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# Developing a supply chain disruption analysis model: Application of colored Petri-nets

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ABSTRACT

As a result of globalization in the past two decades, supply chains are encountering more unknown conditions and risks. One important category of risks is disruptions that block material flowing through a supply chain and that may even result in end-product manufacturing failure. This paper uses a Petri nets-based model as a tool to understand the dissemination of disruptions and to trace the operational performance of a supply chain. The presented approach models how changes propagate through a supply chain and calculates the impact of disruptions on supply chain attributes by concluding the states that are obtainable from a given initial status in the supply chain.



## 1. Introduction

With regard to the complex and dynamic environment of supply chains, uncertainty (generally termed "risk") has been raised as an important concern. The reported dramatic outcomes from risky events demonstrate the importance of proactively managing supply chain risk (Chopra & Sodhi, 2004).

Supply chain risks have been clustered into different groups, and these classifications differ between papers (Chopra & Meindl, 2007; Juttner, 2005; Tang, 2006b). Among the supply chain risks types are disruptions resulted from natural disasters, supplier bankruptcy, labor disputes, war, terrorism and social-economic-political instability (Chopra & Meindl, 2007; Craighead, Blackhurst, Rungtusanatham, & Handfiels, 2007; Hendricks & Singhal, 2005c; Kleindorfer & Saad, 2005). Naturally, different authors may suggest dissimilar sources for disruption risks, but disruption risks generally have a low probability and the potential for a large loss. Some papers refer to them as "catastrophic events" (Knemeyer, Zinn, & Eroglu, 2009). They can seriously disrupt or delay material, information and cash flows, which can ruin sales, increase costs or both. How a company gets along such threats depends on the type of disruption and the organization's level of preparedness. Supply chains can use two complementary actions to respond (Pochard, 2003). They can secure their supply chain or they can develop resiliency. Both can be performed in many different ways, and it seems that there is no single best solution. The problem for mangers is to choose a good strategy and to quantify the benefits of various options. In order to determine the most effective method, mangers must be able to analyze disruptive events and their possible effects. Despite the importance of this issue, there is not a rich literature on supply chain disruptions and their effects. This may be due to the newness of this concept, which was primarily developed following the September 11 attacks. Existing studies for detecting the effects of disruptions on a supply chain are based on a single disruptive event, and the interrelationships between different types of disruptions have not been considered. Due to this lack of information, the current paper investigates a mathematical model for determining how disruptions of supply chain components are causally related to each other as well as finding out the way of disruptions' propagation.

The remaining sections of this article are organized as follows: In following section, supply chain disruption studies and existing methods for analyzing a disruption are reviewed. Afterward, proposed model will be introduces, which is clarified using a numeric example and an empirical case study. Finally, the paper concludes with a brief summary.

## 2. Literature review

### 2.1. Supply chain disruption

Relative to the most business practices, the occurrence of a disruptive event is an extraordinary and unusual situation. While a significant amount of researches has been reported in the area of supply chains, there have been relatively little investigations conducted in the area of understanding the global impacts of supply chain disruptions (Wu, Blackhurst, & Grady, 2007). Fig. 1 shows the categories of published research in this field.

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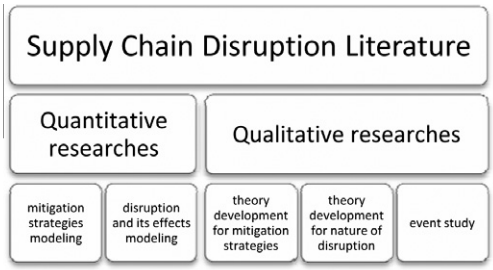


**Fig. 1.** Categories of disruption's published researches.

Along these lines, Lee and Wolfe (2003) presented strategies for reducing vulnerability to security losses that may cause disruptions. Kleindorfer and Saad (2005) introduced a conceptual framework to estimate and reduce the effects of disruptions. Norrman and Jansson (2004) studied a fire accident at Ericsson Inc.'s subsupplier and the company's solution for mitigating the likelihood of such events as a proactive plan. Tang (2006a) proposed robust strategies for mitigating disruption effects, and Pochard (2003) discussed an empirical solution based on dual-sourcing to mitigate the likelihood of disruptive events. Marley (2006) discussed lean management, integrative complexity and tight coupling, as well as their relationships with disruption effects. Papadakis (2006), based on an empirical analysis, demonstrated the financial implications of supply chain design, particularly on the differences between pull- and push-type designs. Hendricks and Singhal (2005a) shed light on the effects of supply chain glitches that result in production or shipment delays and estimated their impact on shareholder wealth. In another report, Hendricks and Singhal (2003) showed that supply chain disruptions have negative effects on financial performance measures, as well as on operating income and return on assets. Craighead et al. (2007) illustrated the relationship between supply chain structure and disruption severity based on their observations from different case studies. Yu and Qi (2004) demonstrated mathematical models for demand disruptions while Qi, Bard, and Yu (2004) examined quantity discount policy when demand disrupts. Xiao and Yu (2006) developed a game model to study evolutionarily stable strategies (ESS) of retailers in quantity-setting duopoly situations with homogeneous goods and analyzed the effects of demand and supply disruptions on the retailers' strategies. Xiao, Qi, and Yu (2007) investigated the coordination mechanism of a supply chain with one manufacturer and two competing retailers when the demands are disrupted. Similarly, Xiao and Qi (2008) studied the coordination of a supply chain with one manufacturer and two competing retailers after the production cost of the manufacturer was disrupted. Tomlin (2006) suggested two different groups of strategies, mitigation and contingency, prior to a disruption and discussed the values of these two choices for managing a supply chain disruption. Chopra, Reinhardt, and Mohan (2007) focused on the importance of decoupling recurrent supply risk from disruption risk and of planning appropriate mitigation strategies.

All of the aforementioned strategies can be categorized into two main types, preventive and recovery, and preventive solutions can be categorized as follows:

- Robustness strategies (Tang, 2006a).
- Resiliency strategies (Rice & Caniato, 2003; Sheffi & Rice, 2005).
- Security-based strategies (Hale & Moberg, 2005; Lee & Whang, 2005; Rice & Caniato, 2003; Sheffi, 2001).
- Agility strategies (Chopra & Sodhi, 2004; Hendricks & Singhal, 2005b, 2005c; Li, Lin, Wang, & Yan, 2006; Tang, 2006b).

All these strategies to manage supply chain disruption, have a critical assumption that the supply chain managers are not aware of the time of disruption occurrences but experts can estimate vulnerable parts of the chain and the amount of disruption effects if it occurs, consequently they define some applicable policies. In general, because of the unpredictability and complex effects of disruption, some researchers (Knemeyer et al., 2009; Norrman & Jansson, 2004) choose proactive approaches. A catastrophic event has a very low probability of occurrence, but tremendous consequences if it occurs, and supply chains are increasingly susceptible to catastrophic events. So supply chain decision makers should put a priority for proactively planning these types of events (Knemeyer et al., 2009).

*2.2. Supply chain disruption analysis*

Despite the few papers on disruption analysis, some researchers have applied simulation models to predict supply chain behavior, and these simulations include models for tracing the effects of uncertainty (Petrovic, 2001), order release mechanisms (Chan, Nelson, Lau, & Ip, 2002), business processes and inventory control parameters (Jain, Workman, Collins, & Ervin, 2001). Kleijnen and Smits (2003) distinguish four simulation types for supply chain management (SCM): spreadsheet simulation, system dynamics (SD), discrete-event dynamic systems (DEDS) simulation, and business games, which are discussed and compared by Kleijnen (2005).

Some researchers have presented methods such as system dynamics (Wilson, 2006) and network-based procedures (Li et al., 2006; Liu, Kumar, & Aalst, 2007; Wu et al., 2007) to demonstrate disruptions effects. Wilson (2006) investigates the effect of transportation disruption on supply chain performance by applying system dynamics. Disruptions, however, are discrete events, and in order to scrutinize them, there is a serious need for discrete simulation methods. One creative method in this field is the use of Petri net approaches. Liu et al. (2007), Blackhurst, Wu, and Craighead (2008) and Wu et al. (2007) address Petri net-based models to illustrate and predict the propagation of disruptions through the supply chain.

Blackhurst et al. (2008) presented a methodology that extends the concept of basic Petri nets to discover supply chain conflicts before they occur. The approach involves linking hierarchical levels of the supply chain system and detecting conflicts that occur when single entities, each optimized for their own operations, are combined in a supply chain.

Liu et al. (2007) proposed Petri nets extended with time and color as a formalism for managing events. They designed seven basic patterns to capture modeling concepts that commonly arise in supply chains. They also showed how to combine the patterns to build a complete Petri net and analyze it using dependency graphs and simulation.

Wu et al. (2007) presented a network-based approach to model supply chain and the effects of a disruption and perturbation on it. The proposed approach (DA-NET) extends the concept of reachability analysis; and focuses on how disruptions can propagate through a supply chain and affect its performance. This model is a creative and practical approach, but it is independent of disruption type and does not consider interrelationships among different disruptions. It also does not consider that some disruptions are completely dependent on another or that one disruption may reduce the likelihood or severity of another. For instance, a sanction disruption may enhance the likelihood of unpredictable price decreases or labor disputes. Here, we propose a model that supports this condition as well as different disruptions. This feature allows decision makers to predict different situations in order to not only reduce response time, cost, inventory level and bullwhip effects, but also to increase flexibility and agility.