Catastrophic supply chain disruptions and supply network changes: A study of the 2011 Japanese earthquake from a supply network complexity view

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Abstract

Catastrophic supply chain disruptions can significantly damage the operational and financial performance of firms. While a growing body of literature on supply network structures has studied what influences supply networks' vulnerability to supply chain disruptions and capability to recover from the disruptions, it remains unclear how supply network structures change after major supply chain disruptions. Using a natural experiment approach, this study investigates how firms' ego supply network structures change after experiencing the catastrophic supply chain disruptions caused by the 2011 Tōhoku earthquake and tsunami in Japan.

Introduction

Supply chain disruptions can significantly damage the operational and financial performance of firms (Hendricks & Singhal, 2005; Wagner & Bode, 2008). Building supply chain resilience helps firms mitigate the impact of disruptions more effectively and recover more quickly. Supply chain resilience is the sum of two opposing forces: the vulnerability of the supply chain to shocks, and the capability to respond to and recover from these shocks. The growing body of work on supply network structures offers important contributions to both the vulnerability and capability aspects of supply chain resilience. Research on supply network structures goes beyond looking at the cumulative impact of dyadic relationships and focuses on the opportunities and challenges that arise from the complex inter-relationships in the network (Choi & Kim, 2008). Within the context of supply chain disruption and resilience, network-level studies have adopted a complexity perspective in explaining why supply chains are vulnerable to external shocks when the network is large and there are many dyadic relationships between the network partners (Bode & Wagner, 2015; Choi & Krause, 2006; Scheibe & Blackhurst, 2018).

Although there has been significant research on the impact of supply network complexity on supply chain resilience and disruption recovery, what still remains unclear is the impact of disruptions, particularly catastrophic disruptions, on supply network structures. If supply network complexity exposes firms to higher supply chain risks, the firms that suffered from major disruptions may attempt to reduce the overall levels of complexity to make their supply chains more resilient by adjusting their supply network structures. To our knowledge, no research has focused on the structural changes in supply networks after significant supply chain disruptions. In fact, there is relatively little work on the transformation of supply networks in general.

In short, there are two gaps in the research on the relationship between supply network structures and supply chain resilience. First, there is not enough understanding of how disruptions shape supply network structures. Second, there is very limited work on how and why supply network structures change. Building on the literature on supply chain risk and resilience, supply network complexity, and network structural changes, we aim to understand how supply network structures—specifically supply network complexity—change after firms experience catastrophic supply chain disruptions.

Theoretical Background

The supply chain resilience of a firm is the sum total of its vulnerabilities, which are the basic elements that make it sensitive to disruptions, and the capabilities that help it to overcome them (Pettit et al., 2010, 2013; Sheffi & Rice, 2005). The scale of its supply network can be a significant driver of a firm's vulnerability (Pettit et al., 2013). Moreover, the vulnerability of the individual companies in the supply network have a knock-on effect in that "the failure of any one element in it could cause the whole network to fail' (Rice & Caniato, 2003: p. 22).

More recent research has aimed at pinpointing what exactly about the network structure creates this vulnerability and thereby reduces resilience. In that regard, supply network complexity has been an influential and informative concept. The "complexity perspective" of supply chain resilience proposes that a firm having an excessive number of ties with other companies and the interrelationships between these companies could potentially both become a gateway for the propagation of disruptions and hinder an effective disruption response (Bode & Wagner, 2015; Choi & Krause, 2006; Craighead et al., 2007; Kim et al., 2015; Scheibe & Blackhurst, 2018). Influential studies based on the complexity perspective (e.g., Choi & Krause, 2006; Kim et al., 2015) have used the NK model (Kauffman & Levin, 1987; Levinthal, 1997) where "N" represents the number of suppliers of a focal firm and "K" represents the interrelationships between them. These correspond to the degree centrality and density metrics in network analysis.

Degree centrality captures the importance of an individual firm in the network (Borgatti & Li, 2009; Kim et al., 2011). The more central a firm is the better it has access to resources (Lu & Shang, 2017), yet this advantage also comes at a cost: Past studies have suggested that the more central a firm is, the more likely it is to experience a supplier induced disruption (Bode & Wagner, 2015; Perrow, 1984). Moreover, the number of network ties impacts the extent of coordination efforts of the focal firm (Kim et al., 2011). It is positively related to the level of transaction intensity a focal firm faces (Bode & Wagner, 2015; Powell et al., 2005) and can result in a high level of operational burden for the firm (Bode & Wagner, 2015; Borgatti & Li, 2009; Kim et al., 2011; Kim et al., 2015). Consequently, a firm's ability to mitigate or respond to disruptions decreases as the number of supply chain partners increases (Bode & Wagner, 2015).

Density is a network-level measure and captures the level of connectedness in the network (Kim et al., 2011). Conceptually, there has been support for both a positive and a negative link between network density and resilience (Choi & Krause, 2006; Kim et al., 2015). On the one

hand, if there are redundancies in interrelationships between other members of the supply network, the network could be more resilient to the destruction of one of these links (Janssen et al., 2006). However, dense networks can propagate the impact of a supply chain disruption across the supply network and increase the systematic risk in the network (Scheibe & Blackhurst, 2018). In addition, a high number of interrelationships can increase the coordination costs of disruption recovery efforts (Craighead et al., 2007).

Past studies have explored how supply network complexity affects efforts to recover from supply chain disruption. However, to our knowledge, there is no research to date that investigates how the complexity of firms' supply networks changes after experiencing such disruptions. Considering the evidence of the negative role of supply network complexity in preventing and recovering from supply chain disruptions, firms that have recently experienced such disruptions may choose to restructure their supply networks to reduce their complexity. The answer also contributes to unexplored questions around the dynamic nature of supply networks, which we discuss in the next section.

Hypothesis Development

In-degree centrality dictates the level of influence a firm has in its network and the quality and the quantity of resources it is able to access through its partners (Bellamy et al., 2014; Borgatti & Li, 2009). However, firms that have a high level of in-degree centrality on the supply side also tend to face significant coordination challenges (Kim et al., 2011). The high number of suppliers increases the frequency and complexity of transactions for the buying firm, creating various operational pressures (Bode & Wagner, 2015; Kim et al., 2011; Kim et al., 2015). This would suggest that high in-degree centrality could undermine a firm's efforts to respond to a supply chain disruption. If, as suggested by previous research, the complexity of its supplier network impeded a firm's efforts to respond to a recent catastrophic disruption effectively, the firm could attempt to reduce the number of suppliers and rationalize the size of its supply base after the disruption.

Furthermore, the firm's existing ties with other companies can become a gateway for the propagation of an upstream disruption (Bode & Wagner, 2015; Borgatti & Li, 2009; Kim et al., 2015). When considering the dimension of network complexity that focuses on the number of the companies in a supply network (Bode & Wagner, 2015; Kim et al., 2015), in-degree centrality indicates the likelihood of the firm being impacted by the propagation of an upstream disruption. Therefore, a firm that has experienced this recently within its supply network is more likely to be driven to streamline its supply base.

Finally, firms are constantly on the lookout for new suppliers that can provide quality components and services as well as new knowledge and innovation (Yan et al., forthcoming). This activity of adjusting the network needs to be supported by a munificent environment (Koka et al., 2006) as well as the firms' own resources. A major natural disaster reduces structural, infrastructural, or financial resources, thus in turn, reducing environmental munificence. Moreover, responding to catastrophic supply chain disruptions requires a company-wide resource mobilization, relegating other needs of the firm, including tie creation, to a secondary position. Thus, reduced environmental munificence as well as available resources within the firm will slow down a buying firm's tie creation activities with new suppliers. For these reasons, we hypothesize that:

> Hypothesis 1: Firms that experience catastrophic supply chain disruptions will have fewer suppliers after the disruption, compared to the firms that do not experience the disruption.

Similar to the buying firms that would attempt to reduce their supply network complexity

by reducing their number of suppliers after experiencing catastrophic disruptions, customers of affected firms will also aim to reduce complexity by streamlining their supply networks. This is partially due to the propagation effect discussed earlier. If a firm is affected by supply chain disruption, that disruption will be propagated to some, if not all of its customers (Han and Shin, 2016). Therefore, the firms that are known to have been affected by a major disruption could face difficulties in keeping some existing customers and attracting new ones, at least temporarily.

Furthermore, even if customers prefer to continue their relationship with the focal firm, the impact of the disruption on the financial health of the customers may make it untenable. Disruptions tend to lead to a number of unplanned expenses and restrict access to financial resources, which can lower customers' liquidity and cash reserves. Simultaneously, customers can experience higher levels of demand uncertainty themselves. Catastrophic natural disasters are, therefore, often accompanied by a reduction in customer demand (Park et al., 2013).

In terms of attracting new customers, firms may face another challenge. Firms face significant pressures to grow by acquiring more customers. Such tie creation activity, however, requires significant resources. Furthermore, increases in the customer base tend to correspond to an increase in the resources needed to support these customers. In other words, growing the customer base and maintaining it requires a firm to have the resources, either within its own corporate boundaries or accessible through its business environment, to support its growth (Koka et al., 2006). As discussed earlier, a major natural disaster and the ensuing catastrophic supply chain disruption tends to deplete the internal and external resources necessary to support creating new links. Therefore, we hypothesize:

> Hypothesis 2: Firms that experience catastrophic supply chain disruptions will have fewer customers after the disruption, compared to the firms that do not experience the disruption.

A dense ego supply network with many interrelationships between the focal firm's supply chain partners can expose the focal firm to a high level of supply risk (Choi and Krause, 2006). If a supplier delivers products to other suppliers or customers of a focal firm, an event that disrupts the supply network is more likely to affect the focal firm's operations negatively. For example, when a system or industry level disruption (e.g., the earthquake) increases demand or supply volatility, multiple companies in the network simultaneously rush to secure alternative supply. In a dense network, this could lead to resource cannibalization, where a supplier's capacity that could have been allocated to the focal firm's demand is directed to other players in the focal firm's network (Lee et al., 1997). Similarly, in a tightly connected supply network, an accident at a supplier can disrupt a focal firm's operations both directly and indirectly through other buying firms who also supply to the focal firm (Scheibe & Blackhurst, 2018). This "supply chain disruption propagation" is more pronounced in supply networks where supply chain partners across multiple tiers of the supply chain are connected with each other (i.e., in supply networks with higher ego network density).

In addition, responding to a supply chain disruption requires extensive coordination between a buyer and its supplier for collective sense-making (Johnson et al., 2013; Krause et al., 2007) and resource mobilization (Ambulkar et al., 2015; Olcott & Oliver, 2014). Responding to catastrophic supply chain disruptions may sometimes require joint efforts at the network level (Olcott & Oliver, 2014). When such network-level efforts are required, connections between the focal firm's supply chain partners can come at additional coordination costs for firms involved (Choi & Krause, 2006; Choi & Wu, 2009; Craighead et al., 2007). This would be especially true for large companies with a high number of supply chain partners. The consequence of experiencing these coordination costs during the recovery period is likely to

put a downward pressure on ego network density.

After experiencing a major supply chain disruption, firms would realize the dangers of supply chain disruption propagation and challenges of coordinating during recovery in densely connected supply networks. Therefore, firms with recent experience of a major supply chain disruption would be expected to simplify their networks. If several firms that are directly or indirectly connected to the focal firm decide to reduce their number of direct ties, the cumulative effect of these firm-level decisions should also lower the ego supply network density for the focal firm. Therefore, we hypothesize:

> Hypothesis 3: Firms that experience catastrophic supply chain disruptions will have lower ego supply network density after the disruption, compared to the firms that do not experience the disruption.

Methodology
To build our sample, we used as our starting point the 2011 Forbes Global 2,000 list. Next, using the Global Industry Classification Standard (GICS), we excluded firms from service sectors such as finance, banking, and insurance, leaving 934 firms in our initial sample from nine sectors as described by the Forbes Global industry list. Furthermore, we used the FactSet supply chain relationship database to capture these firms' supply network structures.

In terms of measures, we calculated the in-degree centrality, out-degree centrality, and ego network density for each firm using UCINET 6.3. We used industry sector dummy variables and pre-earthquake (2010) financial variables (log of total assets, log of the number of employees, log of inventory, return-on-assets, cost-of-goods-sold-to-sales, cash-to-sales, and debt-to-equity) to control for industry and firm-specific factors. The variables were also used during the process of propensity score matching.

To capture the changes in supply network structures after the earthquake, we computed the differences between pre- and post-earthquake supply network variables (Δ In-degree centrality, Δ Out-degree centrality, and Δ Ego network density). The differences were computed by subtracting the values of supply network variables measured one year prior to the earthquake (2010) from the values of the same variables measured one year after the earthquake (2012). These differenced measures were used as the dependent variables.

Afterwards, we compared these dependent variables of the firms in the treatment group (the Japanese firms affected by the earthquake) with those of the firms in the control group (the firms not affected by the earthquake but with characteristics similar to the treatment group). From the initial sample of 934 Forbes Global 2000 firms, we selected those in the treatment group based on two criteria. First, they have headquarters in Japan. Second, these firms experienced the earthquake in 2011 and reported consequential operational damages in their annual reports at the end of the same fiscal year. We downloaded the 2011-2012 annual reports from Thomson Reuters ONESOURCE. We identified 76 Japanese firms that experienced operational damages from the earthquake and assigned all these 76 firms to the treatment group.
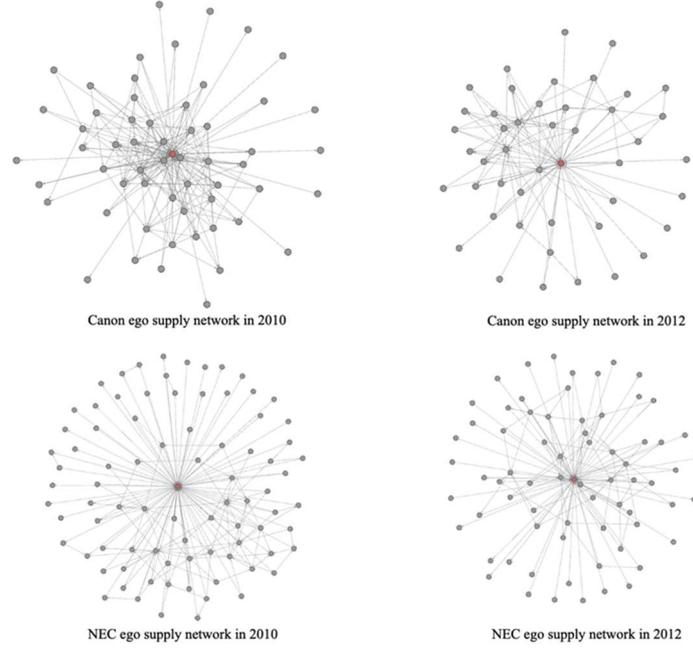
Figure 1. Ego supply networks before and after the earthquake

We employed propensity score matching to construct a sample of control group firms that did not report operational damages caused by the earthquake and have industry- and firm-level characteristics similar to the treated firms. The calculated probabilities from the probit estimation, the propensity scores in this context, are then used to determine the similarities between the characteristics of the treated and untreated observations. Structural changes of a supply network can be induced by exogenous forces as well as endogenous forces and past network characteristics, (Walker et al., 2000). This means that it is necessary that the firms in the treatment and control groups have similar ego supply network structures before the earthquake. We used the number of suppliers, number of customers, and ego network density measured in 2010 for selecting control firms that share similar network characteristics with treated firms. Each firm in the treatment group is matched with one control firm that has the nearest propensity score to the treated firm, yielding the final sample of 152 firms.

We indicate differences between pre- and post-earthquake supply network variables (*Δ In-degree centrality, Δ Out-degree centrality, and Δ Ego network density*) as *Δ Network$_i$* and set up the following regression equation to estimate the impact of the earthquake on the supply network structure:

$$\Delta Network_i = \beta \times Earthquake_i + \gamma'X_i + \varepsilon_i,$$

where i indicates the firm and Earthquake is a binary variable that equals one for the treatment group and zero for the control group. X is the vector of control variables and ε is the error term. Since *Δ Network$_i$* denotes the change in the supply network structure after the earthquake, the sign of the regression coefficient β effectively indicates whether the change for the treatment group is positive or negative compared to that for the control group.

Results

To check whether our findings are robust to using different time lags in calculating the dependent variables, we computed alternative measures of the dependent variables by subtracting the values of the network structure variables measured in 2010 from those

measured in 2011 and 2013. The results the models are consistent with the main results that support H$_1$ and H$_2$. However, the insignificant coefficient for Earthquake in the eco network density model for 2013, that two years after the earthquake, the firms that were affected by it did not have reduced levels of ego network centrality compared to the firms in the control group. Therefore, we conclude that H$_3$ is only partially supported.

In addition, to examine whether the differences in the dependent variables between treatment and control groups are driven by the earthquake or any pre-existing trend before the earthquake in 2011, we tested whether the two groups had parallel trends in 2009 and 2010. For this pre-earthquake parallel trend analysis, we computed the differences in the three dependent variables (*Δ In-degree centrality, Δ Out-degree centrality,* and *Δ Ego network density*) by subtracting 2009 values from 2010 values. This result indicates that the two groups had similar trends in in-degree centrality, out-degree centrality, and ego network density prior to the earthquake and strengthens the evidence that the differences between treatment and control groups after the earthquake are caused by the earthquake.

Conclusion and Discussion
Our paper contributes to the supply network and resilience literature by investigating whether catastrophic supply chain disruptions caused by exogenous events, such as the 2011 Tōhoku earthquake and tsunami, lead to significant structural changes in the supply networks of the affected companies.

Our analysis shows that the firms that were disrupted by the earthquake have seen a reduction in the number of their suppliers compared to the firms that were not. This finding contributes to the literature on the relationship between supply network complexity and supply chain resilience. Previous research on supply network complexity and supply chain risk or resilience has established that a relatively simpler supply network structure would (1) have a lower likelihood of upstream disruptions being propagated to the buying firm (Perrow, 1984; Bode and Wagner, 2015) and (2) enhance the buying firm's recovery efforts through less coordination burden with its suppliers (Bode and Wagner, 2015; Borgatti and Li, 2009; Kim et al., 2011; Kim et al., 2015).

Our results show that, in addition to the above, after firms experience catastrophic supply chain disruptions, they also witness changes in their supply network structures tending toward lower complexity. We reviewed multiple possible reasons for this, some initiated by the company and others driven by their supply chain partners or the new reality of the business environment. Although we cannot distinguish the exact drivers, what is clear is that, in our sample, there is a shift toward less complex supply chain structures.

Our results resonate with the complexity perspective, which also brings into question an alternative perspective on how the supply chain structure relates to supply chain resilience. The redundancy view postulates that having a larger number of redundant suppliers can be beneficial for the buying firm's performance in responding to disruption, since the larger the supplier base, the higher the likelihood of finding available capacity and capability among its suppliers (Lomi & Pattison, 2006; Sheffi & Rice, 2005). If that is the case, we would expect an increase in the number of suppliers. We did not find support for this argument. Still, we need to be cautious with this assessment; the disruption may also trigger supply network changes where less proactive and less efficient suppliers are replaced with more proactive and efficient suppliers. The net effect could still be lower numbers of suppliers. Alternatively, the decrease in firm resources and environmental munificence due to the disruptions may make it difficult for affected firms to manage multiple redundant suppliers. Then, even if the firm's preference would be to increase the number of redundant suppliers after the disruption, they may not be able to do so. Identifying precise reasons for these changes would be an interesting avenue for future study.

Our findings also suggest that the firms affected by the earthquake have reduced numbers of customers compared to the firms that did not report disruptions caused by the earthquake. Unlike the changes observed in the number of suppliers, the reduction in the number of customers, that is the out-degree centrality, after the earthquake is not likely to be the focal firm's deliberate response to the disruption. Extant literature in supply chain management has investigated the impact of upstream network complexity on disruption mitigation and recovery (e.g., Bode & Wagner, 2015; Kim et al., 2015). Other than the fact that there has been a missed research opportunity on the downstream side of the supply chains, we would also argue that this question deserves attention as the driving force of the post-disruption changes in the supplier and customer sides are likely to be fundamentally different and may require different responses from the focal firm. The firms that experienced catastrophic supply chain disruptions do not have an incentive to deliberately decrease the number of customers and risk losing additional sales opportunities. Rather, the reduction in the post-disruption number of customers is likely to be driven largely by the existing and potential customers' efforts to reduce complexity in their upstream supply networks. As a part of their own supply chain risk management strategies, for example, customers of the firms that experienced severe supply chain disruptions may not retain those firms as suppliers (Polyviou et al., 2018). Similarly, potential customers may also be reluctant to establish new buyer-supplier relationships with the firms that experienced severe supply chain disruptions. Moreover, the company-wide recovery efforts by the focal firm impacted by a severe supply network disruption often require significant resource reprioritization (Ambulkar et al., 2015; Bode et al., 2011). This could result in a reduction in the amount of resources available for attracting new customers.

In addition, our analysis provides empirical evidence that firms that are impacted by major supply chain disruptions tend to have reduced levels of ego network density compared with those unaffected by the disruptions. Past literature has considered the performance implications of high ego network density for focal firms. For instance, buying firms can obtain operational benefits through the suppliers that are connected to each other, in the form of access to additional resources or information pooling and sharing (Choi & Wu, 2009; Wu & Choi, 2005). Some buying firms are known for actively encouraging connections between their suppliers (Dubois & Fredriksson, 2008; Wu & Choi, 2005) or creating ties with lower-tier suppliers (Chae et al., 2019; Choi & Linton, 2011) increasing the ego network density in their supply networks. However, it has also been suggested that an increase in the ego network density may have detrimental results; interconnections among customers may negatively influence suppliers' profitability (Kim, 2017). In the context of supply chain disruptions and recovery, interconnections between the supply chain partners could increase the likelihood of a disruption being propagated to the buying firm and bring additional coordination challenges in the recovery efforts (Choi & Krause, 2006; Han & Shin, 2016; Scheibe & Blackhurst, 2018).

Our findings imply that buying firms and their customers may prefer maintaining lower levels of ego network density in their supply networks after realizing through major supply chain disruptions the challenges associated with the high level of interdependencies (i.e., higher ego network density) in managing supply chain risks. On the other hand, a different body of the supply chain risk and resilience literature suggests that close relationships between partners would be useful in responding to catastrophic supply chain disruptions since they generate social capital for network-level sense-making and resource mobilization (Olcott & Oliver, 2014; Ambulkar et al., 2015). Similarly to the results for the centrality measures, our findings provide empirical support that, after a catastrophic disruption, firms face lower supply network complexity in the form of a decreased level of ego network density compared to unaffected firms.

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