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A quantitative analysis of disruption risk in a multi-echelon supply chain

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ABSTRACT

We demonstrate how system resilience can be improved by focusing on a supply chain network as a whole. We analyze inventory placement and back-up methodologies in a multi-echelon network and view their effect on reducing supply chain risk. We focus on risk from both supply disruptions and demand uncertainty and compare their impacts and mitigating strategies. A simulation model developed to capture an actual network for a consumer packaged goods company is used for the analysis. We present analysis and insights for multi-echelon networks and show how network utilization and proactive planning enable reductions in supply chain disruption impact.

1. Introduction

1.1. Motivation

While disruptions in the supply chain are a realistic possibility that companies must address, most supply chain models fail to capture them sufficiently. Most literature that includes the possibility for disruption in supply focuses on single facilities or pairs of echelons in a supply chain, even though disruptions can have long and lasting effects throughout the supply chain. In this paper, we consider a real supply chain and realistic estimates for disruption possibilities in that supply chain to examine the impacts of those disruptions and how they can best be mitigated.

Examples of disruptions are not difficult to find. For instance, one consumer packaged goods company told us about a customs strike that led to a breakdown of their supply chain. When customs went on strike in a South American country, no raw materials could be shipped to their plant there. While the plant had planned to carry 3 weeks worth of raw material inventory, they happened to only have 1 week's worth on hand because additional material was in transit. Thus after a week, production shut down at that facility. This was a serious issue, as facility fixed costs and labor costs were still incurred. The product could not be manufactured elsewhere, either; while the same functional product was made at another plant in the company's global network, it was found that packaging and labeling issues meant that plant could not back up the South American plant. When the strike ended after the second week, employees were paid overtime to try to catch upon production. In all, only a few days' worth of production was not shipped on time, but the total cost to the company was estimated at a million dollars.

This example highlights the importance of advanced planning for supply chain continuity, not just individual facility continuity. Aside from having extra raw material inventory, there was no way the South American plant could have continued production. However, if plans had been put in place for the other plants in the company's network to be able to successfully back each other up, the company might have prevented the stoppage in material flow and reduced the overtime needed at the disrupted facility. In the final analysis, what matters is the company's ability to serve its customers. Consequently, supply chains must be examined on a network-level in order to understand their true level of risk-exposure.

At the same time, the goal of firm's management efforts should not necessarily be to eliminate risks, it should be to become more *risk-informed*. In the financial arena, analysts are expected to make investment decisions based on risk, and riskier investments often have the potential for higher returns. Similarly, firms who maintain operations with higher risk levels (low redundancy and lean inventories, for example), may have higher opportunities for being competitive. It is important for a firm to be aware of its supply chain risk levels so that it can evaluate its investments and make decisions based on its own level of risk tolerance.

1.2. Risk flows

System resilience and system reliability are often used interchangeably when discussing the dependability of a system in terms of delivering desired performance over time. Strictly speaking,

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resilience refers to the ability of a system or component to bounce back from a setback whereas reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time, or even resist failure. From a reliability studies and engineering systems perspective, system reliability is a direct function of component reliability: 50 locations with 99% reliability implies a system reliability of 0.99^{50}, which is a small number giving the system a small chance of succeeding. Since most engineering systems cannot inventory service or machine performance, for critical systems the only option to make the system more resilient is to build flexibility through redundancy at the component level in the system, for example, equipping a plane with extra engines to be used in case of the failure of the primary engine. Adding flexibility through redundancy increases systems' resilience and reduces the risk of failure.

Interestingly, firms typically treat a supply chain as an engineering system and by analogy think about system resilience as a component-level challenge. However, in supply chains, it is not necessarily true that system resilience equates to component resilience. It is important to note that supply chains have two additional buffers available to deal with performance problems (the third buffer of capacity is available in both cases): inventory and time. It is prudent therefore to leverage all three in tandem to be effective. Therefore, to deliver a high level of performance in the presence of significant disruptions, supply chain do not necessarily need to make each and every component (location in the network) perform at a high level at all times. A judicious mix of supply chain reliability, system buffers and effective recovery logic is key to making a supply chain resilient.

If supply chain resiliency is the goal, which it should be, a simple solution is to carry finished goods inventory at the most downstream location. In this case, regardless of the resilience of the individual upstream components, the system is resilient (although disruptions or damage to the finished goods themselves could still cause issue). In short, if a company has finished goods inventory available, it can always meet demand for that product. This has the added advantage of reacting in the shortest time, which is a key competitive advantage in today's world. However, there are a few problems with this solution and over time these problems have become very critical. First, cost is a big issue and by definition, finished goods have the most value and thus are the most expensive to carry. The second problem is location of this inventory. While it may be best to carry it as close to the customer as possible, that adds to the total system inventory level if there are too many locations (the value of risk pooling is lost). Thirdly, if the product has been finished, then raw material and efforts have been committed to a SKU (the value of postponement is lost); in the case of SKU proliferation this could be a problem, since demand uncertainty will drive the inventory very high. In this sense, it is better to have inventory upstream in as uncommitted a location or SKU as possible, while keeping in mind the response time for demand and disruptions.

Regarding inventory quantities to be carried at a location, we know that for a single facility subject to upstream disruptions, we would want the probability of stocking out to be less than $1-p/p+h$, where p is the penalty cost for a stock-out and h is the holding cost for positive inventory (Tomlin, 2006). In a multi-echelon system, this solution is not as straightforward, since inventory may be held at multiple levels with varying costs per level. Decisions regarding inventory levels across the supply chain must take inventory cost structure as well as disruption risk into account.

Thus, from a supply chain resilience point of view, we propose that it is important to know how risk flows through the system and look for insights accordingly. To this end, we examine how disruptions impact each node in the network and the risk flows through an end-to-end supply chain. We study the system-level impact of each disruption by running multiple scenarios and viewing how the system does or does not recover based on the mitigation strategies employed.

1.3. Modeling approach

The model discussed in this paper was constructed based on our work with a large consumer packaged goods (CPG) firm who wished to gain a better understanding of their current risk levels and how they could become more resilient. They selected a representative end-to-end supply chain in their network consisting of two products, multiple plants, and multiple distribution centers. We constructed a large simulation model of this network to learn how risk and mitigation techniques work in their system and discuss the learning in this paper.

We present the structure of the network and risk analysis inputs in Section 3, and then focus on using the model to study the behavior of the system in Section 4. Specifically, in that section, we focus on the following questions:

- Where should inventory be held in the network to minimize total costs and meet minimum average service levels?
- What is the best response type for back-up capabilities? Specifically, is a quick, small volume response or a slower, higher volume response better?
- How do the effects of demand spikes differ from supply disruption risks?
- How do customer reactions impact performance?

In our numerical analysis in Section 4, we show how the cost structure impacts the answer to the first question, and how the location of disruptions in the network affects the following two questions. We also examine customer behavior to answer the last question, comparing lost sales and time-dependent backordering. We then discuss insights in Section 5 and conclusions in Section 6. We first present relevant literature in the following section.

2. Literature

The body of literature on supply disruptions has increased since events such as 9/11 and Hurricane Katrina brought attention to the need to address this risk. Additionally, the susceptibility of supply chains to disruption risk is increased by global growth and certain business initiatives such as Just-In-Time (JIT). Not all risk is negative if it provides a competitive advantage, but firms should be aware how much risk they can handle. Simchi-Levi et al. (2002) discuss the risk involved in a JIT system because those systems typically lack flexible options if something goes wrong. The authors stress the importance of sharing risk throughout the supply chain. Sheffi (2001) encourages firms to examine their risk levels and consider keeping strategic inventory reserves to protect against catastrophic events.

Tang (2006) provides a review of supply chain risk management and classifies strategies for supply chain robustness in two categories: those that increase a supply chains *efficiency*, and those that increase its *resilience*. Strategies which make the supply chain more efficient increase a facility's operational ability to handle a disruption; business continuity planning within single sites tends to focus on this approach. Resilience, however, focuses on the ability of the firm to sustain operation and recovery quickly in the face of a disruption. We focus on resilient approaches in the numerical evaluations that we perform in this paper.

Increasing a firm's supply chain resilience is largely dependant on what options a system has to react as a system if a disruption