

Supply Chain Game Theory Network Models for Disaster Relief

Anna Nagurney

Eugene M. Isenberg Chair in Integrative Studies
Director of the Virtual Center for Supernetworks
Isenberg School of Management
University of Massachusetts
Amherst, Massachusetts 01003

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Many thanks to Professors Rob Curry and Nick Moore for the invitation to speak in your Mathematics Colloquium series!



I was on your beautiful campus when I was interviewed for a faculty position when I was completing my PhD in Applied Mathematics at Brown University.

Outline

- ▶ Background and Inspiration
- ▶ Methodology - The VI Problem
- ▶ Game Theory Model for Post-Disaster Humanitarian Relief
- ▶ The Algorithm
- ▶ A Case Study on Hurricane Katrina
- ▶ An Extension of the Model and Application to Tornadoes in Western Massachusetts
- ▶ Additional Research on Game Theory and Disaster Relief
- ▶ Game Theory and Blood Supply Chains
- ▶ Cybercrime and Cybersecurity
- ▶ Summary and Conclusions

Background and Inspiration

Work in the Naval Defense Sector

After receiving my undergraduate degrees from Brown University in Applied Mathematics and in Russian Language and Literature, I worked in the naval defense sector in beautiful Newport, Rhode Island. My work for two different companies focused on software development for submarines, and, later, on mathematical modeling using networks and optimization. Newport is also the location of the Naval War College.



First Conference Presentation and Publication

My research work at NUSC, now NUWC (Naval Undersea Warfare Center), was presented at a conference at the Naval Postgraduate School in Monterey, California. The title of my paper was, "The Role of Optimal Routing in Multiplatform Naval Task Force Operations," published in the *Proceedings of the Second MIT/ONR Workshop on Distributed Communication and Decision Problems Motivated by Naval C³ Systems*.



I was the only female speaker at this conference.

Off to Grad School for a PhD

Very soon I realized that I wanted a PhD because of the research and my interest in teaching!

Dr. Stella Dafermos was the only female professor at the time in either Engineering or Applied Mathematics at Brown University. I became her first PhD student.



EQUILIBRIUM MODELING, ANALYSIS AND COMPUTATION: THE CONTRIBUTIONS OF STELLA DAFERMOS

ANNA NAGURNEY

(University of Massachusetts, Amherst, Massachusetts)

Received June 1993; accepted August 1993

The research effort in the last fifty (50) years towards the construction in equilibrium modeling, analysis, and computation, and provides a list of key published papers.

On April 5, 1988, with the death of Dr. Stella Dafermos, Professor of Applied Mathematics and Engineering at Brown University, Providence, Rhode Island, the operations research community lost one of its truly original discoverers. Throughout her career, she was the dominant force in developing rigorous mathematical foundations for modeling, analyzing, and numerically computing the behavior of equilibrium systems. Her research applications have ranged from computer systems to transportation systems to economics.

EQUILIBRIUM MODELING

In her first paper, based on her thesis and published in 1969, she introduced the equilibrium behavior of systems as a constrained network problem in their own right, rather than as a means of solving their flows. The growing equilibrium modeling community has followed her lead in this direction, and many modeling and analysis techniques have been developed.

These research applications include, as well as the theoretical models, the theory of tolls, queues, and the theory of queues.

Since then, developed in her paper of 1970, was based on optimization problems, with the observation that the equilibrium behavior of systems can be modeled as an optimization problem. This approach, known as the "optimization approach," has been widely used in the modeling of equilibrium systems. It has been applied to a wide range of problems, including the modeling of traffic flow, the modeling of queueing systems, and the modeling of economic systems.

In 1980, she made a fundamental discovery by observing that the equilibrium behavior of systems can be modeled as a constrained network problem. This discovery has been widely used in the modeling of equilibrium systems. It has been applied to a wide range of problems, including the modeling of traffic flow, the modeling of queueing systems, and the modeling of economic systems.

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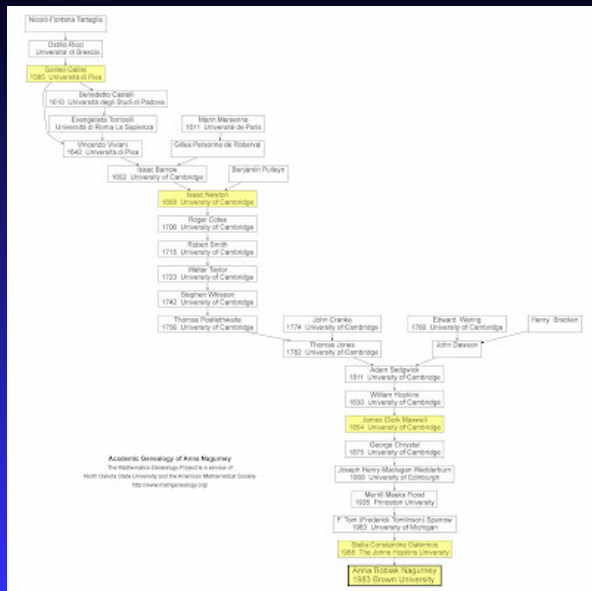
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Stella was the second female to receive a PhD in Operations Research (OR) in the US and that was from Johns Hopkins.

On the Shoulders of Giants - Academic Genealogy



Connections to the US Navy Continue

I had a job offer to be a professor at the US Naval Academy in Annapolis, Maryland but joined the faculty at the University of Massachusetts Amherst.

The connections to the US Navy continue with my brother and niece working in the defense sector and with my niece on the USS Zumwalt, being based in San Diego now.



I spoke at the Naval Academy in Cartagena, Colombia in August 2019



I Work on the Modeling of Network Systems



Much of My Recent Research Has Been on Supply Chains



Some of My Books



Networks in Transportation and Logistics

Networks have assisted in transportation and logistics in numerous sectors, including defense.

The science of networks dates to **1736 - Euler** - the earliest paper on graph theory - Königsberg bridges problem. **1781 - Monge**, who had worked under Napoleon Bonaparte, publishes what is probably the first paper on transportation in minimizing cost.

And, one of my favorite sayings that I share with my students in my Humanitarian Logistics and Healthcare class is:

“There is an old military saying, which speaks volumes: Armchair generals talk strategy. Real generals talk logistics.”

I Teach Humanitarian Logistics and Healthcare



Network Models Are Also Very Useful in Disaster Relief



Network Models for Healthcare Supply Chains



Examples of Some Disasters

- The Indonesian tsunami (and earthquake), December 26, 2004;
- Hurricane Katrina, August 23, 2005;
- The Sichuan earthquake on May 12, 2008;
- The Haiti earthquake that struck on January 12, 2010 and the Chilean one on February 27, 2010;
- The triple disaster in Japan on March 11, 2011;
- Superstorm Sandy, October 29, 2012;
- Hurricanes Harvey, Irma, and Maria that struck in 2017 and Hurricanes Florence and Michael in 2018;
- Typhoons striking China, Japan, and Africa in 2019 and a series of earthquakes hitting Puerto Rico in January 2020;
- The WHO declared the COVID-19 pandemic on March 11, 2020;
- Record breaking wild fires in California and the west in 2020.

Hurricane Katrina, Fukushima, and Superstorm Sandy

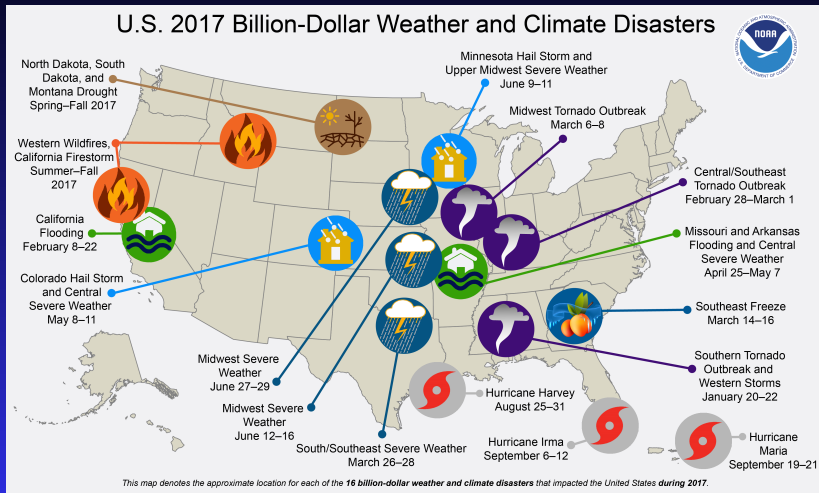


2017 Set a Record for Losses from Natural Disasters

Hurricane Harvey, which made landfall in Texas in August 2017, was the most costly disaster of 2017, causing losses of \$85 billion. *The New York Times* reports that, together with Hurricanes Irma (hitting Florida) and Maria (devastating Puerto Rico), **the 2017 hurricane season caused the most damage ever, with losses reaching \$215 billion.**

Plus, the **damage from wildfires in California** drove insured losses to about \$8 billion.

Billion Dollar Disasters in the United States in 2017



Challenges Associated with Disaster Relief

- Timely delivery of relief items is challenged by damaged and destroyed infrastructure (transportation, telecommunications, hospitals, etc.).
- Shipments of the wrong supplies create congestion and materiel convergence (sometimes referred to as the second disaster).
- ● Within three weeks following the 2010 earthquake in Haiti, 1,000 NGOs were operating in Haiti. News media attention of insufficient water supplies resulted in immense donations to the Dominican Red Cross to assist its island neighbor. Port-au-Prince was saturated with both cargo and gifts-in-kind.
- ● After the Fukushima disaster, there were too many blankets and items of clothing shipped and even broken bicycles.
- ● After Katrina, even tuxedos were delivered to victims.

Better coordination among NGOs is needed.

Challenges Associated with Disaster Relief

The NGO Balancing Act and Driving Forces



According to Charity Navigator, there are 1.4 million registered NGOs in the US. \$410 billion in donations given to US nonprofits and charities in 2017.

Need for Game Theory Network Models for Disaster Relief

Therefore, there is a need to develop appropriate analytical tools that can assist NGOs, as well as governments, in the modeling of complex interactions in disaster relief to improve outcomes.

Methodology - The VI Problem

Methodology - The Variational Inequality Problem

We utilize the theory of variational inequalities for the formulation, analysis, and solution of both centralized and decentralized supply chain network problems.

Definition: The Variational Inequality Problem

The finite-dimensional variational inequality problem, $VI(F, \mathcal{K})$, is to determine a vector $X^ \in \mathcal{K}$, such that:*

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

where F is a given continuous function from \mathcal{K} to R^N , \mathcal{K} is a given closed convex set, and $\langle \cdot, \cdot \rangle$ denotes the inner product in R^N .

Methodology - The Variational Inequality Problem

The vector X consists of **the decision variables** – typically, the flows (products, prices, etc.).

\mathcal{K} is the **feasible set representing how the decision variables are constrained** – for example, the flows may have to be nonnegative; budget constraints may have to be satisfied; similarly, quality and/or time constraints may have to be satisfied.

The function F that enters the variational inequality represents **functions that capture the behavior in the form of the functions such as costs, profits, risk, etc.**

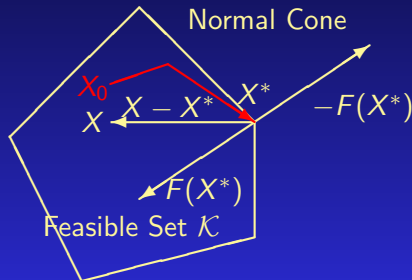
The variational inequality problem contains, as special cases, such mathematical programming problems as:

- systems of equations,
- optimization problems,
- complementarity problems,
- game theory problems, operating under Nash equilibrium,
- and is related to the fixed point problem.

Hence, it is a natural methodology for a spectrum of supply chain network problems from centralized to decentralized ones.

Geometric Interpretation of $\text{VI}(F, \mathcal{K})$ and a Projected Dynamical System (Dupuis and Nagurney, Nagurney and Zhang)

In particular, $F(X^*)$ is “orthogonal” to the feasible set \mathcal{K} at the point X^* .



Associated with a VI is a Projected Dynamical System, which provides the natural underlying dynamics.

To model the **dynamic behavior of complex networks**, including supply chains, we utilize *projected dynamical systems* (PDSs) advanced by Dupuis and Nagurney (1993) in *Annals of Operations Research* and by Nagurney and Zhang (1996) in our book *Projected Dynamical Systems and Variational Inequalities with Applications*.

Such nonclassical dynamical systems are now being used in evolutionary games (Sandholm (2005, 2011)),

ecological predator-prey networks (Nagurney and Nagurney (2011a, b)),

even **neuroscience** (Girard et al. (2008),

dynamic spectrum model for cognitive radio networks (Setoodeh, Haykin, and Moghadam (2012)),

Future Internet Architectures (Saber, Nagurney, Wolf (2014); see also Nagurney et al. (2015)).

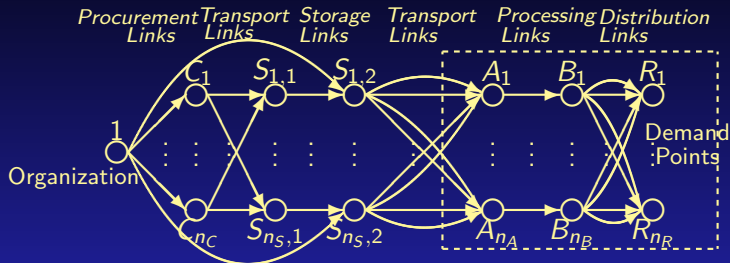
Optimization Models and Disaster Relief

Numerous studies have focused on optimization frameworks in the context of disaster relief:

Haghani and Oh (1996) - Ozdamar et al. (2004) - Yi and Kumar (2007) - Yi and Ozdamar (2007) - Tzeng et al. (2007) - Balcik, Beamon, and Smilowitz (2008) - Nair and Miller-Hooks (2009) - Nagurney and Qiang (2009) - Balcik et al. (2010) - Rawls and Turnquist (2010) - Mete and Zabinsky (2010) - Salmeron and Apte (2010) - Falasca and Zobel (2011) - Nagurney, Yu, and Qiang (2011) - Nagurney et al. (2012) - Caunhye, Nie, and Pokharel (2012) - Vogiatzis, Walteros, and Pardalos (2013) - Holguin-Veras et al. (2013) - Duran et al. (2013) - Vogiatzis and Pardalos (2016) - Nagurney and Nagurney (2016) - Gutjahr and Nolz (2016) - Grass and Fischer (2016) - Nagurney and Qiang (2020)

Additional references on models in humanitarian logistics can be found in the surveys by Ortuno et al. (2013), Liberatore et al. (2013), and Hoyos, Morales, and Akhavan-Tabatabaei (2015).

Time in Disaster Relief



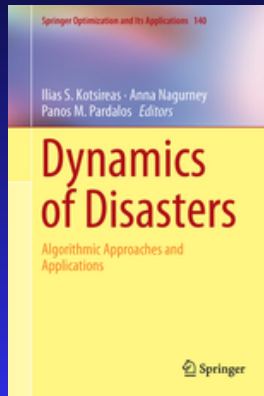
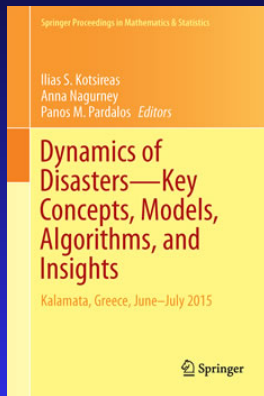
Network Topology of the Integrated Disaster Relief Supply Chain

A. Nagurney, A. H. Masoumi, and M. Yu, "An Integrated Disaster Relief Supply Chain Network Model with Time Targets and Demand Uncertainty." In: *Regional Science Matters: Studies Dedicated to Walter Isard*, P. Nijkamp, A. Rose, and K. Kourtit, Editors, Springer International Publishing Switzerland (2015), pp 287-318.

Game Theory Model for Post-Disaster Humanitarian Relief

Game Theory and Disaster Relief

Although there have been quite a few optimization models developed for disaster relief there are very few game theory models.



Game Theory and Disaster Relief

We developed the first Generalized Nash Equilibrium (GNE) model for post-disaster humanitarian relief, which contains both a financial component and a supply chain component. The Generalized Nash Equilibrium problem is a generalization of the Nash Equilibrium problem (cf. Nash (1950, 1951)).



“A Generalized Nash Equilibrium Network Model for Post-Disaster Humanitarian Relief,” Anna Nagurney, Emilio Alvarez Flores, and Ceren Soylu, *Transportation Research E* **95** (2016), pp 1-18.

Some Literature

Our disaster relief game theory framework entails competition for donors as well as media exposure plus supply chain aspects. We now highlight some of the related literature on these topics.

- Natsios (1995) contends that the cheapest way for relief organizations to fundraise is to provide early relief in highly visible areas.
- Balcik et al. (2010) note that the media is a critical factor affecting relief operations with NGOs seeking visibility to attract more resources from donors. They also review the challenges in coordinating humanitarian relief chains and describe the current and emerging coordination practices in disaster relief.

Some Literature

- Olsen and Carstensen (2003) confirmed the frequently repeated argument that media coverage is critical in relation to emergency relief allocation in a number of cases that they analyzed.
- Van Wassenhove (2006) also emphasizes the role of the media in humanitarian logistics and states that following appeals in the media, humanitarian organizations are often flooded with unsolicited donations that can create bottlenecks in the supply chain.
- Coles and Zhuang (2011) discuss the potential of cooperative game theory in disaster recovery operations and provided a critique.
- Zhuang, Saxton, and Wu (2014) develop a model that reveals the amount of charitable contributions made by donors is positively dependent on the amount of disclosure by the NGOs. **They emphasize that there is a dearth of existing game-theoretic research on nonprofit organizations.**

Game Theory and Disaster Relief

Although there have been quite a few optimization models developed for disaster relief there are very few game theory models.

- Toyasaki and Wakolbinger (2014) constructed the first models of financial flows that captured the strategic interaction between donors and humanitarian organizations using game theory and also included earmarked donations.
- Muggy and Stamm (2014) provide an excellent review of game theory in humanitarian operations and emphasize that there are many untapped research opportunities for modeling in this area.
- Seaberg, Devine, and Zhuang (2017) review 57 papers from 2006 to 2016 on disaster management and game theory and note that the response phase of disaster management has been the phase researched most intensively.

The Network Structure of the Model

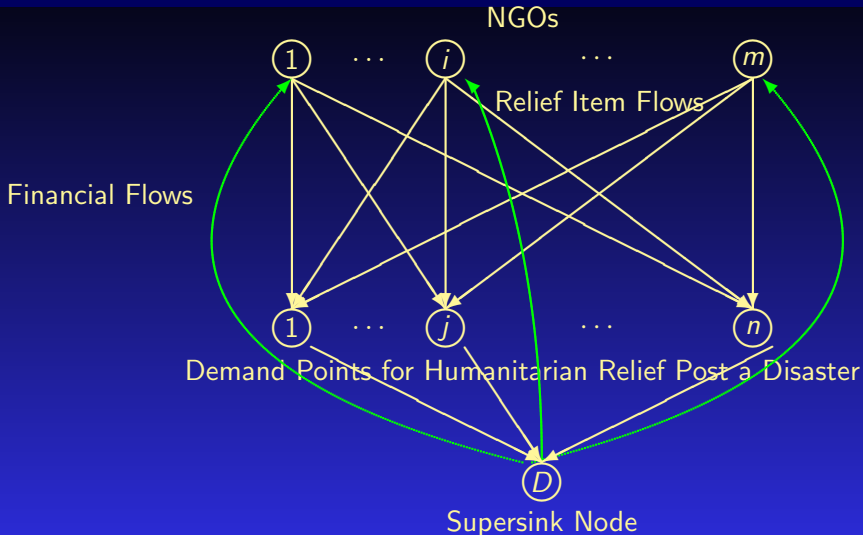


Figure 1: The Network Structure of the Game Theory Model

The Game Theory Model

We assume that each NGO i has, at its disposal, an amount s_i of the relief item that it can allocate post-disaster. Hence, we have the following conservation of flow equation, which must hold for each i ; $i = 1, \dots, m$:

$$\sum_{j=1}^n q_{ij} \leq s_i. \quad (1)$$

In addition, we know that the product flows for each i ; $i = 1, \dots, m$, must be nonnegative, that is:

$$q_{ij} \geq 0, \quad j = 1, \dots, n. \quad (2)$$

Each NGO i incurs a cost, c_{ij} , associated with shipping the relief items to location j , denoted by c_{ij} , where we assume that

$$c_{ij} = c_{ij}(q_{ij}), \quad j = 1, \dots, n, \quad (3)$$

with these cost functions being strictly convex and continuously differentiable.

The Game Theory Model

In addition, each NGO i ; $i = 1, \dots, m$, derives satisfaction or utility associated with providing the relief items to j ; $j = 1, \dots, n$, with its utility over all demand points given by $\sum_{j=1}^n \gamma_{ij} q_{ij}$. Here γ_{ij} is a positive factor representing a measure of satisfaction/utility that NGO i acquires through its supply chain activities to demand point j .

Each NGO i ; $i = 1, \dots, m$, associates a positive weight ω_i with $\sum_{j=1}^n \gamma_{ij} q_{ij}$, which provides a monetization of, in effect, this component of the objective function.

Similar objective function terms have also been used in Nagurney and Li (2017) in the case of hospital competition in terms of prices and quality of care.

The Game Theory Model

Finally, each NGO i ; $i = 1, \dots, m$, based on the media attention and the visibility of NGOs at location j ; $j = 1, \dots, n$, acquires funds from donors given by the expression

$$\beta_i \sum_{j=1}^n P_j(q), \quad (4)$$

where $P_j(q)$ represents the financial funds in donation dollars due to visibility of all NGOs at location j . Hence, β_i is a parameter that reflects the proportion of total donations collected for the disaster at demand point j that is received by NGO i .

Expression (4), therefore, represents the financial flow on the link joining node D with node NGO i .

The Game Theory Model

Each NGO i seeks to maximize its utility with the utility corresponding to the financial gains associated with the visibility through media of the relief item flow allocations, $\beta_i \sum_{j=1}^n P_j(q)$, plus the utility associated with the supply chain aspect of delivery of the relief items, $\omega_i \sum_{j=1}^n \gamma_{ij} q_{ij} - \sum_{j=1}^n c_{ij}(q_{ij})$.

The optimization problem faced by NGO i ; $i = 1, \dots, m$, is, hence,

$$\text{Maximize} \quad \beta_i \sum_{j=1}^n P_j(q) + \omega_i \sum_{j=1}^n \gamma_{ij} q_{ij} - \sum_{j=1}^n c_{ij}(q_{ij}) \quad (5)$$

subject to constraints (1) and (2).

The Game Theory Model

We also have that, at each demand point j ; $j = 1, \dots, n$:

$$\sum_{i=1}^m q_{ij} \geq \underline{d}_j, \quad (6)$$

and

$$\sum_{i=1}^m q_{ij} \leq \bar{d}_j, \quad (7)$$

where \underline{d}_j denotes a lower bound for the amount of the relief items needed at demand point j and \bar{d}_j denotes an upper bound on the amount of the relief items needed post the disaster at demand point j .

We assume that

$$\sum_{i=1}^m s_i \geq \sum_{j=1}^n \underline{d}_j, \quad (8)$$

so that the supply resources of the NGOs are sufficient to meet the minimum financial resource needs.

The Game Theory Model

Each NGO i ; $i = 1, \dots, m$, seeks to determine its optimal vector of relief items or strategies, q_i^* , that maximizes objective function (5), subject to constraints (1), (2), and (6), (7).

Because of a result of Li and Lin (2013), this GNE model can actually be reformulated as an optimization problem.

The Game Theory Model

Theorem: Optimization Formulation of the Generalized Nash Equilibrium Model of Financial Flow of Funds

The above Generalized Nash Equilibrium problem, with each NGO's objective function (5) rewritten as:

$$\text{Minimize} \quad -\beta_i \sum_{j=1}^n P_j(q) - \omega_i \sum_{j=1}^n \gamma_{ij} q_{ij} + \sum_{j=1}^n c_{ij}(q_{ij}) \quad (9)$$

and subject to constraints (1) and (2), with common constraints (6) and (7), is equivalent to the solution of the following optimization problem:

$$\text{Minimize} \quad -\sum_{j=1}^n P_j(q) - \sum_{i=1}^m \sum_{j=1}^n \frac{\omega_i \gamma_{ij}}{\beta_i} q_{ij} + \sum_{i=1}^m \sum_{j=1}^n \frac{1}{\beta_i} c_{ij}(q_{ij}) \quad (10)$$

subject to constraints: (1), (2), (6), and (7).

The Game Theory Model

Variational Inequality (VI) Formulation

The solution q^* with associated Lagrange multipliers λ_k^* , $\forall k$, for the supply constraints; Lagrange multipliers: λ_l^{1*} , $\forall l$, for the lower bound demand constraints, and Lagrange multipliers: λ_l^{2*} , $\forall l$, for the upper bound demand constraints, can be obtained by solving the VI problem: determine $(q^*, \lambda^*, \lambda^{1*}, \lambda^{2*}) \in R_+^{mn+m+2n}$:

$$\begin{aligned} & \sum_{k=1}^m \sum_{l=1}^n \left[- \sum_{j=1}^n \left(\frac{\partial P_j(q^*)}{\partial q_{kl}} \right) - \frac{\omega_k \gamma_{kl}}{\beta_k} + \frac{1}{\beta_k} \frac{\partial c_{kl}(q_{kl}^*)}{\partial q_{kl}} + \lambda_k^* - \lambda_l^{1*} + \lambda_l^{2*} \right] \\ & \quad \times [q_{kl} - q_{kl}^*] \\ & + \sum_{k=1}^m (s_k - \sum_{l=1}^n q_{kl}^*) \times (\lambda_k - \lambda_k^*) + \sum_{l=1}^n \left(\sum_{k=1}^n q_{kl}^* - \underline{d}_l \right) \times (\lambda_l - \lambda_l^{1*}) \\ & + \sum_{l=1}^n (\bar{d}_l - \sum_{k=1}^m q_{kl}^*) \times (\lambda_l^2 - \lambda_l^{2*}) \geq 0, \forall (q, \lambda, \lambda^1, \lambda^2) \in R_+^{mn+m+2n}, \end{aligned} \tag{11}$$

The Game Theory Model

Variational Inequality (VI) Formulation, continued

where λ is the vector of Lagrange multipliers: $(\lambda_1, \dots, \lambda_m)$, λ^1 is the vector of Lagrange multipliers: $(\lambda_1^1, \dots, \lambda_n^1)$, and λ^2 is the vector of Lagrange multipliers: $(\lambda_1^2, \dots, \lambda_n^2)$.

The Algorithm

The Algorithm

We utilize the Euler Method, which is one of the algorithms induced by the general iterative scheme of Dupuis and Nagurney (1993).

Explicit Formulae for the Euler Method Applied to the Game Theory Model

We have the following closed form expression for the product flows $k = 1, \dots, m; l = 1, \dots, n$, at each iteration:

$$q_{kl}^{\tau+1} = \max\{0, \{q_{kl}^{\tau} + a_{\tau}(\sum_{j=1}^n (\frac{\partial P_j(q^{\tau})}{\partial q_{kl}}) + \frac{\omega_k \gamma_{kl}}{\beta_{kl}} - \frac{1}{\beta_k} \frac{\partial c_{kl}(q_{kl}^{\tau})}{\partial q_{kl}} - \lambda_k^{\tau} + \lambda_l^{1\tau} - \lambda_l^{2\tau})\}\}$$

the following closed form expressions for the Lagrange multipliers associated with the supply constraints, respectively, for $k = 1, \dots, m$:

$$\lambda_k^{\tau+1} = \max\{0, \lambda_k^{\tau} + a_{\tau}(-s_k + \sum_{l=1}^n q_{kl}^{\tau})\}.$$

The Algorithm

The following closed form expressions are for the Lagrange multipliers associated with the lower bound demand constraints, respectively, for $l = 1, \dots, n$:

$$\lambda_l^{1^{\tau+1}} = \max\{0, \lambda_l^{1^{\tau}} + a_{\tau}(-\sum_{k=1}^n q_{kl}^{\tau} + \underline{d}_l)\}.$$

The following closed form expressions are for the Lagrange multipliers associated with the upper bound demand constraints, respectively, for $l = 1, \dots, n$:

$$\lambda_l^{2^{\tau+1}} = \max\{0, \lambda_l^{2^{\tau}} + a_{\tau}(-\bar{d}_l + \sum_{k=1}^m q_{kl}^{\tau})\}.$$

Hurricane Katrina Case Study



Hurricane Katrina Case Study

Making landfall in August of 2005, Katrina caused extensive damage to property and infrastructure, left 450,000 people homeless, and took 1,833 lives in Florida, Texas, Mississippi, Alabama, and Louisiana (Louisiana Geographic Information Center (2005)).

Given the hurricane's trajectory, most of the damage was concentrated in Louisiana and Mississippi. In fact, 63% of all insurance claims were in Louisiana, a trend that is also reflected in FEMA's post-hurricane damage assessment of the region (FEMA (2006)).

Hurricane Katrina Case Study

The total damage estimates range from \$105 billion (Louisiana Geographic Information Center (2005)) to \$150 billion (White (2015)), making Hurricane Katrina not only a far-reaching and costly disaster, but also a very challenging environment for providing humanitarian assistance.

We consider 3 NGOs: the Red Cross, the Salvation Army, and Others and 10 Parishes in Louisiana.

Hurricane Katrina Case Study

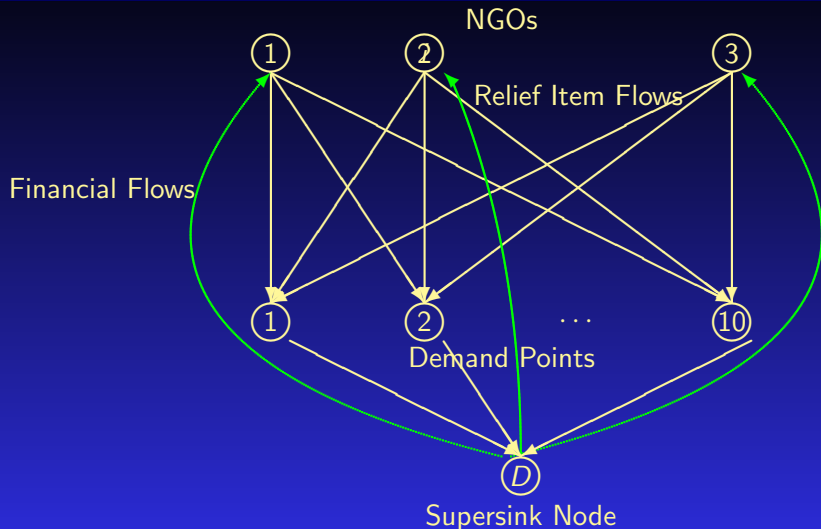


Figure 2: Hurricane Katrina Relief Network Structure

Hurricane Katrina Case Study

The structure of the P_j functions is as follows:

$$P_j(q) = k_j \sqrt{\sum_{i=1}^m q_{ij}}.$$

The weights are:

$$\omega_1 = \omega_2 = \omega_3 = 1,$$

with $\gamma_{ij} = 950$ for $i = 1, 2, 3$ and $j = 1, \dots, 10$.

Hurricane Katrina Case Study

Hurricane Katrina Demand Point Parameters					
Parish	Node j	k_j	\underline{d}_j	\bar{d}_j	p_j : % of homes with major damage
St. Charles	1	8	16.45	50.57	2.4
Terrebonne	2	16	752.26	883.82	6.7
Assumption	3	7	106.36	139.24	1.9
Jefferson	4	29	742.86	1,254.89	19.5
Lafourche	5	6	525.53	653.82	1.7
Orleans	6	42	1,303.99	1,906.80	55.9
Plaquemines	7	30	33.28	62.57	57.5
St. Barnard	8	42	133.61	212.43	78.4
St. James	9	9	127.53	166.39	1.2
St. John the Baptist	10	7	19.05	52.59	6.7

Hurricane Katrina Case Study

We then estimated the cost of providing aid to the Parishes as a function of the total damage in the area and the supply chain efficiency of each NGO. We assume that these costs follow the structures observed by Van Wassenhove (2006) and randomly generate a number based on his research with a mean of $\hat{p} = .8$ and standard deviation of $s = \sqrt{\frac{.8(.2)}{3}}$.

We denote the corresponding coefficients by π_i . Thus, each NGO i ; $i = 1, 2, 3$, incurs costs according to the following functional form:

$$c_{ij}(q_{ij}) = \left(\pi_i q_{ij} + \frac{1}{1 - p_j} \right)^2.$$

Hurricane Katrina Case Study

Data Parameters for NGOs Providing Aid					
NGO	i	π_i	γ_{ij}	β_i	s_i
Others	1	.82	950	.355	1,418
Red Cross	2	.83	950	.55	2,200
Salvation Army	3	.81	950	.095	382

Table 2: NGO Data for the Generalized Nash Equilibrium Problem for Hurricane Katrina

Hurricane Katrina Case Study

Generalized Nash Equilibrium Product Flows (in Millions of Aid Units)			
Demand Point	Others	Red Cross	Salvation Army
St. Charles	17.48	28.89	4.192
Terrebonne	267.023	411.67	73.57
Assumption	49.02	77.26	12.97
Jefferson	263.69	406.68	72.45
Lafourche	186.39	287.96	51.18
Orleans	463.33	713.56	127.1
Plaquemines	21.89	36.54	4.23
St. Barnard	72.31	115.39	16.22
St. James	58.67	92.06	15.66
St. John the Baptist	18.2	29.99	4.40

Table 3: Flows to Demand Points under Generalized Nash Equilibrium

Hurricane Katrina Case Study

The total utility obtained through the above flows for the Generalized Nash Equilibrium for Hurricane Katrina is 9,257,899, with the Red Cross capturing 3,022,705, the Salvation Army 3,600,442.54, and Others 2,590,973.

In addition, we have that the Red Cross, the Salvation Army, and Others receive 2,200.24, 1418.01, and 382.31 million in donations, respectively.

The relief item flows meet at least the lower bound, even if doing so is very expensive due to the damages to the infrastructure in the region.

Hurricane Katrina Case Study

Furthermore, the above flow pattern behaves in a way that, after the minimum requirements are met, any additional supplies are allocated in the most efficient way. For example, only the minimum requirements are met in New Orleans Parish, while the upper bound is met for St. James Parish.

The Nash Equilibrium Solution

If we remove the shared constraints, we obtain a Nash Equilibrium solution, and we can compare the outcomes of the humanitarian relief efforts for Hurricane Katrina under the Generalized Nash Equilibrium concept and that under the Nash Equilibrium concept.

The Nash Equilibrium Solution

Nash Equilibrium Product Flows			
Demand Point	Others	Red Cross	Salvation Army
St. Charles	142.51	220.66	38.97
Terrebonne	142.50	220.68	38.93
Assumption	142.51	220.66	38.98
Jefferson	142.38	220.61	38.74
Lafourche	142.50	220.65	38.98
Orleans	141.21	219.59	37.498
Plaquemines	141.032	219.28	37.37
St. Barnard	138.34	216.66	34.59
St. James	142.51	220.65	38.58
St. John the Baptist	145.51	220.66	38.98

Table 4: Flows to Demand Points under Nash Equilibrium

The Nash Equilibrium Solution

Under the Nash Equilibrium, the NGOs obtain a higher utility than under the Generalized Nash Equilibrium. Specifically, of the total utility 10,346,005.44, 2,804,650 units are received by the Red Cross, 5,198,685 by the Salvation Army, and 3,218,505 are captured by all other NGOs.

Under this product flow pattern, there are total donations of 3,760.73, of which 2,068.4 are donated to the Red Cross, 357.27 to the Salvation Army, and 1,355 to the other players.

The Nash Equilibrium Solution

It is clear that there is a large contrast between the flow patterns under the Generalized Nash and Nash Equilibria. For example, the Nash Equilibrium flow pattern results in about \$500 million less in donations.

While this has strong implications about how collaboration between NGOs can be beneficial for their fundraising efforts, the differences in the general flow pattern highlights a much stronger point.

Additional Insights

Under the Nash Equilibrium, NGOs successfully maximize their utility. Overall, the Nash Equilibrium solution leads to an increase of utility of roughly 21% when compared to the flow patterns under the Generalized Nash Equilibrium.

But they do so at the expense of those in need. In the Nash Equilibrium, each NGO chooses to supply relief items such that costs can be minimized. On the surface, this might be a good thing, but recall that, given the nature of disasters, it is usually more expensive to provide aid to demand points with the greatest needs.

Additional Insights

With this in mind, one can expect oversupply to the demand points with lower demand levels, and undersupply to the most affected under a purely competitive scheme. This behavior can be seen explicitly in the results summarized in the Tables.

For example, St. Charles Parish receives roughly 795% of its upper demand, while Orleans Parish only receives about 30.5% of its minimum requirements. That means that much of the 21% in 'increased' utility is in the form of waste.

In contrast, the flows under the Generalized Nash Equilibrium guarantee that minimum requirements will be met and that there will be no waste; that is to say, *as long as there is a coordinating authority that can enforce the upper and lower bound constraints, the humanitarian relief flow patterns under this bounded competition will be significantly better than under untethered competition.*

An Extension of the Model Published in New Book

At the Dynamics of Disasters conference in Greece, July 5-9, 2017, we presented the paper: “A Variational Equilibrium Network Framework for Humanitarian Organizations in Disaster Relief: Effective Product Delivery Under Competition for Financial Funds,” A. Nagurney, P. Daniele, E. Alvarez Flores, and V. Caruso, now published in *Dynamics of Disasters: Algorithmic Approaches and Applications*, 2018, pp 109-133, Springer International Publishing Switzerland.



The Extended Model

The extended model captures competition for logistic services, has more general cost functions as well as financial donation functions and uses general altruism benefit functions, where the costs associated with logistics are now given by:

$$c_{ij} = c_{ij}(q), \quad i = 1, \dots, m; j = 1, \dots, n.$$

Each NGO i ; $i = 1, \dots, m$, based on the media attention and the visibility of NGOs at demand point j ; $j = 1, \dots, n$, receives financial funds from donors given by the expression

$$\sum_{j=1}^n P_{ij}(q),$$

where $P_{ij}(q)$ denotes the financial funds in donation dollars given to NGO i due to visibility of NGO i at location j . We introduce an altruism/benefit function B_i ; $i = 1, \dots, m$, such that

$$B_i = B_i(q).$$

Extension of the Model

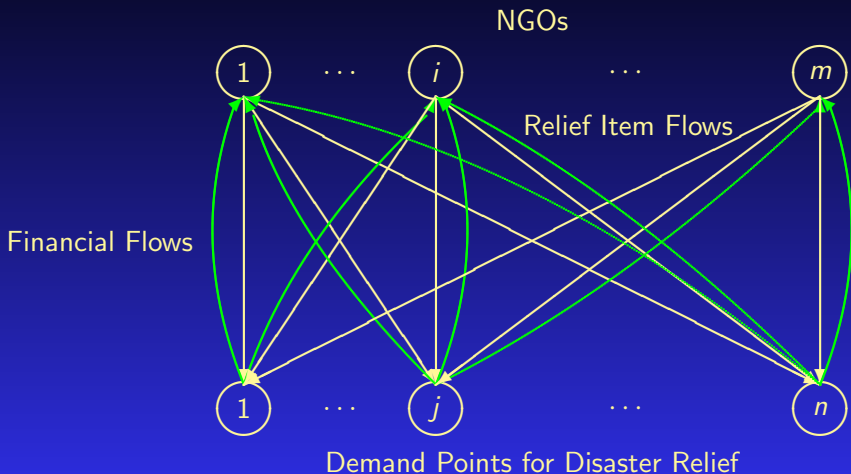


Figure 3: The Network Structure of the Extended Game Theory Model

The Extended Model

The utility function of NGO i ; $i = 1, \dots, m$, is now:

$$\text{Maximize } U_i(q) = \sum_{j=1}^n P_{ij}(q) + \omega_i B_i(q) - \sum_{j=1}^n c_{ij}(q)$$

with the same constraints imposed as the original Generalized Nash Equilibrium model for post-disaster relief.

In the new model, we can no longer reformulate the Generalized Nash Equilibrium as an optimization problem but do so as a Variational Equilibrium, which is a specific kind of GNE (cf. Facchinei and Kanzow (2010), Kulkarni and Shanbhag (2012)) and, hence, we can apply variational inequality theory.

The Extended Model

Definition: Variational Equilibrium

A strategy vector q^ is said to be a variational equilibrium of the above Generalized Nash Equilibrium game if $q^* \in K, q^* \in S$ is a solution of the variational inequality:*

$$-\sum_{i=1}^m \langle \nabla_{q_i} U_i(q^*), q_i - q_i^* \rangle \geq 0, \quad \forall q \in K, \forall q \in S.$$

where the feasible set K_i for each NGO i is:

$$K_i \equiv \{q_i \mid (1) \text{ and } (2) \text{ hold}\}.$$

and $K \equiv \prod_{i=1}^m K_i$. Also,

$$S \equiv \{q \mid (6) \text{ and } (7) \text{ hold}\}.$$

The Extended Model

By utilizing a variational equilibrium, we can take advantage of the well-developed theory of variational inequalities, including algorithms (cf. Nagurney (1999) and the references therein), which are in a more advanced state of development and application than algorithms for quasivariational inequality problems.

Also, the Lagrange multipliers associated with the common constraints are then the same for each NGO and this has a nice economic fairness interpretation.

The Extended Model

The Variational Inequality Formulation of the Generalized Nash Equilibrium for the Extended Model:

Find $(q^, \delta^*, \sigma^*, \varepsilon^*) \in R_+^{mn+m+2n}$:*

$$\begin{aligned} & \sum_{i=1}^m \sum_{j=1}^n \left[\sum_{k=1}^n \frac{\partial c_{ik}(q^*)}{\partial q_{ij}} - \sum_{k=1}^n \frac{\partial P_{ik}(q^*)}{\partial q_{ij}} - \omega_i \frac{\partial B_i(q^*)}{\partial q_{ij}} + \delta_i^* - \sigma_j^* + \varepsilon_j^* \right] \\ & \quad \times (q_{ij} - q_{ij}^*) + \sum_{i=1}^m \left(s_i - \sum_{j=1}^n q_{ij}^* \right) \times (\delta_i - \delta_i^*) \\ & \quad + \sum_{j=1}^n \left(\sum_{i=1}^m q_{ij}^* - \underline{d}_j \right) \times (\sigma_j - \sigma_j^*) + \sum_{j=1}^n \left(\bar{d}_j - \sum_{i=1}^m q_{ij}^* \right) \times (\varepsilon_j - \varepsilon_j^*) \geq 0, \\ & \quad \forall q \in R_+^{mn}, \forall \delta \in R_+^m, \forall \sigma \in R_+^n, \forall \varepsilon \in R_+^n. \end{aligned}$$

The Case Study - Tornadoes Strike Massachusetts

Our case study is inspired by a disaster consisting of a series of tornadoes that hit western Massachusetts on June 1, 2011. **The largest tornado was measured at EF3. It was the worst tornado outbreak in the area in a century (see Flynn (2011)). A wide swath from western to central MA of about 39 miles was impacted.**



The tornado killed 4 persons, injured more than 200 persons, damaged or destroyed 1,500 homes, left over 350 people homeless in Springfield's MassMutual Center arena, left 50,000 customers without power, and brought down thousands of trees.

The Case Study - Tornadoes Strike Massachusetts

FEMA estimated that 1,435 residences were impacted with the following breakdowns: 319 destroyed, 593 sustaining major damage, 273 sustaining minor damage, and 250 otherwise affected. FEMA estimated that the primary impact was damage to buildings and equipment with a cost estimate of \$24,782,299.

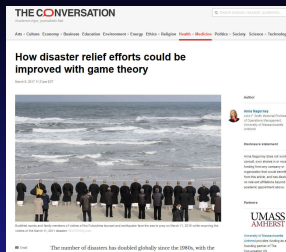
Total damage estimates from the storm exceeded \$140 million, the majority from the destruction of homes and businesses.

Especially impacted were the city of Springfield and the towns of Monson and Brimfield. It has been estimated that, in the aftermath, the Red Cross served about 11,800 meals and the Salvation Army about 20,000 meals (cf. Western Massachusetts Regional Homeland Security Advisory Council (2012)).

We consider the American Red Cross and the Salvation Army as the NGOs, who provide the meals, which are the flows. The demand points are: Springfield, Monson, and Brimfield.

We find in multiple examples comprising our case study of Massachusetts tornadoes that the NGOs garner greater financial funds through the Generalized Nash Equilibrium solution, rather than the Nash equilibrium one. Moreover, the needs of the victims are met under the Generalized Nash Equilibrium solution.

Writing OpEds on the Topic



Writing OpEds in the Pandemic

On August 4, 2020, I published an article in *The Conversation*,

“The Raging Competition for Medical Supplies is not a Game, but Game Theory Can Help.”



On September 18, 2020, I published another article in *The Conversation*,

“Keeping Coronavirus Vaccines at Subzero Temperatures During Distribution Will Be Hard, but Likely Key to Ending Pandemic.”

Writing OpEds in the Pandemic

On January 8, 2021, my article,

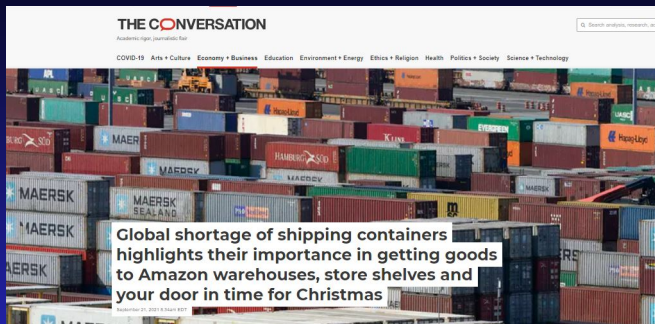
“Vaccine Delays Reveal Unexpected Weak Link in Supply Chains: A Shortage of Workers,” appeared in *The Conversation*.



On September 21, 2021, I published the article,

“Global Shortage of Shipping Containers Highlights Their Importance in Getting Goods to Amazon Warehouses, Store Shelves and Your Door in Time for Christmas,” also in *The Conversation*.

Writing OpEds in the Pandemic



My article, in one month, was read by over 315,000 readers; was reprinted by Fast Company, and remains the most read article authored by a UMass Amherst Professor in *The Conversation* since its founding 10 and a half years ago.

Some of the Media Coverage During the Pandemic



Many of the Media Interviews Have Been Fascinating



Additional Research on Game Theory and Disaster Relief

Additional Research on Game Theory and Disaster Relief

“A Multitiered Supply Chain Network Equilibrium Model for Disaster Relief with Capacitated Freight Service Provision,” A. Nagurney, in *Dynamics of Disasters: Algorithmic Approaches and Applications*, 2018, pp 85-108, Springer International Publishing Switzerland.

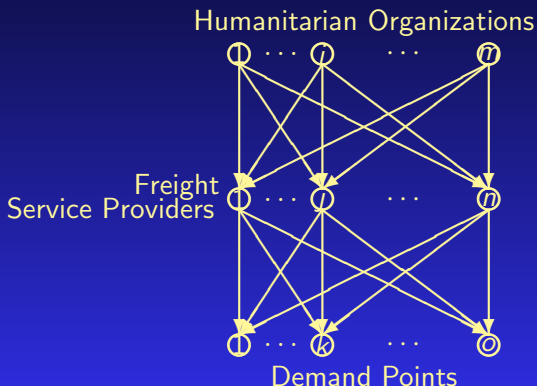
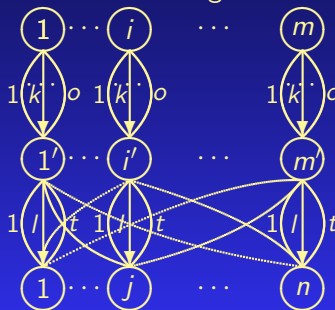


Figure 4: The Multitiered Disaster Relief Humanitarian Organization and Freight Service Provision Supply Chain Network

Additional Research on Game Theory and Disaster Relief

“An Integrated Financial and Logistical Game Theory Model for Humanitarian Organizations with Purchasing Costs, Multiple Freight Service Providers, and Budget, Capacity, and Demand Constraints,” A. Nagurney, M. Salarpour, and P. Daniele, *International Journal of Production Economics* **212** (2019), pp 212-226.

Humanitarian Organizations



Purchasing Options
at Different Locations

Freight Service Providers

Demand Locations

Additional Research on Game Theory and Disaster Relief

“How to Increase the Impact of Disaster Relief: A Study of Transportation Rates, Framework Agreements and Product Distribution,” T. Gossler, T. Wakolbinger, A. Nagurney, and P. Daniele, *European Journal of Operational Research* **274(1)**, (2019), pp 126-141.



Game Theory and Blood Supply Chains

Blood Supply Chains

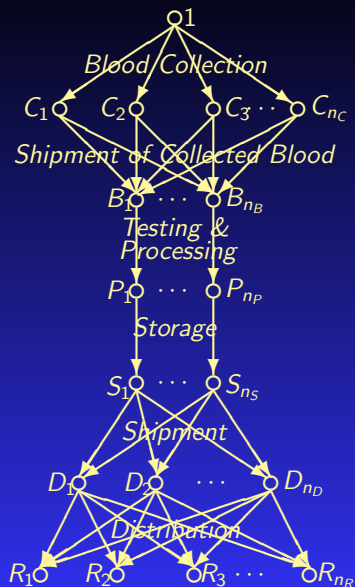
The American Red Cross is the major supplier of blood products to hospitals and medical centers satisfying about **40%** of the demand for blood components nationally.



Blood Supply Chains

- ▶ The shelf life of platelets is 5 days and of red blood cells is 42.
- ▶ Over 36,000 donations are needed everyday in the US.
- ▶ Blood is a perishable product that cannot be manufactured but must be donated.
- ▶ As of February 1, 2018, the American Red Cross was facing a critical emergency need for blood and platelet donors. Severe winter weather forced the cancellation of hundreds of blood drives, resulting in nearly tens of thousands donations uncollected. In addition, there is now flu in the US close to epidemic levels.
- ▶ There is increasing competition among blood service organizations for donors and, overall, there has been a decrease in demand because of improved medical procedures.
- ▶ Pressure to reduce costs is resulting in mergers and acquisitions in the blood services industry.

Supply Chain Network Topology for a Regionalized Blood Bank



ARC Regional Division

Blood Collection Sites

Blood Centers

Component Labs

Storage Facilities

Distribution Centers

Demand Points

Blood Supply Chains

Nagurney, Masoumi, and Yu (2012) developed a supply chain network optimization model for the management of the procurement, testing and processing, and distribution 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.

Blood Supply Chains

In the paper, “Mergers and Acquisitions in Blood Banking Systems: A Supply Chain Network Approach,” A.H. Masoumi, M. Yu, and A. Nagurney, *International Journal of Production Economics* **193** (2017), pp 406-421, we constructed network models to assess possible synergies associated with mergers and acquisitions among blood service organizations, taking into account capacities and frequencies of various supply chain network link activities.

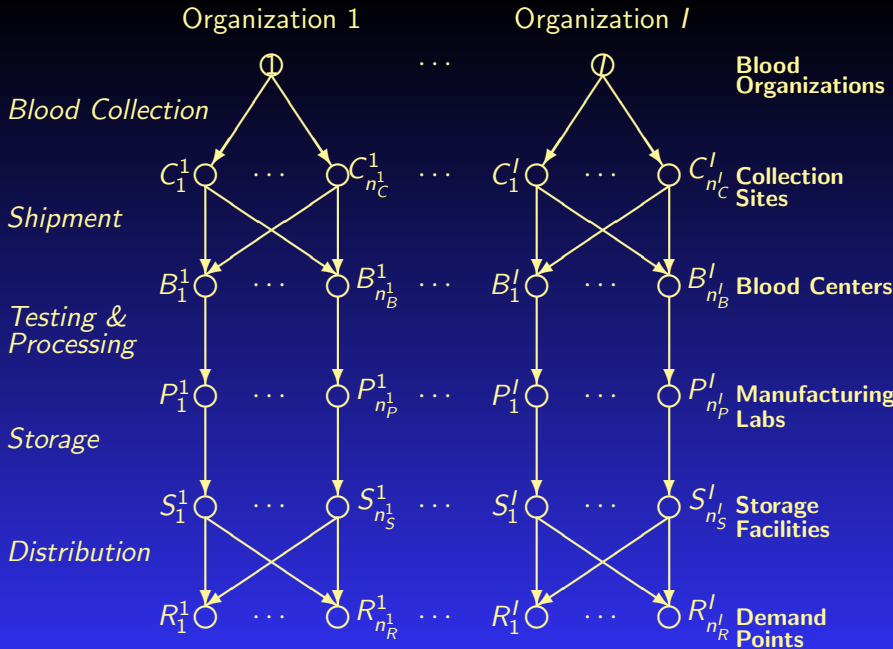


Figure 6: Supply Chain Network Topology Pre-Merger

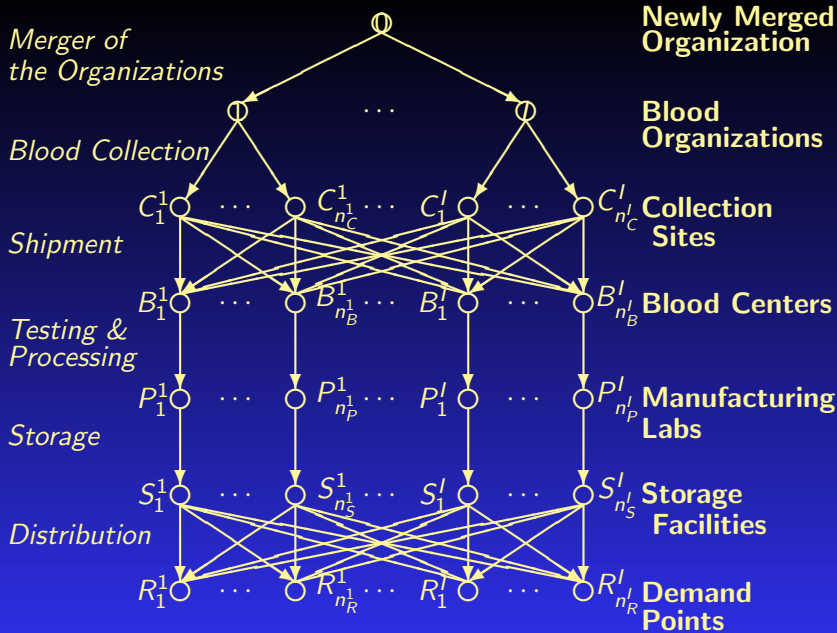


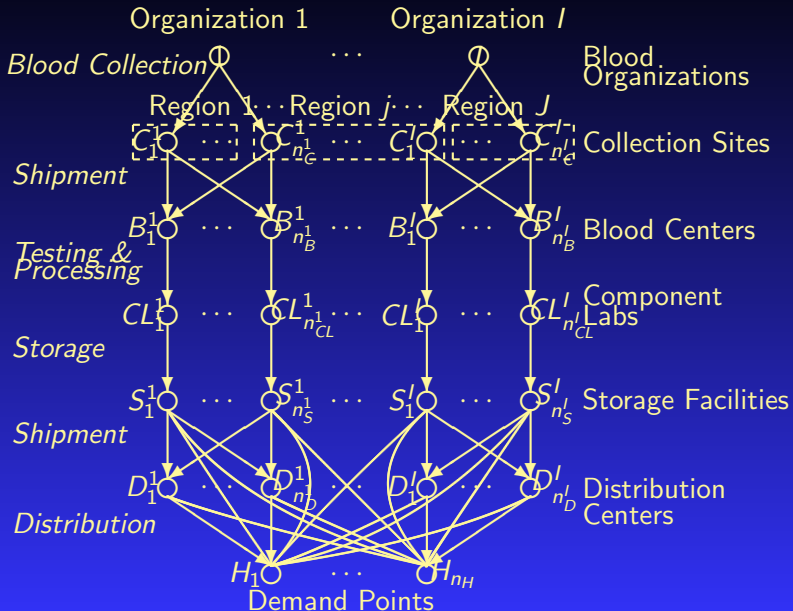
Figure 7: Supply Chain Network Topology Post-Merger

Blood Supply Chain Competition

The paper, "Supply Chain Network Competition Among Blood Service Organizations: A Generalized Nash Equilibrium Framework," co-authored with Pritha Dutta, *Annals of Operations Research* **275(2)** (2019), pp 551-586.

This paper builds on our work, "Competition for Blood Donations: A Nash Equilibrium Network Framework," *Omega* **212** (2019), pp 103-114.

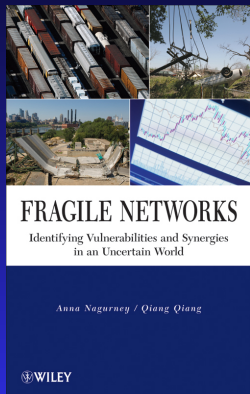
Blood Supply Chain Competition



Cybercrime and Cybersecurity

How I Became Interested in Cybersecurity

One of my books, written with a UMass Amherst PhD alum, was “hacked” and digital copies of it posted on websites around the globe.



In a sense, this may be viewed as a compliment since clearly someone had determined that it has some sort of *value*.

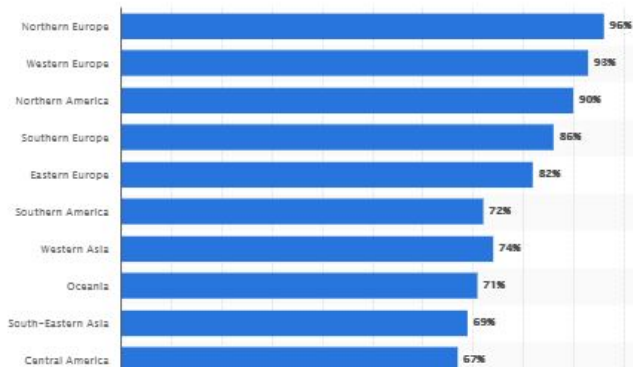
The publisher John Wiley & Sons was notified and lawyers got involved but how do you contact and then influence those responsible for postings on rather anonymous websites?

About the same time news about cyberattacks was getting prominent attention in the media and there were those interested in working with us on related research on cybersecurity.

The Internet has transformed the ways in which individuals, groups, organizations communicate, obtain information, access entertainment, and conduct their economic and social activities.

In 2012, there were over 2.4 billion users. In 2019, the number of Internet users surpassed 4.3 billion users, more than half of the world's population.

Global internet penetration rate as of January 2021, by region



Some Recent Major Cyberattacks

- **Equifax:** In September 2017, it was revealed that names, SSNs, birthdates, drivers' license information, and credit card numbers on about 143 million U.S. consumers was compromised in a cybersecurity breach that began in mid-May and was discovered only on July 29, 2017 (Bloomberg (2017)). In late February 2018, Equifax disclosed that it had discovered that an additional 2.4 million U.S. consumers were affected by the cyberattack (Reuters (2018)).



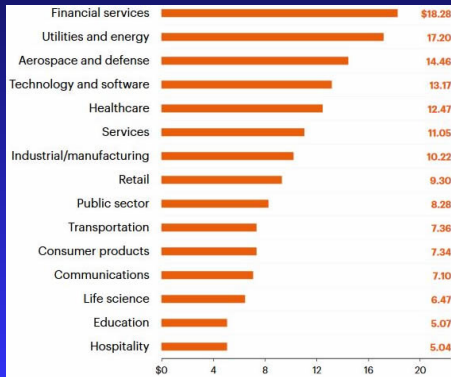
- **"WannaCry" ransomware:** Began in mid-May 2017. It crippled National Health Services (NHS) hospitals in the UK, hobbling emergency rooms, delaying vital medical procedures, and creating chaos (WIRED (2017)).

Some Recent Major Cyberattacks

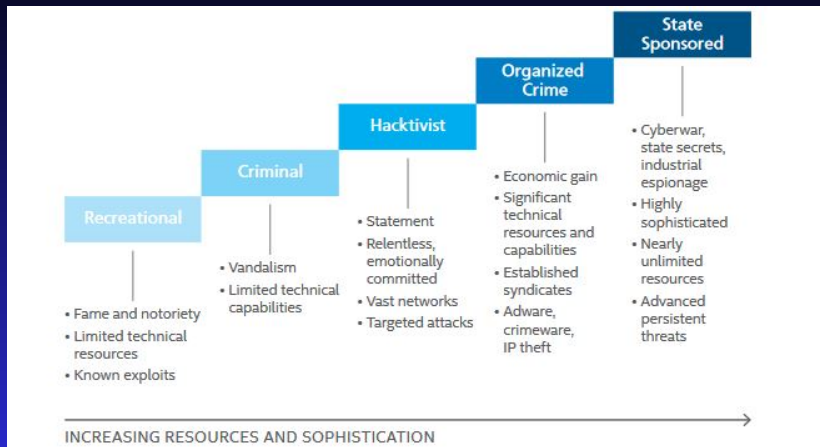
- **Banks:** The Carbanak group, also known as Anunak, was exposed in 2015 after supposedly stealing upwards of \$1 billion from more than 100 banks across 30 countries (The New York Times (2015)).
- **US Office of Personnel Management:** In June 2015, OPM discovered that sensitive information, including SSNs of 21.5 million federal employees was stolen (WIRED (2016)).
- **Sony Pictures Entertainment** The attack on Sony in 2014 destroyed data on more than 3,000 computers and disclosed prerelease films and embarrassing emails of executives (Fortune (2015)).
- **Target, Home Depot, Michaels Stores, Staples, and eBay:** These were breached in 2014 - card data and personal information of millions of customers were stolen (The New York Times (2015)).

Cost of Cybercrime

- **Cybercrimes are costly for organizations.** According to Forbes (2017), cybercrime will cost the world about \$6 trillion per year on average through 2021. All industries fall victim to cybercrime, but to different degrees. **Average annual costs per company caused by global cybercrime as of 2017 by sector (in million US\$) (Ponemon (2017))**



Changing Attacker Profiles

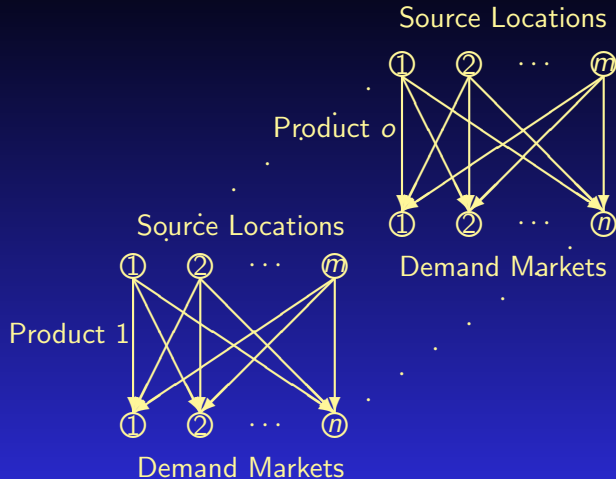


McAfee Labs Threats Report, August 2015

Clearly, hackers go where there is money.



Perishability and Cybercrime in Financial Products



The model is constructed in the paper, "A Multiproduct Network Economic Model of Cybercrime in Financial Services," A. Nagurney, *Service Science* **7(1)** (2015), pp 70-81.

Cybersecurity and Supply Chains



Supply chains are also vulnerable to cyberattacks and can serve as entre points

Some Other Examples of Our Cybersecurity Work

“Multifirm Models of Cybersecurity Investment Competition vs. Cooperation and Network Vulnerability,” A. Nagurney and S. Shukla, *European Journal of Operational Research* **260(2)** (2017), pp 588-600.

“A Supply Chain Network Game Theory Model of Cybersecurity Investments with Nonlinear Budget Constraints,” A. Nagurney, P. Daniele, and S. Shukla, *Annals of Operations Research* **248(1)** (2017), pp 405-427.

“Cybersecurity Investments with Nonlinear Budget Constraints: Analysis of the Marginal Expected Utilities,” P. Daniele, A. Maugeri, and A. Nagurney. In: *Operations Research, Engineering, and Cyber Security*, Th.M. Rassias and N.J. Daras (Eds.), Springer International Publishing Switzerland (2017), pp 117-134.

Summary and Conclusions

Summary and Conclusions

- ▶ In this talk, a game theory network model for post-disaster relief was presented, **which integrates financial flows and logistical flows**, with NGOs competing for financial funds from donors while also seeking to deliver the needed supplies.
- ▶ The model, because of common constraints on the demand side, in order to ensure that the needed supplies are delivered in the correct amounts without an oversupply, is a **Generalized Nash Equilibrium (GNE) model**, which can be challenging to solve.
- ▶ Because of the structure of the functions comprising the objective functions of the NGOs, the governing GNE conditions can be reformulated as an optimization problem. We utilize then a VI construct for effective and efficient computational purposes when we consider **a case study on Hurricane Katrina**.

Summary and Conclusions

- ▶ An extension of the model is then given, which makes use of **the concept of a Variational Equilibrium** and results from a case study based on tornadoes in Massachusetts outline.
- ▶ The results show that, **by doing better from a victim's perspective, the NGOs can also gain financially.**
- ▶ Additional recent related game theory models in the nonprofit sector for both disaster relief and **blood supply chains** are also highlighted as well as some of our work on **cybercrime and cybersecurity**.
- ▶ We have also now constructed two stage stochastic game theory models for disaster relief.

Thank You!



The Virtual Center for Supernetworks



Supernetworks for Optimal Decision-Making and Improving the Global Quality of Life

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<p>Center Associates of the Virtual Center for Supernetworks</p>		<p>The Virtual Center for Supernetworks is an interdisciplinary center at the Isenberg School of Management that advances knowledge on large-scale networks and integrates operations research and management science, engineering, and economics. Its Director is Dr. Anna Nagurney, the John F. Smith Memorial Professor of Operations Management.</p> <p>Mission: The Virtual Center for Supernetworks fosters the study and application of supernetworks and serves as a resource on networks ranging from transportation and logistics, including supply chains, and the Internet, to a spectrum of economic networks.</p> <p>The Applications of Supernetworks Include: decision-making, optimization, and game theory; supply chain management; critical infrastructure from transportation to electric power networks; financial networks; knowledge and social networks; energy, the environment, and sustainability; cybersecurity; Future Internet Architectures; risk management; network vulnerability, resiliency, and performance metrics; humanitarian logistics and healthcare.</p>				
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Announcements and Notes	Photos of Center Activities	Photos of Network Innovators	Friends of the Center	Course Lectures	Fulbright Lectures	UMass Amherst INFORMS Student Chapter
Professor Anna Nagurney's Blog	Network Classics	Doctoral Dissertations	Conferences	Journals	Societies	Archive

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