Synergies and Vulnerabilities of Supply Chain Networks in a Global Economy

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Outline

- Today’s Supply Chain Networks
- Major Recent Supply Chain Disruptions
- Motivation for Our Research
- Network Vulnerabilities and Supply Chain Networks
- Mergers and Acquisitions and Supply Chain Network Synergies
- Summary and Conclusions
Supply chain networks are the underpinning skeletons of the business world. These networks, more and more, are global in nature, with products consisting of parts manufactured in different regions of the world, assembled in yet other locations, and then shipped across continents and oceans to retailers and consumers.

Such complex networks consist of manufacturers (and their suppliers), shippers and carriers using various modes of transportation, distribution centers where the products are stored, and, ultimately, sent from to the customers.

Supply chains involve many decision-makers interacting with one another, sometimes competing, and at other times necessarily cooperating.
Depiction of a Supply Chain Network
Supply chain networks depend on infrastructure networks for their effective and efficient operations from: manufacturing and logistical networks, to transportation networks, to electric power networks, financial networks, and telecommunication networks, most, notably, the Internet.

No supply chain, logistics system, or infrastructure system is immune to disruptions and as long as there have been supply chains there have been disruptions.

However, in the past decade there have been vivid high-profile examples of supply chain disruptions and their impacts. Supply chain disruptions and the associated risk are major topics now in theoretical and applied research, as well as in practice, since risk in the context of supply chains may be associated with the production/procurement processes, the transportation/shipment of the goods, and/or the demand markets.
Transportation, Communication, and Energy Networks

Bus Network

Iridium Satellite Constellation Network

Satellite and Undersea Cable Networks

British Electricity Grid
# Components of Common Networks

<table>
<thead>
<tr>
<th>Network System</th>
<th>Nodes</th>
<th>Links</th>
<th>Flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation</td>
<td>Intersections, Homes, Workplaces, Airports, Railyards</td>
<td>Roads, Airline Routes, Railroad Track</td>
<td>Automobiles, Trains, and Planes,</td>
</tr>
<tr>
<td>Manufacturing and logistics</td>
<td>Workstations, Distribution Points</td>
<td>Processing, Shipment</td>
<td>Components, Finished Goods</td>
</tr>
<tr>
<td>Communication</td>
<td>Computers, Satellites, Telephone Exchanges</td>
<td>Fiber Optic Cables, Radio Links</td>
<td>Voice, Data, Video</td>
</tr>
<tr>
<td>Energy</td>
<td>Pumping Stations, Plants</td>
<td>Pipelines, Transmission Lines</td>
<td>Water, Gas, Oil, Electricity</td>
</tr>
</tbody>
</table>
Tennessee Railroad Freight Flows
Natural Gas Pipeline Network in the US
Moreover, in recent decades, the focus has been on lean supply chains and, although such supply chains may work well when the environment is predictable and steady, they may be very sensitive to disruptions since they lack redundancy and slack in their systems.

Furthermore, firms today may be much less vertically integrated (and, clearly, more global). Decades ago, Ford Motor Company and other automobile manufacturers and even IBM produced their products, essentially in their entirety.

Lynn (2006) has argued that globalization has led to extremely fragile supply chains. Suppliers today may be in parts of the world that are unstable and subject to natural disasters, political instability, and strife.
In fact, Craighead, Blackhurst, Rungtusanatham, and Handfield (2007) have argued that supply chain disruptions and the associated operational and financial risks are the most pressing issue faced by firms in today’s competitive global environment.

Notably, the focus of research has been on “demand-side” risk, which is related to fluctuations in the demand for products, as opposed to the “supply-side” risk, which deals with uncertain conditions that affect the production and transportation processes of the supply chain.
Several recent major disruptions:

▶ In March 2000, a lightning bolt struck a Philips Semiconductor plant in Albuquerque, New Mexico, and created a 10-minute fire that resulted in the contamination of millions of computer chips and subsequent delaying of deliveries to its two largest customers: Finland’s Nokia and Sweden’s Ericsson.

▶ Ericsson used the Philips plant as its sole source and reported a $400 million loss because it did not receive the chip deliveries in a timely manner whereas Nokia moved quickly to tie up spare capacity at other Philips plants and refitted some of its phones so that it could use chips from other US suppliers and from Japanese suppliers.

▶ Nokia managed to arrange alternative supplies and, therefore, mitigated the impact of the disruption.

▶ Ericsson learned a painful lesson from this disaster.
Another Major Supply Chain Disruption

Another major disruption to supply chains:

- The West Coast port lockout in 2002, which resulted in a 10 day shutdown of ports in early October, typically, the busiest month. 42% of the US trade products and 52% of the imported apparel go through these ports, including Los Angeles. The Pacific Maritime Association (PMA) locked out members of the International Longshore and Warehouse Union (ILWU) forcing cargo ships to sit idly in ports from Seattle to San Diego and holding up the loading and unloading of potentially billions of dollars of cargo. Estimated losses were one billion dollars per day.

- Walmart and Costco planned months in advance and Walmart anticipated the lockout and had extra inventory shipped to Hawaii and Alaska.

- Port operations and schedules did not return to normal until 6 months after the strike ended!
Yet Other Major Supply Chain Disruptions

► The impact of Hurricane Katrina, which hit in 2005, with the consequence that 10% - 15% of total U.S. gasoline production was halted, not only raised the oil price in the U.S., but also overseas (see, e.g., Canadian Competition Bureau (2006)). More recently, we saw the impact of Hurricane Gustav where people in the Southeast experienced major gas shortages.

► The world price of coffee rose 22% after Hurricane Mitch struck the Central American republics of Nicaragua, Guatemala, and Honduras, which also affected supply chains worldwide (Fairtrade Foundation (2002)).
As summarized by Sheffi (2005), one of the main characteristics of disruptions in supply networks is “the seemingly unrelated consequences and vulnerabilities stemming from global connectivity.”

Indeed, supply chain disruptions may have impacts that propagate not only locally but globally and, hence, a holistic, system-wide approach to supply chain network modeling and analysis is essential in order to be able to capture the complex interactions among decision-makers.
In addition, to demonstrate the dependence of supply chain networks on other infrastructure networks, including the Internet, we highlight the following:

According to Kembel (2000) the cost of downtime (in terms of lost revenue) for several online companies if their computers and/or telecomm networks are down (for one hour of downtime):

- Ebay: $225,000;
- Amazon.com: $180,000;
- Brokerage Company: $6,450,000.

(These costs do not include employee costs nor loss of goodwill.)
Disasters in Transportation Networks

www.salem-news.com

www.boston.com
Disasters in Electric Power Networks

www.cellar.org

media.collegepublish.com

www.crh.ncaa.gov
Motivation for Our Research

Hence, the rigorous modeling and analysis of supply chain networks, in the presence of possible disruptions is imperative since disruptions may have lasting major financial consequences.

Hendricks and Singhal (2005) analyzed 800 instances of supply chain disruptions experienced by firms whose stocks are publicly traded. They found that the companies that suffered supply chain disruptions experienced share price returns 33 percent to 40 percent lower than the industry and the general market benchmarks. Furthermore, share price volatility was 13.5 percent higher in these companies in the year following a disruption than in the prior year.

A company that experiences a supply chain disruption can expect to experience significant decreases in sales growth, stock return, and shareholder wealth for two years or more following the incident (Hendricks and Singhal (2003, 2005)). It is evident that only well-prepared companies can effectively cope with supply chain disruptions.
The Supply Chain's Impact on Stock Price

<table>
<thead>
<tr>
<th>% Increase in Stock Price</th>
<th>Event</th>
</tr>
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<tbody>
<tr>
<td>6</td>
<td>1% Revenue Increase</td>
</tr>
<tr>
<td>6</td>
<td>1% Operational Expenses Decrease</td>
</tr>
<tr>
<td>5</td>
<td>20% Inventory Reduction</td>
</tr>
<tr>
<td>5</td>
<td>5% Fixed-Asset Utilization Increase</td>
</tr>
<tr>
<td>3</td>
<td>5% Days Sales Decrease</td>
</tr>
</tbody>
</table>

Source: S&P 500 Survey 2002

Supply Chain Management Review • March 2005
Wagner and Bode (2007), in turn, designed a survey to empirically study the responses from executives of firms in Germany regarding their opinions as to the factors that impact supply chain vulnerability. The authors found that demand-side risks are related to customer dependence while supply-side risks are associated with supplier dependence, single sourcing, and global sourcing.
The goal of supply chain risk management is to alleviate the consequences of disruptions and risks or, simply put, to increase the robustness of a supply chain. However, there are very few quantitative models for measuring supply chain robustness.

Snyder and Daskin (2005) examined supply chain disruptions in the context of facility location. The objective of their model was to select locations for warehouses and other facilities that minimize the transportation costs to customers and, at the same time, account for possible closures of facilities that would result in re-routing of the product. However, as commented in Snyder and Shen (2006), “Although these are multi-location models, they focus primarily on the local effects of disruptions.”
To-date, most supply disruption studies have focused on a local point of view, in the form of a single-supplier problem (see, e. g., Gupta (1996) and Parlar (1997)) or a two-supplier problem (see, e. g., Parlar and Perry (1996)).

Very few studies/papers have examined supply chain risk management in an environment with multiple decision-makers and in the case of uncertain demands (cf. Tomlin (2006)).
We believe that it is imperative to study supply chain modeling and risk management from a holistic point of view and to capture the interactions among the multiple decision-makers in the various supply chain network tiers.

More companies are now using strategies to ensure quick recovery and business continuity following disruptions (Walmart, IBM, etc.)
Of course, in order to study supply chain robustness, an informative and effective performance measure is first required. Beamon (1998, 1999) reviewed the supply chain literature and suggested directions for research on supply chain performance measures, which should include criteria on efficient resource allocation, output maximization, and flexible adaptation to the environmental changes (see also, Lee and Whang (1999), Lambert and Pohlen (2001), and Lai, Ngai, and Cheng (2002)).
We emphasize that different supply performance measures can be devised based on the specific nature of the problem. In any event, the discussion here is not meant to cover all the existing supply chain performance measures. Indeed, we are well aware that it is a daunting task to propose a supply chain performance measure that covers all aspects of supply chains.
Characteristics of Networks Today Including Supply Chains

- *Large-scale nature* and complexity of network topology;

- *Congestion*; in the US we are experiencing a freight capacity crisis;

- the *interactions among networks* themselves such as in transportation versus telecommunications;

- *Dynamics* and global reach; increasing risk and uncertainty.
• alternative behaviors of the users of the network

- System-optimized (S-O) (centralized supply chain) versus

- user-optimized (U-O) (decentralized supply chain),

which may lead to paradoxical phenomena (Braess Paradox and the Merger Paradox).
Network Equilibrium Problem
Derived from Transportation

(U-O Problem)
Network Equilibrium

The network equilibrium conditions are then given by:
For each path \( p \in P_w \) and every O/D pair \( w \):

\[
C_p \begin{cases} 
  = \lambda_w, & \text{if } x_p^* > 0 \\
  \geq \lambda_w, & \text{if } x_p^* = 0
\end{cases}
\]

where \( \lambda_w \) is an indicator, whose value is not known a priori. These equilibrium conditions state that the user costs on all used paths connecting a given O/D pair will be minimal and equalized.
The Braess (1968) Paradox

Assume a network with a single O/D pair (1,4). There are 2 paths available to travelers: \( p_1 = (a,c) \) and \( p_2 = (b,d) \).

For a travel demand of 6, the equilibrium path flows are \( x_{p_1}^* = 3 \) and \( x_{p_2}^* = 3 \) and

The equilibrium path travel cost is

\[
C_{p_1} = C_{p_2} = 83.
\]

\[
c_{a}(f_{a}) = 10 \ f_{a} \quad c_{b}(f_{b}) = f_{b} + 50 \\
c_{c}(f_{c}) = f_{c} + 50 \quad c_{d}(f_{d}) = 10 \ f_{d}
\]
Adding a new link creates a new path $p_3=(a,e,d)$.

The original flow distribution pattern is no longer an equilibrium pattern, since at this level of flow the cost on path $p_3$, $C_{p_3}=70$.

The new equilibrium flow pattern network is

$x_{p_1}^* = x_{p_2}^* = x_{p_3}^* = 2$.

The equilibrium path travel costs:

$C_{p_1} = C_{p_2} = C_{p_3} = 92$. 

$c_e(f_e) = f_e + 10$
The 1968 Braess article has been translated from German to English and appears as

On a Paradox of Traffic Planning

by Braess, Nagurney, Wakolbinger

in the November 2005 issue of Transportation
The NE Paradigm is the Unifying Paradigm:

- Transportation Networks
- The Internet
- Financial Networks
- Decentralized Supply Chains.
The Equivalence of Decentralized Supply Chains and Transportation Networks

Supply Chain - Transportation Supernetwork Representation

Financial Network

Logistical (Product Supply Chain) Network

Physical Transportation Network

Transaction cost information
Demand or order information
Travel time information
Unexpected issues information

Real-Time Information System

Two-way information exchanges between specific decision-makers

Nagurney, Ke, Cruz, Hancock, Southworth, Environment and Planning B (2002).
Electric Power Supply Chains
The Electric Power Supply Chain Network

The Transportation Network Equilibrium Reformulation of Electric Power Supply Chain Networks

Electric Power Supply Network

Transportation Chain Network

Electric Power Supply Chain Network with Fuel Suppliers

In 1952, Copeland wondered whether money flows like water or electricity.
The Transportation Network Equilibrium Reformulation of the Financial Network Equilibrium Model with Intermediation

We have shown that *money* as well as *electricity* flow like *transportation* and have answered questions posed fifty years ago by Copeland and by Beckmann, McGuire, and Winsten!
Additional disasters that have demonstrated the importance and the vulnerability of network systems.

Examples:

- 9/11 Terrorist Attacks, September 11, 2001;
- The biggest blackout in North America, August 14, 2003;
- Two significant power outages in September 2003 -- one in the UK and the other in Italy and Switzerland;
- Hurricane Katrina, August 23, 2005;
- The Minneapolis I35 Bridge Collapse, August 1, 2007
- The severance of the Mediterranean cable in 2008.
Our Research on Network Efficiency, Vulnerability, and Robustness


A New Network Performance/Efficiency Measure with Applications to Infrastructure Networks including Supply Chains
The network performance/efficiency measure $\mathcal{E}(G,d)$, for a given network topology $G$ and fixed demand vector $d$, is defined as

$$\mathcal{E}(G,d) = \frac{\sum_{w \in W} \frac{d_w}{\lambda_w}}{n_w},$$

where $n_w$ is the number of O/D pairs in the network and $\lambda_w$ is the equilibrium disutility for O/D pair $w$.

**Importance of a Network Component**

**Definition: Importance of a Network Component**

The importance, $I(g)$, of a network component $g \in G$ is measured by the relative network efficiency drop after $g$ is removed from the network:

$$I(g) = \frac{\Delta \mathcal{E}}{\mathcal{E}} = \frac{\mathcal{E}(G, d) - \mathcal{E}(G - g, d)}{\mathcal{E}(G, d)} ,$$

where $G - g$ is the resulting network after component $g$ is removed.
The Approach to Study the Importance of Network Components

The elimination of a link is treated in the N-Q network efficiency measure by removing that link while the removal of a node is managed by removing the links entering and exiting that node.

In the case that the removal results in no path connecting an O/D pair, we simply assign the demand for that O/D pair to an abstract path with a cost of infinity. Hence, our measure is well-defined even in the case of disconnected networks.

The measure generalizes the Latora and Marchiori network measure for complex networks.
Assume a network with two O/D pairs: \( w_1=(1,2) \) and \( w_2=(1,3) \) with demands: \( d_{w_1}=100 \) and \( d_{w_2}=20 \).

The paths are:
for \( w_1 \), \( p_1=a \); for \( w_2 \), \( p_2=b \).

The equilibrium path flows are:
\( x_{p_1}^*=100 \), \( x_{p_2}^*=20 \).

The equilibrium path travel costs are:
\( C_{p_1}=C_{p_2}=20 \).
### Importance and Ranking of Links and Nodes

<table>
<thead>
<tr>
<th>Link</th>
<th>Importance Value from Our Measure</th>
<th>Importance Ranking from Our Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>0.8333</td>
<td>1</td>
</tr>
<tr>
<td>$b$</td>
<td>0.1667</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node</th>
<th>Importance Value from Our Measure</th>
<th>Importance Ranking from Our Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.8333</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0.1667</td>
<td>3</td>
</tr>
</tbody>
</table>
Example - Sioux Falls Network

The network data are from LeBlanc, Morlok, and Pierskalla (1975).

The network has 528 O/D pairs, 24 nodes, and 76 links.

The user link cost functions are of Bureau of Public Roads (BPR) form.
The Bureau of Public Roads (BPR) link cost functional form is:

$$c_a(f_a) = t_a^0 \left[ 1 + k \left( \frac{f_a}{u_a} \right)^\beta \right] \quad \forall a \in L$$

where $k$ and $\beta$ are greater than zero and the $u$’s are the practical capacities on the links.
Example - Sioux Falls Network
Link Importance Rankings
The Advantages of the N-Q Network Efficiency Measure

• The measure captures demands, flows, costs, and behavior of users, in addition to network topology;
• The resulting importance definition of network components is applicable and well-defined even in the case of disconnected networks;
• It can be used to identify the importance (and ranking) of either nodes, or links, or both; and
• It can be applied to assess the efficiency/performance of a wide range of network systems.
• It is applicable also to elastic demand networks (Qiang and Nagurney, Optimization Letters (2008)).
• It has been extended to dynamic networks (Nagurney and Qiang, Netnomics, in press).
The focus of the robustness of networks (and complex networks) has been on the impact of different network measures when facing the removal of nodes on networks.

We focus on the *degradation of links through reductions in their capacities* and the effects on the induced costs in the presence of known demands and different functional forms for the links.
The Time-Dependent (Demand-Varying) Braess Paradox and Evolutionary Variational Inequalities
Recall the Braess Network where we add the link e.
The Solution of an Evolutionary (Time-Dependent) Variational Inequality for the Braess Network with Added Link (Path)

Demand(t) = t

Braess Network with Time-Dependent Demands

Equilibrium Path Flow

Demand(t) = t

Paths 1 and 2
Path 3
In Demand Regime I, only the new path is used.
In Demand Regime II, the Addition of a New Link (Path) Makes Everyone Worse Off!
In Demand Regime III, only the original paths are used.

Network 1 is the Original Braess Network - Network 2 has the added link.
The new link is NEVER used after a certain demand is reached even if the demand approaches infinity.

Hence, in general, except for a limited range of demand, building the new link is a complete waste!
In the paper:


we have extended the performance measure of Nagurney and Qiang to handle disruptions in supply chains under risk and uncertainty.
Where Are We Now?

Empirical Case Study

- New England electric power market and fuel markets
- 82 generators who own and operate 573 power plants
- 5 types of fuels: natural gas, residual fuel oil, distillate fuel oil, jet fuel, and coal
- Hourly demand/price data of July 2006 (24 × 31 = 744 scenarios)
- 6 blocks (L1 = 94 hours, and Lw = 130 hours; w = 2, ..., 6)
The New England Electric Power Supply Chain Network with Fuel Suppliers
Predicted Prices vs. Actual Prices ($/Mwh)
Today, supply chains are more extended and complex than ever before. At the same time, the current competitive economic environment requires that firms operate efficiently, which has spurred research to determine how to utilize supply chains more effectively.

There is also a pronounced amount of merger activity. According to Thomson Financial, in the first nine months of 2007 alone, worldwide merger activity hit $3.6 trillion, surpassing the total from all of 2006 combined.

Notable examples: Kmart and Sears in the retail industry in 2004 and Federated and May in 2005, Coors and Molson in the beverage industry in 2005, and the recently proposed merger between Anheuser Busch and InBev.
According to Kusstatscher and Cooper (2005) there were five major waves of Merger & Acquisition (M & A) activity:

The First Wave: 1898-1902: an increase in horizontal mergers that resulted in many US industrial groups;

The Second Wave: 1926-1939: mainly public utilities;

The Third Wave: 1969-1969: *diversification* was the driving force;

The Fourth Wave: 1983-1986: the goal was efficiency;

The Fifth Wave: 1997 until the early years of the 21st century: *globalization* was the motto.

In 1998, M&As reached $2.1 trillion worldwide; in 1999, the activity exceeded $3.3 trillion, and in 2000, almost $3.5 was reached.
A survey of 600 executives involved in their companies’ mergers and acquisitions (M&A) conducted by Accenture and the Economist Unit (see Byrne (2007)) found that less than half (45%) achieved expected cost-saving synergies.

Langabeer and Seifert (2003) determined a direct correlation between how effectively supply chains of merged firms are integrated and how successful the merger is. They concluded, based on the empirical findings of Langabeer (2003), who analyzed hundreds of mergers over the preceding decade, that

Improving Supply Chain Integration between Merging Companies is the Key to Improving the Likelihood of Post-Merger Success!
Recently, we introduced a system-optimization perspective for supply chains in which firms are engaged in multiple activities of production, storage, and distribution to the demand markets and proposed a cost synergy measure associated with evaluating proposed mergers:


In that paper, the merger of two firms was modeled and the demands for the product at the markets, which were distinct for each firm prior to the merger, were assumed to be fixed.
Figure 1: Case 0: Firms A and B Prior to Horizontal Merger (Nagurney (2008a))
Figure 2: Case 1: Firms A and B Merge (Nagurney (2008a))
Figure 3: Case 2: Firms A and B Merge (Nagurney (2008a))
Figure 4: Case 3: Firms A and B Merge (Nagurney (2008a))
The measure that we utilized in Nagurney (2008a) to capture the gains, if any, associated with a horizontal merger Case $i$; $i = 1, 2, 3$ is as follows:

$$S^i = \left[ \frac{TC^0 - TC^i}{TC^0} \right] \times 100\%,$$

where $TC^i$ is the total cost associated with the value of the objective function $\sum_{a \in L^i} \hat{c}_a(f_a)$ for $i = 0, 1, 2, 3$ evaluated at the optimal solution for Case $i$. Note that $S^i$; $i = 1, 2, 3$ may also be interpreted as synergy.
The Supply Chain Network Oligopoly Model (Nagurney (2008b))

Figure 5: Supply Chain Network Structure of the Oligopoly
Mergers Through Coalition Formation

Figure 6: Mergers of the First $n_1'$ Firms and the Next $n_2'$ Firms
This framework can also be applied to teaming of humanitarian organizations in the case of humanitarian logistics operations.
In this talk we have demonstrated the richness of network concepts for quantifying synergies as well as vulnerabilities associated with supply chain networks in the global economy. The need for performance metrics as well as analytics has never been more profound nor more feasible. By focusing on interdisciplinary research and practice we can better identify which nodes and links in supply chain networks truly matter and whether or not to participate in any merger based on potential and predetermined synergies.