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Supply chain vulnerability assessment: A network based visualization and clustering analysis approach

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ABSTRACT

Supply chains are large, complex, and often unpredictable. Purchasing and supply managers and supply chain risk managers need methods and tools to enable them to quickly understand how unexpected disruptions in the supply chain start and grow and to what extent will they negatively impact the flow of goods and services. This paper introduces a methodological approach that can be used by both researchers and managers to quickly visualize a supply chain, map out the propagation path of disruptive events from the supply side to the end customer and understand potential weaknesses in the supply chain design; taking into account the structure, connectivity, and dependence within the supply chain. The approach incorporates a Petri net and Triangularization Clustering Algorithm to offer insights into a supply chain network's vulnerabilities and can be used to efficiently assess supply chain disruption mitigation strategies, especially in complex and difficulty to analyze supply chain systems.

1. Introduction

Globally competing firms have inherently large and complex supply chain systems that are particularly vulnerable to disruptive events (Blackhurst et al., 2005a; Craighead et al., 2007; Manuj and Mentzer, 2008; Giannakis and Louis, 2011). These complex supply chains have garnered much attention considering methods and means to understand their nature and their risk vulnerability (Tang, 2006; Sodhi et al., 2012). A disruption in the supply chain may lead to other entities failing and may even result in entire portions of the supply chain failing (Jüttner and Maklan, 2011). Supply chain vulnerability is the susceptibility or exposure to a disruptive event in the supply chain (Wagner and Bode, 2006; Bhamra et al., 2011; Ghadge et al., 2012; Wagner and Neshat, 2012). Prior literature has discussed steps for managing disruptive events in the supply chains as first identifying the potential disruptions, next assessing the likelihood and potential impact and finally selecting and implementing a mitigation strategy (Chopra and Sodhi, 2004; Manuj and Mentzer, 2008). The identification step can occur before the disruption occurs allowing managers to proactively avoid or reduce the impact of the disruption (Craighead et al., 2007; Knemeyer et al., 2009). Conversely, the disruption may be unavoidable leading to more reactive planning (Craighead et al., 2007). When a supply chain is vulnerable to a disruption, the goal is to develop resilience in the supply chain, such that after a disruption has occurred the network can be leveraged to regain a desired service level as quickly as possible (Ambulkar et al., 2015; Pettit et al., 2013). Managing vulnerabilities is difficult because supply chains are interconnected with high levels of supply and demand uncertainty. Because of the complexity and interconnected nature of supply chains and their effect on disruption propagation, it is essential to understand the structure of the supply chain and its vulnerability to disruptions (Wagner and Neshat, 2010; Mizgier et al., 2013). When purchasing and supply managers restrict their focus solely on first tier suppliers they may not perceive disruption events moving in their supply chain until it is too late (Tang et al., 2009). Therefore, a method for understanding supply chain vulnerability would be useful to purchasing and supply managers to reconfigure the network structure and relationships or reposition capacity and resources to reduce the risk or effects of disruptions. While there are many types of disruptions that occur in supply chain networks, we focus on the specific disruption of node failure. That is to say, when a node in the supply network is no longer able to produce, ship, or transship products or services, the supply network has experienced a disruption.

Researchers employ various techniques including optimization,

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simulation, and regression to understand and explain supply chain networks. Recently, analytics methods have gained traction, creating greater diversity in approaching a very complex set of problems and giving supply chain research a fuller perspective (Waller and Fawcett, 2013a). These methods find their roots in World War II with Dantzig's simplex method but have expanded through ERP into business intelligence (Sahay and Ranjan, 2008), and most recently to supply chain analytics (Waller and Fawcett, 2013b; Souza, 2014). The challenge purchasing and supply managers face is to employ appropriate analytical methods to help decision making in the face of a supply chain disruption.

Statistics, optimization and simulation are commonly used by researchers and managers to understand characteristics, behaviors, and nature of supply chains. Techniques like regression are used to describe theoretical models (e.g. Chong et al., 2015) or predictive analytics (Lindsey et al., 2014). Optimization has been used to search a problem space for the best solution given a set of constraints, and simulation can model the behavior and dynamics of systems (Tomlin, 2006; Griffis et al., 2012). The choice of technique is often a function of the problem and the maturity of the organization (de Oliveira et al., 2012).

In addition to these approaches, many researchers use heuristics and other techniques to gain analytical insights into supply chain problems (e.g. Memari et al., 2015). However, each of these methods is not without its limitations (Chapman et al., 2002; Zhang et al., 2011). When considering supply chain vulnerabilities, the need to understand a particular structure, model, or set of variables can prove problematic. Tang (2006) suggests reducing the impact of disruptions on supply chain operations by proactively forming strategic alliances with multiple suppliers in different countries. Ghadge et al. (2012) reach the same conclusion arguing for systems thinking. However, true systems thinking is a challenging task given that purchasing and supply managers have difficulty in monitoring suppliers more than two tiers from a focal firm. As a result, purchasing and supply managers are often caught unaware when a disruption that began several tiers upstream can cascade to the focal firm (Scheibe and Blackhurst, 2017). In fact, recent research has called for studies that adopt a more systems based lens and look at network based models to understand how disruptions impact supply chains (Van der Vegt et al., 2015). A similar call to action had been issued by Nair and Vidal (2011) to investigate a way to understand which nodes in a network should be fortified for protection against supply chain against disruptions. Finally, Kirilmaz and Erol (2017) note that the use of quantitative methods in supply chain risk management is insufficient and call for more tools to address supply chain vulnerability.

In this paper, we answer these calls through the development an approach that helps visualize and understand supply chain structure and assess vulnerability in that structure to supply chain disruptions (Min and Zhou, 2002; Blackhurst et al., 2005a; Zsidisin et al., 2005; Skipper and Hanna, 2009). The contribution of this research is the combination of Petri nets with Triangularization Clustering Algorithm (TCA) to assess disruption vulnerability of a supply chain based on its the structure. This approach will map out the propagation path of disruption events, and uncover vulnerabilities stemming from the supply chain design: the structure, connectivity and dependence within the supply chain. Triangles are the basic unit for measuring network structure and redundancy (Cheng et al., 2009), and have been used to quantify structure and flow in networks. Network nodes are interconnected, and thus it is important to measure more than nearness as proximate distance may not convey the strength of relationship between nodes. Triangularized clustering approaches have been used to identify network redundancies (Schank and Wagner, 2004) and structural invariances across websites (Zhou et al., 2007). This approach, once applied, provides novel insights into how the structure of a supply chain can impede or enable a disruption to propagate. When a firm's supply chain is hit with a disruption, it is not only important to know which node in the supply chain is directly hit, but it is also important to know all possible scenarios for disruption propagation. We combine the Petri net approach with a clustering algorithm, the Triangularization Clustering (TCA), which identifies clusters and other network characteristics in order to gain insights into the vulnerabilities of the system. By combining these two methods into a new methodological approach, we build upon prior research to develop an assessment of supply chain vulnerability based on the structure of the supply chain and analyze how the structure of a supply chain can facilitate or hinder the propagation of a disruption. This insight is lacking in the literature and offers new knowledge to assess and manage disruptions in the supply chain.

In the following sections we introduce and illustrate the utility of our proposed decision model by first considering an exemplar service parts supply chain for an automotive firm to illustrate the functionality of our approach. In Section 2, we introduce a Petri net and clustering algorithm combination to identify structural and procedural vulnerabilities in the supply chain. We demonstrate the applicability of our approach with our automotive firm example. Next, we provide insights on vulnerability for the service parts supply chains, and finally, we provide interesting extensions to our methodological approach with respect to supply chain disruption mitigation. The model presented in this research is appealing to both industry and the academy because it provides a road map for purchasing and supply managers to evaluate their supply base and network both in terms of connectivity and contractual agreements and processes.

2. Methodological approach

The Petri net, developed originally by Carl Petri for modeling communication protocols, has evolved into a graphical and mathematical tool for representing and analyzing discrete event systems (Zurawski and Zhou, 1994), including manufacturing systems (e.g., Venkatesh et al., 1996; Yan et al., 1999; Yu et al., 2003) and supply chains (e.g., Blackhurst et al., 2004; Chen et al., 2005; Fridgen et al., 2015). As a graphical tool, the Petri net is a bipartite graph using nodes and arcs to visually map a system, while, as a mathematical tool, it can be embedded with mathematical functions for analysis of system properties.[1] Petri nets are proven tools for modeling complex and dynamic systems as well as for evaluating network structure (Tuncel and Alpan, 2010; Zhang et al., 2011). It is essential to understand that the logic (or mathematical functions) that can be embedded in a Petri net can cause the model to become non-linear. This is both a strength and weakness intrinsic to the Petri net. It is a weakness because it prevents the network from being solvable in an optimization fashion, and it is a strength because it allows a network to more accurately represent reality in terms of contractual agreements, processes and procedures. We will describe this in greater detail and illustrate an example with the automotive firm.

To properly introduce fundamental concepts and terminologies related to the Petri net and how our methodological approach may be used to predict supply chain vulnerability, we present an example of how a supply chain can be represented by the Petri net. There are several open source Petri net tools available for research such as WoPeD (http://woped.dhbw-karlsruhe.de/woped/). Fig. 1 shows a six-tier Service Parts Supply Chain for a U.S. heavy equipment manufacturer. This Service Parts Supply Chain is a subsection of a more complete supply chain; its structure was identified through interviews conducted with various supply chain managers employed by the U.S. heavy equipment manufacturer.

As shown, the Service Parts Supply Chain is comprised of three U.S.-based distribution centers (DC 1, 2, and 3) belonging to the same firm. DC 1 and DC 2 supply items to DC 3, who supplies items to the Manufacturing Facility. DC 1 and DC 2 also supply items to each other as needed. The Manufacturing Facility serves four dealer locations

[1] A more complete discussion of Petri nets can be found in Murata (1989) and Zurawski and Zhou (1994).