Supply Chain Management under the Threat of Disruptions

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Introduction

Every supply chain, logistics system, and infrastructure network is subject to disruptions. Although supply chain disruptions have existed as long as supply chains have, they have only recently begun to receive significant attention from practitioners and researchers. One reason for this increase in interest is the recent spate of high-profile disruptions, including September 11, the west-coast port lockout of 2002, and hurricanes Katrina and Rita in 2005. Another reason is the focus in recent decades on the philosophy of "lean" supply chain management, which calls for slimmed-down systems with little redundancy or slack. Although lean supply chains are efficient when the environment behaves as predicted, they are extremely fragile, and disruptions can leave them virtually paralyzed. Evidently, there is some value to having slack in a system.

Supply chains are multi-location entities, and disruptions are almost never purely local—rather, they cascade through the system, with upstream disruptions causing downstream stockouts. For example, in 1998, two strikes at General Motors parts plants led to shutdowns of over 100 other parts plants, which caused closures of 26 assembly plants, finally resulting in vacant dealer lots for months (Brack 1998). Another, scarier, example relates to port security:

> National-security analysts estimate that if a terrorist attack closed New York Harbor in winter New England and upstate New York would run out of heating fuel within ten days. Even temporarily hampering the port's operations would have immeasurable cascading effects. (Finnegan 2006)

Despite this, very little research has considered disruptions in multi-location settings. Instead, the current research focuses on single-location systems and examines the purely local effects of supply disruptions. The research discussed below begins to fill this gap by studying disruptions in multi-location settings.

Supply uncertainty (SU) and demand uncertainty (DU) share several similarities. In both cases, the problem boils down to not having enough supply to meet the demand, and it may be irrelevant whether this mismatch occurs because of too much demand or too little supply. Moreover, firms may use similar strategies to protect against SU and DU—for example, they may hold extra inventory, utilize multiple suppliers, or try to improve their forecasts of uncertain events.

These similarities bring good news and bad. The good news is that we have been studying supply chains under DU for decades, and we know a lot about them. The bad news is that much of the conventional wisdom under DU is exactly wrong under SU. This motivates a need to study supply chains under SU, to understand how they behave, and to develop strategies for coping with supply disruptions.

Related Literature

The first major body of literature on supply disruptions began in the early 1990s and attempts to embed supply disruptions into classical inventory models, positing that the firm's supplier may be disrupted when the firm wishes to order. (See Nahmias 2005 for an introduction to inventory theory or Zipkin 2000 for a more advanced treatment.) Examples include models based on the economic order quantity (EOQ) model (Parlar and Berkin 1991, Berk and Arreola-Risa 1994), the (R,Q) model (Gupta 1996, Parlar 1997), and the (s,S) model (Arreola-Risa and DeCroix 1998). These models are generally less tractable than their reliable-supply counterparts.

A more recent body of literature examines higher-level, strategic decisions made by the firm in the face of disruptions. For example, Tomlin (2006) explores various strategies for coping with disruptions, including inventory, dual sourcing, and acceptance (that is, simply accepting the disruption risk and not protecting against it) and shows that the optimal strategy changes as the disruption "profile" changes—say, from frequent but short to rare but long. Tomlin and Snyder (2006) examine how the answers to these questions change when the firm has advanced warning of an impending disruption. Lewis, Erera, and White (2005) consider the effect of border closures on lead times and costs. Chopra, Reinhardt, and Mohan (2005) evaluate the error that results from "bundling" disruptions and yield uncertainty (another form of supply uncertainty) when making inventory decisions.

Another body of literature considers disruptions in the context of facility location problems. Here, the objective is to choose locations of warehouses or other facilities to minimize the transportation cost to customers, while also accounting for the possible closures of facilities and subsequent re-routing of product. These models represent perhaps the only research to date that considers disruptions in a multi-location supply chains, and even these models consider primarily the local effects of disruptions. See Snyder et al. (2006) for a review. See Daskin (1995) or Drezner and Hamacher (2002) for an introduction to facility location theory.

Supply vs. Demand Uncertainty

In this section, I discuss results from a recent paper (Snyder and Shen 2006) that examines the differences between SU and DU in multi-echelon supply chains. (An *echelon* is like a level of the supply chain: factories, warehouses, retailers, etc.) The work is divided into several studies, each of which examines two possible answers to a question of supply chain design or management. Each study demonstrates that the optimal answer under SU is different from that under DU by simulating the systems under each strategy and evaluating the mean cost of each.

Although I use terminology suggestive of private-sector supply chains (e.g., "firms" and "retailers"), the results discussed in this paper are equally applicable to non-commercial networks such as those from the military, health care, and humanitarian sectors.

Centralization vs. Decentralization

Consider a system with one warehouse that serves N retailers (Figure 1). Under DU, it is well known that if the holding costs are equal at the two echelons and transportation times are negligible, then it is optimal to hold inventory at the warehouse (a *centralized* system) rather than at the individual retailers (a *decentralized* system). This is due to the famous *risk-pooling effect* (Eppen 1979), which says that the total inventory requirement is smaller in the centralized system, since the inventory requirement is proportional to the standard deviation of demand; the standard deviation is in turn proportional to the square root of N in the centralized system but is linear in N in the decentralized system.

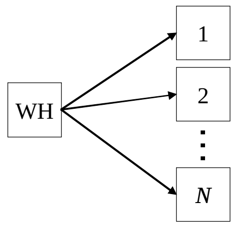

Figure 1. One-warehouse, multi-retailer system.

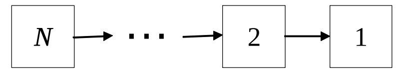

Figure 2. Serial system.

Now consider the system under SU (but deterministic demand). If inventory sites are subject to disruptions, it may be preferable to hold inventory at the retailers rather than at the warehouse. Under the decentralized strategy, a disruption affects only a fraction of the retailers, while a disruption affects the whole supply chain under the centralized strategy. In fact, the *mean* costs of the two strategies are the same, but the decentralized strategy results in a smaller *variance* of cost. This is due to what Snyder and Shen (2006) call the ***risk-diversification effect***, which says that disruptions are equally frequent in either system but are less severe in the decentralized one.

These competing tendencies—toward consolidation under DU and diversification under SU—play out in the model introduced by Jeon, Snyder, and Shen (2006). This model chooses where to locate facilities to minimize the expected cost of location, transportation, inventory, and disruptions. The inventory component is derived from the model by Shen, Coullard, and Daskin (2003), which tends to open fewer facilities than classical models because of inventory economies of scale and the risk-pooling effect. The disruption component is based on the model by Snyder and Daskin (2005), which tends to open more facilities because of the risk-diversification effect. The model by Jeon, Snyder, and Shen (2006) balances these tendencies.

Inventory Placement

In a serial system such as the one in Figure 2, a common question is which stages should hold inventory. Under DU, the tendency is to push inventory as far upstream as possible ("upstream" is to the left in Figure 2), since the cost of holding inventory tends to increase as one moves downstream in a supply chain. Under SU, however, the tendency is reversed: It is preferable to hold inventory downstream, since such inventory can be used to protect against disruptions anywhere in the supply chain.

Hub-and-Spoke vs. Point-to-Point Networks

Figure 3 depicts two possible networks for a firm with a single factory wishing to distribute product to multiple retailers. The network in Figure 3(a) is a ***hub-and-spoke*** network, with an intermediate warehouse that holds inventory and distributes it to the retailers, while that in Figure 3(b) is a ***point-to-point*** network in which the warehouse is bypassed and the retailers hold the inventory. Many firms operate hub-and-spoke networks because of the economies of scale and other savings from consolidating inventory locations. Even absent economies of scale, the hub-and-spoke network is optimal under DU because of the risk-pooling effect: We have fewer inventory stocking locations, and hence a smaller total inventory requirement. On the other hand, under SU, the point-to-point network is preferred due to the risk-diversification effect: More stocking locations means reduced severity of disruptions.

Figure 3. (a) Hub-and-spoke network and (b) point-to-point network. The sites that hold inventory are shaded.

Supplier Redundancy

Consider a single firm with a single supplier. The question here is, what would be the value of adding additional, backup, suppliers? Let's suppose that each supplier has sufficient capacity to meet, say, the mean demand plus a few standard deviations. Then, under DU, the value of the backup suppliers is small—they fill in only when the demand exceeds the capacity, which happens infrequently. On the other hand, the backup suppliers play a vital role under SU, since they can provide capacity both to meet demand *during* a disruption to the primary supplier and to ramp back up after *after* a disruption.

The Cost of Reliability

A firm that is used to planning primarily for DU may recognize the importance of planning for SU but may be reluctant to do so if it requires a large up-front investment in inventory or infrastructure. Fortunately, a small amount of extra inventory goes a long way in protecting against disruptions. Figure 4 depicts the tradeoff between the vulnerability of a system to disruptions (on the *y*-axis, measured by the percentage of demands that cannot be met immediately) and the cost under DU (on the *x*-axis), i.e., the cost the firm is used to considering. Each point represents a possible solution, with the left-most solution representing the optimal solution if there are no disruptions. This solution is cheap but very vulnerable to disruptions. The left-hand portion of the curve is steep, suggesting that large improvements in reliability are possible with only small increases in DU cost. For example, the second point has 21% fewer stockouts but is only 2% more expensive. This trend is fairly common and has been identified in other contexts, including facility location with disruptions (Snyder and Daskin 2005).

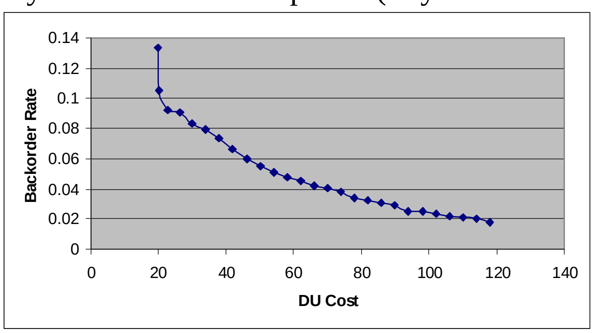

Figure 4. Tradeoff curve.

Conclusions

This paper has explored the differences between supply and demand uncertainty in multi-echelon supply chains. The results show that the two types of uncertainty have different optimal strategies in terms of centralization, inventory placement, and supply chain structure. In fact, the optimal strategy for dealing with supply uncertainty is, in many cases, the exact opposite from that for demand uncertainty. However, we are not suggesting that firms are currently doing everything wrong. Rather, we are arguing that although demand uncertainty brings about certain tendencies in supply chain management (tendencies toward centralization, etc.), supply uncertainty suggests opposite tendencies that should be accounted for more than they currently are. In practice, both demand and supply uncertainty are present, and the optimal strategy should consider the interaction between the two. Fortunately, we have also shown that it can be relatively inexpensive to shift this balance enough to account for supply uncertainty adequately.

Acknowledgments

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