chain vulnerability (Sheffi & Rice, 2005), global supply chain disruption risk management (Manuj & Mentzer, 2008), supply chain agility (Braunscheidel & Suresh, 2009), and proactive planning for catastrophic events (Knemeyer et al., 2009). Still, many opportunities remain to better understand factors that increase (or decrease) disruption risk in a supply chain. In fact, researchers have noted that today's supply chains have constrained and limited resources (Kern et al., 2012) causing supply chain risk management to come at a cost or trade-off (Wagner & Bode, 2008). Therefore, supply chain managers want to know where supply chains are most vulnerable in order to properly allocate valuable resources (Chopra & Sodhi, 2004; Kern et al., 2012).

Measuring Supply Chain Disruptions

Supply chain disruptions are defined as "unplanned and unanticipated events that disrupt the normal flow of goods and material in a supply chain and, as a consequence, expose firms to operational and financial risks" (Craighead, Blackhurst, Rungtusanatham, & Handfield, 2007; Ellis, Henry & Shockley, 2010). Craighead et al. (2007) focused on the severity aspect of disruptions, while Ellis et al. (2010) used the probability for disruptions and the magnitude of disruptions to cover supply chain disruptions. We enhance this conceptualization with increased granularity of the components of *disruption risk* in terms of the following components:

- Stoppages where flow is completely halted.
- Reductions in flow where a disruption in the supply chain causes the expected flow of material to slow down or not be delivered in the time frame or quantity anticipated.
- Close calls which we define as disruptions that were prevented at the last minute.
- Disruption duration defined as the time until normal operation flow was restored.
- The spread of the disruptions all the way through the supply chain. This accounts for the propagation or contagious nature of the disruption in the supply chain. In other words, how much of the supply chain was affected.

In doing so, we put the actual event (Melnyk, Pagell, Jorae, & Sharp, 1995) of a supply chain disruption, and its characterizing components, at the center of the study. The disruptive event can be thought of as a supply chain risk that has been *realized*. While Ellis et al. (2010) conceptualized overall supply chain disruption risk as the probability of a risk occurring in the future and potential magnitude of the disruption, we will focus on the more detailed components of the realized disruption event, rather than emphasize the aggregated, overall supply chain disruption risk. This detailed view will allow for a more differentiated description of the association between our supply chain design variables and the various components of disruptions. When we are referring to risk of disruptions in the remainder of the article we are referring to the supply chain manager's perceptions of the level of the individual components of disruptions that occurred in their supply chains (stoppages, reductions, close calls, duration, and spread).

Relevant dimensions of a disruption include the frequency of its occurrence and its duration (in other words, how long does it take to solve the disruption). We conceptualize frequency as stoppages, close calls, and reductions. Furthermore, supply chain disruptions may spread through the supply chain (Blackhurst, Craighead, Elkins, & Handfield, 2005) and supply chain disruption risks are often interrelated (Chopra & Sodhi, 2004). In other words, one disruption may affect the functionality of other supply chain elements (upstream or downstream) and recent research has called for further studies to help firms understand the interconnectedness of supply chain disruption risk (Manuj & Mentzer, 2008). Hence, for this study, we define with the key factors of a supply chain disruption with increased granularity in order provide a deeper understanding of supply chain disruption risk. First, we proceed to measure disruption risk from three unique perspectives in relation to a focal firm: the inbound material flow from the supplier (supply side), the internal production processes (internal), and the outbound material flow to the customer (customer side). Such a conceptualization is consistent with recent research in complex systems (Bozarth, Warsing, Flynn, & Flynn, 2009), in supply chain design impact on vulnerability (Sheffi, 2005) and in the mitigation of supply chain disruption risks with flexibility (Tang & Tomlin, 2008). Sheffi (2005) states that these three perspectives encompass the entire supply chain and, in addition, provides a definition for each along with many rich examples related to supply side, internal and demand side disruptions:

- Supply side disruptions: These disruptions occur on the inbound or supply side of the supply chain. Examples (Sheffi, 2005, pp. 28–29): A supplier to GM had a chemical spill at a chip plant (semiconductor) which contaminated the chips used in all GM key fobs (keyless entry systems). Without the key fobs, GM was unable to sell its cars. Another example is the steel shortage in 2004 which shut down three of the four Japanese Nissan plants. The shortage was caused by increasing demand from China and led to an inability to provide steel to all customers.
- Internal disruptions: These disruptions occur inside the companies facilities. Example (Sheffi, 2005, p. 29): In 2003, a tornado hit a GM facility in Oklahoma. The plant was up and running seven weeks later, but it was estimated that earnings were hurt by $168 million dollars (Hawkins, 2003).
- Customer side disruptions: These disruptions occur on the outbound or customer facing side of the supply chain. Example (Sheffi, 2005, pp. 229–231): Caterpillar, Inc. is the world-wide largest manufacturer of heavy equipment for the mining and construction industries. If a customer has a piece of equipment break down, the costs can be crippling with an estimated cost of downtime by one of Caterpillar's mining customers of up to $30,000 per hour. To mitigate this risk, Caterpillar focuses on its ability to quickly deliver spare parts to its customer. This is a challenge due to an estimated 500,000 different spare parts needed for customers around the world. Caterpillar, therefore, looks to its supply chain design and how close they can be to customers by developing a joint partnership for inventory with the vast network of Caterpillar dealers allowing them to be a close to the customer as possible.

We find this distinction of the three disruption locations important because (i) it encompasses the entire supply chain, (ii) it distinguishes between partners of the supply chain a company may have control over (internal) and parts that a company may have some influence over (supply side), and (iii) it is impacted by the supply chain design in terms of co-location decisions and the impact of lead time.

Next, our primary focus is on the actual occurrence of the disruption (realized disruption risk). Because we define disruptions as negative impacts on the material flow within the supply chain in accordance with the extant literature (Hendricks & Singhal, 2005; Craighead et al., 2007; Ellis et al., 2010), we use flow stoppages and flow reductions as two dimensions of supply chain disruptions. In addition, we use duration and spread to assess the magnitude of the negative event. Therefore, we assess disruption risk in terms of stoppages, reductions, close calls, duration, and spread. We focus on the *occurrence* of the event and not the *aftermath*, specifically excluding the loss dimension of a disruption as previous research has soundly shown that disruptions are negative events and can lead to loss (Hendricks & Singhal, 2005; Ellis et al., 2010). In other words, we contend that loss is an *outcome* and is a function of stoppages, reductions, close calls, duration, and spread.

Our research design calls upon managers to assess risk and give their opinions on the levels and frequency of risk. Yates and Stone (1992) suggest that managers' risk perceptions are based on the probability and magnitude of loss in any given scenario which are combined by the manager to form risk perception. This approach has been used by Ellis et al. (2010) to form a construct of overall supply chain disruption risk driven by a buyers' judgment. Zsidisin and Wagner (2010) examined the perception of supply management professionals on various sources of risk and Zsidisin (2003) investigated characteristics of the supply base that impacted managerial perceptions of supply chain risk. In this article, we build upon this prior work to investigate the perceptions of supply chain managers regarding how they assess supply chain disruption risk from the inbound material flow from the supplier (supply side), the internal production processes (internal), and the outbound material flow to the customer (customer side) to determine the perceived benefit to co-location decisions on the supply chain customer side and the supply side considering the impact on supply chain lead time and the components of disruption risk in terms of stoppages in flows, reductions in flow, close calls (disruptions that were prevented at the last minute), disruption duration (time until normal operation flow was restored), and the spread of the disruption through the supply chain. We note that the perceptions in our study are based on disruptions that were realized or actually occurred.

Supply Chain Design

Supply chain design decisions have an impact on where resources are placed and should likely affect the vulnerability of the supply chain. A co-located supply chain represents the "put all eggs in one basket" strategy. In a co-location design, entities (for example, suppliers and plants) are clustered together (co-located) and are, thereby, exposed to the same external disruption risk sources; one recent example is the terrible tsunami that hit Japan in 2011, devastating much of the mainland and crippling the successful supply chains of automakers Toyota and Honda (Takahashi, 2012). Conversely, a geographically diverse supply chain network is more "hedged" against such common risk sources and represents an alternative strategy. Clusters are defined as "geographic concentrations of interconnected companies" and are discussed in detail in the seminal work of Porter (1990, 1998). Recent research has highlighted cluster theory as a "rich set of well-tested concepts that are generally missing from the current research base. Incorporating these concepts into future research has the potential to improve our understanding of how decisions regarding supply chain location and partnering are currently made, and what role location-based benefits should play in these decisions" (Bozarth, Blackhurst, & Handfield, 2007, p. 156). Adding interest to this question is that there are differing recommendations related to this dispersion versus co-location question with regards to the level of supply chain disruption risk.

To justify our investigation of supply chain design using clusters or co-location design decisions, we draw upon Porter's cluster theory (1990, 1998), which states that having "geographic concentrations of interconnected companies" offers competitive advantage in the form of higher productivity increased by access to labor and suppliers, better motivation and comparative measurement, information and knowledge sharing, complementarities, increased incentives, and higher levels of innovation. Cluster theory and the implications for supply chain management have also been discussed in a case study by DeWitt, Giunipero, and Melton (2006), in which the authors recommended that firms should make supply chain location decisions with clusters in mind, as co-location may offer improved performance both at the firm and supply chain level. In a case study investigating the benefits of clusters, Patti (2006) found that clusters led to improved supply chain performance.

Reichart and Holweg (2008) state that the design and configuration of a supply chain can offer a firm competitive advantage. This is echoed by Alcácer (2006) who discusses the strategic value of location choices. These design decisions may range from co-locations of two supply chain partners to a more encompassing design strategy of clustering with the creation of "supplier parks" where many suppliers in close proximity to an Original Equipment Manufacturer (OEM). Indeed, co-location is actively used in today's supply chains. In one prominent example, Volkswagen Group of America unveiled an onsite supplier park consisting of two massive buildings (as large as nine American football fields) at its Chattanooga, TN site in September of 2010 (Pare, 2010). This supplier park is an example of firms locating nearer to the customer. Another such example is Nissan's announcement in July 2013 of a 1 million-square-foot campus for its suppliers near Nissan's vehicle assembly plant in central Mississippi (Pettus, 2013). Clearly, there are advantages to co-location of entities in a supply chain which allow the use just-in-time (JIT) practices (Reichart & Holweg, 2008), thereby reducing transportation lead time as well as reducing transportation costs. Other benefits in the literature related to co-location include, increased productivity and innovation, higher levels of trust among partners, improved problem solving abilities, and improved knowledge and information sharing among supply chain partners (Porter, 1998; Sheffi, 2010; Ellram, Tate, & Petersen, 2013). In fact, Ellram et al. (2013) state that the ability to deliver value to the customer is key to the decision of location.

However, Craighead et al. (2007) have urged managers to question the wisdom of co-location when considering supply chain disruption risk. A disruption at one point in the supply chain may spread to other parts of the supply chain and lead to the shutdown of the supply chain (Blackhurst et al., 2005). Bounds, Tighe, and Guthrie (2009) demonstrate how interdependence in cluster of co-located entities could lead to a "toppling" of the cluster. Higher supply chain density is known to lead to higher levels of risk as a disruption could have the potential to affect a large portion of a supply chain. Chan, Kumar, Tiwari, Lau, and Choy (2008) also discuss the issue of supplier location, cautioning companies to consider factors such as distance to the supplier, natural disasters, political stability, exchange rates, and terrorism and crime rates. Kleindorfer and Saad (2005) urge the use of diversification of facility locations in order to reduce supply chain disruption risk.

However, the impact of lead times in a supply chain cannot be ignored. Longer lead times slow a supply chain's reaction time and flexible adaptation to disruption. In fact, Christopher and Peck (2004, p. 6) state "companies have moved from domestic to global sourcing in search of lower unit costs. However, that definition of cost is too limited—it does not always take account of the increased risk to the supply chain through extended/lead times, reliance on partners who themselves may be vulnerable to external events, or the potential loss of control." These long lead times can be created by long distances and transportation times between supply chain links, as well as a lack of cooperation among hubs that slows reaction times and order fulfillment. Still, to be clear, co-location and lead times are distinct in this study since our measure of lead time includes issues beyond transportation time (i.e., internal coordination and slower order fulfillment).

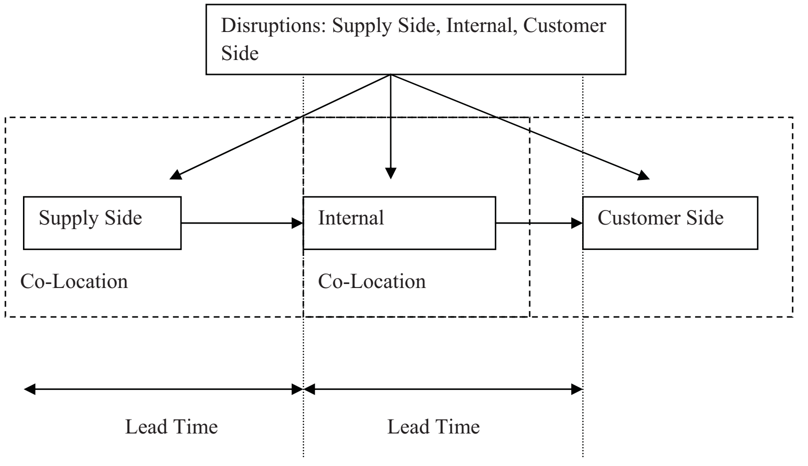
HYPOTHESES DEVELOPMENT

Our research questions aim to examine the relationship between supply chain location decisions and supply chain disruptions. The unit of analysis for this study is the focal firm's supply chain for a major product line (Habermann, 2009). We chose this perspective for this study for several reasons. First, the risk evaluation and risk management in financial markets focuses on individual firms. For this reason, the evaluation of supply chain disruption risk ought to take a similar firm-focused perspective to best capture this insight, which is a perspective that has also been employed in by Hendricks and Singhal (2005). In addition, the focus on a single, major product line avoids issues stemming from possible supply chain design differences across different product lines in the focal firm. Focusing on a single major product line within the focal firm for this study helps to avoid any confusion for the survey respondent and provides a less convoluted view of a product line–specific supply chain. Finally, we examine disruptions at the upstream, internal, and downstream parts of the focal firm's supply chain. Hence, it is crucial to keep the unit of analysis consistent across all three parts of the supply chain. Using a single product line allows the capture product line–specific disruptions at the upstream, internal, and downstream parts of the focal firm's supply chain. Our conceptual model is represented in Figure 1. We assess the co-location of the focal firm with its suppliers and its customer separately, as is also shown in Figure 1. Finally, we distinguish conceptually between the lead time from the supplier to the focal firm and the lead time from the focal firm to the customer.

Typically, we tend to use a single theory, or perspective to examine any given phenomenon in supply chain management. However, there is a growing urge to design studies that compare competing, plausible explanations of the same phenomenon (Stinchcombe, 1968; Singleton & Straits, 1999; Van de Ven, 2007). Juxtaposing or comparing competing explanations of a phenomenon is often referred to as "carving at the joints" as postulated by Plato (Van de Ven, 2007, p. 21). This research design leverages the knowledge base of the different perspectives and compares them empirically with the status quo in the real world. Such research presents a higher likelihood of advancing theory and practice at the same time.

This study will use the "carving at the joints" approach to formulate our hypotheses, as the literature on the topic offers perspectives from both sides—(i) that co-location of firms offers many competitive advantages and (ii) that co-location can have a potentially detrimental effect on supply chain disruption risk when a disruptive event occurs. Interestingly, a similar lack of consensus

Figure 1: Conceptual model.



regarding co-location decisions can be seen in the literature on product development performance in supply chains (Gerwin & Ferris, 2001; Swink, Talluri, & Pandejpong, 2006). One side points out that co-location decisions increase operating costs and often create inefficient behaviors that reduce overall performance in the supply chain (Kessler, 2000). Other researchers have shown that co-location within the supply chain can positively influence performance through better coordination between the supply chain partners (Hinds & Mortensen, 2005; Gulati & Puranam, 2009). We believe that this dichotomous theoretical view of co-location also applies to the influence of co-location on supply chain disruption risk, setting out to empirically test these competing hypotheses.

Speier, Whipple, Closs, and Voss (2011) discuss how supply chain design decisions traditionally focused on reducing transportation costs, but now extend to include measures of supply chain disruption risk. Reichart and Holweg (2008) note when production needs are less than anticipated, supply chain disruption risk in co-located chains may increase. That is, co-location can also reduce supply chain flexibility when lower than anticipated capacity utilization cannot be redeployed to other customers or products (usually due to contracts or agreements). Porter (1990) cautions against other potential drawbacks to clusters including group think, regulatory inflexibility, and restrictive unions. Even, Sheffi (2005, p. 31) states that “multinational companies realize that many disruptions are tied to geography: floods, earthquakes, political upheaval, fluctuating exchange rates, and other potential causes of disruption are focused on certain geographical locations.” Craighead et al. (2007) found a positive relationship between disruption severity and the density of the supply chain (how entities are co-located together in close geographic proximity). For example, one manager participating in their study explained that his firm is more concerned with regional disruptions that affect co-located groups of supplier than with disruptions that only affect a specific supplier.

A cautionary approach to co-location is also reinforced by Deane, Craighead, and Ragsdale (2009), who extend the idea of co-location to risks affecting an entire geographical area, thus affecting many nodes in a supply chain if they are in close proximity. In conclusion, co-located firms exhibit a higher risk for severe disruptions than a less densely designed supply chain whether it be on the supplier side or the customer side.

Hence, we believe that co-location might be exemplary of the problem of putting "all your eggs in one basket." The strategy may work well so long as nothing goes wrong, but once a disruption occurs it affects several supply chain entities, multiplying the impact of a single disruption. This leads us to our first two hypotheses regarding co-location:

H1a: Co-location with one's suppliers is associated with higher levels of disruption risk.

H1b: Co-location with one's customers is associated with higher levels of disruption risk.

There is, of course, a competing argument to be made that the co-location of supply chain partners improves coordination of work activities and, thus, reduces the supply chain disruption risk. Patti (2006) discusses the advantages to co-located clusters as identified by Porter and adds lower transportation time, lower costs, and lower lead times to the tally. Wu, Yue, and Sim (2006) discussing the context of China, consider labor cost advantage as only part of the picture; co-locations are also cited as a significant advantage due to the sharing of investment costs, capacity aggregation, and reduction in inventory requirements as well as reduction in transportation time, cost, and variability (Porter, 1998; DeWitt et al., 2006; Patti, 2006; Wu et al., 2006).

Furthermore, Reichart and Holweg (2008) offer a very detailed literature review on the advantages of co-location decisions in the automotive industry. The main advantages with regard to disruption avoidance are increased flexibility, delivery reliability, organizational and technological integration, and improvements in quality and ability to handle complexity. All of these capabilities have been cited as beneficial for creating a reliable supply chain (Sheffi, 2005). Choi and Krause (2006, p. 642) specifically state that: "It would be easier for a focal company to coordinate activities with suppliers if they share a common culture and work norms and suppliers are in close geographical proximity." Choi and Krause (2006) use the traditional keiretsu structure in Japanese supply networks as an example of suppliers that are found in the same geographical area where the focal firm is located. They conclude that increased geographical distances increases the supply chain complexity, which in turn leads to higher disruption risks. Conversely, close proximity, or co-location of supply chain partners, increases the reliability and decreases the disruption risk. This leads to our second, opposite set of hypotheses:

H2a: Co-location with one's suppliers is associated with lower levels of disruption risk.

H2b: Co-location with one's customers is associated with lower levels of disruption risk.

As supply chain options increase, we have seen companies buying parts and selling products around the globe, with supply chains involving greater distances and more facilities on different continents. The result is longer lead times which can have a detrimental effect on the resilience of the supply chain. One of the main issues with long lead times is that they increase the time horizon of uncertainty (often reflected in higher safety stock levels), which makes forecasting challenging (Sheffi, 2005). Chopra and Sodhi (2004) discuss drivers of supply chain risk and how long lead times contribute to inaccurate forecasts, increasing uncertainty. Hendricks and Singhal (2005) also associate longer lead times with increases to disruption risk and Christopher, Mena, Khan, and Yurt (2011) discuss globalization as a driver of such longer lead times in a supply chains.

Indeed, lead times have always played a critical role in supply chain design (de Treville, Shapiro, & Hameri, 2004). Hopp and Spearman (2001) used queuing theory to create a set of underlying principles that showed that lead time reduction is beneficial to overall supply chain performance. The negative impact of long lead times not only affects the delivery speed of the supply chain, but can also lead to unwanted outcomes like the bullwhip effect (Chen, Drezner, Ryan, & Simchi-Levi, 2000). However, recently lead times have made news headlines specifically in association with supply chain disruption risk. This has lead some companies to re-evaluate their offshore sourcing policies, as offshoring may present cost advantages, but it also increases lead times and the transportation system may become a weak link in the supply chain, susceptible to its own disruptions (Sheffi, 2002). While we show how lead time has been discussed in the literature, this relationship has not been empirically tested. We believe that overall lead times (not just transportation times) are responsible for increases in supply chain disruption risk.

H3a: Longer supply lead times with one's suppliers are associated with higher levels of disruption risk.

H3b: Longer delivery lead times with one's customers are associated with higher levels of disruption risk.

Finally, we are interested which among the supply side or customer side (upstream vs. downstream) decisions regarding co-location and lead time are more significantly associated with disruptions in the various locations. We note that much of the supply chain disruption literature has focused on the supply side (e.g., Tomlin, 2006; Chopra, Reinhardt, & Mohan, 2007; Ellis et al., 2010; and Zsidisin & Wagner, 2010). Because our study is from the perspective of the focal firm, do upstream (supplier side) factors of co-location and lead time have more or less impact that downstream (customer side) co-location and lead time factors? By separating our hypotheses to look at the supply side and customer side separately, we are able to provide additional insight into supply chain design decisions. In other words, we seek to understand which will more significantly impact disruption risk.

Because disruptions may propagate through the supply chain and grow in intensity through that propagation (Blackhurst et al., 2005; Craighead et al., 2007), there may be a perception that supply side problems have the opportunity to cut off the complete material flow to downstream partners. Propagation may be articulated as an accumulation effect or snowball effect, in which the downstream partners bear the burden of the upstream decisions and as the disruption grows in intensity and scope it may become default to halt its path. While it is common to classify risks by supply side and customer side (Kouvelis, Chambers, & Wang, 2006; Wagner & Bode, 2006; Manuj & Mentzer, 2008; Kern et al., 2012), much of the supply chain risk literature focuses on the supply side (Choi & Krause, 2006). For example, in a case study by Craighead et al. (2007) studying the severity of supply chain disruptions, most of the examples is on the supply side. In fact, the wisdom of sourcing from supplier clusters is called into question when considering supply chain risk (Craighead et al., 2007). Therefore, we present the following hypotheses.

H4a: The impact of supply side co-location decisions is larger than the impact of customer side co-location decisions on disruption risk.

H4b: The impact of supply side lead times is larger than the impact of the customer side lead times on disruption risk.

METHODOLOGY

We measure disruption risk from three different perspectives in relation to a focal firm: inbound from the supplier (supply side), internal production flow, and outbound to the customer (customer side). This three perspectives conceptualization is consistent with recent research in complex systems (Bozarth et al., 2009) as well as risk (Sheffi, 2005). Our primary focus is on the occurrence of the disruption. Hence, we use flow stoppages, flow reductions (Craighead et al., 2007), and close calls (Sheffi, 2005) as dimensions of disruptions. We also use duration (time to recover from a disruption, see Sheffi, 2005) and spread to assess the magnitude of the disruption (how far the disruption will spread through the supply chain, see Blackhurst et al., 2005). All of these dimensions (e.g., stoppages, reductions, close calls, duration, and spread) are intended to provide more insights as to why negative events occur in the supply chain and how to prevent them with careful planning.

A note: we assess co-location with suppliers and co-location with customers separately (Figure 1). This configuration allows us to differentiate between the two sides of co-location strategy. Overall lead times are accessed on the supply side from the supplier to the focal firm. On the customer side, overall lead time is measured from the focal firm to the customer (please see the measurement section).

Data Collection

The data collection for this study consists of several pretests, a large-scale pilot test, and a main data collection effort. All steps of the data collection were administered entirely online.

Pretest and Pilot Study

The pretest stage of the data collection was used to ensure the constructs' content validity, which is particularly crucial when using single-item measures.

Content validity reflects how adequately the content for the study has been sampled (Nunnally, 1978), and the construction of the survey instruments using sensible methods grounded in the literature is the basis to ensure content validity. A common method for assessing content validity is to ask content experts to evaluate the measurement instruments. Four academic and eight managerial content experts were asked to assess the survey items using a variation of the classic think-aloud procedures (Duncker, 1945). The use of "verbalizations as indicators of cognition" is a well-established data collection technique, and various studies have verified that think-aloud procedures can lead to better designed survey instruments. Think-aloud procedures have been employed to improve the readability of written documents (Shriver, 1984, 1991) and have been used during the initial stages of survey development to gather information to improve the accessibility and readability of survey instruments for the respondents (Nolan & Chandler, 1996; Camburn, Correnti, & Taylor, 2000). In this way, think-aloud procedures and other assessment evaluation techniques present important information about the survey instruments and the overall survey design. In our case, the online surveys used text boxes for respondents to make remarks regarding the word choice, clarity, phrasing, and content of each measurement item. We used the collected comments to improve the wording of the questions using a lingo that would be more easily understood by our supply chain management respondents.

Subsequently, we conducted a pilot study to evaluate the psychometric properties of our survey measures. The survey was administered following Dillman's (2000) commonly used structure for data collection, which is widely used for empirical operations management studies (Koufteros, Vonderembse, & Doll, 1998; Nahm, Vonderembse & Koufteros, 2003). The pilot study was conducted with members of a Yahoo! user group for supply chain management professionals. E-mails were sent to approximately 250 members, resulting in a survey response of 57 supply chain professionals, representing a response rate of 23%. This sample size of the pilot study is relatively large compared to other pilot studies, increasing the power of our exploratory analysis (Koufteros et al., 1998; Nahm et al., 2003; Shah & Ward, 2007). The data collected during the pretests and pilot study were not used for the main data analysis in this study, as they were only intended to aid in the identification of measurement dimensions, readability and clarity of the questions, and the overall establishment of content validity for the measurement instruments.

Main Data Collection

The main data collection effort was conducted with the members of an organization of supply chain management professionals. The member list for the survey instrument was composed of supply chain professionals that matched three specific characteristics. First, the person worked for a manufacturing firm. Second, the person had a high- or mid-level position within the organization (the job titles indicated senior manager upward). Third, the person was listed in the organization's database as a supply chain management contact in their firm. The survey was administered through the organization of supply chain management professionals and limited to an initial contact e-mail and a final reminder e-mail. We received 108 usable responses, with a corresponding response rate of 11%.

Table 1a: Descriptive statistics of respondents(Part 1)

How much experience do you have in	<1 Year	1–2 years	2–5 years	5–10 years	>10 years
Your industry	.00%	5.26%	22.81%	12.28%	59.65%
Your firm	1.75%	7.02%	31.58%	21.05%	38.60%
Your current position	3.51%	14.04%	42.11%	26.32%	14.04%

Table 1b: Descriptive Statistics of Respondents (Part 2)

	Very confident	Confident	Somewhat confident	A little confident	Not at all
How confident were you in answering the questionnaire	18.81%	61.16%	16.53%	3.50%	.00%

Table 1a indicates that our respondents have substantial experience in their field of expertise. The respondents have significant experience within their current position, firm, and industry. This experience is also reflected in Table 1b which captures the confidence the respondents exhibited in answering our questionnaire. Almost 80% of respondents were "very confident" or "confident" answering our questions.

The majority of respondents answered all the survey questions and we sent a reminder to respondents to fill out the complete survey instrument. The remaining missing items were very minor and the vast majority of the response usable for the later data analysis. We used several techniques to address the missing data to check for any sensitivity of the results to such missing data. Missing values can be distinguished into the following categories:

i. Missing completely at random (MCAR).
ii. Missing at random (MAR).
iii. Not missing a random (NMAR).

The data are considered MCAR if the pattern of the missing values in the data set does not exhibit any dependencies on other variables from the same data set (Indurkhya, 2005). MCAR is a very rigorous stipulation that is necessary for case wise deletion and occurs very seldom in data collected through surveys (Rubin, 1976). SPSS 17 was used to perform Little's MCAR chi-square test (Little, 1988; Little & Rubin, 2002) on all dependent and independent variables. The chi-square test was significant and indicates that our data are not missing completely at random. Alternatively, MAR refers to a missing data pattern which is conditional on an independent or control variable, but not on the dependent variable from the data set (Schafer, 1997). The separate variance *t*-test uses all variables with more than 5% missing values and examines whether the data values are MAR. We created groups by indicator variables (existing vs. missing data values) for every quantitative variable in the data set and are tested for mean differences between the groups. Instead of the group-means, a logistic regression can be utilized to perform this test. Each variable under examination is grouped into missing and

Table 2a: Descriptive statistics of participating firms

Total number of employees	
<100	6.25%
100–249	6.25%
250–499	10.42%
500–999	16.67%
>1,000	60.42%
Approximate annual revenue	
<100 million	10.42%
100–499 million	14.58%
500–999 million	20.83%
1–5 billion	31.25%
6–10 billion	2.08%
>10 billion	20.83%

existing data as the dependent variable for the logistic regression with all the other variables as predictor variables. The missing value analysis indicates that our data are MAR in the data set. Mean replacement, deletion, and an imputation with an Expectation–Maximization algorithm were used to deal with the missing values. The following data analysis to test the research hypotheses was conducted using the three methods for addressing missing values, but did not exhibit significant deviations across the results from the analysis.

Furthermore, we conducted a nonresponse bias test by comparing early respondents to late respondents across all relevant measures included in our later model. We did not detect any significant differences between the late and early responders. Unfortunately, we were not able to contact some of the nonrespondents for further investigation as all the contact was done anonymously through the organization of supply chain management professionals.

However, we would like to point out that we have a slight bias in our sample when it comes to the distribution of our respondents regarding their industries SIC code compared to the U.S. census. We have a higher participation of respondents from the Food, Chemical, Electronics, and Transportation industry compared to the census. This is partially due to the higher relevance of supply chain management in such industries and hence a higher membership rate at professional organizations. We also suspect that it is driven by an increased interest in disruptions in such industries. Especially, food and chemical industries have often been in the news regarding supply chain disruptions and should have an innate interest in such a study. The descriptive statistics of firms is shown in Table 2a and the SIC code comparison is shown in Table 2b.

Measurement

The measures selected for this study are single item as compared to the more frequently used multi-item scales for several reasons. Rossiter (2002) did not find the multiple-item scale as being necessary for measurement when the object (i.e., the focal object being rated) can be conceptualized as concrete and singular. In

Table 2b: SIC codes.*

SIC code	U.S. - Census	Sample
20 – Food and kindred products	5.5%	14.4%
21– Tobacco products	.0%	.0%
22 – Textile mill products	1.6%	.0%
23 – Apparel	6.2%	1.0%
24 – Lumber and wood products	9.7%	.0%
25 – Furniture and fixtures	3.2%	3.1%
26 – Paper and allied products	1.7%	3.1%
27 – Printing and publishing	16.5%	1.0%
28 – Chemicals	3.3%	24.7%
29 – Petroleum	.6%	.0%
30 – Rubber and misc. plastics	4.5%	1.0%
31 – Leather products	.5%	.0%
32 – Stone, clay, glass, and concrete products	4.3%	.0%
33 – Primary metal industries	1.7%	.0%
34 – Fabricated metal products	10.1%	6.2%
35 – Industrial and commercial machinery	14.9%	7.2%
36 – Electronic and other electronic equipments	4.5%	15.5%
37 – Transportation equipments	3.3%	8.2%
38 – Measuring, analyzing, and controlling instruments	3.1%	9.3%
39 – Misc. manufacturing industries	4.8%	2.1%

*A test for group differences was conducted but did not result in any significant differences across groups. In addition, the individual groups are very small which makes sound statistical inferences difficult to attain because of the small sample size per group. Therefore, we chose not to include 19 control variables for the two-digit SEC codes in the models but rather selected to include control variables designed to capture competitiveness and other industry factors which were of greater relevance in the context of supply chain disruptions.

other words, single items are sufficient when the measure completely captures a concept or when measurement reliability does not represent a problem (Shah & Goldstein, 2006). We argue that the measures used in this study are concrete and singular. The disruptions are specific events that we sufficiently described for the respondents to avoid any confusion regarding their content. The disruptions are, without any doubt, not latent/abstract constructs but concrete events that can be measured with single items. Furthermore, co-location of suppliers/customers and lead times are very specific, singular objects that can be validly assessed using single items.

Bergkvist and Rossiter (2009) state that free-standing, tailor-made single-item measures are as valid as single-item measures extracted from multiple-item. Thus, further empirical support is provided to show that multiple-item scales are not always necessary. Furthermore, we also need to emphasize the attractiveness of single-item measures among practitioners. Practitioners prefer single-item measures as they are the norm in practice and their use contributes to their relevance in industry. In addition, the use of single items reduces the overall length of surveys and reduces the cognitive burden of respondents.

Dependent variables

Supply chain disruption can be defined by three critical dimensions. Disruptions are measured using items capturing their frequency (of stoppages, reductions, and close calls), duration, and spread on Likert scales. The measurement items limit the context of disruptions to the supply base by referring to the initial location the disruption occurring within the supply chain. Frequency and duration are critical attributes to assess system reliability and based on disruption models. Failure rate distributions and repair rate distributions are used to assess frequency and duration of disruptions in analytical models (Hopp & Spearman, 2001). Furthermore, we used reductions and close calls, in addition to stoppages of the flow, to assess the susceptibility of the supply chain toward disruptions. Perrow (1999) states that "almost disruptions" are a good indicator for a systems risk levels and Dillon and Tinsley (2008) state that near-miss events (events that have the potential to, but did not, result in loss (Phimister, Oktem, Kleindorfer, & Kunreuter, 2003)) give an opportunity to better understand the resilience of the system. A system can get lucky over a certain period of time and avoid actual disruptions but experience close calls over that period of time.

Three months were selected as a suitable time anchor for survey respondents to recall any details about supply chain disruptions and to collect a representative sample of supply chain disruption occurrences. Similar recall methods are used in the psychology literature when respondents are asked to recall certain life events. We asked the disruption question separately for the supply base, production, and customer base:

> *"During the last three months, how often did your company experience problems in its supply base that caused disruption(s) to the material flow in your supply chain (disabled you to receive needed input factors)?"*

> "*During the last three months, how often did your company experience problems in its production process that caused disruption(s) to the material flow in your supply chain (halted your production)?*"

> "*During the last three months, how often did your company experience problems in its customer base that caused disruption(s) to the material flow in your supply chain (disabled you to deliver final products)?*"

Based on our pretests, we chose a five-point Likert type scale for the answer points (Not once; 1–3 times a month; 1–3 times a week; daily; several times a day). Similar sets of questions were asked about reductions in the flow and close calls in the supply chain. The duration of the disruptions was accessed by asking for a relative measure of time capturing the time period taken to resolve the disruption and return to the normal/planned schedule of operations ranging from very quickly to very slowly (i.e., "How quickly do you usually resolve these disruptions in your supply chain to return to the planned schedule?). The question was asked separately for all three parts of the supply chain. Finally, we used three questions to assess how much disruptions spread that originate in the supply base, production, or customer base (*How much do the disruptions usually spread through your supply chain?*). We selected specific answer options to capture the spread of disruptions throughout the supply chain (remains localized to single plant; spread to other firms; affect small part of supply chain; affect significant part of supply chain, whole supply chain affected).

Independent variables

We deployed two questions each to capture the lead times and the co-location extend in the supply chain. As with disruptions, we make the argument that lead times and co-location are not abstract, latent constructs, but rather concrete and singular, which indicates the use of single-item measures. For lead times, we assessed the supply side and customer side lead time separately. "Our suppliers lead times are too long compared to our competitor's suppliers." The downstream lead times are accessed as follows: "Our order lead times to our customers are too long compared to our competitor's lead times." We selected the comparative wording of these questions for two reasons. First, lead times vary greatly across different industries. Second, the critical aspect of relevance to our research is whether the lead time is unusually long per industry standards. The co-location of the focal firm was accessed with regards to its upstream and downstream supply chain partners. "Our suppliers are co-located within close proximity of our production facilities." and "We co-locate our production facilities within close proximity to our customers."

Control variables

The control variables used in our study were designed to enable us to better isolate the relationship between lead times and co-location decisions with regards to disruption risk. We control for *firm size* using the level of revenue as a measure for size. Because a single product line per firm is the focus for data collection, we use the product/industry-specific descriptors as control variables. Competitive industries are frequently associated with short product life cycles. Reduced product life cycles may shorten the learning curves for companies and increase the potential for disruptions. In addition, short product life cycles force all firms in the supply chain to quickly innovate and ramp up production of new product generations over increasingly shorter time intervals. This increased competitive pressure on the supply chain can be associated with increased chances for disruptions due to the constant newness of the products both in terms of manufacturing processes but also with supply chain relationship and processes with suppliers and customers. Hence, we use the *product life cycle* as an indicator of industry competitiveness and associated disruption risk.

Furthermore, the customization of the product is an indicator of its complexity that could potentially increase the disruption risk. A product becomes more complex as more components are used for the product and more configurations of the product exist. Product complexity could be associated with more options for failure in the supply chain, due to the increase in component/materials suppliers. This variable is also a further indicator for industry competitiveness, as competitiveness may lead to customization as a tool for differentiation from competitors. Therefore, we include a control variable for the level of *customization* of the production. Furthermore, low inventory levels are a potential source of stock-outs and supply chain disruption risk. Ultimately, low inventory levels can be the last

Table 3: Descriptive statistics independent variables

	Mean	Std. Deviation
S. Lead time	2.90	1.175
C. Lead time	2.91	1.26
S. Co-location	2.41	1.13
C. Co-location	2.24	1.10

Table 4: Descriptive Statistics Dependent Variables

Dimension of SC Disruption Risk	Location	Mean	Std. Deviation
Stoppage	*Supply*	2.41	1.23
	Internal	2.33	1.18
	Customer	2.67	.98
Reduction	*Supply*	2.83	1.23
	Internal	2.91	1.36
	Customer	2.73	1.17
Close call	*Supply*	2.42	1.32
	Internal	2.81	1.14
	Customer	2.39	1.24
Duration	*Supply*	2.18	1.04
	Internal	2.02	.97
	Customer	2.11	1.07
Spread	*Supply*	2.26	1.29
	Internal	2.12	1.30
	Customer	2.31	1.27

buffer to stop an escalating disruption from spreading throughout the supply chain. Hence, it appears critical to control for *low inventory* levels to better understand the association of this studies' focal (independent) variables and disruptions. Finally, we control for the *technical capabilities* and *operational practices* regarding the similarities/dissimilarities between the focal firm and its suppliers/customers, because Choi and Krause (2006) postulated that greater dissimilarities increase disruption risk. So, for instance, we examine how if the suppliers and customers to the focal firm are dissimilar in technical capabilities. Please see Appendix A for a complete list of the included measures.

Tables 3 and 4 show the descriptive statistics for the dependents and independent variables. The variables all follow characteristics that are alike to a normal distribution and were included without any further transformations in the subsequent data analysis.

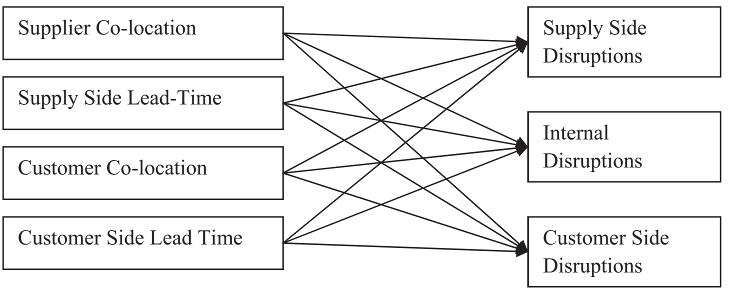
We also need to highlight the correlations between the independent variables in Table 5. Co-location and overall lead time variables are not significantly correlated. They are negatively correlated, which would be expected, but none of the correlations are significant at the .10 level. We need to remind the reader that the lead time does not just include the transportation lead time (which we would expect to be significantly and negatively correlated to co-location) but the overall

Table 5: Correlations of independent variables

	S. Lead Time	C. Lead Time	S. Co-location	C. Co-location
S. Lead time	1	.305**	−.159	−.115
C. Lead time		1	−.119	−.149
S. Co-location			1	.170*
C. Co-location				1

N = *108:* Significant correlations *p < .1; **p < .05.

Figure 2: Seemingly unrelated regression model.



lead time (which includes order, production, and delivery). Since overall lead time includes more factors than transportation, we were able to use these variables in the same regression equations without any multicollinearity problems (see VIF in later section).

Data Analysis

The research design for this study is inherently multistage due to the multitiered nature of supply chains. This indicates the need for a system of equations to test our hypotheses. However, the concrete, rather than latent nature of our measures in the model prevents the use of the widely applied structural equations modeling (SEM).

Instead, the model consists of a set of equations using three dependent variables (Figure 2): supply side disruption, internal disruption, and customer side disruption. A traditional approach to estimating coefficients for these equations is an equation-by-equation ordinary least squares (OLS) regression. However, when considering three equations that examine supply side, internal, and customer side phenomena, it is logical that the error terms in the set of equations may be correlated. A more appropriate technique is to apply a method that can account for the correlation among the error terms by running the model as a system of equations. Simultaneous equation estimations such as two-stage least squares (2SLS) and three-stage least squares (3SLS) are not appropriate, since the set of equations in the model do not contain endogenous regressors.

Seemingly unrelated regression (SUR), or joint generalized least squares, is a more efficient version of OLS for multiple equations systems. The type of cross-equation error correlation seen in Figure 2 can be accounted for by using the econometric technique of SUR; if the error terms of the dependent variables in the set of equations are truly unrelated, the model reduces to a set of OLS regression estimates (Zellner, 1962; Green, 2000).

Zellner (1962) developed the SUR model for a system of potentially correlated regression equations. This system of regression equations is considered "seemingly unrelated" because traditional modeling of the equations would follow separate OLS equations. However, considering the system of equations instead as separate OLS equations ignores the potential correlation among the error terms. If a system of equations uses similar independent variables, then it can be argued the error terms among the equations are correlated. According the Zellner (1962), SUR models are best used when (i) some coefficients are the same or zero among the set of equations; (ii) disturbance terms are correlated across equations; and/or (iii) a set of the same independent variables are seen in the equations. SUR models provide robust regression coefficients when considering a set of potentially correlated equations. In fact, this methodology is underused multivariate technique in empirical research.

An often used specification test for the SUR model is the Breusch–Pagan Test of Independent Errors (Breusch & Pagan, 1980). The Breusch–Pagan Test examines whether or not the error terms among equations are correlated. The null hypothesis is that there is no contemporaneous correlation among errors. The alternative hypothesis is contemporaneous correlation exists across the equations. This test statistic can be generalized for more than two equations. The result of the Breusch–Pagan Test for our equations (comparing supply side, internal, and customer side disruptions) revealed ($p = .00001$) that the error terms across equations are correlated, signifying that SUR is the appropriate technique for the analysis.

SUR has been used in other operations research problems to examine strategies and plant performance measures (Devaraj, Hollingworth, & Schroeder, 2004) and supply chain technology implementation (Autry, Grawe, Daugherty, & Richey, 2010). SUR is an appropriate methodology for this study because it accounts for the correlation between the supply side, internal, and customer side disruptions. The set of equations below indicates an example of the form of equations used in each SUR model. The example is for the disruption frequency stoppage measure. All three equations below were run in the SUR model at the same time. Similar sets of three simultaneous equations were also run for reductions, close calls, duration, and spread as the dependent variable:

$$
\begin{aligned}
\text{Disruption}_{\text{Stop/Supply}} &= \beta_0 + \beta_1 \text{leadtime}_{\text{Supply}} + \beta_2 \text{leadtime}_{\text{cust}} + \beta_3 \text{co} - \text{loc}_{\text{supply}} \\
&\quad + \beta_4 \text{co} - \text{loc}_{\text{cust}} + \mathit{controls}, \\
\text{Disruption}_{\text{Stop/Internal}} &= \beta_0 + \beta_1 \text{leadtime}_{\text{Supply}} + \beta_2 \text{leadtime}_{\text{cust}} + \beta_3 \text{co} - \text{loc}_{\text{supply}} \\
&\quad + \beta_4 \text{co} - \text{loc}_{\text{cust}} + \mathit{controls}, \\
\text{Disruption}_{\text{Stop/Customer}} &= \beta_0 + \beta_1 \text{leadtime}_{\text{Supply}} + \beta_2 \text{leadtime}_{\text{cust}} + \beta_3 \text{co} - \text{loc}_{\text{supply}} \\
&\quad + \beta_4 \text{co} - \text{loc}_{\text{cust}} + \mathit{controls}.
\end{aligned}
$$

We ran five separate SUR analyses (supply, internal, and customer) for each dimension of disruption (stoppages, reductions, close calls, duration, and spread) where the disruption measure is the dependent variable.

We were also interested in the relation of the co-location and lead-time decisions with the disruption variables. As a consequence, we ran supply side and customer side variables simultaneously in our SUR regression equations. In other words, we use co-location with suppliers and check its predictive power in the regression model regarding disruptions as the dependent variable in the supply side, internal, and customer side supply chain links. A similar approach was conducted with all other lead time and co-location variables. For robustness, we used traditional OLS regression to test for multicollinearity among our independent variables in our supply side, internal, and customer side equations using the variance inflation factor (VIF). The VIF values ranged between 1.1 and 3.1 which is below the suggested cut-offs for multicollinearity problems (Wooldridge, 2009).

RESULTS

We will first examine the independent variables occurring in the supply base where either co-location or lead times were found to have significant relationships with disruptions. The supplier's location is significant and negatively ($\beta = -.197$, $p < .10$) associated with the duration of disruptions in the supply base. Supplier co-location is negatively associated with the duration of the disruption, which means that co-location appears to be related to the resolution of disruptions, providing support for Hypothesis 2a. Conversely, co-location with customers is significantly associated with actual flow stoppages ($\beta = .262$, $p < .05$) and reductions in flow ($\beta = .245$, $p < .05$). Hence, co-location with customers is positively associated with the frequency of disruptions, providing support for Hypothesis 1b. We do not find support for Hypotheses 1a and 2b.

The results also show that supplier overall lead times are significantly ($\beta = .314$, $p = .05$) related to the spread of disruptions in the supply base. In other words, long supplier lead times are associated with higher chances that a disruption in the upstream supply base may propagate downstream and grow in severity. No other predictor variables are significant regarding the spread of a disruption throughout a supply chain (Table 1a). The supplier's lead time is also significantly ($\beta = .193$, $p < .10$) associated with the duration of supply side disruptions. This would suggest that disruptions in the supply base appear to last longer for cases when suppliers exhibit long lead times, providing support for Hypothesis 3a. This result fits with our previous finding regarding the link between supplier lead times and the spread of disruptions. The longer a disruption lasts, the more likely it becomes that the disruption can spread through the supply chain. It should also be noted that the customer side lead time had no association with supply side disruption risk. Table 6 presents the SUR results.

None of the variables are significantly associated with the spread of internal disruptions, but several variables exhibit significant relationships with internal disruption duration. Supplier ($\beta = .271$, $p < .05$) and customer ($\beta = .179$, $p < .05$) side lead times are significantly associated with the duration of internal disruptions. Co-location with suppliers ($\beta = -.125$, $p < .10$) is also significantly

Table 6: SUR results

	Dependent Variable														
	Stoppage			Reduction			Close Call			Duration			Spread		
	Supply	Internal	Customer	Supply	Internal	Customer	Supply	Internal	Customer	Supply	Internal	Customer	Supply	Internal	Customer
S. Lead time	.173 (.122)	.108 (.114)	.196* (.101)	.142 (.121)	.132 (.113)	.236** (.099)	.121 (.126)	.367** (.119)	.243** (.104)	.193* (.106)	.271** (.107)	.264** (.101)	.314** (.125)	.046 (.119)	.192* (.107)
C. Lead time	.122 (.102)	.207** (.098)	.041 (.122)	.167 (.105)	.131 (.098)	.243** (.118)	.129 (.111)	.045 (.105)	.053 (.122)	.023 (.088)	.179** (.088)	.114 (.122)	−.051 (.112)	.158 (.108)	.088 (.123)
S. Co-location	−.004 (.108)	−.007 (.102)	.031 (.104)	−.150 (.110)	−.003 (.102)	−.202** (.102)	−.093 (.116)	−.017 (.109)	−.044 (.108)	−.197* (.104)	−.125* (.082)	−.108 (.104)	−.070 (.115)	.090 (.111)	.026 (.110)
C. Co-location	.262** (.106)	.175* (.101)	.072 (.104)	.245** (.109)	.213** (.101)	.083 (.103)	.128 (.115)	.071 (.109)	.105 (.108)	−.084 (.092)	−.083 (.096)	.011 (.105)	.056 (.115)	−.078 (.111)	.016 (.111)
	Controls														
Firm size	−.059 (.128)	.073 (.122)	.311** (.128)	−.131 (.130)	−.067 (.122)	.162 (.126)	−.016 (.138)	.105 (.131)	.231* (.132)	−.118 (.110)	−.238** (.116)	−.137 (.129)	.087 (.138)	.054 (.133)	−.002 (.135)
Tech capabilities	−.236 (.149)	−.297** (.142)	−.427** (.149)	.085 (.152)	−.084 (.141)	−.073 (.146)	−.197 (.161)	−.303** (.152)	−.336** (.154)	−.011 (.128)	.410** (.135)	.045 (.150)	.121 (.162)	.288* (.156)	.136 (.158)
Ops practices	.102 (.131)	.083 (.125)	.031 (.132)	−.095 (.134)	−.048 (.125)	−.115 (.130)	.194 (.142)	.039 (.135)	−.020 (.136)	−.031 (.112)	−.253** (.119)	−.008 (.132)	−.174 (.142)	−.429** (.137)	−.289** (.139)
Prod life cycle	.016 (.089)	.101 (.085)	.048 (.089)	.026 (.091)	.117 (.085)	.137 (.088)	.004 (.097)	.100 (.092)	.107 (.093)	.212** (.077)	.107 (.081)	.157* (.090)	.120 (.097)	.112 (.094)	.079 (.095)
Prod customization	.177** (.092)	.259** (.087)	.281** (.090)	.122 (.094)	.174** (.087)	.154* (.088)	.038 (.099)	.044 (.093)	−.033 (.093)	−.064 (.079)	−.005 (.083)	.139 (.090)	.088 (.099)	.075 (.095)	.169* (.094)
SC geo region	−.123 (.091)	−.024 (.080)	.084 (.080)	.044 (.084)	.105 (.078)	−.012 (.075)	−.022 (.084)	.000 (.078)	.080 (.073)	.195** (.079)	−.057 (.075)	−.082 (.080)	.036 (.080)	−.012 (.076)	.029 (.070)
Low Inventory	.096 (.113)	.143 (.099)	.022 (.101)	.113 (.104)	.251** (.096)	−.174* (.094)	−.015 (.103)	−.096 (.095)	−.073 (.091)	.366** (.098)	.237** (.093)	.072 (.099)	−.152 (.098)	.081 (.092)	−.037 (.086)
R^2	.23	.30	.23	.19	.30	.25	.09	.18	.17	.43	.37	.22	.09	.15	.13

Sample size for all models: **$N = 108$.**
Results are listed as coefficients and *standard errors (parentheses).*
$^*p < .1$; $^{**}p < .05$.
We used a series of Wald test comparisons (Wald, 1943) to evaluate the differences between the supply side and customer side coefficients (significant differences are shaded in Table 6).

and negatively associated with the duration of internal disruptions, which would indicate that co-location is related to reduced durations of internal disruptions (as was the case with supply base disruptions), providing additional support for Hypothesis 2a.

The relationships between customer side co-location with flow stoppages ($\beta = .262, p < .05$) and flow reductions ($\beta = .175, p < .05$) for internal disruptions shows a pattern that is similar to the one we already discovered for supply side disruptions. In both cases, customer co-location is associated with increased levels of disruption stoppages and reductions. There is also a relationship between customer side lead times ($\beta = .207, p < .05$) and stoppages, providing partial support for Hypothesis 3b. Longer overall lead times are associated with higher levels of stoppages at the internal location. Customer side design features (lead times and co-locations) are associated with higher levels of internal disruption risk, providing additional support for Hypothesis 1b. At the same time, supplier co-location is negatively associated with internal disruption risk, that is, higher levels of supplier co-locations are associated with lower levels of internal disruption risk, confirming our findings for both supply side disruption risk and Hypothesis 2a.

Supplier lead times are significantly ($\beta = .192, p = .10$) related to the spread of disruptions on the customer side, a fact that provides additional support for Hypothesis 3a. Supplier lead times ($\beta = .264$, $p = .05$) are also related to the duration of customer side disruptions and to flow stoppages on the customer side ($\beta = .196, p = .05$). Supplier lead times ($\beta = .236, p = .05$), customer lead times ($\beta = .243$, $p = .05$), and supplier co-location ($\beta = -202$, $p = .05$) are all associated with reductions in the flow at the customer side. The co-location of suppliers is negatively related to the reductions and lowers customer side disruption risk, providing additional support for Hypothesis 2a.

For Hypotheses 4a and 4b, we compared the effect sizes of all of the coefficients from our SUR results. As we were only interested in whether customer side or supply side results were larger, the comparison included nonsignificant coefficients. (A coefficient can be nonsignificant, that is, not significantly different from 0, still significantly different from another coefficient.) We used a series of Wald test comparisons (Wald, 1943) to evaluate the differences between the supply side and customer side coefficients (significant differences are shaded in Table 6). We used the standardized coefficients to compare the effect size of the coefficients across the individual equations. Both horizontal and vertical comparisons were made with significance differences determined as $p < .1$. Wald test results showed differences between the supplier side and customer side design variables for the close call measure and the spread measure. In both cases, the supplier side lead time was significantly larger than the coefficient for the customer side lead time. From this, we can infer that the effect size of design features is only slight, though somewhat larger on the supply side than on the customer side. We conclude partial support for Hypothesis 4b, but do not find support for Hypothesis 4a.

DISCUSSION, LIMITATIONS, AND FUTURE RESEARCH

Our data analysis shows that a differentiated perspective on design characteristics and disruptions is needed. We find that lead time/co-location decisions have different associations with the different disruption components. Our results show that supply side lead times appear to be the most critical factor among those we studied that relate to disruption risk. Overall lead time has a negative relationship with disruptions across all disruption components. The supply side lead time shows up as significant in nine cases (while all others top out at four significant occurrences). Furthermore, the Wald test indicates that supply side sources seem to have a slight edge over customer side sources in their relationship with disruption risk measures. However, the results of the Wald test must be read with caution, as not many coefficients were significantly different from each other. In combination with the results from the SUR models, however, a stronger case can be made for the relevance of managing the supply side of the supply chain with extra care, as it appears more critical for disruption risk (especially when we also consider that the significant results for supplier co-location with negative coefficients). In other words, co-location with suppliers is associated with a shorter duration of disruptions. This link could be explained through enhanced collaboration between co-located partners. It appears that the co-location with suppliers might enhance the collaboration with one's suppliers which would aid in preventing and mitigating supply chain disruptions. This finding is consistent with studies regarding the co-location with suppliers for new product development literature that has shown that co-location benefits product development performance by improving coordination between focal firms and supplier organizations (Hinds & Mortensen, 2005; Gulati & Puranam, 2009). This improved coordination also improves the supply chains' resilience to disruptions, as the supplier and focal firm can quickly and jointly respond to the disruption and minimize its duration and spread.

However, we do not see a similar positive associations or benefits when the focal firm is co-located with customers. The co-location with customers is associated with higher frequencies of disruptions and does not show a decrease in the duration of disruptions. We suspect that this surprising finding relates to the perspective through which we approached this study—we looked at disruptions in terms of the focal firm's perspective. The focal firms in our study focus more heavily on assuring that flow of goods from their suppliers into their facilities. If there is a disruption on the supplier side, we speculate that focal firm sees an ability to influence the impact by co-locating, reducing lead time and establishing stronger partnerships with its supply base. If there is a disruption of the customer side, the burden falls more to the customer to communicate and solve that problem by working with *their* suppliers (in this case, the focal firms in our study).

Our research contributes to the literature in several significant ways. First, this article represents one of the rare empirical examinations of supply chain design and disruption risk. Second, it looks at specific dimensions of supply chain design that are relevant for today's supply chain managers: co-location decisions and lengthened lead times produced by outsourcing. Third, this study goes beyond aggregated disruption measures by measuring five different dimensions of disruption in three different strategic locations. That is, our study is attempting to build on previous work and show a more differentiated and fine-grained approach to further our understanding of disruptions. Fourth, we show that the relationship between supply chain design variables and the components of disruptions is not as straight forward as some readers might have expected. Especially, the co-location decision in the supply chain (and the benefit, or harm for disruption management) seem to depend on the focal firm's power in the supply chain. A powerful focal firm appears to force suppliers to co-locate and experiences benefits through the reduced duration of disruptions. At the same time, if the focal firm co-locates with the customers it experiences an increase in the frequency of disruptions without seeing any benefits of the co-location. Fifth, longer lead times seem to be associated with higher levels of disruption risk. Specifically, supply side lead times are significantly associated across most disruption components, while customer lead times show less of an association with disruptions. Sixth, we see an overall tendency that supply side factors seem to be the most relevant to the focal firm. They can be good (in the case of co-location with suppliers) or bad (as in the case of supply lead times). In summary, the managers of the focal firm should aim at actively managing the upstream side of their firm.

However, as in any research there are some limitations that we need to address as well. Disruptions such as natural disasters (hurricanes, volcano ash, earthquakes) that affect an entire geographical region may have a bigger impact on co-located entities. Previous literature shows a clear differentiation between low-frequency/high-impact and high-frequency/low-impact disruptions (Sheffi & Rice, 2005); low-frequency events (such as "acts of God" or intentional attacks on a network) are more severe if critical nodes can be taken out all at once—indicating that co-location is a suboptimal choice. This is a very straightforward conclusion understood by military strategists for centuries. That said, our study design was based on a survey, not a case study of a particular low-frequency event. The design of the data collection makes it more likely that we are capturing high-frequency events, as respondents are more likely to be able to easily reflect on such events and their commonalities and possible causes. These more frequent disruptions are due to a variety of operational problems and are of high relevance to supply chain managers, as they impact their day-to-day work.

Future research needs to investigate in deeper detail how co-location and lead time decisions impact disruption risk. It seems, from our work, that co-location has a mitigating effect on the duration of disruptions. Models should test for the moderation/mediation variables that are responsible for this improved resilience. The main factors here are derived from the literature on supply chain integration and collaboration, and it seems likely that co-located firms are using information and collaboration to facilitate the integration of their operations and quicker response times with regards to disruptions. Interestingly, while co-locating firms may risk higher exposure to disruptions affecting an entire geographic region, Porter (1998) discusses how clusters can offer increased flexibility which can enhance supply chain agility (Swafford, Ghosh, & Murthy, 2006). Porter (1998, p. 83) discusses how clusters may allow firms to react quickly both in sourcing items and understanding changing customer demand:

> "They also provide the capacity and the flexibility to act rapidly. A company within a cluster often can source what it needs to implement innovations more quickly. Local suppliers and partners can and do get closely involved in the innovation process, thus ensuring a better match with customers' requirements."

In addition, this work could have interesting extensions looking at dual sourcing and optimal supply chain design. For example, Allon and Von Mieghem (2010) investigate dual sourcing in a global supply (near-shore and off-shore locations) to determine an optimal base-surge allocation. This type of supply chain design could be interesting to examine in more detail in terms of disruption risk management and cost trade-offs.

With regards to long lead times, firms should mitigate potential problems "by investing in visibility tools. Even in cases in which these tools provide only partial coverage, they help moderate problems by allowing timely responses" (Sheffi, 2002, p.5). Globalization means that lead times become increasingly more variable and forecasts become less accurate, so firms should significantly increase their collaboration throughout the supply chain. When firms become aware about problems early enough, they can take countermeasures such as expediting shipment, finding alternative sources, and adjusting customer expectations (Sheffi, 2002). Our conceptualization of disruption risk in terms of stoppages and reductions in flows, close calls (disruptions that were prevented at the last minute), disruption duration (time until normal operation flow was restored), and the spread of the disruption through the supply chain may have interesting extensions related to improved risk management tools. The impact of reductions in flow should also be examined more closely as compared to full stoppages. In addition, future research could extend our understanding of close calls (near-misses) in a supply chain context in terms of learning and improved supply chain risk management.

We also see a need for researchers to explore the differences in our results from the three areas (supply side, internal, and customer side). We speculate that there are interesting findings to be discovered as to why supply side co-location, for example, helps to *mitigate* disruptions, while customer side co-location *worsens* the disruption. Perhaps issues of governance, control, and power influence these effects where a focal firm may have more power and control over its supplier as opposed to its customers. The focal firm might also be hedging as to where allocating scarce resources will be most powerful. Another interesting opportunity may lie in investigating in more depth supplier co-location and the reduction in disruption duration where co-location may influence the velocity and flexibility as discussed by Sheffi and Rice (2005), Jüttner and Maklan (2011), and Li, Li, Wang, and Yan (2006). Finally, we find it interesting that lead times have the largest impact on disruption duration and that supplier lead times do, in fact, influence the frequency of customer side disruption occurrence. Simulation modeling and mathematical models are also suggested as tools for researchers to explore downstream propagation effects and delayed impacts.

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APPENDIX: COMPLETE LIST OF MEASURES

Dimensions of Supply Chain Disruption Risk

(1) FREQUENCY – STOPPAGE: During the last three months, how often did your company experience problems (in its supply base, and/or customer base, and/or production process) that caused disruption(s) to the material flow in your supply chain (disabled you to receive needed input factors, and/or halted your production, and/or deliver final products)?
- Supply Base (Not Once, 1–3 times a month, 1–3 times a week, Daily, Several times a day)
- Production (Not Once, 1–3 times a month, 1–3 times a week, Daily, Several times a day)
- Customer base (Not Once, 1–3 times a month, 1–3 times a week, Daily, Several times a day)

(2) FREQUENCY – REDUCTION: During the last three months, how often did your company experience problems (in its supply base, and/or customer base, and/or production process) that caused disturbances to the material flow in your supply chain (reduced your ability to receive needed input factors, and/or halted your production, and/or deliver final products)?

- Supply Base (Not Once, 1–3 times a month, 1–3 times a week, Daily, Several times a day)
- Production (Not Once, 1–3 times a month, 1–3 times a week, Daily, Several times a day)
- Customer base (Not Once, 1–3 times a month, 1–3 times a week, Daily, Several times a day)

(3) CLOSE-CALL: During the last three months, how often did your company experience problems (in its supply base, and/or customer base, and/or production process) that nearly caused a disruption or disturbance to the material flow in your supply chain if quick actions had not been taken?
- Supply Base (Not Once, 1–3 times a month, 1–3 times a week, Daily, Several times a day)
- Production (Not Once, 1–3 times a month, 1–3 times a week, Daily, Several times a day)
- Customer base (Not Once, 1–3 times a month, 1–3 times a week, Daily, Several times a day)

(4) DURATION: How quickly do you usually resolve these disruptions/disturbances in your supply chain to return to the planned schedule?
- Supply Base (Very Fast, Fast, Neutral, Slow, Very Slow)
- Production (Very Fast, Fast, Neutral, Slow, Very Slow)
- Customer base (Very Fast, Fast, Neutral, Slow, Very Slow)

(5) SPREAD: How much do disruptions/disturbances usually spread through your supply chain?
- Supply Base (Remains localized to single plants, Spread to other firms, Affect small part of supply chain, Affect significant part of supply chain, Whole supply chain is affected)
- Production (Remains localized to single plants, Spread to other firms, Affect small part of supply chain, Affect significant part of supply chain, Whole supply chain is affected)
- Customer base (Remains localized to single plants, Spread to other firms, Affect small part of supply chain, Affect significant part of supply chain, Whole supply chain is affected)

The following items were scored on a five-point Likert type scale from (Strongly Agree—Strongly Disagree)

Lead-time*:

(1) "Our suppliers lead times are too long compared to our competitor's suppliers."

(2) "Our order lead times to our customers are too long compared to our competitor's lead times."

Co-Location:

(1) "Our suppliers are co-located within close proximity of our production facilities."

(2) "We co-locate our production facilities within close proximity to our customers."

*We selected the comparative wording of these questions for two reasons. First, lead times vary greatly across different industries. Second, the critical aspect of relevance to our research is whether the lead time is unusually long per industry standards.

CONTROL VARIABLES

The following items were scored on a five-point Likert type scale from (Strongly Agree – Strongly Disagree)

- The life cycle of our products is short.
- Our product is highly customized to meet customer demands.
- Our supply chain is organized by geographic regions.
- Low inventories prevent our suppliers from responding to our requests.
- Low end-product inventory levels prevent us from responding to demand changes.

The following items were scored on a five-point Likert type scale from (Very similar – very different):

Please indicate whether your customers are similar or dissimilar to your company with regard to the following characteristics:

- Technical Capabilities
- Operational Practices

Please indicate whether your suppliers are similar or dissimilar to your company with regard to the following characteristics:

- Technical Capabilities
- Operational Practices

Firm Size was assessed with a five-point scale ranging from less than $100 million in revenue to more than $5 billion in revenue (Less than $100 million; $100–499 million; $500–999 million; $1–5 billion; more than $5 billion)

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