Managing Disruptions to Supply Chains

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For as long as there have been supply chains, there have been disruptions, and no supply chain, logistics system, or infrastructure network is immune to them. Nevertheless, supply-chain disruptions have only recently begun to receive significant attention from practitioners and researchers. One reason for this growing interest is the spate of recent high-profile disruptions, such as 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 chains, 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.

A third reason for the growing attention paid to disruptions is that firms are much less vertically integrated than they were in the past, and their supply chains are increasingly global. A few decades ago, many firms manufactured products virtually from scratch. For example, IBM used to talk, only slightly hyperbolically, about sand and steel entering one end of the factory and computers exiting the other. In contrast, today's firms tend to assemble final products from increasingly complex components, which are procured from suppliers rather than produced in-house. These suppliers are located throughout the globe, many in regions that are unstable politically or economically or subject to wars and natural disasters. In his recent book *End of the Line*, Barry Lynn (2006) argues that this globalization has led to extremely fragile supply chains.

Supply chain disruptions can have significant physical costs (e.g., damage to facilities, inventory, electronic networks, and infrastructure) and subsequent losses due to downtime. A recent study (Kembel, 2000) estimates the cost of downtime (in terms of lost revenue) for several on-line industries that cannot function if their computers are down. For example, the cost of one hour of downtime for Ebay is estimated at $225,000, for Amazon.com, $180,000, and for brokerage companies $6,450,000. Note that these numbers do not include the cost of paying employees who cannot work because of an outage (Patterson, 2002) or the cost of losing customers' good will. Moreover, a company that experiences a supply chain disruption can expect to face significant declines in sales growth, stock returns, and shareholder wealth for two years or more following the incident (Hendricks and Singhal, 2003, 2005a, 2005b).

The huge costs of disruptions show that business continuity is vital to business success, and many companies are actively pursuing strategies to ensure operational continuity and quick recovery from disruptions. For example, Wal-Mart operates an Emergency Operations Center that responds to a variety of events, including hurricanes, earthquakes, and violent criminal attacks. This facility receives a call from at least one store with a crisis virtually every day (Leonard, 2005). Other firms have outsourced their business continuity and recovery operations.

IBM and SunGard, the two main players in this field, provide secure data, systems, networks, and support to keep businesses running smoothly during and after disruptions.

Supply chains are multi-location entities, and disruptions are almost never local—they tend to cascade through the system, with upstream disruptions causing downstream "stockouts." In 1998, for example, strikes at two General Motors parts plants led to shutdowns of more than 100 other parts plants, which caused closures of 26 assembly plants and led to vacant dealer lots for months (Brack, 1998). Another, scarier, example relates to port security (Finnegan 2006):

> 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.

Nevertheless, very little research has been done on disruptions in multi-location systems. Current research is focused mostly on single-location systems and the local effects of disruptions. The research discussed below is a step toward filling this gap.

Underlying Concepts

Supply uncertainty (SU) and demand uncertainty (DU) have several similarities. In both cases, the problem boils down to having too little supply to meet demand, and it may be irrelevant whether the mismatch occurs because of too much demand or too little supply. Moreover, firms have used similar strategies—holding extra inventory, using multiple suppliers, or improving their forecasts—to protect against both SU and DU.

These similarities offer both good and bad news. The good news is that supply chains under DU have been studied for decades, and we know a lot about them. The bad news is that much of the conventional wisdom about DU is exactly wrong for SU. Thus, we need research on supply chains under SU to determine how they behave and to develop strategies for coping with disruptions in supply.

Related Literature

In the early 1990s, researchers began to embed supply disruptions into classical inventory models, assuming that a firm's supplier might experience a disruption when the firm wished to place an 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 (Berk and Arreola-Risa, 1994; Parlar and Berkin, 1991), the (R,Q) model (Gupta, 1996; Parlar, 1997), and the (s,S) model (Arreola-Risa and DeCroix, 1998). All of these models are generally less tractable than their reliable-supply counterparts, although they can still be solved easily using relatively simple algorithms.

More recent literature has addressed higher level, strategic decisions made by firms in the face of disruptions. For example, Tomlin (2006) explores strategies for coping with disruptions, including inventory, dual sourcing, and acceptance (i.e., simply accepting the risk of disruption and not protecting against it) and shows that the optimal strategy changes as the disruption characteristics change (e.g., disruptions become longer or more frequent). Tomlin and Snyder (2006) examine how strategies change when a firm has advance warning of an impending disruption. Lewis, Erera, and White (2005) consider the effects 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 SU) when making inventory decisions.

Only a very small body of literature is focused on disruptions in multi-location supply chains. Hopp and Yin (2006) investigated optimal locations for capacity and inventory buffers in a multi-location supply chain and concluded that, as potential disruptions become more severe, buffer points should be located closer to the source of disruptions. Kim, Lu, and Kvam (2005) evaluated the effects of yield uncertainty in a three-tier supply chain. They addressed the consequences of the decision maker's risk-aversion, an important factor when modeling infrequent but high-impact events.

A growing literature addresses disruptions in the context of facility location. Here, the objective is to choose locations for warehouses and other facilities that minimize transportation costs to customers and, at the same time, account for possible closures of facilities that would necessitate re-routing of the product. Although these are multi-location models, they focus primarily on the local effects of disruptions (see Snyder et al. [2006] for a review). We discuss these models in greater detail below.

Supply Uncertainty vs. Demand Uncertainty

In the sections that follow, we discuss the differences between SU and DU in multi-echelon supply chains. (An *echelon* is a "tier" of a supply chain, such as a factory, warehouse, retailer, etc.) We consider several studies, each of which examines two possible answers to a question of supply-chain design or management. Each study demonstrates that one answer is optimal for SU while the opposite answer is optimal for DU. Some of these results may be proven theoretically. Others are demonstrated using simulation by Snyder and Shen (2006).[1]

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[1] Although we use terminology suggestive of private-sector supply chains (e.g., "firms" and "retailers"), the results discussed in this paper are also applicable to noncommercial supply networks (e.g. military, health care, and humanitarian networks).

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 the optimal strategy is to hold inventory at the warehouse (a *centralized* system) rather than at the individual retailers (a *decentralized* system). This is because of the *risk-pooling effect*, which says that the total mean cost is smaller in the centralized system because cost is proportional to the standard deviation of demand. The standard deviation, in turn, is proportional to the square root of *N* in the centralized system but is linear in the decentralized system (Eppen, 1979). Although the assumptions of equal holding costs and negligible lead times are unrealistic, the risk-pooling effect and the insights that arise from it are applied widely in supply chain planning and management.

Now consider the same system under SU (with deterministic demand). In this case, if inventory sites are subject to disruptions, it may be preferable to hold inventory at the retailers rather than at the warehouse. Under this decentralized strategy, a disruption would affect only a fraction of the retailers; under a centralized strategy, a disruption would affect the whole supply chain. 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 referred to as the *risk-diversification effect*, which says that disruptions are equally frequent in either system, but they are less severe in the decentralized system (Snyder and Shen, 2006).

Inventory Placement

In a serial system (Figure 2), a common question is which stages should hold inventory. Under DU, the tendency is to push inventory as far upstream as possible (to the left in Figure 2), because 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, where it can protect against disruptions elsewhere in the supply chain. For example, this might mean that a manufacturing firm should hold inventory of raw materials under DU but of finished goods under SU.

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

Figure 3 shows two possible networks for a firm with a single factory that wants to distribute its product to multiple retailers. The network in Figure 3a is a *hub-and-spoke* network, with intermediate warehouses that hold inventory and distribute it to retailers. The network in Figure 3b is a *point-to-point* network in which the warehouses are bypassed and retailers hold the inventory. Many firms operate hub-and-spoke networks because of economies of scale and other savings from consolidating inventory locations. Even absent economies of scale, however, the hub-and-spoke network is optimal under DU because of the risk-pooling effect (there are fewer inventory-stocking locations, hence a smaller total inventory requirement). Under SU, however, the point-to-point network is preferable because of the risk-diversification effect (increasing the number of stocking locations reduces the severity of disruptions).

A relevant analogy comes from the airline industry. Large U.S. carriers have primarily adopted a hub-and-spoke model because of the economies of scale it offers regarding airport infrastructure and the scheduling of flight connections. However, when a disruption (e.g., a thunderstorm) occurs at a hub, it can affect the carrier’s entire domestic flight network. In contrast, smaller carriers have tended to adopt point-to-point networks that allow flight schedules to be somewhat more flexible and reactive.

Supplier Redundancy

Consider a single firm with a single supplier trying to determine the value of adding backup suppliers. Suppose that each supplier has sufficient capacity to meet the mean demand plus a few standard deviations. Under DU, backup suppliers have little value because they would fill in only when demand exceeds capacity, which happens infrequently. Under SU, however, backup suppliers play a vital role because they provide capacity both to meet demand *during* a disruption to the primary supplier and to ramp up supply *after* a disruption.

Facility Location

Classical facility-location models choose locations for plants, warehouses, and other facilities to minimize transportation cost or achieve some other measure of proximity to both suppliers and customers (Daskin, 1995; Drezner and Hamacher, 2002), typically ignoring both DU and SU. A recent model finds that under DU the optimal number of facilities decreases because of the risk-pooling effect and economies of scale from consolidation (Shen, Coullard, and Daskin, 2003). Conversely, when facilities face potential disruptions (i.e., under SU) the optimal number of facilities increases because of the risk-diversification effect (Snyder and Daskin, 2005). A model currently under development incorporates both DU and SU, thus balancing these competing tendencies (Jeon, Snyder, and Shen, 2006).

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 toward protecting against disruptions. Figure 4 shows the trade-offs 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, measured in the cost the firm is used to considering).

Each point in Figure 4 represents a possible solution, with the left-most point 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 small increases in cost. For example, the second point shows 21 percent fewer stockouts but is only 2 percent more expensive. This trend is fairly common and has been identified in other contexts, including facility location with disruptions (Snyder and Daskin, 2005).

Conclusions

Studies of SU and DU in multi-echelon supply chains show that the two types of uncertainty require different strategies in terms of centralization, inventory placement, and supply-chain structure. In fact, the optimal strategy for dealing with SU is, in many cases, the exact opposite of the optimal strategy for DU. However, we are not suggesting that firms are currently doing everything wrong. Rather, we are arguing that, although DU leads to certain tendencies in supply-chain management (e.g., centralization), SU suggests opposite strategies that should also be considered when making supply-chain decisions. Fortunately, it can be relatively inexpensive to shift the balance enough to account for SU, in the sense that the trade-offs between the two types of uncertainty are favorable.

In virtually all practical settings, both DU and SU are present, and the optimal strategy must account for interactions between them. For example, since upstream inventory is cost effective under DU but downstream inventory is most helpful under SU, a firm may wish to adopt a hybrid strategy that combines the advantages of both. For example, many firms hold inventory of both raw materials (upstream) and finished goods (downstream), with raw material inventory accounting for the bulk of the firm's inventory holdings but finished goods inventory acting as a key buffer against uncertainty. Alternately, a hybrid strategy may involve holding inventory near the middle of the supply chain (rather than at both ends). For example, Dell holds inventory of sophisticated components, assembling them into finished goods only after orders are placed.

It is our hope that researchers will continue investigating the causes and effects of supply-chain disruptions, as well as strategies for coping with them. One important area for future research is the development of analytical tools for understanding the interdependence of risks faced by a supply chain. A single event (e.g., an economic downturn or a bird-flu pandemic) might cause multiple types of disruptions (e.g., a shortage of raw materials and absenteeism among the firm's own workforce), and these risks may be subtly related. In other words, the supply chain's total risk may not be a simple sum of its parts.

Another promising avenue for future research is to develop strategies for designing resilient supply chains. How can a supply chain's infrastructure be designed so that buffers are located in the right places and in the right quantities to protect against disruptions and other forms of uncertainty? What forms should these buffers take (e.g., inventory, capacity, redundant supply)?

Many of the analytical models for designing and managing supply chains under uncertainty assume that the decision maker has some knowledge of the risk of disruption, for example, the probability that a disruption will occur or the expected duration of a disruption. In practice, these parameters can be very hard to estimate. Therefore, we suggest, as a third area for future research, the development of models that are insensitive to errors in these parameters.

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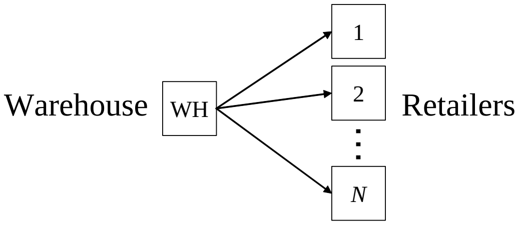


Figure 1. One-warehouse, multi-retailer system.

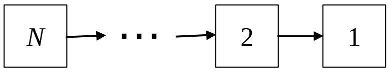
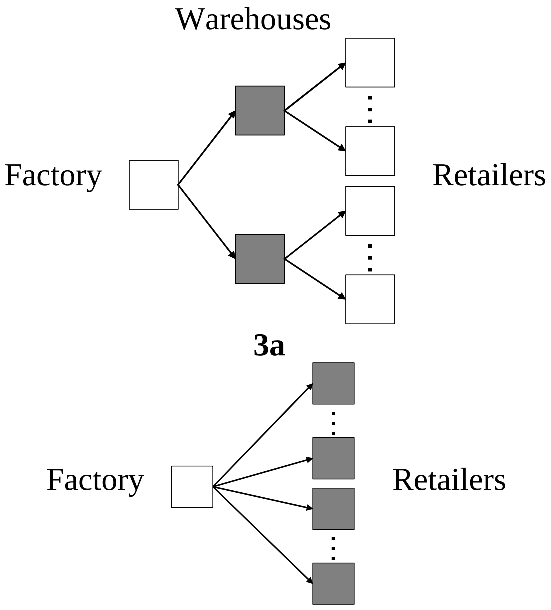


Figure 2. Serial system. Each stage represents a processing activity or a physical location.



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3b

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

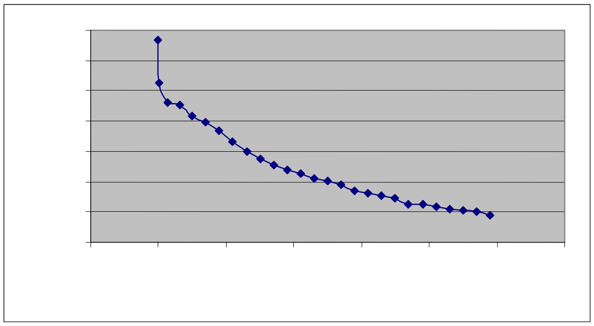

Figure 4. Tradeoff curve.