Strategic Formation and Reliability of Supply Chain Networks

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We study the incentives that independent self-interested agents have in forming a resilient supply chain network in the face of disruptions and competition. Competing suppliers are subject to yield uncertainty and congestion. Competing retailers make sourcing decisions based on price and reliability. Under yield uncertainty only, retailers—benefiting from supply variance—concentrate their links on a single supplier, counter to the idea that they should mitigate yield uncertainty by multi-sourcing. When congestion is added, the resulting networks resemble bipartite expanders known to be resilient, thus, providing the first example of endogenously formed resilient supply chains.

CCS Concepts: • Theory of computation → Algorithmic game theory; Market equilibria; Network games; Network formation; • Applied computing → Supply chain management.

Additional Key Words and Phrases: supply chain; network formation; uncertainty; congestion; equilibrium

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Supply chains are the backbone of the global economy. Disruptions to them can be costly. They happen because the individual components of the chain are subject to yield uncertainty (a supplier comes up short on the ordered product quantity) as well as lead time uncertainty (customers of overly congested suppliers experience delivery delays). The degree of uncertainty can be large. For example, the production yields at the disk drive manufacturer Seagate have been reported to be as low as 50%. Centrally managed and controlled supply chains invest in mitigating these disruptions. Decentralized supply chains, however, must rely upon the self-interest of their individual components to maintain the resilience of the entire chain.

One might think that the incentives of an individual component in the chain should align with the chain as a whole. A supplier, for example, should be rewarded with greater business if it invests in reducing the possibility of its being disrupted relative to its competitors. However, a supplier’s customers can also hedge against disruption by multi-sourcing. Thus, a potential customer may prefer to source from many low-cost unreliable suppliers rather than a few highly reliable but costlier suppliers. Reducing the frequency of disruptions affects output prices. If prices adjust to clear markets, increased throughput may result in lower market prices. Thus, one must compare the profits earned from high volumes with low margins with those generated from lower volumes but with higher margins. It is not obvious which will dominate.

In this paper, we examine the strategic formation of a two-tier supply chain network by independent self-interested agents. Retailers occupy the first tier and suppliers—the second tier. (Some
of our results straightforwardly translate to the case of an arbitrary number of tiers.) The price at which trade takes place between tiers is set to clear the market through a linear inverse demand curve. Retailers—indeed independently and simultaneously, playing a single-shot network formation game—decide ex ante which suppliers to source product from. There is also a cost for linking to a supplier (it may take, on average, six months to a year to qualify a new supplier).

Every agent present in the supply chain is subject to yield uncertainty which affects their capacity. It is modeled as a Bernoulli random variable. Yield uncertainty can arise from the nature of the production process (e.g., farming industry has a highly volatile yield), natural disasters, or labor strikes. The resulting random output of each tier is rationed among agents in the downstream tier in proportion to their demands. Every supplier in the chain is also subject to congestion, and the resulting congestion costs are borne by the retailers. Congestion in our model has at least two interpretations. One is a delay cost associated with lead time uncertainty. The second is a “soft” supply constraint.

We analyze pure strategy Nash equilibria of the supply chain network formation game engaged by the retailers, aiming to answer the question of whether a decentralized supply chain network resilient to disruptions will form endogenously in the presence of competition and different types of uncertainty. The three major findings of our analyses are as follows:

1. With only yield uncertainty and no congestion, retailers create a sparse network, with a single link per retailer, and concentrate links on a single supplier. This generalizes to the case of more than two tiers where the corresponding supply chain network is almost a chain. Link concentration runs counter to the common wisdom about the benefits of multi-sourcing. Link concentration helps retailers secure low upstream prices in the presence of high upstream yield, and low expenditures in case of the target upstream supplier’s failure. Retailers, therefore, benefit from supply variance. It suggests that competition can amplify output uncertainty. The network formed in our model is dramatically different from the ones that are assumed in the existing literature (such as a $k$-tier supply chain network having the form of a complete $k$-partite graph).

2. In the presence of yield uncertainty and congestion, the formed network is sparse, yet well-connected resembling a multi-partite expander graph. They have been shown to have good resilience properties in the context of centrally organized supply chains. Congestion, unlike yield uncertainty, encourages retailers to split their demand across several suppliers to lower congestion costs. Thus, our work provides the first example of the endogenous formation of resilient supply chain networks, without an explicit concern for resilience being encoded in the payoffs.

3. Yield uncertainty and congestion have fundamentally different implications for supply chains. In the presence of yield uncertainty only, each supplier has a unilateral incentive to increase its average yield. With both yield uncertainty and congestion, a unilateral reduction in congestion costs unconditionally benefits that supplier, but increasing the average yield could make a supplier worse off! This is because high yield results in market saturation, which leads to low prices and profits for market members.

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Extended Abstract. The full paper is available at https://victoramelkin.com/pub/supply-chains/.