Supernetworks in Healthcare and Humanitarian Operations

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- Extensions to Perishable Products and Blood Supply Chains for the Red Cross
- Teaming in Humanitarian Operations and Network Synergies
- Summary, Conclusions, and Suggestions for Future Research

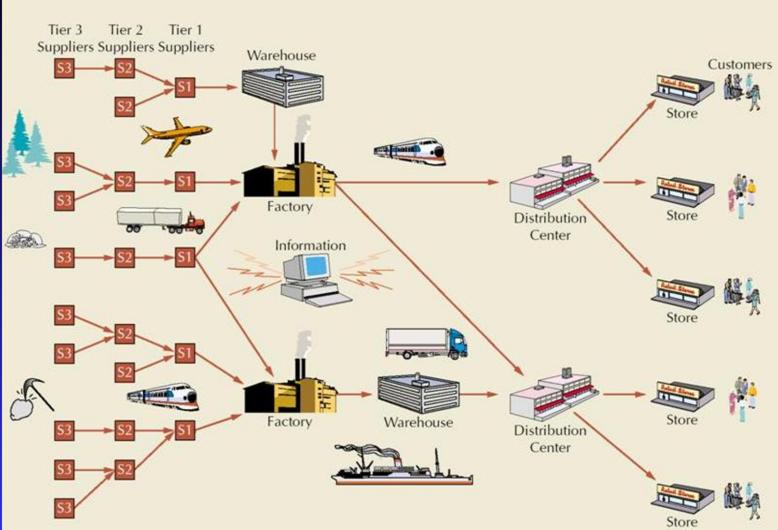
Background and Motivation

Supply chains are the *critical infrastructure and backbones* for the production, distribution, and consumption of goods as well as services in our globalized *Network Economy*.

Supply chains, in their most fundamental realization, *consist of manufacturers and suppliers, distributors, retailers, and consumers at the demand markets*.

Today, supply chains may span thousands of miles across the globe, involve numerous suppliers, retailers, and consumers, and be underpinned by multimodal transportation and telecommunication networks.

A General Supply Chain



Examples of Supply Chains That We Focus on in This Talk

Healthcare Supply Chains

Humanitarian Relief

Supply chains may be characterized by *decentralized decision-making* associated with the different economic agents or by *centralized* decision-making.

Supply chains are, in fact, *Supernetworks*.

Hence, *any formalism that seeks to model supply chains and to provide quantifiable insights and measures must be a system-wide one and network-based.*

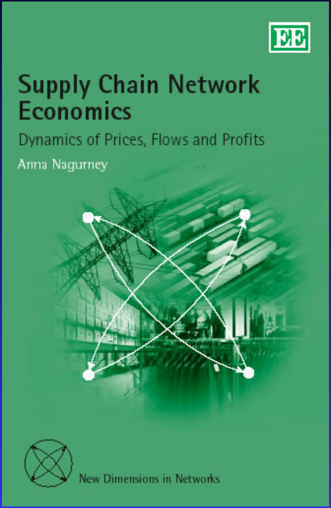
Indeed, such crucial issues as the stability and resiliency of supply chains, as well as their adaptability and responsiveness to events in *a global environment of increasing risk and uncertainty* can only be rigorously examined from the view of supply chains as network systems.

Characteristics of Supply Chains and Networks Today

- *large-scale nature* and complexity of network topology;
- *congestion*, which leads to nonlinearities;
- *alternative behavior of users of the networks*, which may lead to paradoxical phenomena;
- *possibly conflicting criteria associated with optimization*;
- *interactions among the underlying networks themselves*, such as the Internet with electric power networks, financial networks, and transportation and logistical networks;
- recognition of *their fragility and vulnerability*;
- policies surrounding networks today may have major impacts not only economically, but also *socially, politically, and security-wise*.

Changes in the availability of supplies, price shocks, as well as disruptions to transportation modes or telecommunications may have negative effects and consequences that propagate throughout the supply chain.

Our Approach to Supply Chain Network Analysis and Design



A Challenging Network Design Problem

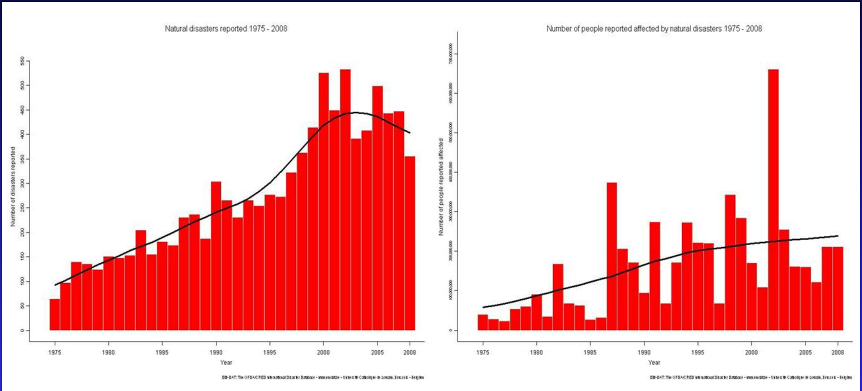
and

Model for Critical Needs with Outsourcing

The number of disasters is increasing globally, as is the number of people affected by disasters. At the same time, with the advent of increasing globalization, viruses are spreading more quickly and creating new challenges for medical and health professionals, researchers, and government officials.

Between 2000 and 2004, the average annual number of disasters was 55% higher than in the period 1994 through 1999, with 33% more humans affected in the former period than in the latter (cf. Balcik and Beamon (2008) and Nagurney and Qiang (2009)).

Natural Disasters (1975–2008)



However, although the average number of disasters has been increasing annually over the past decade the average percentage of needs met by different sectors in the period 2000 through 2005 identifies significant shortfalls.

According to Development Initiatives (2006), based on data in the Financial Tracking System of the Office for the Coordination of Humanitarian Affairs, from 2000-2005, the average needs met by different sectors in the case of disasters were:

- 79% by the food sector;
- 37% of the health needs;
- 35% of the water and sanitation needs;
- 28% of the shelter and non-food items, and
- 24% of the economic recovery and infrastructure needs.

Hurricane Katrina in 2005

Hurricane Katrina has been called an "American tragedy," in which essential services failed completely (Guidotti (2006)).

Haiti Earthquake in 2010

Delivering the humanitarian relief supplies (water, food, medicines, etc.) to the victims was a major logistical challenge.

The Triple Disaster in Japan on March 11, 2011

H1N1 (Swine) Flu

As of May 2, 2010, worldwide, more than 214 countries and overseas territories or communities have reported laboratory confirmed cases of pandemic influenza H1N1 2009, including over 18,001 deaths (www.who.int).

Parts of the globe experienced serious flu vaccine shortages, both seasonal and H1N1 (swine) ones, in late 2009.

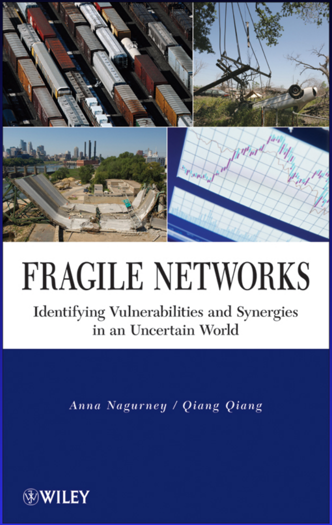
An Example of a Critical Medicine Shortage – Cytarabine

In the past year, the US experienced shortages of the critical drug, cytarabine, due to manufacturer production problems.

Due to the severity of this medical crisis for leukemia patients, Food and Drug Administration is exploring the possibility of importing this medical product (Larkin (2011)).

Hospira re-entered the market in March 2011 and has made the manufacture of cytarabine a priority ahead of other products.

Fragile Networks



We are living in a world of *Fragile Networks*.

Background and Motivation

Underlying the delivery of goods and services in times of crises, such as in the case of disasters, pandemics, and life-threatening major disruptions, are supply chains, without which essential products do not get delivered in a timely manner, with possible increased disease, injuries, and casualties.

It is clear that better-designed supply chain networks would have facilitated and enhanced various emergency preparedness and relief efforts and would have resulted in less suffering and lives lost.

Supply chain networks provide the logistical backbones for the provision of products as well as services both in corporate as well as in emergency and humanitarian operations.

Here we focus on supply chains in the case of

Critical Needs Products.

Critical Needs Products

Critical needs products are those that are essential to the survival of the population, and can include, for example, vaccines, medicine, food, water, etc., depending upon the particular application.

The demand for the product should be met as nearly as possible since otherwise there may be additional loss of life.

In times of crises, a system-optimization approach is mandated since the demands for critical supplies should be met (as nearly as possible) at minimal total cost.

An Overview of Some of the Relevant Literature

- M. J. Beckmann, C. B. McGuire, and C. B. Winsten (1956) *Studies in the Economics of Transportation*, Yale University Press, New Haven, Connecticut.
- S. C. Dafermos and F. T. Sparrow (1969) "The Traffic Assignment Problem for a General Network," *Journal of Research of the National Bureau of Standards* **73B**, 91-118.
- D. E. Boyce, H. S. Mahmassani, and A. Nagurney (2005) "A Retrospective on Beckmann, McGuire, and Winsten's *Studies in the Economics of Transportation*," *Papers in Regional Science* **84**, 85-103.
- A. Nagurney (2009) "A System-Optimization Perspective for Supply Chain Network Integration: The Horizontal Merger Case," *Transportation Research E* **45**, 1-15.

- A. Nagurney, T. Woolley, and Q. Qiang (2010) "Multiproduct Supply Chain Horizontal Network Integration: Models, Theory, and Computational Results," *International Journal of Operational Research* **17**, 333-349.
- A. Nagurney (2010) "Formulation and Analysis of Horizontal Mergers Among Oligopolistic Firms with Insights into the Merger Paradox: A Supply Chain Network Perspective," *Computational Management Science* **7**, 377-401.
- A. Nagurney (2010) "Supply Chain Network Design Under Profit Maximization and Oligopolistic Competition," *Transportation Research E* **46**, 281-294.
- Z. Liu and A. Nagurney (2011) "Supply Chain Outsourcing Under Exchange Rate Risk and Competition," *Omega* **39**, 539-549.

This part of the presentation is based on the paper:

"Supply Chain Network Design for Critical Needs with Outsourcing,"

A. Nagurney, M. Yu, and Q. Qiang (2011), *Papers in Regional Science* **90**, 123-142.

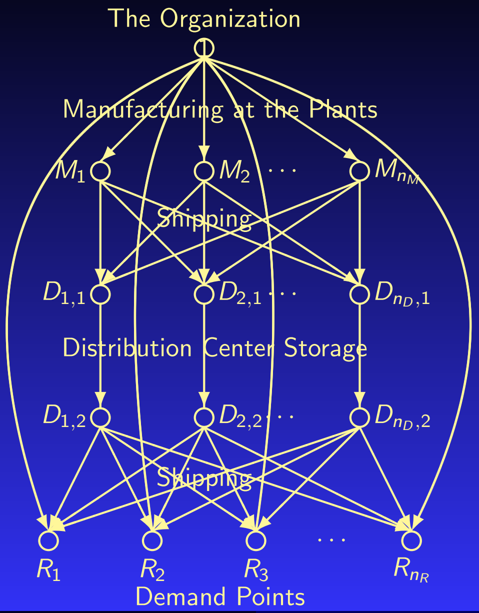
where additional background as well as references can be found.

We assume that the organization (government, humanitarian one, socially responsible firm, etc.) is considering n_M manufacturing facilities/plants; n_D distribution centers, but must serve the n_R demand points.

The supply chain network is modeled as a network $G = [N, L]$, consisting of the set of nodes N and the set of links L. Let L^1 and L^2 denote the links associated with "in house" supply chain activities and the outsourcing activities, respectively. The paths joining the origin node to the destination nodes represent sequences of supply chain network activities that ensure that the product is produced and, ultimately, delivered to those in need at the demand points.

The optimization model can handle both design (from scratch) and redesign scenarios.

Supply Chain Network Topology with Outsourcing



The Links

The possible manufacturing links from the top-tiered node 1 are connected to the possible manufacturing nodes of the organization, which are denoted, respectively, by: $M_1, \ldots, M_{n_M}$.

The possible shipment links from the manufacturing nodes, are connected to the possible distribution center nodes of the organization, denoted by $D_{1,1}, \ldots, D_{n_D,1}$.

The links joining nodes $D_{1,1}, \ldots, D_{n_D,1}$ with nodes $D_{1,2}, \ldots, D_{n_D,2}$ correspond to the possible storage links.

There are possible shipment links joining the nodes $D_{1,2}, \ldots, D_{n_D,2}$ with the demand nodes: $R_1, \ldots, R_{n_R}$.

There are also outsourcing links, which may join the top node to each bottom node (or the relevant nodes for which the outsourcing activity is feasible, as in production, storage, or distribution, or a combination thereof). The organization does not control the capacities on these links since they have been established by the particular firm that corresponds to the outsource link.

The ability to outsource supply chain network activities for critical needs products provides alternative pathways for the production and delivery of products during times of crises such as disasters.

Demands, Path Flows, and Link Flows

Let d_k denote the demand at demand point k; $k = 1, \ldots, n_R$, which is a random variable with probability density function given by $\mathcal{F}_k(t)$. Let x_p represent the nonnegative flow of the product on path p; f_a denote the flow of the product on link a.

Conservation of Flow Between Path Flows and Link Flows

$$f_a = \sum_{p \in P} x_p \delta_{ap}, \quad \forall a \in L, \tag{1}$$

that is, the total amount of a product on a link is equal to the sum of the flows of the product on all paths that utilize that link. $\delta_{ap} = 1$ if link a is contained in path p, and $\delta_{ap} = 0$, otherwise.

Supply Shortage and Surplus

Let

$$v_k \equiv \sum_{p \in P_{w_k}} x_p, \quad k = 1, \ldots, n_R, \tag{2}$$

where v_k can be interpreted as the *projected demand* at demand market k; $k = 1, \ldots, n_R$. Then,

$$\Delta_k^- \equiv \max\{0, d_k - v_k\}, \quad k = 1, \ldots, n_R, \tag{3}$$

$$\Delta_k^+ \equiv \max\{0, v_k - d_k\}, \quad k = 1, \ldots, n_R, \tag{4}$$

where Δ_k^- and Δ_k^+ represent the supply shortage and surplus at demand point k, respectively. The expected values of Δ_k^- and Δ_k^+ are given by:

$$E(\Delta_k^-) = \int_{v_k}^{\infty} (t - v_k)\mathcal{F}_k(t)d(t), \quad k = 1, \ldots, n_R, \tag{5}$$

$$E(\Delta_k^+) = \int_0^{v_k} (v_k - t)\mathcal{F}_k(t)d(t), \quad k = 1, \ldots, n_R. \tag{6}$$

The Operation Costs, Investment Costs and Penalty Costs

The total cost on a link is assumed to be a function of the flow of the product on the link. We have, thus, that

$$\hat{c}_a = \hat{c}_a(f_a), \quad \forall a \in L. \tag{7}$$

We denote the nonnegative existing capacity on a link a by $\bar{u}_a$, $\forall a \in L$. Note that the organization can add capacity to the "in house" link a; $\forall a \in L^1$. We assume that

$$\hat{\pi}_a = \hat{\pi}_a(u_a), \quad \forall a \in L^1. \tag{8}$$

The expected total penalty at demand point k; $k = 1, \ldots, n_R$, is,

$$E(\lambda_k^- \Delta_k^- + \lambda_k^+ \Delta_k^+) = \lambda_k^- E(\Delta_k^-) + \lambda_k^+ E(\Delta_k^+), \tag{9}$$

where λ_k^- is the unit penalty of supply shortage at demand point k and λ_k^+ is that of supply surplus. Note that $\lambda_k^- E(\Delta_k^-) + \lambda_k^+ E(\Delta_k^+)$ is a function of the path flow vector x.

The Supply Chain Network Design Optimization Problem

The organization seeks to determine the optimal levels of product processed on each supply chain network link (including the outsourcing links) coupled with the optimal levels of capacity investments in its supply chain network activities subject to the minimization of the total cost.

The total cost includes the total cost of operating the various links, the total cost of capacity investments, and the expected total supply shortage/surplus penalty.

The Supply Chain Network Design Optimization Problem

$$\text{Minimize} \quad \sum_{a \in L} \hat{c}_a(f_a) + \sum_{a \in L^1} \hat{\pi}_a(u_a) + \sum_{k=1}^{n_R} (\lambda_k^- E(\Delta_k^-) + \lambda_k^+ E(\Delta_k^+)) \tag{10}$$

subject to: constraints (1), (2) and

$$f_a \leq \bar{u}_a + u_a, \quad \forall a \in L^1, \tag{11}$$

$$f_a \leq \bar{u}_a, \quad \forall a \in L^2, \tag{12}$$

$$u_a \geq 0, \quad \forall a \in L^1, \tag{13}$$

$$x_p \geq 0, \quad \forall p \in P. \tag{14}$$

The Feasible Set

We associate the Lagrange multiplier ω_a with constraint (11) for link $a \in L^1$ and we denote the associated optimal Lagrange multiplier by ω_a^*. Similarly, Lagrange multiplier γ_a is associated with constraint (12) for link $a \in L^2$ with the optimal multiplier denoted by γ_a^*. These two terms may also be interpreted as the price or value of an additional unit of capacity on link a. We group these Lagrange multipliers into the vectors ω and γ, respectively. Let K denote the feasible set such that

$$K \equiv \{(x, u, \omega, \gamma) | x \in R_+^{n_P}, u \in R_+^{n_{L^1}}, \omega \in R_+^{n_{L^1}}, \text{and}\, \gamma \in R_+^{n_{L^2}}\}.$$

Theorem

The optimization problem is equivalent to the variational inequality problem: determine the vector of optimal path flows, the vector of optimal link capacity enhancements, and the vectors of optimal Lagrange multipliers $(x^*, u^*, \omega^*, \gamma^*) \in K$, such that:

$$\sum_{k=1}^{n_R} \sum_{p \in P_{w_k}} \left[\frac{\partial \hat{C}_p(x^*)}{\partial x_p} + \sum_{a \in L^1} \omega_a^* \delta_{ap} + \sum_{a \in L^2} \gamma_a^* \delta_{ap} + \lambda_k^+ P_k \left(\sum_{p \in P_{w_k}} x_p^* \right) \right.$$

$$\left. -\lambda_k^- \left(1 - P_k \left(\sum_{p \in P_{w_k}} x_p^* \right) \right) \right] \times [x_p - x_p^*]$$

$$+ \sum_{a \in L^1} \left[\frac{\partial \hat{\pi}_a(u_a^*)}{\partial u_a} - \omega_a^* \right] \times [u_a - u_a^*] + \sum_{a \in L^1} [\bar{u}_a + u_a^* - \sum_{p \in P} x_p^* \delta_{ap}] \times [\omega_a - \omega_a^*]$$

$$+ \sum_{a \in L^2} [\bar{u}_a - \sum_{p \in P} x_p^* \delta_{ap}] \times [\gamma_a - \gamma_a^*] \geq 0, \quad \forall (x, u, \omega, \gamma) \in K. \qquad (15)$$

Theorem (cont'd.)

In addition, (15) can be reexpressed in terms of links flows as: determine the vector of optimal link flows, the vectors of optimal projected demands and link capacity enhancements, and the vectors of optimal Lagrange multipliers $(f^*, v^*, u^*, \omega^*, \gamma^*) \in K^1$*, such that:*

$$\sum_{a\in L^1}\left[\frac{\partial \hat{c}_a(f_a^*)}{\partial f_a}+\omega_a^*\right]\times[f_a-f_a^*]+\sum_{a\in L^2}\left[\frac{\partial \hat{c}_a(f_a^*)}{\partial f_a}+\gamma_a^*\right]\times[f_a-f_a^*]$$

$$+\sum_{a\in L^1}\left[\frac{\partial \hat{\pi}_a(u_a^*)}{\partial u_a}-\omega_a^*\right]\times[u_a-u_a^*]$$

$$+\sum_{k=1}^{n_R}\left[\lambda_k^+P_k(v_k^*)-\lambda_k^-(1-P_k(v_k^*))\right]\times[v_k-v_k^*]+\sum_{a\in L^1}[\bar{u}_a+u_a^*-f_a^*]\times[\omega_a-\omega_a^*]$$

$$+\sum_{a\in L^2}[\bar{u}_a-f_a^*]\times[\gamma_a-\gamma_a^*]\geq 0, \quad \forall (f,v,u,\omega,\gamma)\in K^1, \qquad (16)$$

where $K^1 \equiv \{(f,v,u,\omega,\gamma)|\exists x\geq 0,$ *and* $(1),(2),(13),$ *and* (14) *hold, and* $\omega \geq 0, \quad \gamma\geq 0\}$.

Applications to Vaccine Production

and

Emergencies

By applying the general theoretical model to the company's data, the firm can determine whether it needs to expand its facilities (or not), how much of the vaccine to produce where, how much to store where, and how much to have shipped to the various demand points. Also, it can determine whether it should outsource any of its vaccine production and at what level.

The firm by solving the model with its company-relevant data can then ensure *that the price that it receives for its vaccine production and delivery is appropriate* and that it recovers its incurred costs and obtains, if negotiated correctly, an equitable profit.

Applications to Emergencies

A company can, using the model, prepare and plan for an emergency such as a natural disaster in the form of a hurricane and identify where to store a necessary product (such as food packets, for example) so that the items can be delivered to the demand points in a timely manner and at minimal total cost.

The Algorithm, Explicit Formulae,

and

Numerical Examples

The Algorithm

At an iteration τ of the Euler method (see Dupuis and Nagurney (1993) and Nagurney and Zhang (1996)) one computes:

$$X^{\tau+1} = P_{\mathcal{K}}(X^{\tau} - a_{\tau} F(X^{\tau})), \tag{17}$$

where $P_{\mathcal{K}}$ is the projection on the feasible set $\mathcal{K}$ and F is the function that enters the variational inequality problem: determine $X^* \in \mathcal{K}$ such that

$$\langle F(X^*)^T, X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{K}, \tag{18}$$

where $\langle \cdot, \cdot \rangle$ is the inner product in n-dimensional Euclidean space, $X \in R^n$, and $F(X)$ is an n-dimensional function from $\mathcal{K}$ to R^n, with $F(X)$ being continuous.

The sequence $\{a_{\tau}\}$ must satisfy: $\sum_{\tau=0}^{\infty} a_{\tau} = \infty$, $a_{\tau} > 0$, $a_{\tau} \to 0$, as $\tau \to \infty$.

Explicit Formulae for (17) to the Supply Chain Network Design Variational Inequality (15)

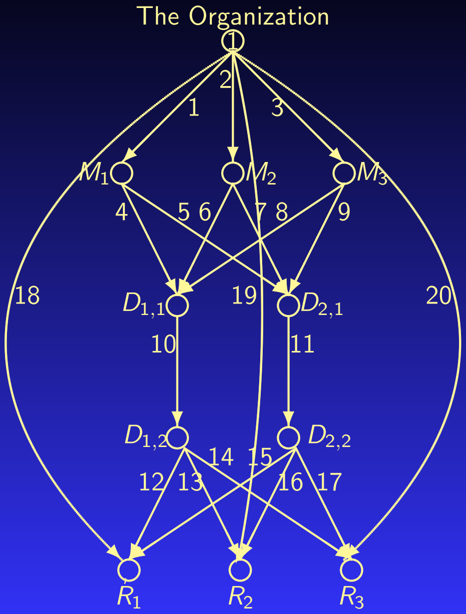
$$x_p^{\tau+1} = \max\{0, x_p^\tau + a_\tau(\lambda_k^-(1 - P_k(\sum_{p\in P_{w_k}} x_p^\tau)) - \lambda_k^+ P_k(\sum_{p\in P_{w_k}} x_p^\tau)$$

$$-\frac{\partial \hat{C}_p(x^\tau)}{\partial x_p} - \sum_{a\in L^1} \omega_a^\tau \delta_{ap} - \sum_{a\in L^2} \gamma_a^\tau \delta_{ap})\}, \forall p \in P; \quad (19)$$

$$u_a^{\tau+1} = \max\{0, u_a^\tau + a_\tau(\omega_a^\tau - \frac{\partial \hat{\pi}_a(u_a^\tau)}{\partial u_a})\}, \quad \forall a \in L^1; \quad (20)$$

$$\omega_a^{\tau+1} = \max\{0, \omega_a^\tau + a_\tau(\sum_{p\in P} x_p^\tau \delta_{ap} - \bar{u}_a - u_a^\tau)\}, \quad \forall a \in L^1; \quad (21)$$

$$\gamma_a^{\tau+1} = \max\{0, \gamma_a^\tau + a_\tau(\sum_{p\in P} x_p^\tau \delta_{ap} - \bar{u}_a)\}, \quad \forall a \in L^2. \quad (22)$$


The Organization
1
1
2
3
M_1
M_2
M_3
4
5 6
7 8
9
18
19
20
$D_{1,1}$
$D_{2,1}$
10
11
$D_{1,2}$
$D_{2,2}$
14 15
12 13
16 17
R_1
R_2
R_3

Example 1

The demands at the three demand points followed a uniform probability distribution on the intervals $[0,10]$, $[0,20]$, and $[0,30]$, respectively:

$$P_1(\sum_{p\in P_{w_1}} x_p) = \frac{\sum_{p\in P_{w_1}} x_p}{10}, \quad P_2(\sum_{p\in P_{w_2}} x_p) = \frac{\sum_{p\in P_{w_2}} x_p}{20},$$

$$P_3(\sum_{p\in P_{w_3}} x_p) = \frac{\sum_{p\in P_{w_3}} x_p}{30},$$

where $w_1 = (1, R_1)$, $w_2 = (1, R_2)$, and $w_3 = (1, R_3)$.
The penalties were:

$$\lambda_1^- = 50, \quad \lambda_1^+ = 0; \quad \lambda_2^- = 50, \quad \lambda_2^+ = 0; \quad \lambda_3^- = 50, \quad \lambda_3^+ = 0.$$

The capacities associated with the three outsourcing links were:

$$\bar{u}_{18} = 5, \quad \bar{u}_{19} = 10, \quad \bar{u}_{20} = 5.$$

We set $\bar{u}_a = 0$ for all links $a \in L^1$.

Table: Total Cost Functions and Solution for Example 1

Link a	$\hat{c}_a(f_a)$	$\hat{\pi}_a(u_a)$	f_a^*	u_a^*	ω_a^*	γ_a^*
1	$f_1^2 + 2f_1$	$.5u_1^2 + u_1$	1.34	1.34	2.34	–
2	$.5f_2^2 + f_2$	$.5u_2^2 + u_2$	2.47	2.47	3.47	–
3	$.5f_3^2 + f_3$	$.5u_3^2 + u_3$	2.05	2.05	3.05	–
4	$1.5f_4^2 + 2f_4$	$.5u_4^2 + u_4$	0.61	0.61	1.61	–
5	$f_5^2 + 3f_5$	$.5u_5^2 + u_5$	0.73	0.73	1.73	–
6	$f_6^2 + 2f_6$	$.5u_6^2 + u_6$	0.83	0.83	1.83	–
7	$.5f_7^2 + 2f_7$	$.5u_7^2 + u_7$	1.64	1.64	2.64	–
8	$.5f_8^2 + 2f_8$	$.5u_8^2 + u_8$	1.67	1.67	2.67	–
9	$f_9^2 + 5f_9$	$.5u_9^2 + u_9$	0.37	0.37	1.37	–
10	$.5f_{10}^2 + 2f_{10}$	$.5u_{10}^2 + u_{10}$	3.11	3.11	4.11	–
11	$f_{11}^2 + f_{11}$	$.5u_{11}^2 + u_{11}$	2.75	2.75	3.75	–
12	$.5f_{12}^2 + 2f_{12}$	$.5u_{12}^2 + u_{12}$	0.04	0.04	1.04	–
13	$.5f_{13}^2 + 5f_{13}$	$.5u_{13}^2 + u_{13}$	0.00	0.00	0.45	–

Table: Total Cost Functions and Solution for Example 1 (continued)

Link a	$\hat{c}_a(f_a)$	$\hat{\pi}_a(u_a)$	f_a^*	u_a^*	ω_a^*	γ_a^*
14	f_{14}^2	$.5u_{14}^2 + u_{14}$	3.07	3.07	4.07	–
15	$f_{15}^2 + 2f_{15}$	$.5u_{15}^2 + u_{15}$	0.00	0.00	0.45	–
16	$.5f_{16}^2 + 3f_{16}$	$.5u_{16}^2 + u_{16}$	0.00	0.00	0.45	–
17	$.5f_{17}^2 + 2f_{17}$	$.5u_{17}^2 + u_{17}$	2.75	2.75	3.75	–
18	$10f_{18}$	–	5.00	–	–	14.77
19	$12f_{19}$	–	10.00	–	–	13.00
20	$15f_{20}$	–	5.00	–	–	16.96

Note that the optimal supply chain network design for Example 1 is, hence, as the initial topology but with links 13, 15, and 16 removed since those links have zero capacities and associated flows. Note that the organization took advantage of outsourcing to the full capacity available.

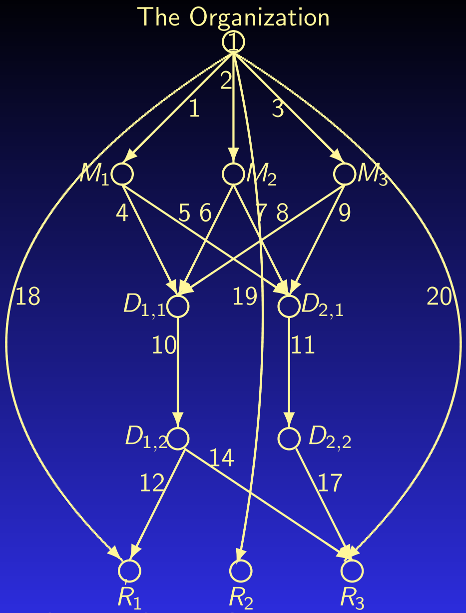


Figure: The Optimal Supply Chain Network Design for Example 1

Example 2

Example 2 had the identical data to that in Example 1 except that we now assumed that the organization had capacities on its supply chain network activities where $\bar{u}_a = 10$, for all $a \in L^1$.

Table: Total Cost Functions and Solution for Example 2

Link a	$\hat{c}_a(f_a)$	$\hat{\pi}_a(u_a)$	f_a^*	u_a^*	ω_a^*	γ_a^*
1	$f_1^2 + 2f_1$	$.5u_1^2 + u_1$	1.84	0.00	0.00	–
2	$.5f_2^2 + f_2$	$.5u_2^2 + u_2$	4.51	0.00	0.00	–
3	$.5f_3^2 + f_3$	$.5u_3^2 + u_3$	3.85	0.00	0.00	–
4	$1.5f_4^2 + 2f_4$	$.5u_4^2 + u_4$	0.88	0.00	0.00	–
5	$f_5^2 + 3f_5$	$.5u_5^2 + u_5$	0.97	0.00	0.00	–
6	$f_6^2 + 2f_6$	$.5u_6^2 + u_6$	1.40	0.00	0.00	–
7	$.5f_7^2 + 2f_7$	$.5u_7^2 + u_7$	3.11	0.00	0.00	–
8	$.5f_8^2 + 2f_8$	$.5u_8^2 + u_8$	3.47	0.00	0.00	–
9	$f_9^2 + 5f_9$	$.5u_9^2 + u_9$	0.38	0.00	0.00	–

Table: Total Cost Functions and Solution for Example 2 (continued)

Link a	$\hat{c}_a(f_a)$	$\hat{\pi}_a(u_a)$	f_a^*	u_a^*	ω_a^*	γ_a^*
10	$.5f_{10}^2 + 2f_{10}$	$.5u_{10}^2 + u_{10}$	5.75	0.00	0.00	–
11	$f_{11}^2 + f_{11}$	$.5u_{11}^2 + u_{11}$	4.46	0.00	0.00	–
12	$.5f_{12}^2 + 2f_{12}$	$.5u_{12}^2 + u_{12}$	0.82	0.00	0.00	–
13	$.5f_{13}^2 + 5f_{13}$	$.5u_{13}^2 + u_{13}$	0.52	0.00	0.00	–
14	f_{14}^2	$.5u_{14}^2 + u_{14}$	4.41	0.00	0.00	–
15	$f_{15}^2 + 2f_{15}$	$.5u_{15}^2 + u_{15}$	0.00	0.00	0.00	–
16	$.5f_{16}^2 + 3f_{16}$	$.5u_{16}^2 + u_{16}$	0.05	0.00	0.00	–
17	$.5f_{17}^2 + 2f_{17}$	$.5u_{17}^2 + u_{17}$	4.41	0.00	0.00	–
18	$10f_{18}$	–	5.00	–	–	10.89
19	$12f_{19}$	–	10.00	–	–	11.59
20	$15f_{20}$	–	5.00	–	–	11.96

Note that links 13 and 16 now have positive associated flows although at very low levels.

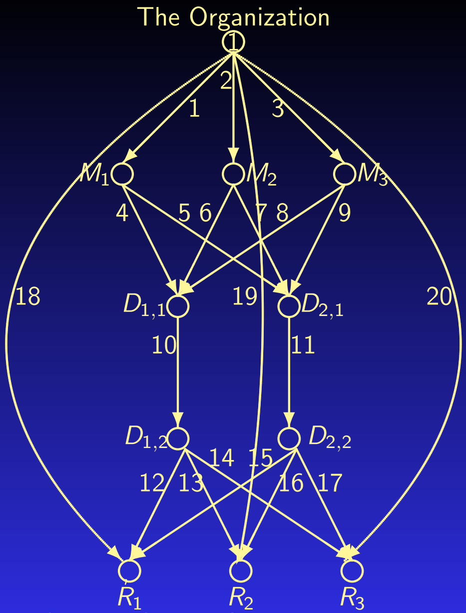


Figure: The Optimal Supply Chain Network Design for Example 2

Example 3

Example 3 had the same data as Example 2 except that we changed the probability distributions so that we now had:

$$P_1\Big(\sum_{p \in P_{w_1}} x_p\Big) = \frac{\sum_{p \in P_{w_1}} x_p}{110},$$

$$P_2\Big(\sum_{p \in P_{w_2}} x_p\Big) = \frac{\sum_{p \in P_{w_2}} x_p}{120},$$

$$P_3\Big(\sum_{p \in P_{w_3}} x_p\Big) = \frac{\sum_{p \in P_{w_3}} x_p}{130}.$$

Table: Total Cost Functions and Solution for Example 3

Link a	$\hat{c}_a(f_a)$	$\hat{\pi}_a(u_a)$	f_a^*	u_a^*	ω_a^*	γ_a^*
1	$f_1^2 + 2f_1$	$.5u_1^2 + u_1$	4.23	0.00	0.00	–
2	$.5f_2^2 + f_2$	$.5u_2^2 + u_2$	9.06	0.00	0.00	–
3	$.5f_3^2 + f_3$	$.5u_3^2 + u_3$	8.61	0.00	0.00	–
4	$1.5f_4^2 + 2f_4$	$.5u_4^2 + u_4$	2.05	0.00	0.00	–
5	$f_5^2 + 3f_5$	$.5u_5^2 + u_5$	2.18	0.00	0.00	–
6	$f_6^2 + 2f_6$	$.5u_6^2 + u_6$	3.28	0.00	0.00	–
7	$.5f_7^2 + 2f_7$	$.5u_7^2 + u_7$	5.77	0.00	0.00	–
8	$.5f_8^2 + 2f_8$	$.5u_8^2 + u_8$	7.01	0.00	0.00	–
9	$f_9^2 + 5f_9$	$.5u_9^2 + u_9$	1.61	0.00	0.00	–
10	$.5f_{10}^2 + 2f_{10}$	$.5u_{10}^2 + u_{10}$	12.34	2.34	3.34	–
11	$f_{11}^2 + f_{11}$	$.5u_{11}^2 + u_{11}$	9.56	0.00	0.00	–
12	$.5f_{12}^2 + 2f_{12}$	$.5u_{12}^2 + u_{12}$	5.82	0.00	0.00	–
13	$.5f_{13}^2 + 5f_{13}$	$.5u_{13}^2 + u_{13}$	2.38	0.00	0.00	–

Table: Total Cost Functions and Solution for Example 3 (continued)

Link a	$\hat{c}_a(f_a)$	$\hat{\pi}_a(u_a)$	f_a^*	u_a^*	ω_a^*	γ_a^*
14	f_{14}^2	$.5u_{14}^2 + u_{14}$	4.14	0.00	0.00	–
15	$f_{15}^2 + 2f_{15}$	$.5u_{15}^2 + u_{15}$	2.09	0.00	0.00	–
16	$.5f_{16}^2 + 3f_{16}$	$.5u_{16}^2 + u_{16}$	2.75	0.00	0.00	–
17	$.5f_{17}^2 + 2f_{17}$	$.5u_{17}^2 + u_{17}$	4.72	0.00	0.00	–
18	$10f_{18}$	–	5.00	–	–	34.13
19	$12f_{19}$	–	10.00	–	–	31.70
20	$15f_{20}$	–	5.00	–	–	29.66

The optimal supply chain network design for Example 3 has the initial topology since there are now positive flows on all the links. It is also interesting to note that there is a significant increase in production volumes by the organization at its manufacturing plants.

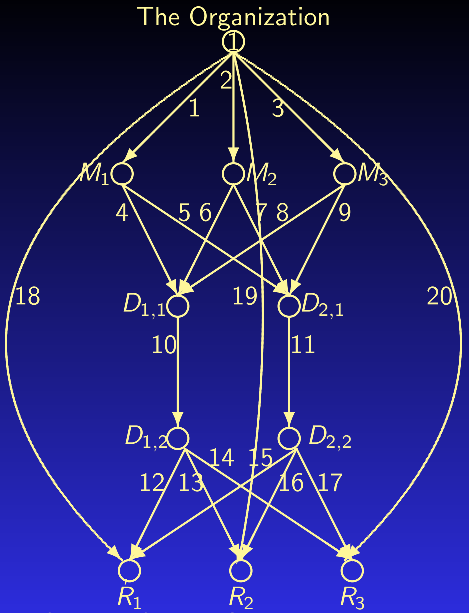


Figure: The Optimal Supply Chain Network Design for Example 3

Extensions to Perishable Products

and

Blood Supply Chains for the Red Cross

A. Nagurney, A. Masoumi, and M. Yu (2010) "Supply Chain Network Operations Management of a Blood Banking System with Cost and Risk Minimization."

- Over 39,000 donations are needed everyday in the United States, and the blood supply is frequently reported to be just 2 days away from running out (American Red Cross (2010)).
- Hospitals with as many days of surgical delays due to blood shortage as 120 a year have been observed (Whitaker et al. (2007)).
- The national estimate for the number of units blood products outdated by blood centers and hospitals was 1,276,000 out of 15,688,000 units (Whitaker et al. (2007)).

The American Red Cross is the major supplier of blood products to hospitals and medical centers satisfying over 45% of the demand for blood components nationally (Walker (2010)).

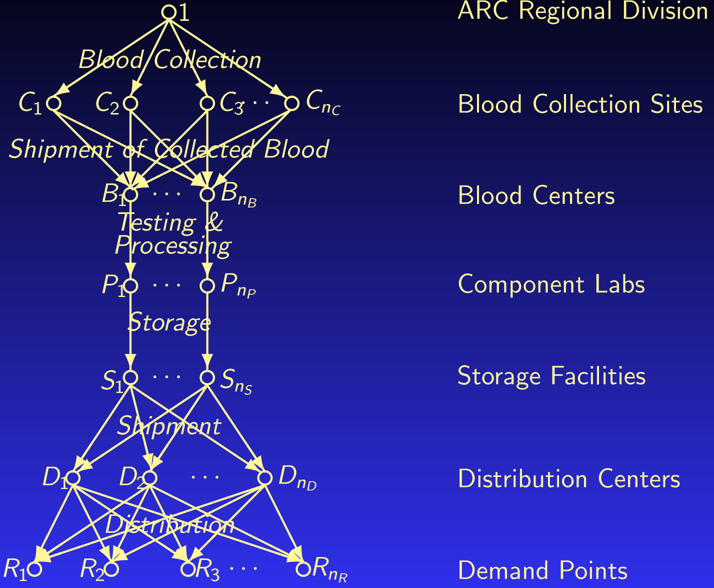
American Red Cross
Together, we can save a life

Background and Motivation

The hospital cost of a unit of red blood cells in the US had a 6.4% increase from 2005 to 2007.

In the US, this criticality has become more of an issue in the Northeastern and Southwestern states since this cost is meaningfully higher compared to that of the Southeastern and Central states.

Supply Chain Network Topology for a Regionalized Blood Bank



We developed a supply chain network optimization model for the management of the procurement, testing and processing, and distribution of a perishable product – that of human blood.

Novel features of the model include:

- It captures *perishability of this life-saving product* through the use of arc multipliers;
- It contains *discarding costs* associated with waste/disposal;
- It handles *uncertainty* associated with demand points;
- It assesses *costs associated with shortages/surpluses at the demand points*, and
- It quantifies the *supply-side risk* associated with procurement.

Teaming in Humanitarian Operations and Network Synergies

A successful team depends on the ability to measure the anticipated synergy of the proposed team, which can be viewed as a merger (cf. Chang (1988)).

- A. Nagurney (2009) "A System-Optimization Perspective for Supply Chain Network Integration: The Horizontal Merger Case," *Transportation Research E* **45**, 1-15.

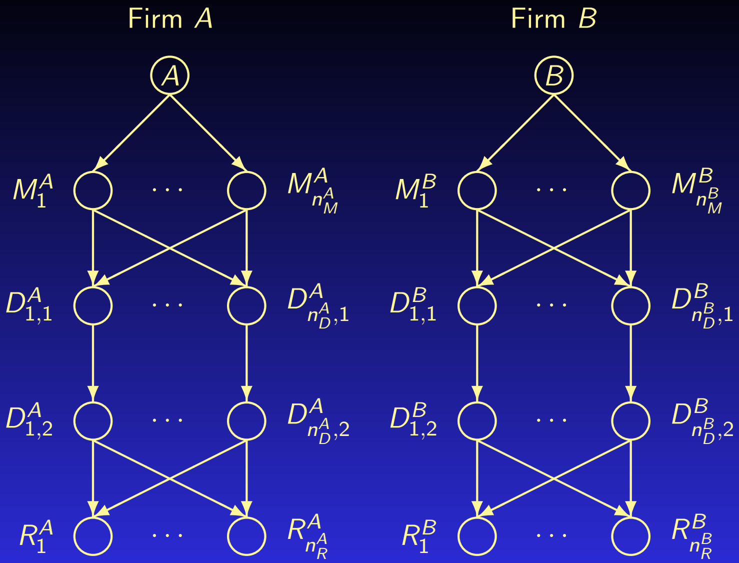


Figure: Case 0: Organizations A and B Prior to a Horizontal Merger

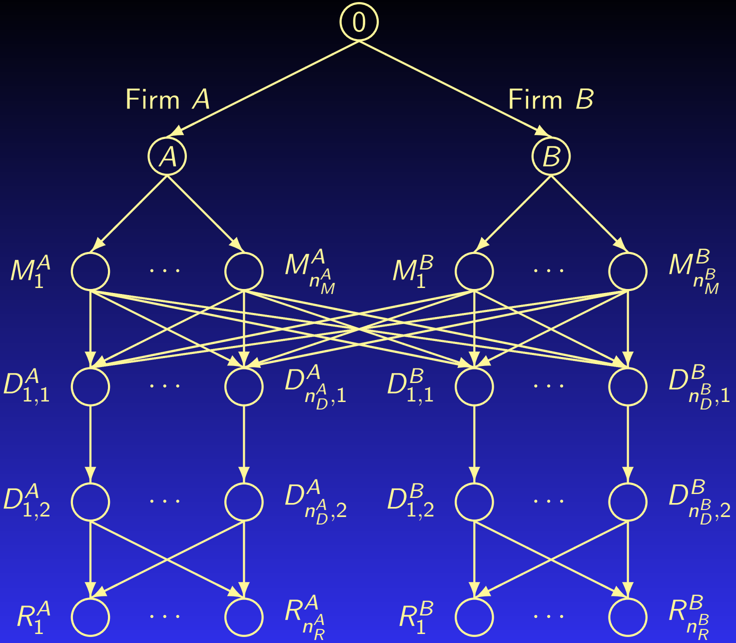


Figure: Case 1: Organizations A and B Team Up or "Merge"

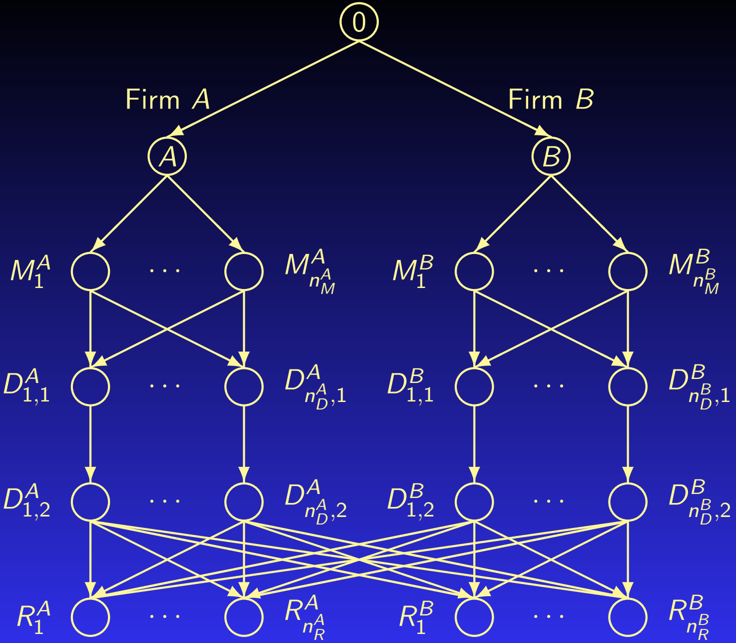


Figure: Case 2: Organizations A and B Merge

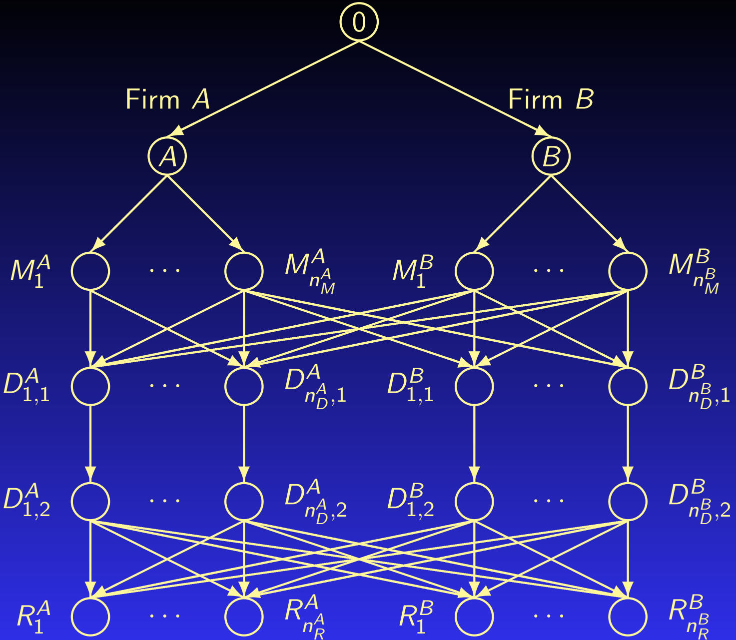


Figure: Case 3: Firms A and B Merge

Synergy Measure

The measure that we utilized in Nagurney (2009) to capture the gains, if any, associated with a horizontal merger Case i; $i = 1, 2, 3$ is as follows:

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

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 $\mathcal{S}^i$; $i = 1, 2, 3$ may also be interpreted as *synergy*.

This model can be applied to the teaming of organizations in the case of humanitarian operations.

Bellagio Conference on Humanitarian Logistics

See: http://hlogistics.som.umass.edu/

Summary, Conclusions,

and

Suggestions for Future Research

- We emphasized the *importance of capturing behavior* in supply chain modeling, analysis, and design.
- We developed an *integrated framework for the design of supply chain networks for critical products* with outsourcing.
- The model utilizes cost minimization within a system-optimization perspective as the primary objective and captures rigorously the uncertainty associated with the demand for critical products at the various demand points.
- The supply chain network design model allows for the investment of enhanced link capacities and the investigation of whether the product should be outsourced or not.
- The framework *can be applied in numerous situations* in which the goal is to produce and deliver a critical product at minimal cost so as to satisfy the demand at various demand points, as closely as possible, given associated penalties for under- and over-supply.

- Our recent research in supply chain network analysis and design has also considered perishable products, as in our blood supply chain contributions.

- In addition, we have been heaving involved in *constructing mathematical models that capture synergies in mergers and acquisitions with the inclusion of risk*.

- Our research in supply chains has also led us to other time-sensitive products, such as *fast fashion*, and

- Finally, we are now working on modeling disequilibrium dynamics and equilibrium states in ecological predator-prey networks, that is, supply chains in nature.

- We expect that future research will include design for robustness and resiliency, which is critical for healthcare.

- Some recent research that we have begun in this direction: "Modeling of Supply Chain Risk Under Disruptions with Performance Measurement and Robustness Analysis," Q. Qiang, A. Nagurney, and J. Dong (2009), in *Managing Supply Chain Risk and Vulnerability: Tools and Methods for Supply Chain Decision Makers*, T. Wu and J. Blackhurst, Editors, Springer, London, England, 91-111.

THANK YOU!

For more information, see: http://supernet.som.umass.edu