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Supply Network Drivers of Risk and Performance

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In this chapter we review historical and contemporary research in economics, operations management, and finance that adopts a network perspective for modeling interactions between agents. We argue that incorporating extended network characteristics in the analysis can yield unique insights compared to the analysis done at the level of dyads or local neighborhoods. We show how new network-based models contribute to the academic debate and advance our understanding of supply network drivers of performance and risk.

Key words: supply networks, supply chain management, financial performance, operational performance, innovation, risk

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1. Introduction

The way firms do business has changed dramatically during last decades. Factors that contribute to this change are technological, i.e., advancements in electronics, the internet, information and communication technology, often referred to as the Third industrial revolution; and competitive, i.e., the unrelenting pressure from increasingly open and global markets to reduce costs. The supply chains – being the circulatory system of the businesses – have changed too. Among most frequently reported changes are globalization, specialization, complexity, lean processes, and information availability (World Economic Forum 2012). Due to these changes, costs indeed have come down, contributing to better performance outcomes. At the same time, supply chains have become more vulnerable to a broad range of threats including extreme weather, cyberattacks, increased stakeholder scrutiny of environmental and social practices, as well as political, military, and financial crises. Thus, risk management in supply chains, or, more generally, in a *supply network*, has become a higher priority for more than 90% of businesses surveyed by the World Economic Forum (2012).

Despite the increased focus on the management of supply networks, most businesses lack the information about what is happening end-to-end in their supply chains. Recent industry studies report that only 25% of businesses have full information on their supply chains, while the rest reported knowing little to none (Robotics Business Review 2014). Given the connected nature of businesses, taking stock of the changes in supply chains is the first step toward understanding their vulnerabilities and opportunities. Moreover, since businesses or even supply chains can no longer be considered in isolation, they should be considered as a part of the overarching supply network. In this chapter, we study the link between a firm's performance, risk, and its supply network.

The network lens provides a unique perspective on firms' performance and risk, undetectable under traditional dyadic or serial supply chain frameworks. For example, a firm's performance is affected by its own productivity, but also by productivity shocks to its immediate suppliers or suppliers in tier-two or beyond. The effect of shocks can be amplified or dampened, depending on the location of the shock and the structure of the network. This could be due to the aggregation of shocks from immediate suppliers or beyond, or a propagation of a shock from a particularly influential supplier. For example, networks play a role in determining the aggregate or local variability of demand. An aggregation of orders from multiple customers can change the demand variability profile and mitigate customers' bullwhip effect. At the same time, the network lens can identify influential companies for propagation of shocks from one industry to another, and such companies are not necessarily the ones with the most customers and suppliers. In fact, companies connected to suppliers and customers from different communities could be just as important. The structural composition of a firm's upstream and downstream supply network and the firm's centrality in the network affects its ability to lower costs, drive operational best practices, and increase knowledge exchange and spillovers from its suppliers and customers.

Networks emerge in multiple contexts ranging from economics to telecommunications to biology, and scholars have made substantial efforts to characterize them. In economics, the origins of network thinking can be traced to the Physiocratic school of economic thought of the 18th century and, specifically, the Tableau Economique work of Francois Quesnay (1766). It was an early attempt to formalize a multi-sector economy where each sector needs inputs from other sectors to sustain its output. Some hundred and fifty years later, taking the ideas of Tableau Economique to the U.S. context, Wassily Leontief (1936) presented foundations of input-output analysis, a building block of nearly all modern multi-sectoral (or network) economic models. The prominent network models in mathematics include Erdos and Rényi (1960) who developed a random graph model, where edges between nodes form with the same probability. While elegant, the model does not describe some of the features observed in real world networks, such as the emergence of nodes with an extremely large number of connections and the relatively small shortest-path distance between the nodes. To account for these features, Price (1976) developed the so-called scale-free network model where the probability of a link formation to a node is proportional to the number of links to the node (the model was later independently re-discovered by Barabási and Albert 1999). More recent models of the formation of supply networks based on agents' economic rationality include Oberfield (2018) and Acemoglu and Azar (2017).

Throughout the years, network thinking has advanced further in the fields of operations management and finance. In subsequent sections we review basic notions of network representation and characteristics and delve into literature to summarize progress made by adopting the network perspective. We conclude with summarizing open questions and directions for future research.

2. Characteristics of Supply Networks

The analysis of networks is deeply grounded in graph theory. Below we give a minimally sufficient overview of graph theoretic concepts that will be used in subsequent sections and discuss the link between the theory and empirical data on supply networks.

Any network can be represented by a graph $G = (N, A)$, where $N = \{1, ..., n\}$ is the set of nodes, and $A = [a_{ij}]_{i,j \in N}$ is the adjacency matrix, $a_{ij} = 1$ if there is a directed link from node i to node j in the network, and $a_{ij} = 0$ otherwise. Nodes represent production agents, e.g., firms or industries, and links represent buyer-supplier relationships.[1] Matrix A captures the structure of the network, and whenever we refer to the network structure, we will generally mean properties of matrix A. The powers of matrix A capture the path distance between nodes. The shortest path distance between nodes i and j is k_{ij}, if and only if $k_{ij} = \min\{\kappa : [a_{ij}]^{\kappa} = 1\}$.

The nodes immediately connected to node i, via incoming or outgoing links, represent the immediate neighborhood (or ego) of node i. A local l-neighborhood of node i consists of all nodes j, such that $k_{ij} \leq l$ or $k_{ji} \leq l$. One could also differentiate between l-supply and l-customer neighborhoods, by including the respective subset of nodes from the l-neighborhood. Setting $l \to \infty$ for any node i would recover the entire supply network if the network is connected, or its connected component otherwise.

Graph-theoretic measures can represent structural characteristics of the network at the node, local neighborhood, or the network level. At the node level, the notion of centrality is by far the most common reflection of a firm's importance due to its structural position in the network. The simplest form of this is in-degree and out-degree centrality. The row sums of adjacency matrix $A = [a_{ij}]_{i,j \in N}$ provide values for out-degree centrality as the number of outgoing ties to direct customers of firm i. Similarly, the column sums provide values for the number of incoming ties from its direct suppliers. Note, that node's i degree centrality incorporates information only from its immediate neighborhood. Another way to measure firm's centrality is to incorporate information about links and centralities of other nodes in the network. One common form of centrality that factors in wider-reaching links is closeness centrality (Freeman 1979), which is defined as the sum of distances

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[1] One can also think about A as the material requirement matrix, where a_{ij} is equal to the value of inputs from i required for \$1 output of j. If nodes are industries, this matrix is commonly called the cost share or input-output (IO) matrix.

to or from all other nodes, where distance is captured as the number of links along the shortest path between nodes i and j. Greater levels of closeness also offer more opportunities for the firm to navigate the network with autonomy, offering multiple ports to retrieve reliable information about demand shifts as well as lean approaches used by other customers or suppliers that have yet to have been established as best practices (Kim et al. 2011). Another common expression of centrality is betweenness (Freeman 1977), which reflects the extent that a firm lies along many shortest paths between pairs of other firm nodes in its supply network. Nodes with high betweenness have been suggested as better positioned to facilitate or control the flows of supply and information across the supply network (Kim et al. 2011). Eigenvector centrality is based on the premise that a firm that is connected to firms that are themselves well connected is better positioned than a node that is connected to an equal number of less connected firms (Bonacich 1972).

At the neighborhood level, network density is a common measure representing the extent of links within a node's direct network and reflects the number of actual links divided by the total number of potential links among a firms direct partners upstream or downstream (Scott 1988). Besides network density, other neighborhood-level measures have been argued to represent desirable attributes to build a node's social capital, but with somewhat opposing views. The most well-known debate is that social capital is generated by a network of strongly interconnected nodes (the network closure argument) while other scholars argue that social capital is generated by a network in which nodes are positioned to broker links between otherwise disconnected segments (the structural hole argument, Burt 2017).

Lastly, network level measures can be helpful for more aggregate studies, such as the whole network of an organization, industry, or economy. Common measures at the network level are the degree centrality distribution, the average shortest path distance between nodes, the clustering coefficient, and the community structure. The clustering coefficient represents the extent to which the network contains localized clusters of dense connectivity. Put another way, it measures the proportion of triples for which transitivity holds, i.e., if node i is connected to j and k, then by transitivity, j and k are connected. Community extends the notion of clustering further and is defined as a set of nodes such that the probability of having a link within the set is substantially larger than the probability of having a link between a node in the set and a node outside the set.

Data for empirical characterization of supply networks can be obtained from several data sources. The U.S. Bureau of Labor Statistics (2019) reports the Input-Output matrices annually, and similar data is available for other countries. Input output matrices fully represent flows between industries, albeit at an aggregate level. At the firm-level, popular data sources include the Standard and Poors Compustat Customer Segment, Bloomberg SPLC, and Factset Revere databases. A visualization of the automaker supply network can be seeing in Figure 1 is based on supply chain data from FactSet. It is apparent, that the size and complexity of the network are growing.

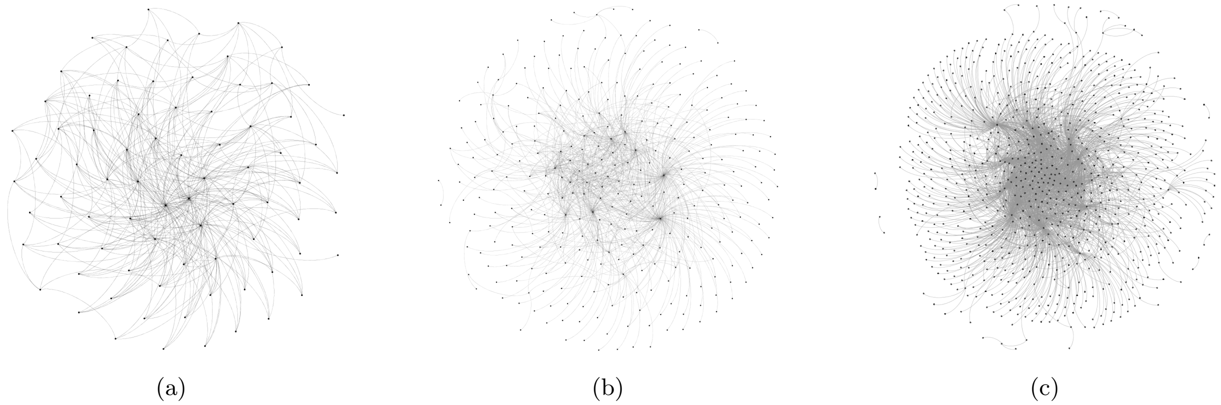
(a) (b) (c)

Figure 1 Automaker supply network for years (a) 2003; (b) 2008; (c) 2013

3. Networks and Performance

The structural configuration of a firm's interconnected portfolio of upstream supplier and downstream customer relationships plays an important role in influencing its financial and operational performance as well as its innovation. We start with reviewing implications of networks for financial performance and highlight insights unique to the network setting. We then continue with operational and innovation performance.

3.1. Financial Performance

Firms do not operate in isolation. Thus, it is reasonable to assume that a firms financial performance could be affected by its suppliers or customers. The credit for a pioneering work in establishing the co-movement between stock returns of firms linked by buyer-supplier relationships belongs to Cohen and Frazzini (2008). Their key question is: what happens to a supplier when one of its key customers (Cohen and Frazzini (2008) use the Compustat segment key customers data) has negative news? The answer is: immediately, nothing, but over next several weeks time, the return will be negative. They attribute the effect to a limited (at the time) attention of investors to the news of economically related companies, such as key customers. In their own words: "the strategy of buying firms whose customers had the most positive returns and selling short firms whose customers had the most negative returns yields abnormal returns of 1.55% per month". Curiously, after Cohen and Frazzini's work and a contemporary related paper by Menzly and Ozbas (2010) became public, this arbitrage opportunity almost disappeared, and the attention to the data on economic relationships grew substantially. A follow up work by Agarwal et al. (2017) uses data from 2013 and reports much smaller abnormal returns to the trading strategy analogous to Cohen and Frazzini (2008) and Menzly and Ozbas (2010). In fact, the returns are still positive and statistically significant only when the supply chain partners do not appear simultaneously in online search results.

The focus of above papers is on the immediate customers, i.e., a limited portion of the supply network. An important question is whether the supply network as whole is informative for the financial performance? While this is still a subject of ongoing research, the preliminary answer appears to be yes. Ahern (2013), use the IO matrices to test the hypothesis that industries that are more central in the supply network earn higher stock returns. They focus on the eigenvector centrality as their key measure (see §2). They also show that more central industries have a greater systematic risk, measured by market beta. Because eigenvector centrality accounts for centralities of nodes a focal node is connected to, their method extends beyond an immediate neighborhood of a focal node and is a consequence of structure of the full supply network.

The work of Herskovic (2018) identifies an additional network-related factor that is relevant for financial performance. The factor is sparsity and it reflects the density and importance of inter-sectoral linkages. Similarly to centrality, sparsity is derived from the full network structure, IO matrices, in particular. But, unlike centrality, sparsity does not vary node by node. A more sparse network would have fewer linkages, but each of them would be stronger. The paper finds that sparsity represents a source of risk, and stocks whose returns are more exposed to sparsity command a greater excess return.

Moving from an industry-level to a firm-level network representation, Gofman et al. (2017) show that firms further away from final consumers have higher excess returns relative to the final goods producers. To identify the effect, they construct a firm-level measure of upstreamness in the supply network, or layer. The layer is defined as the shortest path distance to firms in consumer-staples and consumer-discretionary segments, as classified by the Global Industry Classification System. Because layer is a firm-level measure, it accounts for variability of upstreamness within an industry segment. Gofman et al. (2017) attribute their result to a greater exposure of firms upstream in the supply network to productivity shocks in the economy, and find the effect intensifies if the economy is more competitive.

Compared with industry-level, the analysis of networks on a more granular firm-level yields more refined and heterogeneous results. Using buyer-supplier relationship data of public U.S. firms from the Bloomberg supply chain relationship (SPLC) database, Wu and Birge (2014) revisit the problems of investors' limited attention and the relationship between centrality and returns. They find that a firm's return can be predicted by its supplier lagged returns, whereas customer lagged returns have minimal impact. The latter finding is consistent with the increased attention to customers' news, in the post Cohen and Frazzini (2008) world, but suggests that the arbitrage, although smaller in magnitude, still exists with respect to the suppliers' news. They also show a more nuanced effect compared to Ahern (2013), where more central (by eigenvector and in-degree centrality measures) manufacturing firms appear to earn lower returns when more and the opposite for more central firms in the transportation, wholesale, and retail sectors, collectively, logistics firms. They suggest that network may have different risk implications, hence returns, for the manufacturers and logistics firms. While the former may use it to as a hedging tool, for the latter it may aggregate shocks and increase their exposure to systematic risk.

3.2. Operational Performance

A firm's strategy to concentrate or diversify its supply chain for sustained performance has long been studied. As firms sought new value-added and cost-reduction strategies to combat the increasingly dynamic and competitive environment after economic recessions in the late 1980s and early 1990s, one such strategy was to focus on a concentrated supply base of first-tier subcontractors to purchase complete assemblies and systems components. Shortly after this period, Nishiguchi (1994) synthesized findings related to consolidation from examining supply chains of firms in fourteen countries including Japan, the U.S., and Britain. In his book, he demonstrates how a concentrated first-tier supplier approach lead to institutiuonal arrangements that promoted continuous improvement in quality and reductions in cost via problem solving-oriented commitments between consolidated supplier partners. The findings were largely from in-depth interviews, surveys, field visits, and aggregate asset assessments of firms. Further, concentration, quality, and cost activity were not explicity captured and studies were not conducted over time. An earlier work by Corbett and Karmarkar (2001) also examines the impact of consolidation of upstream and downstream tiers in the supply chain on performance. They develop an explicit model of post-entry competition in multitier serial supply chains with deterministic demand and find that, in a two-tier setting, the number of supply chain partners in one tier directly impacts the profitability of a firm in the other tier. For example, this would imply that the number of parts fabrication suppliers upstream is a driver of a final product assembly firm's profit. Similarly, that a parts fabrication supplier's profitability is affected directly by the number of final product assembly partners downstream. When extending from a two-tier to an M-tier serial supply chain, they conclude that the relative profitability of a firm in a particular tier only depends on the respective concentration of firms in the same focal tier and fixed costs, and not on their respective variable costs (Corbett and Karmarkar 2001). Though they refer to the number of supply chain partners at each tier as the level of concentration, one limitation is that it assumes all partners are symmetric rather than weighting by some measure of importance (e.g., volume purchased, criticality).

Two largely unexplored phenomena that extend the more binary question of whether to consolidate one's supply chain are (i) the actual levels of cost concentration that are in place between a customer firm and its supplier base and (ii) the sales concentration among suppliers as a natural by-product of supply consolidation among customers. Both phenomena have important implications for firms and their extended supply networks. A common way to reflect this is through the balance of a firm's cost of goods sold (COGS) across its downstream suppliers and its sales revenue across its upstream customers, i.e., its concentration of costs upstream and revenue downstream that comes by aggregating each customer-supplier dyad relationship.

Centering upstream in the supply network, a sourcing strategy concentrated on a relatively small number of suppliers can position firms to exert greater influence in driving favorable supply chain practices that decrease transaction costs and increase the diffusion of knowledge in the supply network (Lanier Jr et al. 2010). Firms purchasing a higher percentage of their resources from fewer suppliers can facilitate more integration and lead to greater returns on firm performance by cost savings from scale economies (Cachon and Harker 2002, Belavina and Girotra 2012). A greater concentration of a firm's spend on its suppliers has been linked to greater business incentives from the customer in the future, which has been found to make the supplier more likely to share their cost structure and process capabilities and lead to stronger commitment in joint knowledge transfer activities (Modi and Mabert 2007). Further, the strategy of a customer to extract greater volume from a more concentrated set of suppliers is a suggested approach to help incentivize suppliers to make investments that facilitate speedier recovery from disruptions (Jain et al. 2015). Using component-level sourcing transactions data of over two million import manifests, they observe a 16% faster recovery to 99% of the supply-chain's native state with a one standard deviation decrease in supplier diversification.

On the other hand, for firms that predominantly outsource, concentrating their supply base has been associated with lower quality performance as measured by product recalls (Steven et al. 2014). This could be attributed to the more dependence on any one supplier and an increased ability of any supplier to engage in opportunistic behavior. Firms operating at mean levels of outsourcing and lower, however, appear to reap transaction and coordination cost benefits associated with outsourcing while mitigating effects on quality by concentrating their outsourcing behaviors among fewer suppliers. Steven et al. (2014) observe an interesting contingency factor that might help explain the competing benefits, where concentrating the supply base impacts operational performance (in this case, quality) in opposing ways depending upon outsourcing levels.

Conversely, focusing on downstream concentration of customers, there appear to be far more competing outcomes on performance. On the positive side, manufacturing firms with more concentrated customer networks may enjoy reduced coordination costs related to ordering, production, scheduling, and delivery in just-in-time (JIT) systems (Kinney and Wempe 2002). However, major customers may leverage their bargaining power in a relationship to pressure suppliers to maintain a higher fill rates, which lead to increased inventory stock and holding periods for the suppliers (Ak and Patatoukas 2016). Major customers can also leverage power to pressure suppliers to maintain responsibility of ownerships through their finished goods logging until the product is actually used or sold by the customer (Ak and Patatoukas 2016, Kelly and Gosman 2000). In fact, contributing to a larger proportion of a firm's revenue is likely to lead to a greater commitment and long-term orientation with the partner, but with the customer in a better position to absorb any ensuing benefits attributable from an established relationship with the said supplier (Lavie 2006).

A downstream customer portfolio of partners with strong relative bargaining power may impede on a supplier's performance due to a decreased share of relational rents while having to invest more in the relationship. The lack of a signal from a supplier or its ability to reach alternative outlets for achieving its objectives can weaken its negotiating position, increase its switching costs, and thus increase its dependence on partnering customers in the network (Lavie 2007). A natural question arising for firms serving as both customers and suppliers in a supply network is how to reconcile the competing tradeoffs associated with concentrating its relationships upstream and downstream for improved overall performance.

The bulk of above research focuses on the immediate suppliers or customers, while ignoring direct relationships among suppliers and among customers in the first tier and beyond. Incorporating insights from the extended supply (or customer) network and identification of its structural characteristics that impact operating performance is still an open question. Two seminal works by Choi et al. (2001) and Choi and Krause (2006) emphasize this call for further research to reconcile such a question by conceptualizing implications of supply network structure on a firm's ability to integrate and coordinate its supply chain activities as well as access knowledge to improve its technologies and reduce operating costs. Netessine et al. (2009) also emphasize the limitation of existing supply chain management research on simple supply chain characterizations and monopolistic or stylized situations as opposed to more holistic approaches to represent complex supply networks. They also note an emerging shift in supply chain management thinking from competition at the supply chain level to competition via orchestration of supply networks.

Supply network structure may manifest either (i) directly or (ii) indirectly to influence firm performance. Directly, it can influence a firm's ability to lower costs, drive operational best practices, and increase knowledge exchange and spillovers from its suppliers and customers (Dyer 1996, Dyer and Hatch 2004). Analyzing supplier, customer, and alliance relationships in the electronics industry, Basole et al. (2017b) find evidence for the centrality of a firm and the interconnectedness among firms in the supply network to positively influence a focal firm's asset utilization, cost performance, and operational efficiency. Lu and Shang (2017) also find some empirical support for an inverted U-shaped relationship between the weighted in-degree centrality (number of 1st tier suppliers divided by weighted product groups) of a firm's upstream supply network and performance as measured by return on assets (ROA) and Tobin's Q. Indirectly, supply network structure may accentuate or mitigate another supply chain configuration decision of the firm. For example, Bellamy et al. (2018) analyze Bloomberg SPLC data and find empirical evidence that the closeness centrality and interconnectedness among customers in a firm's downstream supply network moderates the link between its level of supply chain concentration and ROA. There still lies quite some ambiguity in this area in terms of: what salient measures should be used to represent supply network structure, the role that context plays (e.g., industries of focus, the use of directed or undirected links, the network boundary), and the underlying mechanisms that link supply network structure to operational performance.

3.3. Innovation

Studies of innovation or knowledge spillover in networks are numerous and explore various dimensions between firms. Buyer-supplier relationships represent one of such dimensions, thus, supply network structure could facilitate knowledge and information flows among partners to cultivate knowledge critical to driving innovation. Basole et al. (2017a) offer several measures to assess innovation activity in global supply networks: concentration of innovativeness and dependence across geographic location, overlap of technology and knowledge base among supply network partners, concentration of innovation and dependence across supply network tiers, concentration of innovativeness and influence in supply network, and overlap of knowledge complementarity and focus segment between supply network partners. They illustrate these measures and their interpretation with supply chain and patenting data, though the paper is more descriptive and does not test assertions regarding supply networks and innovation. Bellamy et al. (2014) analyze supply networks of firms in the electronics industry and find empirical support that firms more central to the supply network and with more interconnected supply network parters experience greater levels of innovation output. The former network structure characteristic is focused on a firm's effectiveness in accessing channels of knowledge and information in its supply network, while the latter emphasizes the level of interconnectedness between a firm's direct suppliers. The level of innovativeness (prior innovation output history) appears to accentuate the benefits of a more interconnected supply base (Bellamy et al. 2014).

Additional dimensions of inter-firm relationships have also been explored. For example, Wu et al. (2017) track employee job histories to construct a network of labor flow between firms, and study how the structure of that network affects the performance of IT firms. The main finding of that work is that maintaining diversity in hiring can substantially improve productivity of IT firms, but the effect vanishes in other industries. Prior interactions between employees also matter for innovation. A recent study by Zacchia (2019) constructs a network between firms that uses a prior history of collaborations between their employees on patents and find that social interactions augment returns on R&D activities. An open research question that remains is whether and how knowledge spillovers propagate through a supply network. Serpa and Krishnan (2017) address this question for productivity, identifying factors that arise from interacting with more productive partners as by far the most important source of productivity spillovers in supply chains. They estimate a 0.26% increase in supplier's productivity from having a customer base that is 1% more productive. In terms of structural characteristics, they find this prominent source of spillovers to be more pronounced when a supplier firm has a concentrated customer base.

Given that firms interact in multiple dimensions, a question for further research that comes naturally is how to differentiate between the networks in terms of relative importance to a specific aspect of performance, and their complementarities in driving an effect. One could consider augmenting the supply network with an additional type of link resulting in a so-called multi-layer network (Kivelä et al. 2014). The machinery for multi-layer network analysis is growing rapidly. One can reasonably hope that a coordinated management of multiple layers of a network could further improve firms performance.

4. Networks and Risk

Before discussing the role of networks in the risk of a company or set of companies, possibly encompassing the entire network, it is useful to discuss the relevant perspectives on risk events and risk measures, as they vary depending on the context. The first perspective considers the entire network of firms and is concerned with the aggregate volume of output produced by the network. If the network represents all firms in the economy, the output would correspond to the gross domestic product (GDP). Production agents, the nodes in the network, are subject to random shocks that arrive periodically. The shocks can temporarily increase production output or reduce it, possibly to zero. Two natural questions emerge: (i) how do agents' production quantities respond to their own shocks and shocks of other agents in the network? (ii) how does the volatility of aggregate output depend on the network structure? Thus, the corresponding measures of interest are (i) agents production quantities as functions of shocks, and (ii) variability of aggregate output.

The second perspective looks at the local demand as a function of demand shocks and the agents' properties in the local neighborhood. An important topic in this context is whether the time-series patterns of demand change as it propagates from end consumers upstream the supply network. The systematic risk is one of such patterns, representing the component in demand variability that is correlated with the overall state of the economy and, therefore, is not diversifiable. The relevant risk measure in this context is the correlation coefficient between increments in demand and the state of the economy. Another topic in this context is the bullwhip effect and its consequences for demand variability at the various positions in the supply network. The relevant risk measure is the variability of a firm's demand.

The third perspective looks at local output as a function of local supply shocks. Supply shocks can increase or reduce output of the nodes or logistical capacity of the corresponding links. They can come periodically or be one time events with lasting effects. In this context, a natural question to ask is how far, in terms of the chain level in the supply network, and for how long are the effects of supply shocks felt? Thus, the focus is on the local output volatility or on the output volume as a function of time. In the remainder of the chapter, we address each of these contexts in detail, while paying specific attention to the role of networks in informing these phenomena.

4.1. Productivity and Aggregate output

Some fifty years following the seminal work of Leontief (1936), Long and Plosser (1983) developed a dynamic version of the multi-sectoral production model to explain the co-movement observed in various economic time-series, such as sectoral output, prices, employment, etc. Aggregated across industries, the co-movements form a business cycle, i.e., a simultaneous deviation from a long-term trend. An important feature of this model is that sectoral output is subject to random Markovian shocks. Thus, the basic question is, how does an output of one sector depend on a shock at another and can these shocks aggregate to a business cycle? It turns out, that the presence or absence of any business cycle behavior critically depends on the properties of the input-output matrix A. Recall that the a_{ij} element of the input-output matrix is the value of input commodity requirements from industry i for \$1 output of industry j. If the production function is characterized by a Cobb-Douglas form, the input requirements, in equilibrium, are equal to the respective elasticities of industry outputs with respect to commodity inputs.

Assume that sectoral shocks are independent and identically distributed, thus, precluding business cycles to be driven by shocks that are common or correlated across sectors or time. The sectoral output under this setting exhibits gradually decreasing oscillations with period greater than 2 if the eigenvalues of A' are less than one in absolute value. This condition is guaranteed to hold since the rows of A' sum to 1 minus the cost of labor required for \$1 output of j, and, therefore, the deviations of the sectoral outputs from the long-term mean can be written as a sum of lagged shocks multiplied by the respective powers of A. At lag zero, a shock to an industry affects only that industry. Other industries respond to that shock only after a period of time that is dependent on the production technology. In an example of an economy with six sectors, Long and Plosser (1983) find that the response often peaks at a lag of 2 or 3. Thus, the network structure of production informs how shocks in one industry propagate through the rest of the economy. Managers or policymakers can use this knowledge to mitigate the adverse effect of disruptions in adjacent industries.

The ideas of Long and Plosser (1983) were developed further by a body of literature on aggregate fluctuations. The basic question is whether idiosyncratic shocks to firms in a network can result in a large aggregate fluctuation. Note, that Long and Plosser (1983) provide an affirmative answer to this question, yet, with a caveat that the sectoral shocks are fairly aggregate themselves. One argument against aggregate fluctuations might be that at the firm-level, individual independent shocks would cancel each other out. Gabaix (2011) show that this diversification argument does not hold when the distribution of firm sizes is heavy tailed, as observed empirically. Thus, they conclude, shocks to large firms do not cancel out.

Acemoglu et al. (2012) show that shocks need not cancel also when the distribution of links in the production network is asymmetric. The asymmetry exists when the most nodes in the network have just one or a few connections and, at the same time, a number of firms have a very large number of connections. In particular, aggregate fluctuations emerge if distributions of degrees or second-order interconnections in the network are heavy-tailed and follow, for example, the power law. On the contrary, the diversification argument applies and shocks cancel, if a production network is balanced, i.e., the maximum degree of a node does not grow with the size of the economy.

The data appears to lend some empirical support to the heavy tailed distributions of degrees and second-order interconnections at the industry level. However, whether the infinitely growing connectivity can be supported at the firm level is an open question. Analyzing the in-degree data at the firm level, Atalay et al. (2011) find that it has a steep drop at high values, thus decaying more rapidly than power law. From the first principles, a firm focus, horizontal differentiation in competitive markets, development of relationships with suppliers and customers, finite capacity and coordination cost are likely to suppress the growth of individual firm connectivity with the growth of the network. In fact, Osadchiy and Udenio (2019) find that networks become more fragmented over time, in the sense that firms' connections are more limited to a smaller cluster of firms, and relatively few firms link clusters between each other. Thus, at the firm-level, networks could in fact be better described as balanced structures.

4.2. Local demand shocks

Demand fluctuations in the production network originate at the level of final consumers. These fluctuations are transformed as firms facing consumer demand place orders to suppliers. Reasons for the transformation of demand patterns include information distortion, batch size and capacity constraints, order review cycles and lead times, and others. In the network, if a supplier serves multiple customers, these order streams aggregate. Therefore, the supplier faces a demand stream which is an aggregate of transformed final demand streams. What can be said about properties of that demand? Do they change as demand propagates further upstream in the supply network, i.e., as suppliers place orders to their suppliers, and so on?

One important feature of demand is systematic risk, and whether it is founded in firms' operations. Similarly to the systematic risk of financial securities, it is measured as a correlation coefficient between the change in demand and the return on a broad market portfolio over a period of time (Osadchiy et al. 2016). The systematic risk is common to all firms in the economy, thus, it cannot be diversified. In finance, investors demand a greater risk premium for holding securities with high systematic risk, see §3.1. In the real sector, a high systematic risk in demand translates into a lower risk adjusted valuation and a higher cost of capital. To manage systematic risk in demand, firms could engage in costly financial hedging (Gaur and Seshadri 2005).

At the level of retailers, i.e., firms facing end consumer demand, the systematic risk is significant and financial markets give a valuable information signal to retailers about future sales (Osadchiy et al. 2013). Higher upstream in supply networks, as Osadchiy et al. (2016) observe, the systematic risk is greater. They propose two mechanisms that explain the observed amplification of the systematic risk. First, suppliers typically serve more than one customer, so they aggregate (or pool) demand over this set of customers. Risk pooling is a well-studied phenomenon in OM (Eppen 1979). However, as aggregation cancels out idiosyncratic noise, it preserves and potentially amplifies the systematic component. The amplification of systematic risk depends on the relative magnitude and uncertainty in customer orders, and is greater when the orders are similar in magnitude and stochastic properties (e.g., variance of the idiosyncratic component). If customers are identical in terms of size, systematic risk and bill of materials, then, in the limit as the number of customers grows large, the upstream supplier faces demand shocks that are perfectly correlated with market returns. Second, orders to suppliers typically have a substantial lead time. Demand uncertainty over that lead time can have a greater systematic component. A necessary condition for the increase is that demand shocks are correlated not with just contemporaneous, but also with lagged market returns. Given that lead times at downstream layers of the supply network (e.g., retail) are shorter than at the upstream layers (e.g., manufacturing), aggregation over time could explain the observed increase in systematic risk.

Systematic risk captures the covariance in sales growth and broad market index returns. Grounded in operations, it is intimately related to beta, a financial measure of the systematic risk. For beta being a purely empirical construct, the propagation and aggregation of demand shocks in the supply network provide operational microfoundations of the phenomenon. The role of networks can not be overestimated in this regard.

Empirical verification of the systematic risk amplification requires a measure of upstreamness in the supply network. Osadchiy et al. (2016) adopt a traditional three-level classification of upstreamness where retailers are the most downstream, wholesalers are in the middle, and manufacturers are most upstream (see, e.g., Cachon et al. 2007, Bray and Mendelson 2012). While sensible, this classification is not perfect. For example, manufacturers of consumer products are, in principle, less upstream than manufacturers of industrial components. Addressing this gap, Antràs et al. (2012) propose an industry-level measure of upstreamness based on the fraction of final demand and intermediate inputs in the output of an industry. Such a measure can be computed from input-output tables. The variability in upstreamness could explain the observed variability in systematic risk across manufacturing segments.

At the firm level, the upstreamness of a supplier can alternatively be defined as the network distance, i.e., the number of links in a shortest path, to the set of firms serving end consumer demand Gofman et al. (2017). Given the evidence for the bullwhip effect and aggregation of demand, a natural question that emerges is whether the demand variability increases at upstream layers of the supply network. Osadchiy et al. (2018) find that demand variability does not increase at upstream layers of the supply network, despite the evidence that firms amplify the variability of their orders, compared to the variability of demand. To reconcile these two seemingly conflicting findings, Osadchiy et al. (2018) present evidence that firms balance the mix of their customers to smooth demand variability. Put differently, the network of customers appears to shield a supplier from demand spikes of individual customers.

4.3. Local supply shocks

So far, we have discussed productivity and demand shocks. Supply shocks are no less important. The 2011 Tohoku earthquake and tsunami was a major disaster that affected supply chains all over the world. Car manufacturers General Motors (GM) and Peugeot Citroen slowed production because of the shortage of air flow sensors manufactured by Hitachi's plant in the affected area, and Ford and Chrysler had to limit colors of their vehicles because of the shortage of Xirallic, a metallic car paint pigment produced by Japanese Merck's plant (Boudette and Bennett 2011). Analyzing the supply networks of Japanese firms, Carvalho et al. (2016) find that the supply shocks caused by the earthquake affected downstream customers up to 4 links away from disrupted suppliers. The disruption also affected upstream suppliers of stricken firms, although the effect is smaller in intensity and magnitude. Moreover, a firm that did not have a direct connection to a stricken firm, but shared a customer with it, also felt the effect of disruption – a so called horizontal shock propagation. Overall, Carvalho et al. (2016) estimate the economic effect of the 2011 disaster to translate to a 1.2 percentage point reduction of Japan's GDP growth rate, out of which 1.1 percentage points is attributable to the downstream propagation, and approximately 0.5 percentage points to the downstream propagation to tier-two customers and beyond.

Not only major disasters propagate through supply networks. Wang et al. (2019) show that the volatility of idiosyncratic shocks to immediate and tier-two suppliers are associated with the idiosyncratic volatility of a focal firm. Interestingly, the effect of tier-two suppliers is moderated by the so-called "diamond ratio", i.e., the degree of overlap in tier-two suppliers across immediate suppliers of the firm. Thus, similarly to systematic risk, the supply network serves as medium for propagation of idiosyncratic shocks.

An important question for firms is how can they protect against supply disruptions? A great deal of research has been dedicated to answering this question, see Sheffi (2005) for a review. In a two-tier "diamond-shaped" supply chain, Ang et al. (2016) find, a manufacturer relies more on indirect mitigation (as opposed to a direct mitigation in the form of inventory buffers and multi-sourcing) of disruptions occurring at tier two: by offering higher prices and greater penalties, the manufacturer induces tier-1 suppliers to invest more in their own risk mitigation. More recent research has been focusing on the optimal network structures that maximize profit in the presence of disruption risk Bimpikis et al. (2019). It turns out that the optimal network structure depends on whether the optimization is taken from a retailer's (downstream firm) or supplier's (upstream firm) perspective. In both case, the optimal network is V-shaped, with more suppliers than retailers. Yet, the retailer-optimal networks are less balanced, meaning that the variation between the number of firms at each tier is greater.

Assuming that firms can invest in disruption mitigation, a related question is where in a network should such investments should be made? The investments could take the form of node investments minimizing the probability of direct shocks to a firm or link investments minimizing probability of cascading disruptions. What information does a firm need to make such a decision? These questions are addressed in the recent work by Bakshi and Mohan (2019). First, the benefits of investments into mitigation extend beyond the focal firm, protecting downstream firms from a cascading disruption. Second, the optimal investment requires a relatively limited knowledge of the network: the dependence on the attributes of high-tier suppliers decays exponentially, and in the case of rare shocks, the information about tier-1 and tier-2 suppliers is all that is needed.

There is no doubt that the clarity and sharpness of insights from stylized models are valuable. The challenge is, of course, in mapping these models to real world data, a process that requires a verification of underlying assumptions and identifying the effects of first-order importance. There seems to be a gradual convergence between modeling and empirical research on the role of supply networks in performance and risk. The newly available firm-level supply network data provide an opportunity in advancing this goal further.

5. Future Directions

Recent years have advanced our theoretical and empirical understanding of the role of networks in performance and risk. Nonetheless, open questions and question that have only been partially answered still remain. Given complexities of networks it is important to identify salient measures that should be used to represent supply network structure and differentiate between the networks in terms of relative importance to a specific aspect of performance or risk, and their complementarities in driving an effect. A better understanding of the effect of centralities and development of new measures, such as layers and sparsity are important in that regard. The network and performance are deeply interconnected, and in a dynamic setting, shocks in performance could drive the formation of network. Development of theoretically sound and empirically validated mechanisms of endogenous network formation is an active area of research.

It also important to develop contextual and industry specific studies. Designing resilient supply networks is still an important question and even more so at the time when supply chains span continents and trade policy is more uncertain. Further research could explore the role that context plays (e.g., focus or product nature of an industry or firm) in altering the relationship between supply networks and performance. Finally, recognizing that buyer-supplier relationships represent only one dimension of the relationship between firms, one could aim at augmenting the supply network with other sources of network data, e.g., ownership, employment history, prior collaborations, education, and social networks in further search of improvement in performance and management of risk.

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