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Supply network disruption and resilience: A network structural perspective

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ABSTRACT

Increasingly, scholars recognize the importance of understanding *supply network disruptions*. However, the literature still lacks a clear conceptualization of a network-level understanding of supply disruptions. Not having a network level understanding of supply disruptions prevents firms from fully mitigating the negative effects of a supply disruption. Graph theory helps to conceptualize a supply network and differentiate between disruptions at the node/arc level vs. network level. The structure of a supply network consists of a collection of nodes (facilities) and the connecting arcs (transportation). From this perspective, small events that disrupt a node or arc in the network can have major consequences for the network. A failure in a node or arc can potentially stop the flow of material across network. This study conceptualizes supply network disruption and resilience by examining the structural relationships among entities in the network. We compare four fundamental supply network structures to help understand supply network disruption and resilience. The analysis shows that node/arc-level disruptions do not necessarily lead to network-level disruptions, and demonstrates the importance of differentiating a node/arc disruption vs. a network disruption. The results also indicate that network structure significantly determines the likelihood of disruption. In general, different structural relationships among network entities have different levels of resilience. More specifically, resilience improves when the structural relationships in a network follow the *power-law*. This paper not only offers a new perspective of supply network disruption, but also suggests a useful analytical approach to assessing supply network structures for resilience.

1. Introduction

Hendricks and Singhal (2005) found that an announcement of a supply disruption lowers a firm's stock returns on average by 20% six months after the announcement. Recent industry examples highlight the challenges that companies face in recovering from a disruption. For instance, Toyota had a supply network disruption in the aftermath of the 2011 tsunami in Japan. Six months later, Toyota had to idle some plants in North America due to shortage of parts (Ferreira, 2012). Some tsunami-stricken Japanese suppliers could no longer supply the North American plants, which shut them down. Several other examples have been documented, where supply disruptions in one part of the world created problems in another part of the world. One of the authors of this study worked with a multinational personal computer (PC) maker in the wake of the 2011 floods in Thailand, which then led to a disruption of the computer hard-disk industry. As the PC manufacturer executives were investigating their supply network, they became concerned about how a supplier "deep in the supply network" might disrupt their operations. In an increasingly globally connected world, managing supply disruptions involves more than just preventing disruptions at your facilities. It also requires a broader understanding of the overall structure of your supply network.

Many scholars have begun to study supply chain disruptions. These studies have largely focused on assessing vulnerabilities that firms face and/or capabilities they need to manage these vulnerabilities (Ellis et al., 2010; Sheffi, 2007). However, in many cases, supply disruptions (i.e., stoppages of material flows) do not originate from

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a focal firm's facilities, but rather from its supply network. Also, disruptions at the local level do not necessarily lead to network-level disruptions. Consequently, a firm's failure to manage supply disruptions often stems from a lack of understanding of the supply network. Nonetheless, few studies to date have examined how the overall structure of a supply network can affect disruption risks. In addition, research has not offered a formal definition of a supply network disruption. As a result, empirical research cannot fully progress in this area. This study defines a supply network disruption and takes a network structural perspective to address the following questions: *how does the supply network structure influence disruptions, and how can one assess the resilience of supple network structure?*

From a structural perspective, a supply network can be viewed as a collection of nodes (facilities) and arcs (transportation linking facilities) (Borgatti and Li, 2009). A supply disruption thus depends on the structure of the nodes and arcs in the supply network. A disruption of a node or an arc sometimes has little overall effect, but other times can bring down the entire supply network—such as the Thailand floods did for the PC industry. Understanding the overall supply network structure and differentiating between node/arc-level and network-level disruptions can help better manage supply disruptions. Drawing on graph theory, this paper advances a more precise definition of supply network disruption. The definition has implications for how to understand and manage supply disruptions at the network level. An analysis of basic supply network structures demonstrates that the structure of the nodes and arcs in a supply network strongly determines its risk of disruption and resilience. In particular, a supply network will become more resilient when the overall structure of the nodes and arcs follow a *power-law* distribution. Consequently, firms will benefit from a deeper understanding of supply network structure and how it influences disruption risk and resilience at the network-level.

The rest of this article is organized as follows. Section 2 reviews the literature on supply network disruption and resilience. Section 3 draws on graph theory to conceptualize a supply network, disruption, and resilience. Section 4 develops the four basic supply network structures based on the literature and compares these structures on network resilience. Section 5 advances propositions about the connection between supply network structure and resilience. Finally, Section 6 discusses the implications of this study for research and practice.

2. Literature on supply network disruption and resilience

The literature has taken various perspectives on examining supply disruptions and resilience, including behavioral (e.g., Ellis et al., 2010; Wagner and Neshat, 2010), conceptual (e.g., Christopher and Peck, 2004; Kovács and Tatham, 2009; Tang, 2006), qualitative (e.g., Craighead et al., 2007; Jüttner et al., 2003; Sheffi and Rice, 2005), and simulation/modeling (e.g., Nair and Vidal, 2011; Wu et al., 2007; Zhao et al., 2011). For instance, Ellis et al. (2010) used a survey to study how firms make decisions in the face of supply disruptions. Christopher and Peck (2004) offered a conceptual model to classify some sources of supply chain risks and suggest how to overcome those risks. Craighead et al. (2007) employed structured interviews and critical incident technique to understand why disruption severity varies among supply chains. Wu et al. (2007) utilized a modeling approach to understand the propagation of disruptions across supply chain systems. In terms of the level of analysis, the literature also varies from the firm level, to the supply chain, to the supply network. Although this research has produced useful insights from a range of different perspectives, it has also led to confusion—especially when it comes to the level of analysis. Consequently, the literature uses different terms and concepts to define and assess supply network level disruptions and resilience.

In the literature, a supply network disruption is generally defined as an unplanned and unanticipated event that disrupts the normal flow of goods and materials in a supply network (Craighead et al., 2007; Hendricks and Singhal, 2003; Kleindorfer and Saad, 2005; Svensson, 2000), and viewed as a major source of firms' operational and financial risks (Stauffer, 2003). This definition, while offering a general description, does not clearly specify the level at which the disruption occurs and the scope of its effect. This becomes an important distinction since the cause and effect may occur at different levels. The Toyota example serves as a case in point—a disruption occurred in a component plant in Japan (a cause at the node-level), which led to a shutdown in their North American truck production (the effect at the supply network-level). Failure to make this distinction has implications for how we understand and manage disruptions.

The concept of network resilience also has important implications in understanding supply network disruptions (Sheffi, 2007). However, the literature gives no clear consensus on the definition of resilience in the context of supply network disruptions. Table 1 summarizes existing definitions, measures, and levels of analysis of the supply network disruption and resilience. The literature does not provide a clear formal definition of supply network resilience. Some define it as a property (Longo and Oren, 2008), while others describe it as a capability of the supply network (Christopher and Peck, 2004). Still others view resilience as both an inherent property (to absorb shock) and an ability to adapt to changes (Johnson et al., 2013). Furthermore, although scholars have treated the term "disruption" as a companion concept to resilience (Scholten et al., 2014), in many cases they do not formally define "disruption" and assume that it is clearly understood. Ambiguous definitions can lead to confusion and impede scholarly development (Wacker, 2004).

In addition, not clarifying the level of analysis when defining and theorizing about supply network disruptions exacerbates the problem. The literature shows inconsistencies and ambiguity when it comes to the level of analysis. This becomes problematic since the behavior of a network emerges from its elements. For example, Wu et al. (2007) described a supply chain disruption as a "disruption at a susceptible *location* in the supply chain" (p. 1677, emphasis added), which indicates a disruption as defined at the node level. The authors then took a network perspective in their analysis to show how far-reaching the effect of a disruption can propagate across a supply chain. Consequently, there is a disconnect between the conceptual definition (at the node level) and analysis (at the network level). Similarly, Craighead et al. (2007) defined supply chain disruptions as "unplanned and unanticipated events that disrupt the normal flow of goods and materials." Then, they proposed the *node criticality* notion to refer to the importance of a *node* within a supply chain and describe it as what eventually determines the severity of a supply chain-wide disruption. The assumption is that a disruption at a critical node invariably leads to a system-wide disruption via cumulating serious consequences across the entire supply chain. Their definition of supply chain disruption does not clarify or distinguish its cause and effect, leading to inconsistency in the level of focus between definition and analysis. Although these papers advanced our understanding of supply disruptions, at the same time, they lacked clarity.

According to Wacker (2004), a good (operational) definition should be "a concise, clear verbal expression of a unique concept that can be used for strict empirical testing" (p. 631). Nonetheless, few studies (except for Sheffi and Rice, 2005; Zhao et al., 2011) have offered a clear definition at the supply network level, let alone analytical measures. Further, much of the research is qualitative in nature, largely relying on event or case studies (with