Comparative Analysis of Resilience by Supply Network Structure

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Abstract

This research applies Kim, et al.'s (2015) supply network structure archetypes to case data related to two disruptions in three industries in Brazil. A total of seven supply networks were studied, through in-depth interviews and archival documents. The findings suggest that there may be additional supply network structures that are relevant. Centralization appears to be a function of the size of the focal firm. There was evidence of an evolution of supply network structures with focal firm size.

Keywords: Supply Network Structure, Disruption, Resilience, Case Research

Introduction

Conceptualization of a set of buyer-supplier relationships as a complex network, rather than a chain, is a relatively recent phenomenon that mirrors real relationships. Kim, Chen and Linderman (2015) used graph theoretic concepts to describe four supply network structure archetypes, mathematically analyzing their resilience, based on the arcs and nodes impacted by a disruption. We apply Kim, et al.'s (2015) theoretical supply network structure archetypes to rich case data from seven real supply chains, in order to test their applicability. We also examine the resilience of each archetype, in terms of preparedness, response and recovery.

Literature Review

Structural perspective of supply network resilience

Supply network resilience is the ability of a supply network to cope with a disruption, which is an unanticipated event that impacts the flow of goods (Craighead, et al., 2007). Building on graph theory (Diestel, 1991), a supply network is a collection of nodes (factories, warehouses, retailers) connected by arcs (conveyance mechanisms) (Kim, et al., 2015). An arc's head indicates the direction of flow of goods. A node's degree is the number of arcs attached to it, where in-degree is the number of arcs whose heads connect to it and out-degree is the number whose tails connect to it. A sink node, such as a retailer, has a zero out-degree, but a positive in-degree, while a source node, such as a raw material supplier, has a zero in-degree, but a positive out-degree. A walk is an alternating sequence of nodes and arcs. In a connected supply network, there is at least one walk between the source and sink. A supply network disruption can have either a local (node or arc) or global (entire network) effect, potentially leading to a disconnected supply network. The focus of this research is on global supply network disruptions.

Kim, et al. (2015) posit that a supply network's resilience derives from its structure. For example, a supply network with more nodes and arcs is more resilient. Kim, et al. (2015) describe four network archetypes relevant to supply networks, illustrated in Figure 1. The block diagonal archetype (Rivkin & Siggelkow, 2007) has clusters of nodes between the source and sink, with connections within clusters, but not between them. It is typical of a supply network for modular products, where each module supplier is responsible for design, manufacturing and coordinating with its own suppliers. The scale-free archetype (Barabasi & Albert, 1999) is characterized by a few nodes with disproportionately many connections. An example is a supply network where a small group of top-tier suppliers work together to influence supply flows from upstream members. A centralized archetype (Barabasi, 2002) has more highly central nodes that serve as coordinating agents that procure materials, allocate orders, manage subcontractors and market products. The diagonal archetype (Rivkin & Siggelkow, 2007) features sequential connections, where every tier receives supplies from its lower-tier nodes. The nodes can be partitioned into subsets that form tiers, with connections primarily across, rather than within, tiers. This structure is typical of the U.S. automotive industry, where the members of each tier directly select and manage their suppliers in the tier below them (Choi & Hong, 2002).

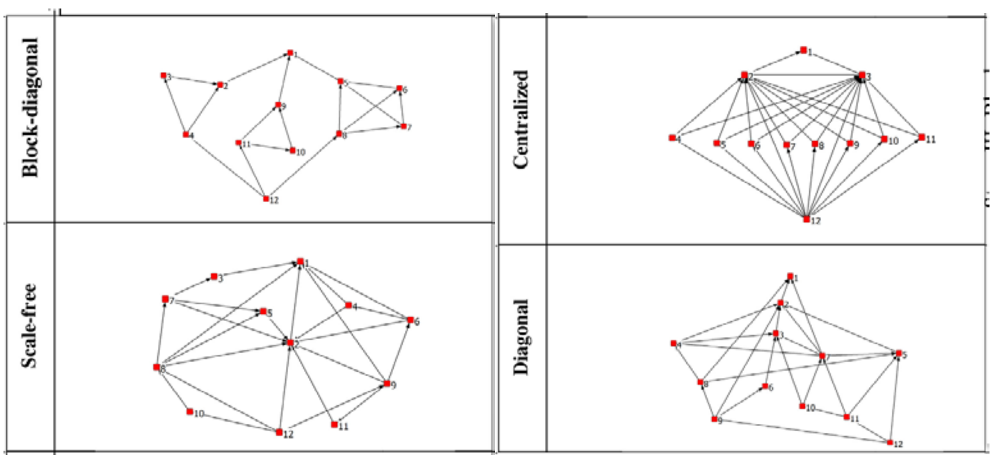

Figure 1. Kim, et al.'s (2015) supply network archetypes

Risk management perspective of supply network resilience

The risk management perspective extends the supply network resilience construct beyond static connections between nodes. In response to a disruption, a focal firm may rearrange its connections and find substitute suppliers, thus it has dynamic connections to other nodes. Ponomarov and Holcomb (2009, p. 131) defined resilience as: "the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function." Supply network resilience is not a binary property, in other words, it exists within a continuum (Blackhurst et al., 2011). It relies on context, with the characteristics that make a node or supply network more or less resilient varying widely, depending on the situation (Pettit et al., 2010). Jüttner et al. (2003) describes risk as potential causes that can lead to adverse events. Mathematically, risk is defined as probability vs. severity (Christopher & Peck, 2004). Thus, risk in a supply network is defined as *any risk to the flow of information, materials, products and processes, from the first supplier until the delivery of the final product to the final user*, referring to factors that lead to a mismatch between supply and demand (Christopher & Peck, 2004).

Resilience can divided into three phases (Jüttner & Maklan, 2011; Jüttner et al, 2003; Lindell, Prater, & Peacock, 2007; Ponomarov & Holcomb, 2009), based on the risks that characterize them. *Preparation* occurs prior to a disruptive event, particularly for events that can be anticipated through warning signs. The initial impact may be sudden, such as with an earthquake or terror attack, or it may be due to gradual deterioration of conditions, such as a drought or recession. The higher the capacity of a supply network to anticipate a disruption, the more effort it will put into articulating resources and preparing itself. The flow of information is critical, not only for identifying imminent disruptions, but also as a warning to those involved. In the *response* stage, the need for coordination of resources begins to be realized, as first responders attempt to control the situation, protect lives, and prevent further damage. The greater a supply network's ability to provide and coordinate resources, the faster it will recover and reduce the impact of the disruption (Lindell et al, 2007). The response can include the use of other suppliers, changing the site of the operation, searching for alternative modes of transportation or implementing other risk mitigation strategies. In the *recovery* phase, the supply network has passed through the worst of the disruption and the operation begins to return to normal. The learning process is relevant for absorbing the impact of the disruption and providing feedback to mitigate the impact of future disruptions. Thus, the risk management perspective of supply network resilience broadens the construct from Kim, et al.'s (2015) focus on response to include prevention and recovery.

Method

Data about two disruptions was collected in seven cases in three industries in Brazil. Each case comprised an end-to-end supply network. One case was the medicine supply network for a hospital, two were supply networks in the dermatology products industry and four were supply networks in the beauty products industry. Disruption 1 was an unexpectedly severe and rapidly spreading virus. Although the World Health Organization (WHO) and the Brazilian Ministry of Health had prepared for a pandemic of H5N1 virus in 2009, they were taken by surprise that the actual virus was H1N1, which had not previously affected humans. By the end of 2009, the WHO had reported over 12,220 deaths worldwide, with 2,051 in Brazil. This led to severe consequences in the supply chain for Oseltamivir Phosphate (Tamiflu), the main antiviral for treatment. Thus, this was a disruption with a severe and sudden impact. Disruption 2 had a more intermediate and gradual impact. It was a change in legislation that affected raw materials supply in the dermatology and beauty products industries. The Brazilian Heritage Regulatory Framework (PM2186) was a provisional measure established by the Brazilian federal government through its Ministry of the Environment. The goal was to "regulate access to the national genetic heritage, protection and access to associated traditional knowledge, sharing of benefits and access to technology and to technology transfer for their conservation and use” (Brasil, 2001), by providing ecological protection to the Amazon region and the indigenous people who gather raw materials there.

The unit of analysis (case) is a supply network. Seven supply networks were strategically selected to include both domestic and multinational focal firms, a mix of medium-sized and large focal firms and stable vs. rapidly changing products that correspond with stable vs. dynamic consumer markets. Although the ultimate consumers of their products vary substantially, each of these supply networks originates with agricultural products as the source node, and they have other nodes that interlock, to some extent.

Case H1 is a healthcare network, with one of the main hospitals (Hosp 1) in Brazil as its focal firm. Hosp 1 is located in São Paulo, which is the largest city in Brazil and the most affected by the H1N1 pandemic. The nodes of H1 selected for study represent those that were most affected by risk management decisions related to H1N1. H1 is comprised of four tiers: (i) Hosp 1, which was responsible for the care of patients, (ii) pharmaceutical industry, which was responsible for providing drugs for patient care, (iii) Department of Epidemiological Surveillance of the Brazilian Ministry of Health, which was responsible for management of the National Epidemiological and Environmental Health Surveillance System, and (iv) Ministry of Health of São Paulo (SES)/Epidemiological Surveillance Center, which sets health policies, under guidelines established by the Brazilian Unified Health System (SUS).

Cases D1 and D2 are set in the dermatology products industry. This industry provides over-the-counter medications for skin conditions ranging from eczema and hives to wrinkles and pimples. D1 is the supply network associated with Dermo 1, a medium sized domestic firm with about 80 franchisees. D2 is the supply network associated with Dermo 2, a somewhat larger domestic firm, with its own manufacturing plant and 93 retail stores. Both Dermo 1 and Dermo 2 started in the 1980s as compounding pharmacies, then evolved to a franchise model.

Cases B1, B2, B3 and B4 are set in the beauty products industry. B1 is the supply network for Beauty 1, which is the Brazilian subsidiary of a large firm headquartered in southern France. B2 is the supply network for Beauty 2, which was formed by 14 Brazilian firms working together to bring French concepts and fragrances to Brazilian customers. B3 is the supply network for Beauty 3, which is the largest Brazilian beauty products firm, as well as the world’s largest perfume and cosmetics franchiser, with 3,800 retail stores. B4 is the supply network for Beauty 4, which is the second largest domestic Brazilian cosmetics firm and the sixth largest direct sales firm in the world (Direct Selling News, 2015).

Each supply network was studied end to end, with multiple interviews in each of the tiers. In total, we conducted 197 in-depth interviews, which were recorded, transcribed, and analyzed. Observations and archival documents were also used. Preliminary analysis was conducted using NVivo, in order to isolate primary themes. Ucinet 6.0 and Net Draw were used to analyze relationships among the supply network members. Kim et al.’s (2015) four archetype supply network structures were applied, as well as analyzing their two propositions in the context of our case data.

Results

Supply network archetypes

H1 used a single linear supply chain, rather than a supply network, with only one walk between the source and sink. This made it highly vulnerable, since disabling any arc or node would disable the entire supply chain. H1’s single linear supply chain suggests that Kim et al.'s (2015) set of archetypes may not be comprehensive, and that there may be other important supply network archetypes.

The dermatology products supply networks D1 and D1 were centralized, with a few key intermediaries. The reasons involve the size of the focal firms and characteristics of their suppliers. Dermo 1 and Dermo 2 are both medium size firms, ranging from 200 to 500 employees, with their own manufacturing facilities. In contrast, the major suppliers in this industry are very large multinational firms, such as Dow Chemical, with thousands of employees globally. Because of the size discrepancies, most dermatology products firms purchase materials from an intermediary firm, following a centralized structure. As the focal firm grows, its network structure becomes more elongated, resembling the diagonal archetype, with less need for intermediary firms as purchase volumes increase and components are purchased directly from the large multinational suppliers.

A similar evolution was observed among the beauty products supply networks. Beauty 2, which is a medium sized firm, is characterized by B2's centralized supply network structure. B1, on the other hand, although it uses some intermediary firms, is more elongated and less centralized than B2, more closely resembling Kim et al (2015)'s diagonal structure. B3's and B4's network structures are best represented by a hybrid with a block-diagonal structure at its foundation and scale-free structures superimposed within each of its clusters. This is due to size and complexity of the focal firms. Beauty 3 has about 4,000 retailers, with 22,000 employees and about 900 franchise owners. Beauty 4 has more than 6,600 direct employees and many thousand others through its resellers. Upstream, B3 and B4 each have more than 5,000 different suppliers for packaging, chemicals, and information. B3 organized its supply base into 42 strategic suppliers for direct supply (among about 300 possible suppliers), and 32 strategic suppliers for indirect supplies (among more than 5,000 possible). Thus, within the block diagonal archetype, scale-free supply networks are embedded. B4 pays particular attention to 33 indigenous communities in the Amazon rain forest.

These findings are reinforced by centrality measures calculated using Ucinet 6.0. We found that larger focal firms had higher levels of centrality in their supply networks. This supports the notion that the structure of a supply network evolves as the focal firm grows and plays a more important role.

Impact of H1N1 pandemic

The Oseltamivir Phosphate (Tamiflu) supply network is long and complex. The manufacturing process is distributed across many countries, beginning with star anise seeds from China, which are processed in Switzerland and the United States, among other locations. The total production cycle for Tamiflu is about one year, which is considered long by pharmaceutical industry standards. Thus, there was no ability to quickly increase production in the face of an unanticipated surge in demand. In addition, because drugs are highly regulated in Brazil, it would have been difficult to purchase Tamiflu inventories held in other countries. Commercially, Tamiflu is sold in the form of capsules or as a powder that can be reconstituted by the addition of water.

The government had stockpiled Tamiflu between 2005 and 2006, expecting to need it for H5N1, which never materialized. It was purchased in powder form in 30 kg barrels, because of its long shelf life and lower price. The rationale was that the government's supply network, which included its own laboratories, would be able to process the powder when it was needed by hospitals. In reality, however, this strategy was ineffective because government laboratories were unable to handle the sudden increases in demand. The supply network was forced to develop alternative solutions for dealing with the situation. Ultimately, it restructured by removing all of the Tamiflu available in the drugstores, so that the government could centralize its distribution. It was then distributed in powder form, using the hospitals' own laboratories to process the powder into the final form for administration to patients.

Impact of environmental legislation

Because PM 2186 was federal legislation, it affected all six of the dermatology and beauty products supply networks studied. It stipulated requirements for dealing with indigenous communities in the Amazon rain forest and other almost unreachable areas, which many firms felt were unreasonable, confusing and costly. Chemical products suppliers to dermatology and beauty products manufacturers spent millions of dollars trying to meet seemingly ever-changing compliance requirements. The confusion is illustrated by one of the focal firms which received an important award for its ecological and sustainable actions towards indigenous communities from the Environmental Minister, just two weeks before it was charged with bio-piracy through PM 2186. PM 2186 included financial penalties for vaguely defined noncompliance. More than $59 million in fines was levied in Operation New Directions, based on the argument that "Brazil's unique species have been exploited for centuries by businesses, which often make fortunes while overlooking local communities (Erickson-Davis, 2010)." This was followed by Operation New Directions II, which levied even higher fines against another 35 firms (IBAMA, 2012). The list of firms fined includes several of the research cases, as well as well-known firms, including Ambev, Avon, Bayer, Eli Lilly, Pfizer, Merck, Novartis, and Unilever. PM 2186 was considered inadequate by scientists, and several appeals have supported the illegality of some of its components.

B4 and B1 were the most strongly affected supply networks, with a severe financial and reputational impact. B1 was particularly impacted because the major reason it initiated business in Brazil was to capitalize on the rich biodiversity there. With the complications and difficulties caused by PM 2186, B1 had difficulty finding suppliers that were able to deal with the requirements. Its response came in the form of restructuring its supply network. Instead of using Amazon rain forest and Pantanal raw materials, it started using fruits and other materials from less regulated areas: "Even when we try very hard - and we do that - we cannot fulfil CEGEN's requirements [through MP 2186], thus, instead of buying from local suppliers in Amazon rain forest, we are buying from local suppliers in Africa." In this way, it was able to mitigate the effect of the disruption.

After B4 was charged with 84 different infractions during Operation New Directions, CEGEN's president then overturned the charges, compounding the confusion. B3, which had a supply network structure similar to B4, did not experience the same impact. The reasons are associated with difference in the networks' downstream strategic focus. While B4's marketing appeal had always focused on nature and the ecological responsibility of its products, suppliers, and processes, B3 appealed to its consumers in different ways. The smaller supply networks (B2, D1, and D2), felt only secondary impacts of this disruption. For example, Dermo 1 temporarily discontinued some of its production lines because a supplier stopped carrying a needed Amazon rain forest raw material. It then quickly recovered by substituting a different raw material offered by the same supplier.

Thus, in terms of resilience, the network structures in our real supply chains did not entirely support Kim et al.'s (2015) second proposition that the closer the structure follows the power law structure (scale-free network), the more resilient it will be. While both B3 and

B4 had very similar network structures that followed the power law, B3 was much more resilient, for reasons unrelated to its supply network structure.

Discussion

Supply Network Structure

Most of the cases used a hybrid combination of Kim, et al.’s (2015) archetype supply network structures. All had a network structure based on the underlying logic of the diagonal archetype, with sequential connections between tiers. The nodes between the source (agricultural products) and the sink (hospitals for medication, estheticians and dermatologists for dermatology products, and retail outlets for beauty products) could be partitioned into subsets of nodes that formed tiers, including agricultural products, chemical suppliers, manufacturing, packaging, research and development, and distribution.

We propose an extension to Kim et al.’s (2015) archetypes, based on our analysis. We suggest that supply network structures are not static; they evolve, following three basic stages: centralized, diagonal, and hybrid diagonal/scale-free. Stage I (centralized) usually manifests when a firm starts. Its smaller size limits its bargaining power, due to lower volume purchases. Thus, it buys from intermediaries, which connect it to a range of suppliers. Examples are found in D1, D2, and B2. Stage II (diagonal) manifests when a firm starts to grow. It becomes less dependent on intermediaries and its structure becomes more elongated. It may still use some intermediaries, however, this is more due to choice, for example because of a long-term relationship or better service, rather than a constraint caused by its volume. B1 provides an example of this structure. Stage III (hybrid diagonal/scale-free) is a block-diagonal structure with a scale-free structure superimposed within each cluster. This stage is manifested in very large firms, whose supply networks are composed of thousands of suppliers, grouped by type of supply and strategic importance. Some centralization occurs within a few first tier suppliers that manage several suppliers and their suppliers. Clusters emerge for different types of supplies. For example, in the dermatology and beauty products industries, clusters include packaging, chemicals, fragrances, and information suppliers. Each cluster follows the power-law Pareto distribution, with very few interactions between clusters. Figure 2 presents the proposed model of evolving supply network structure.

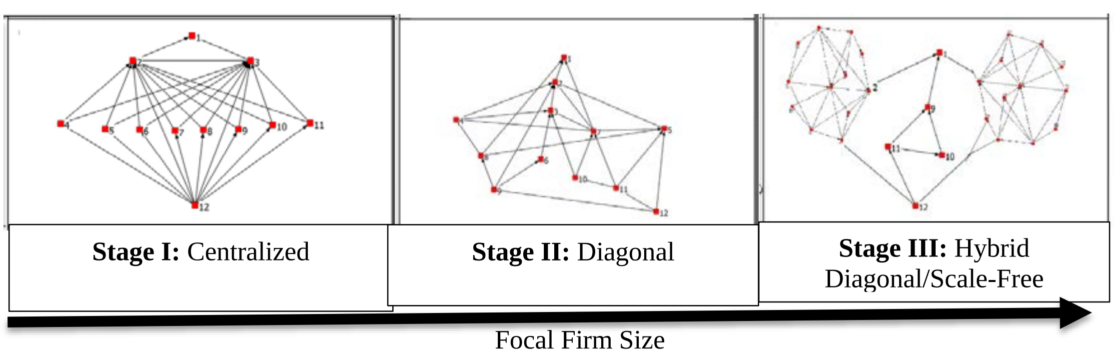

Figure 2. Proposed evolution of supply network structure

These network structures affect supply network resilience, supporting Kim, et al.’s (2015) first proposition. We found that those that had more direct (scale-free) connections with their suppliers reacted more quickly to the disruption, mandating changes by their suppliers. On the other hand, the supply network structures that had primarily indirect connections with their suppliers (centralized) were slower to react, waiting for suppliers to initiate changes. Thus, the recovery phase was slower for the hybrid diagonal/scale-free network structure. This supports Kim, et al.’s (2015) second proposition that the scale-free supply network structure would be most resilient. Direct links with key suppliers hastened the recovery phase, relative to indirect links through intermediaries in the centralized archetypes.

Supply network resilience

We view Kim et al.´s (2015, p.49) proposed definition of supply network resilience as "a network-level attribute to withstand disruptions that may be triggered at the node or arc level" as passive, in the sense that resilience is considered given based on network structure. Our results suggest that resilience may either be planned (for example, pre-designing a network structure to have more alternatives to deal with a potential disruption in an arc or node) or may emerge during a disruption. In both situations, resilience is built upon capabilities including risk perception, collaboration, flexibility, visibility and agility, which help a supply network cope with a disruption.

Moreover, although the literature indicates that resilience may be formed by a set of different capabilities, Kim et al.'s (2015) approach is related only to the flexibility capability. The main function of flexibility is to generate new options for a supply chain to allow its members to deal with disruptions, thus, flexibility plays an important role in the resilience. However, resilience is based on many capabilities, including redesign, change, resource creation, reconfiguration, prioritization, redundancy, availability and robustness, as well as flexibility (Bradaschia & Pereira, 2015). While resilience can be achieved by planning network structure, it can also be achieved by dealing with an unexpected occurrence as it occurs, as H1 did in its restructuring during the H1N1 pandemic. Thus, supply networks are dynamic, evolving over in time and in response to triggering events.

Conclusions

This study contributes to the emerging body of research on analysis of supply network structures in the context of resilience by applying Kim, et al.’s (2015) archetypes to rich case data from real supply networks. It raises the idea that the ideal archetypes may actually appear as hybrid networks in real supply chains, rather than in their pure form. It also supports the notion that the more closely a supply network follows a power-law degree distribution of nodes, the more resilient it will be. Thus, Kim, et al.’s (2015) mathematical analysis was extended by the rich case data of our qualitative analysis.

Potential future extensions supported by this study include analysis of resilience within different blocks or clusters within a supply network structure. Also, in the face of a disruption, a supply network may restructure itself, as D1 and H1 did, to temporarily function with a different structure until it recovers. Our case data also suggests that supply network relationships go beyond simply counting arcs and nodes. In order to understand how a network structure affects resilience, it is important to understand both upstream and downstream supply networks and their power relationships. One of the major extensions that this study proposes to Kim et al.’s (2015) framework is the understanding that a supply network is not static, but rather evolves with the size of the focal firm. Thus, we propose the following:

P$_1$: The centralization of a supply chain is a function of the size of a focal firm

P$_2$: As a focal firm grows, the supply chain becomes less centralized in intermediary firms and more centralized within itself

P$_3$: Supply network structures evolve from centralized to diagonal to hybrid diagonal/scale-free, as a focal firm grows

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