Game Theory Network Models for Disaster Relief

Anna Nagurney

John F. Smith Memorial Professor
Director of the Virtual Center for Supernetworks
Isenberg School of Management
University of Massachusetts
Amherst, Massachusetts 01003

USC Center for Artificial Intelligence in Society

Los Angeles, California, October 7, 2020

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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
- Summary and Conclusions

Background and Inspiration

I Work on the Modeling of Network Systems

Much of My Recent Research Has Been on Supply Chains


Springer Proceedings in Mathematics & Statistics
Ilias S. Kotsireas
Anna Nagurney
Panos M. Pardalos Editors
Dynamics of Disasters—Key Concepts, Models, Algorithms, and Insights
Kalamata, Greece, June–July 2015
Springer
Network Economics
A Variational Inequality Approach
Revised Second Edition
Anna Nagurney
Advances in Computational Economics
Fragile Networks
Identifying Vulnerabilities and Synergies in an Uncertain World
Wiley
A. Nagurney · S. Siokos
Financial Networks
Statics and Dynamics
Advances in Spatial Science
Springer
Some of My Books
EE
Supply Chain Network Economics
Dynamics of Prices, Flows and Profits
Anna Nagurney
Springer Optimization and Its Applications 140
Ilias S. Kotsireas · Anna Nagurney
Panos M. Pardalos Editors
Dynamics of Disasters
Algorithmic Approaches and Applications
Springer
Springer Series in Supply Chain Management
Anna Nagurney
Dong Li
Competing on Supply Chain Quality
A Network Economics Perspective
Springer
Projected Dynamical Systems and Variational Inequalities with Applications
Anna Nagurney
Ding Zhang
EE
Environmental Networks
A Framework for Economic Decision-Making and Policy Analysis
Kanwalroop Kathy Dhanda
Anna Nagurney
Padma Ramanujam
New Horizons in Environmental Economics
General Editors Wallace E. Oates Henk Folmer
EE
Innovations in Financial and Economic Networks
Edited by Anna Nagurney
New Dimensions in Networks
EE
Supernetworks
Decision-Making for the Information Age
Anna Nagurney
June Dong
New Dimensions in Networks
Springer Briefs in Optimization
Anna Nagurney
Min Yu
Amir H. Masoumi
Ladimer S. Nagurney
Networks Against Time
Supply Chain Analytics for Perishable Products
Springer

Networks in Transportation and Logistics

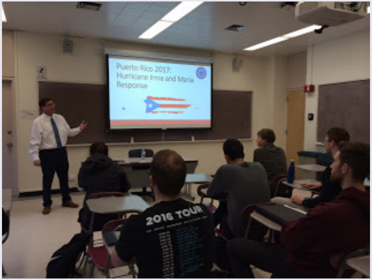
Networks have assisted in transportation and logistics in numerous sectors, including defense.

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 military saying that I share with students in my Humanitarian Logistics and Healthcare class:

Armchair generals talk strategy. Real generals talk logistics.

I Teach Humanitarian Logistics and Healthcare



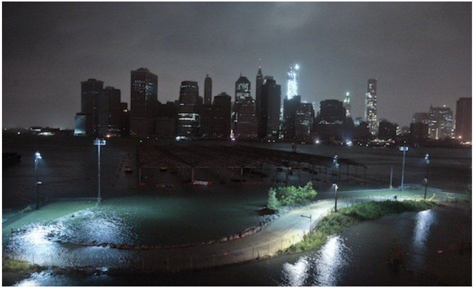
Network Models Are Also Very Useful in Disaster Relief

Network Models for Healthcare Supply Chains

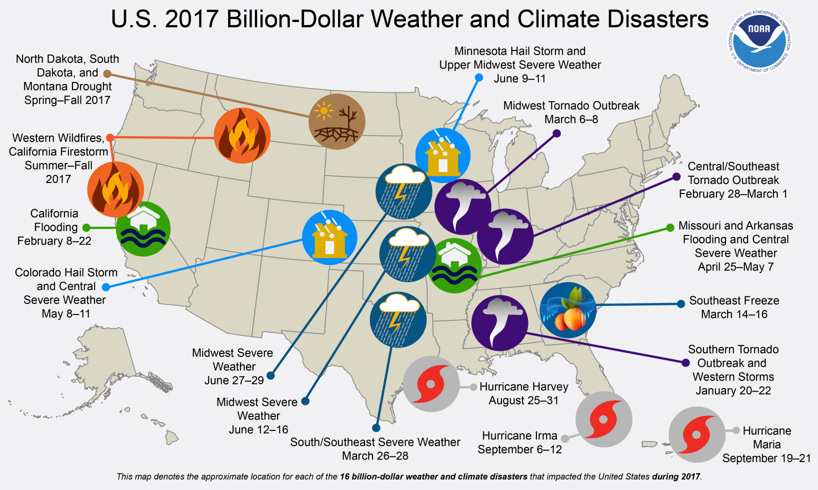
Examples of Some Disasters

- 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;
- The WHO declared the Covid-19 pandemic on March 11, 2020;
- Record-breaking wildfires in California, Oregon, and parts of the west in the US in 2020.

Hurricane Katrina, Fukushima, and Superstorm Sandy



Billion Dollar Disasters in the United States in 2017

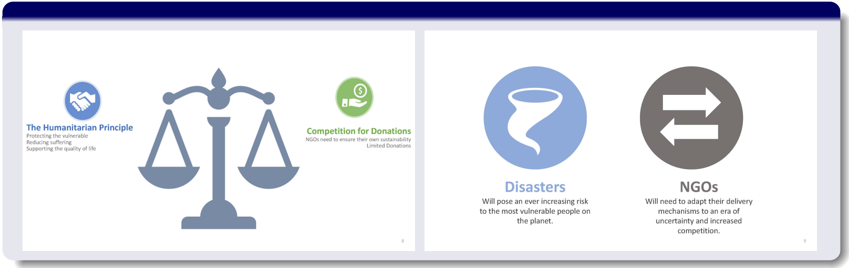


Challenges Associated with Disaster Relief

- 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.** Media attention of insufficient water supplies resulted in immense donations to the Dominican Red Cross to assist its island neighbor.
- 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 about 1.5 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

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, $\mathrm{VI}(F, \mathcal{K})$*, 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.**

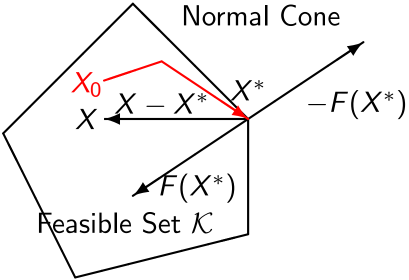
The variational inequality problem contains, as special cases, such mathematical programming problems as:

- 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 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)),

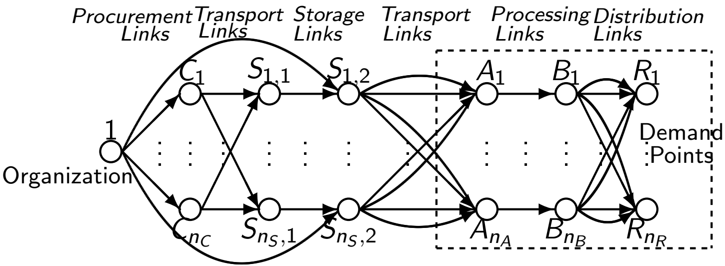
Future Internet Architectures (Saberi, Nagurney, Wolf (2014); see also Nagurney et al. (2015), Marentes et al. (2016)).

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).



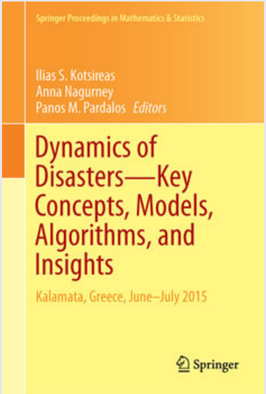
Network Topology of the Integrated Disaster Relief Supply Chain

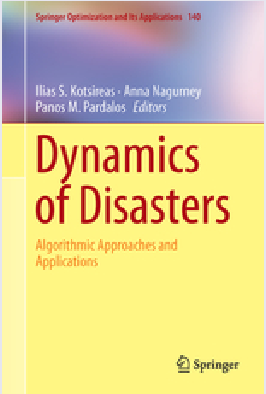
A. Nagurney, A. H. Masoumi, and M. Yu, "An Integrated Disaster Relief Supply Chain Network Model with Time Targets and Demand Uncertainty." In: *Regional Science Matters: Studies Dedicated to Walter Isard*, P. Nijkamp, A. Rose, and K. Kourtit, Editors, Springer International Publishing Switzerland (2015),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

•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**.

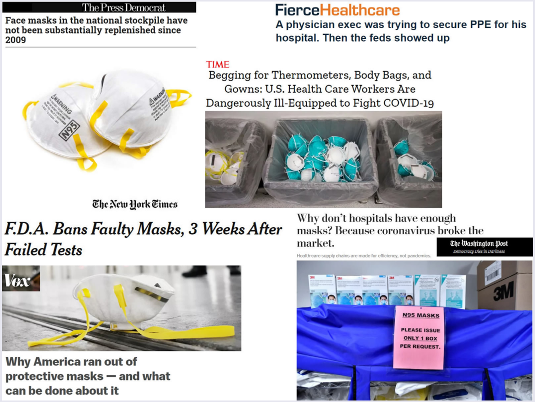
Shortages of Medical Supplies, Including PPEs

• In early March, it was reported that by the Department of Health and Human Services **that the national stockpile had about 12 million N95 respirators and 30 million surgical masks - 1% of the estimated 3.5 billion masks the nation would need in a severe pandemic. Another 5 million N95 masks in the stockpile were expired.**

• **Prior to the coronavirus outbreak, China made half the world's face masks.** When the outbreak took off there, China started to use its supply and hoard what remained. This problem has only spread since, as more countries hoarded medical supplies, with some even banning most PPE exports. So as demand increased due to Covid-19 there was less supply to go around.

• **"We are out of everything, wrote a staffer at a large hospital in Tennessee in mid April. "Providers using one mask for 3+ weeks. Many COVID patients. Zero gowns."**

Where Are the PPEs?



The competition for various medical supplies continues to be intense and game theory can help us to illuminate this important issue in the pandemic healthcare disaster.

Recurring Shortages of PPEs

Dr. Susan R. Bailey, President of the American Medical Association, wrote on August 26, 2020:

• **"It is hard to believe that our nation finds itself dealing with the same shortfalls in PPE witnessed during the first few weeks that SARS-CoV-2 began its unrelenting spread ..."**

• **"But that same situation exists today, and in many ways things have only gotten worse."**

• "The lack of a coordinated national strategy to acquire and distribute PPE has certainly played a role **forcing state governments to compete with each other – and with the federal government as well as foreign nations – to secure masks, gowns, gloves and other gear**."

Raging Competition for Medical Supplies

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."


Competition for Medical Supplies Under Stochastic Demand

The fierce competition for PPEs and other medical supplies also inspired the following work:

"Competition for Medical Supplies Under Stochastic Demand in the Covid-19 Pandemic: A Generalized Nash Equilibrium Framework", A. Nagurney, M. Salarpour, J. Dong, and P. Dutta (2020), to appear in: *Nonlinear Analysis and Global Optimization*, T.M. Rassias, and P.M. Pardalos, Editors, Springer Nature Switzerland AG.

In this paper, we modeled the competition for medical supplies in the Covid-19 pandemic under stochastic demand and a fixed amount of supplies at different points.

The Network Structure of the GNE Game Theory Model

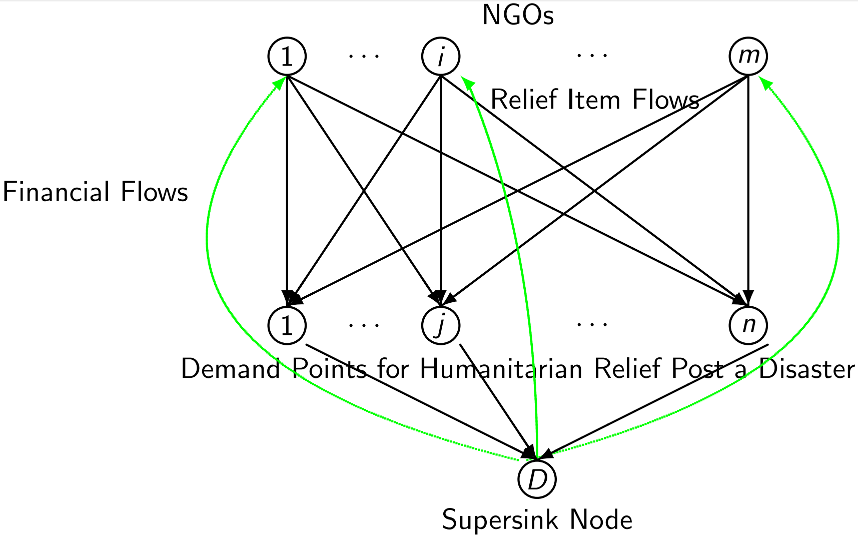


Figure 1: The Network Structure of the Game Theory Model

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; $i = 1, \dots, m$:

$$\sum_{j=1}^{n} q_{ij} \leq s_i. \tag{1}$$

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

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

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

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

with these cost functions being strictly convex and continuously differentiable.

In addition, each NGO i; $i = 1, \ldots, m$, derives satisfaction or utility associated with providing the relief items to j; $j = 1, \ldots, n$, 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; $i = 1, \ldots, m$, 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.

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

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

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.

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; $i = 1, \ldots, m$, is, hence,

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

subject to constraints (1) and (2).

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

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

and

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

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

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

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

The Game Theory Model

Each NGO i; $i = 1, \ldots, m$, 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.

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:

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

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).

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*}, $\forall k$, for the upper bound demand constraints, can be obtained by solving the VI problem: determine $(q^*, \lambda^*, \lambda^{1*}, \lambda^{2*}) \in R_+^{mn+m+2n}$:

$$\sum_{k=1}^{m}\sum_{l=1}^{n}\left[-\sum_{j=1}^{n}(\frac{\partial P_j(q^*)}{\partial q_{kl}}) - \frac{\omega_k \gamma_{kl}}{\beta_k} + \frac{1}{\beta_k}\frac{\partial c_{kl}(q_{kl}^*)}{\partial q_{kl}} + \lambda_k^* - \lambda_l^{1*} + \lambda_l^{2*}\right] \times [q_{kl} - q_{kl}^*]$$

$$+\sum_{k=1}^{m}(s_k - \sum_{l=1}^{n} q_{kl}^*) \times (\lambda_k - \lambda_k^*) + \sum_{l=1}^{n}(\sum_{k=1}^{n} q_{kl}^* - \underline{d}_l) \times (\lambda_l - \lambda_l^{1*})$$

$$+\sum_{l=1}^{n}(\bar{d}_l - \sum_{k=1}^{m} q_{kl}^*) \times (\lambda_l^2 - \lambda_l^{2*}) \geq 0, \; \forall (q, \lambda, \lambda^1, \lambda^2) \in R_+^{mn+m+2n}, \tag{11}$$

Variational Inequality (VI) Formulation, continued

where λ *is the vector of Lagrange multipliers:* $(\lambda_1, \ldots, \lambda_m)$*,* λ^1 *is the vector of Lagrange multipliers:* $(\lambda^1_1, \ldots, \lambda^1_n)$*, and* λ^2 *is the vector of Lagrange multipliers:* $(\lambda^2_1, \ldots, \lambda^2_n)$*.*

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 $k = 1, \ldots, m$; $l = 1, \ldots, n$, 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 $k = 1, \ldots, m$:

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

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

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

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

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

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)).

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.

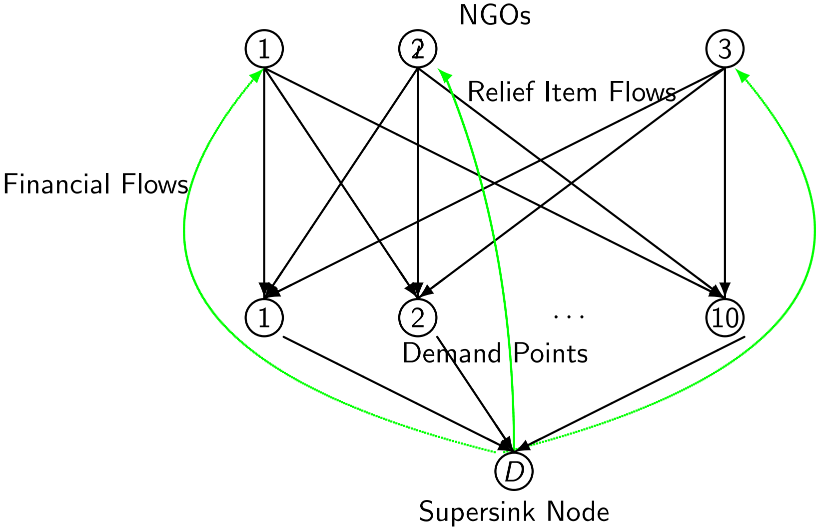


Figure 2: Hurricane Katrina Relief Network Structure

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 $j = 1, \ldots, 10$.

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

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 the 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

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.

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.

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:

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

Each NGO i; $i = 1, \ldots, m$, based on the media attention and the visibility of NGOs at demand point j; $j = 1, \ldots, n$, 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; $i = 1, \ldots, m$, such that

$$B_i = B_i(q).$$

Extension of the Model

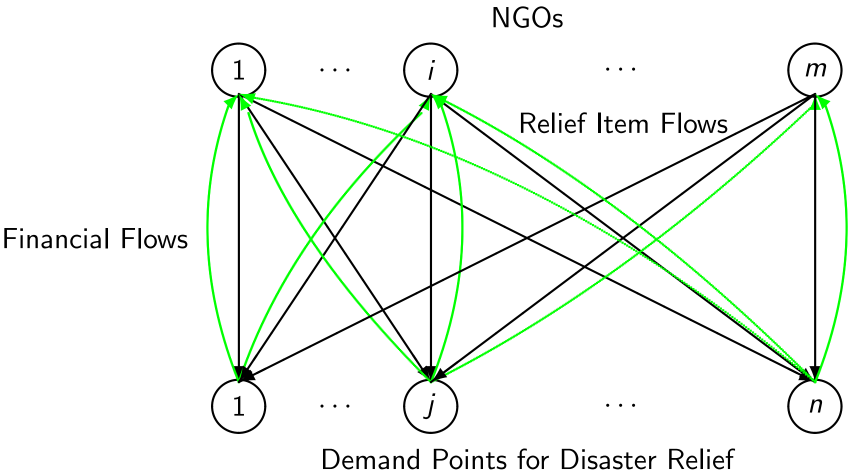


Figure 3: The Network Structure of the Extended Game Theory Model

The Extended Model

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

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

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.

Definition: Variational Equilibrium

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

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

where the feasible set K_i for each NGO i is:

$$K_i \equiv \{q_i | \, (1) \, and \, (2) \, hold\}.$$

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

$$\mathcal{S} \equiv \{q | \, (6) \, and \, (7) \, hold\}.$$

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 Variational Inequality Formulation of the Generalized Nash Equilibrium for the Extended Model:
Find $(q^*, \delta^*, \sigma^*, \varepsilon^*) \in R_+^{mn+m+2n}$:

$$\sum_{i=1}^{m}\sum_{j=1}^{n}\left[\sum_{k=1}^{n}\frac{\partial c_{ik}(q^*)}{\partial q_{ij}} - \sum_{k=1}^{n}\frac{\partial P_{ik}(q^*)}{\partial q_{ij}} - \omega_i \frac{\partial B_i(q^*)}{\partial q_{ij}} + \delta_i^* - \sigma_j^* + \varepsilon_j^*\right]$$

$$\times (q_{ij} - q_{ij}^*) + \sum_{i=1}^{m}\left(s_i - \sum_{j=1}^{n} q_{ij}^*\right) \times (\delta_i - \delta_i^*)$$

$$+\sum_{j=1}^{n}\left(\sum_{i=1}^{m} q_{ij}^* - \underline{d}_j\right)\times(\sigma_j - \sigma_j^*) + \sum_{j=1}^{n}\left(\bar{d}_j - \sum_{i=1}^{m} q_{ij}^*\right)\times(\varepsilon_j - \varepsilon_j^*) \geq 0,$$

$$\forall q \in R_+^{mn}, \forall \delta \in R_+^{m}, \forall \sigma \in R_+^{n}, \forall \varepsilon \in R_+^{n}.$$

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.

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

THE CONVERSATION

Arts + Culture Economy + Business Education Environment + Energy Ethics + Religion Health + Medicine Politics + Society Science + Technology

How disaster relief efforts could be improved with game theory

March 9, 2017 11.21pm EST

Buddhist monks and family members of victims of the Fukushima tsunami and earthquake face the sea to pray on March 11, 2016 while mourning the victims of the March 11, 2011 disaster.

The number of disasters has doubled globally since the 1980s, with the

Author

Anna Nagurney
John F. Smith Memorial Professor of Operations Management, University of Massachusetts Amherst

Disclosure statement

Anna Nagurney does not work for, consult, own shares in or receive funding from any company or organization that would benefit from this article, and has disclosed no relevant affiliations beyond the academic appointment above.

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Chicago Tribune

Response to natural disasters like Harvey could be helped with game theory

By Anna Nagurney

(The Conversation is an independent and nonprofit source of news, analysis and commentary from academic experts.)

Anna Nagurney, University of Massachusetts Amherst

(THE CONVERSATION) The devastation by Hurricane Harvey continues, with the National Weather Service calling the event unprecedented, thus making the response even more complicated.

Nearly half a million people are expected to seek federal aid in the aftermath of the Category 4 hurricane, which already has dumped more than 30 inches on the Houston

SALON

VIDEO NEWS POLITICS ENTERTAINMENT LIFE

THURSDAY, AUG 31, 2017 10:38 AM EST

Time for some game theory: How responses to natural disasters like Harvey could be improved

The damage and losses from natural disasters are estimated to cost us $100 billion a year since 2000

ANNA NAGURNEY, THE CONVERSATION

Homeland Security News Wire

BIOMETRICS BORDER/IMMIG. BUSINESS CYBERSECURITY
PUBLIC SAFETY PUBLIC HEALTH REGIONAL SCI-TECH

Disaster response

How disaster relief efforts could be improved with game theory

By Anna Nagurney

Published 13 March 2017

The number of disasters has doubled globally since the 1980s, with the damage and losses estimated at an average

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.

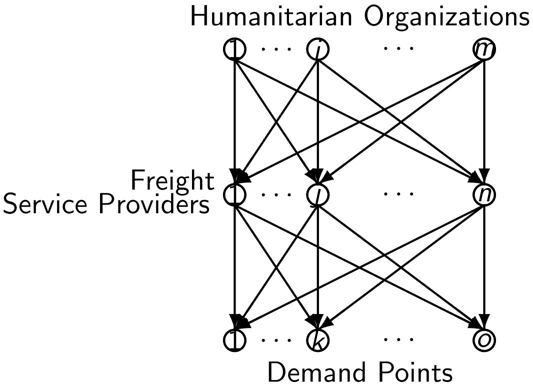
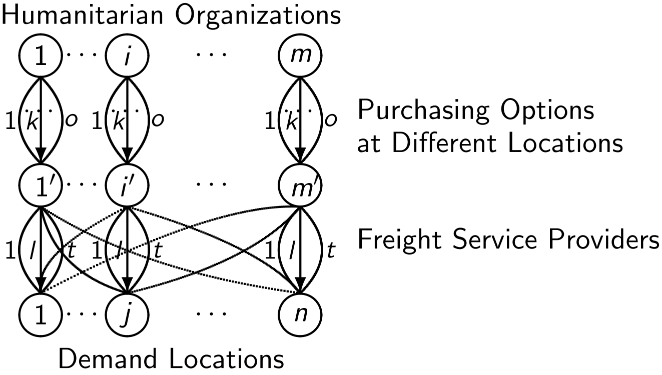


Figure 4: The Multitiered Disaster Relief Humanitarian Organization and Freight Service Provision Supply Chain Network

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.



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

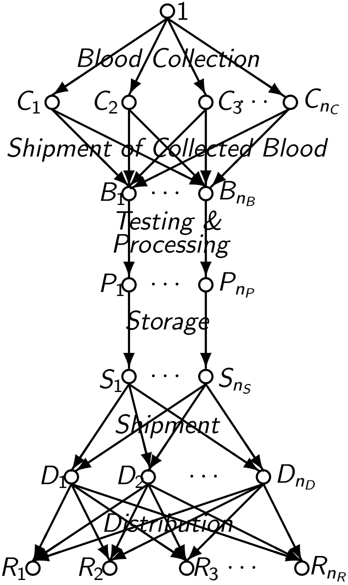
Blood Supply Chains

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.

American Red Cross
Together, we can save a life

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.
- There have been severe blood shortages experiences globally during the Covid-19 pandemic.
- **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**.



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.

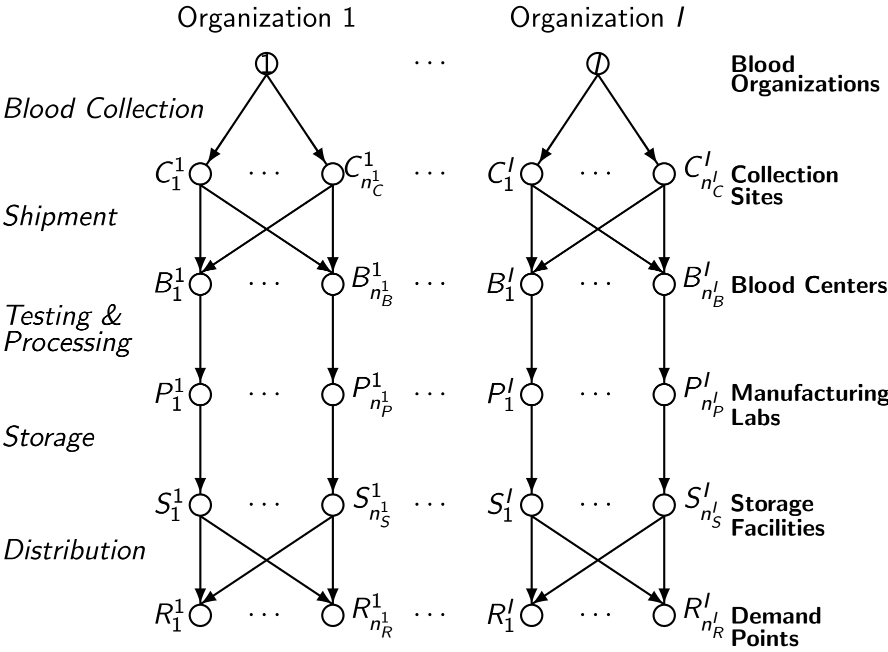


Figure 6: Supply Chain Network Topology Pre-Merger

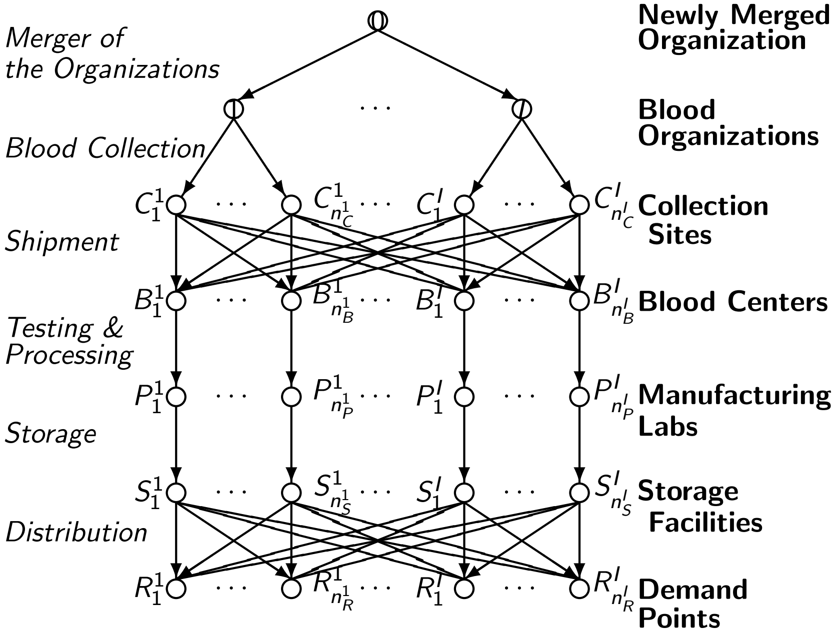


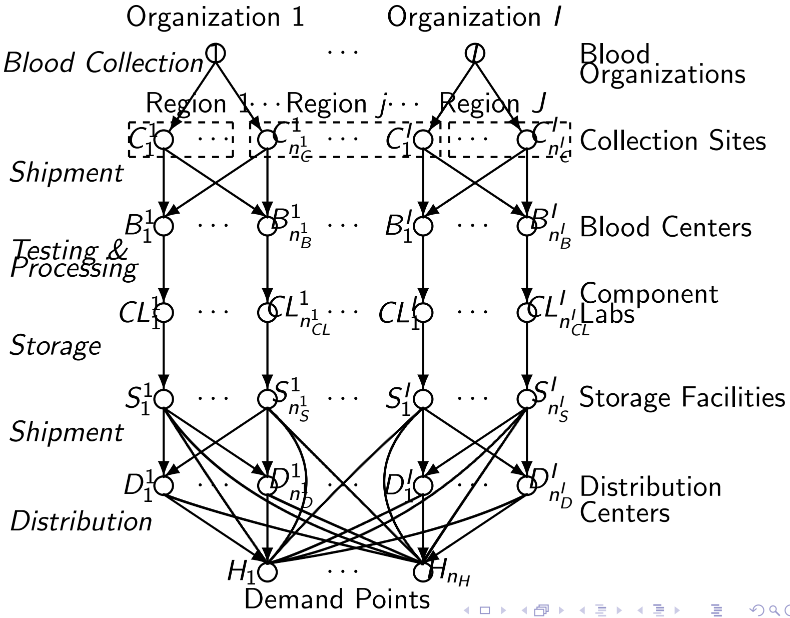
Figure 7: Supply Chain Network Topology Post-Merger

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



Writing OpEds

On March 11, 2020 the WHO declared the pandemic. On March 12 my article on blood supply chains in *The Conversation* appeared and, on March 24 my article in INFORMS *Analytics Coronavirus Chronicles*.

THE CONVERSATION

Academic rigor, journalistic flair

How coronavirus is upsetting the blood supply chain

March 12, 2020 8.05am EDT

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The coronavirus, which causes the disease COVID-19, has created enormous anxiety, uncertainty, and disruption to our lives. Much has already been written about potential shortages of medicines and face masks, but little has been said about something only you and I can provide – lifesaving blood.

Our nation's blood supply is essential to our health care security. Blood transfusions are integral parts of major surgeries. Blood is used in the treatment of diseases, particularly sickle cell anemia and some cancers. Blood is needed for victims who have injuries caused by accidents or natural disasters. Every day, the U.S. needs 36,000 units of red blood cells, 7,000 units of platelets, and 10,000 units of plasma.

I am a professor and director of the Virtual Center for Supernetworks at the University of Massachusetts Amherst. Because of the escalating coronavirus health care crisis, I am deeply concerned the U.S. blood supply chain is under stress. The timing could hardly be worse; the COVID-19 outbreak coincides with our seasonal flus and colds.

Patients need blood in many states

Many states, including Washington, California, Kansas, Pennsylvania, the Carolinas, Massachusetts and Rhode Island, are now calling for blood donations. At the same time, some states are closing schools and other sites that typically host mobile blood drives; even prior to the coronavirus, some events had been canceled. In Massachusetts, the Red Cross announced last September it would no

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March 24, 2020 in Coronavirus Chronicles

The COVID-19 Pandemic and the Stressed Blood Supply Chain

By Anna Nagurney

SHARE: PRINT ARTICLE: https://doi.org/10.1287/LYTX.2020.02.18

Blood is essential to our nation's healthcare security. It is a life-saving product that cannot be manufactured and comes solely from volunteer donors. No substitute for blood has yet been invented. Blood transfusions are integral parts of major surgeries. Blood is a must for saving victims of accidents and natural disasters. Blood is also used in the treatment of certain diseases, including certain cancers. In the United States, 36,000 units of red blood cells are needed daily as are 7,000 units of platelets and 10,000 units of plasma. A typical donation of one pint, which can be divided into red blood cells, plasma and platelets, can save up to three lives. Adults have 8-12 pints of blood.

Even in the best of times, the complex blood supply chain in the United States is under stress. Although 38% of the U.S. population is eligible to donate blood, less than 10% actually does so in a year. Furthermore, issues of seasonality come into play with flu and colds cutting donations; the same for weather-related events and holidays. To further complicate matters, blood is perishable; platelets last five days and red blood cells have a shelf life of 42 days.

The blood banking industry, entrusted with maintaining a sufficient supply of blood, is facing a battle of the century with the COVID-19 pandemic. The timing could not be worse with this year's heavy flu and cold season, and the blood banking industry having recently undergone a massive transformation due to both economics and changes in medical procedures [1]. For example, there is increased competition among blood service organizations for donors [2]. The American Red Cross has closed some testing facilities and even eliminated mobile collection units in parts of the country. There have also been mergers and acquisitions of blood service organizations [3]. On the other hand, hospitals are now requiring less blood for certain procedures as compared to a few years ago because of changes in medical practices. This has resulted in requests for lower prices for blood from blood banks, who still have to cover costs, and some of the new costs include higher testing costs due to diseases such as Zika. And now, because of the COVID-19 pandemic, a major source of blood donations – schools – is removed.

The critical blood supply chain is unique from others that we study in operations research (O.R.) because it requires altruistic donations, collection, testing, processing and distribution to hospitals and medical centers. The blood supply chain can be visualized, modeled and studied as a network [4]. The coronavirus can disrupt the links in the blood supply chain network through a variety of means. If donors are ill, they cannot donate; if the staff is ill, they cannot collect, test, process and distribute blood. If our healthcare workers are compromised, they cannot transfuse.

In China, specifically Wuhan where the coronavirus is generally thought to have originated, blood donations have

Coverage by the Media During the Pandemic

Impacting Policy Through Analytics

On April 22, 2020, a letter from California Attorney General Xavier Becerra to the Admiral Brett Giroir, the Assistant Secretary of the US Department of Health & Human Services, and signed by US Attorney Generals of 21 other states, requested updates, because of the pandemic blood shortages, to blood donation policies that discriminate.

My article in *The Conversation*, **which was reprinted in LiveScience, was the first reference and was cited on the first page.**

Impacting Policy Through Analytics

State of California
Office of the Attorney General
XAVIER BECERRA
ATTORNEY GENERAL

April 22, 2020

Via Electronic Mail

The Honorable Admiral Brett Giroir, MD
Assistant Secretary for Health
U.S. Department of Health & Human Services
Mary E. Switzer Building
330 C Street SW, Room L600
Washington, DC 20024
Attn: ACBTSA-PAHPAIA Sec. 209
ACBTSA@hhs.gov

RE: “Solicitation for Public Comments on Section 209 of the Pandemic and All-Hazards Preparedness and Advancing Innovation Act,” 85 Fed. Reg. 16,372 (March 23, 2020)

Dear Assistant Secretary Giroir:

The undersigned State Attorneys General from California, Colorado, Connecticut, Delaware, the District of Columbia, Hawaii, Illinois, Iowa, Maine, Massachusetts, Michigan, Minnesota, Nevada, New Jersey, New Mexico, New York, Oregon, Pennsylvania, Vermont, and Virginia submit this letter in response to the federal government’s “Solicitation for Public Comments on Section 209 of the Pandemic and All-Hazards Preparedness and Advancing Innovation Act,” (85 Fed. Reg. 16,372). We support the Office of the Assistant Secretary for Health in the U.S. Department of Health and Human Services’ (HHS) efforts and work in maintaining an adequate national blood supply during the COVID-19 pandemic.

An adequate blood supply is critical to the nation’s healthcare. Blood transfusions and blood products are needed for major surgeries, to treat diseases such as sickle cell anemia and some cancers, and to treat victims who have injuries caused by accidents or natural disasters.[1] Every day, the United States needs approximately 36,000 units of red blood cells, nearly 7,000

---

[1] Anna Nagurney, How Coronavirus is Upsetting the Blood Supply Chain, Live Science (Mar. 13, 2020), https://www.livescience.com/coronavirus-blood-supply-chain.html/.

Impacting Policy Through Analytics

Hon. Brett Giroir
April 22, 2020
Page 7

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New Jersey Attorney General

HECTOR BALDERAS
New Mexico Attorney General

LETITIA JAMES
New York Attorney General

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 **game theory in the Covid-19 pandemic**.

- We have also now constructed two stage stochastic game theory models for disaster relief; see our paper: "A Stochastic Disaster Relief Game Theory Network Model," A. Nagurney, M. Salarpour, J. Dong, and L.S. Nagurney, *SN Operations Research Forum* **1, 10** (2020).

Thank You!

For more information: https://supernet.isenberg.umass.edu/