Novel Supply Chain Network Models Inspired by the Covid-19 Pandemic: From Optimization to Game Theory

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Acknowledgments

Many thanks to the INFORMS Chicago Chapter and INFORMS Analytics Society for this invitation.

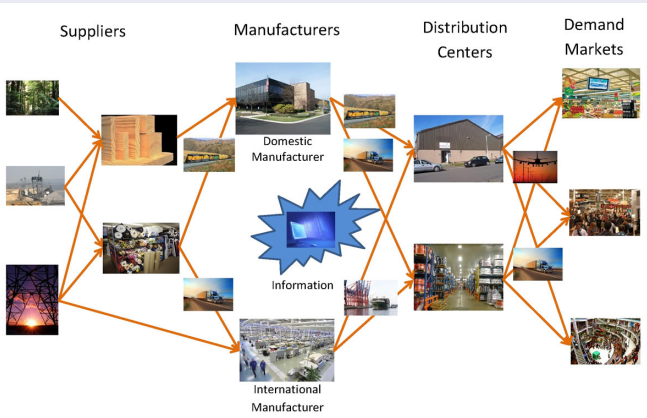
This presentation is dedicated to essential workers, including tech workers, healthcare workers, first responders, farmers, food processors, grocery store workers, and freight service providers, whose selflessness, expertise, and dedication help to sustain us. Thank you.

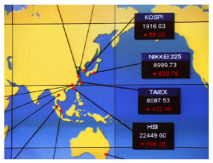
Outline of Presentation

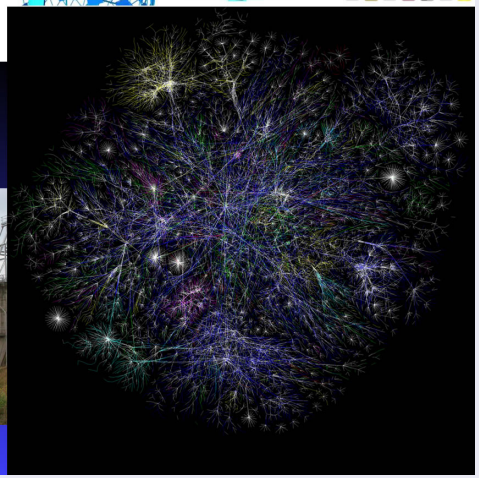
- **Background and Motivation** - Some of Our Relevant Research Pre-Pandemic
- **Optimization and Supply Chain Network Models** Inspired by the Covid-19 Pandemic
  - Food
  - Medical Supplies
- **Game Theory and Supply Chain Network Models** Inspired by the Covid-19 Pandemic
  - Medical Supplies
- **Impacting Policy Through Analytics**

Background and Motivation - Some of Our Relevant Research Pre-Pandemic

I Work on the Modeling of Network Systems





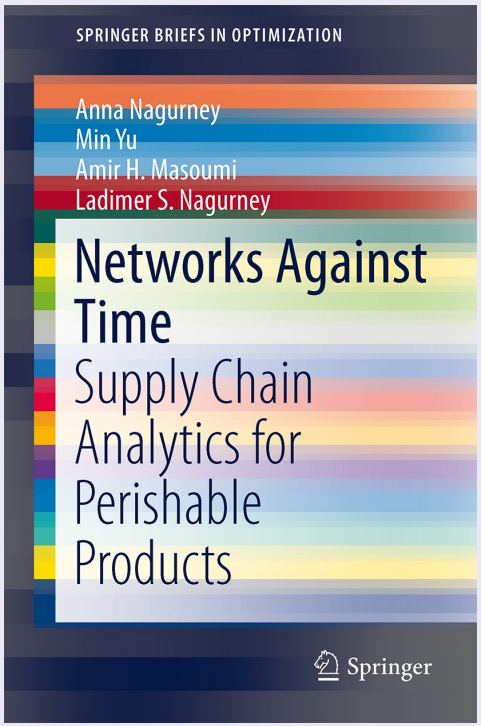


Much of My Recent Research Has Been on Supply Chains

Some of My Books

A Multidisciplinary Approach

In our research on perishable and time-sensitive product supply chains, we utilize results from physics, chemistry, biology, and medicine in order to capture the perishability of various products over time from healthcare products such as blood, medical nucleotides, and pharmaceuticals to food.



Food Supply Chains

Food is essential to our health and well-being. During the Covid-19 pandemic, declared on March 11, 2020 by the World Health Organization, the associated supply chains have suffered major disruptions.

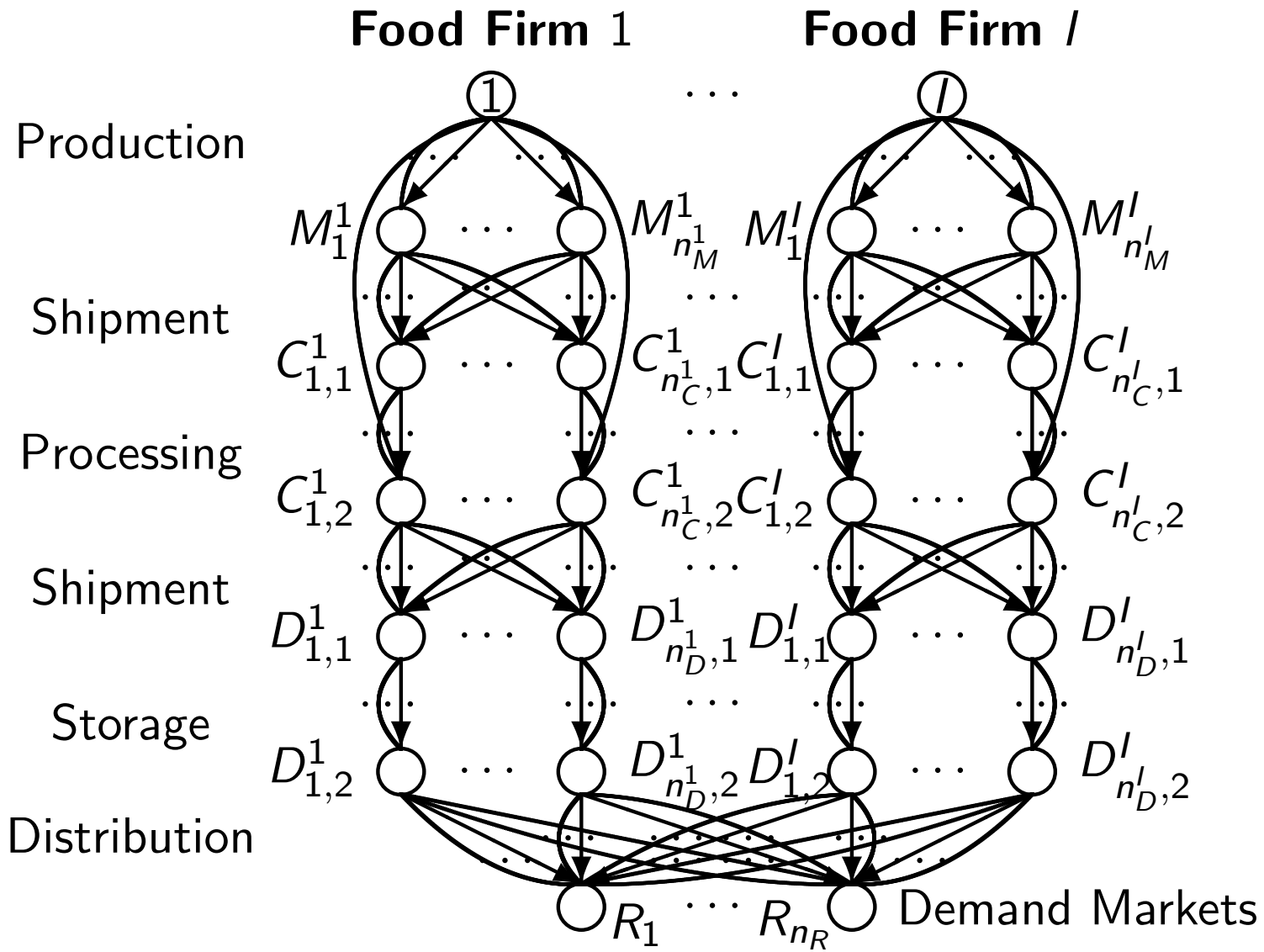
Fresh Produce Food Supply Chains

Our fresh produce supply chain network oligopoly model:

1. captures the deterioration of fresh food along the entire supply chain from a network perspective;
2. handles the time decay through the introduction of arc multipliers;
3. formulates oligopolistic competition with product differentiation;
4. includes the disposal of the spoiled food products, along with the associated costs;
5. allows for the assessment of alternative technologies involved in each supply chain activity.

M. Yu and A. Nagurney, "Competitive Food Supply Chain Networks with Application to Fresh Produce," *European Journal of Operational Research* **224(2) (2013), pp 273-282.**

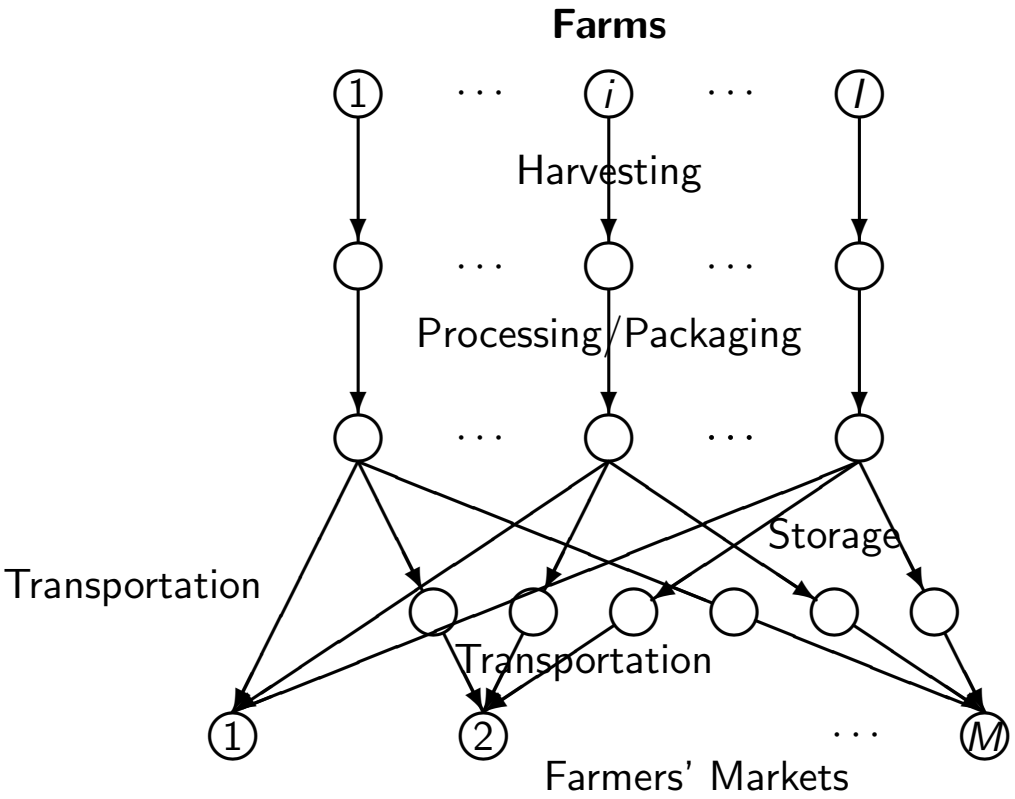
Fresh Produce Food Supply Chains

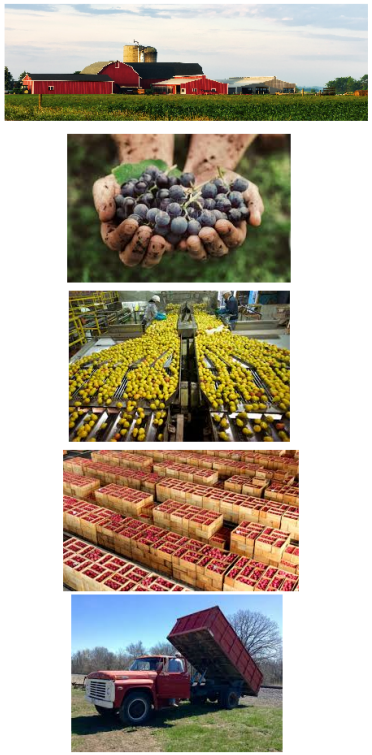


The Fresh Produce Supply Chain Network Topology

Farmers' Markets and Fresh Produce Supply Chains

- The I farms compete **noncooperatively** in an **oligopolistic** manner.
- Products are differentiated based on **quality** at the farmers' markets.





D. Besik and A. Nagurney, "Quality in Competitive Fresh Produce Supply Chains with Application to Farmers' Markets," *Socio-Economic Planning Sciences* **60 (2017), pp 62-76.**

Pharmaceutical Supply Chains

The supply chain generalized network oligopoly model has the following novel features:

1. it handles the perishability of the pharmaceutical product through the introduction of arc multipliers;
2. it allows each firm to minimize the discarding cost of waste / perished medicine;
3. it captures product differentiation under oligopolistic competition through the branding of drugs, which can also include generics as distinct brands.

A.H. Masoumi, M. Yu, and A. Nagurney, "A Supply Chain Generalized Network Oligopoly Model for Pharmaceuticals Under Brand Differentiation and Perishability," *Transportation Research E* **48 (2012), pp 762-780.**

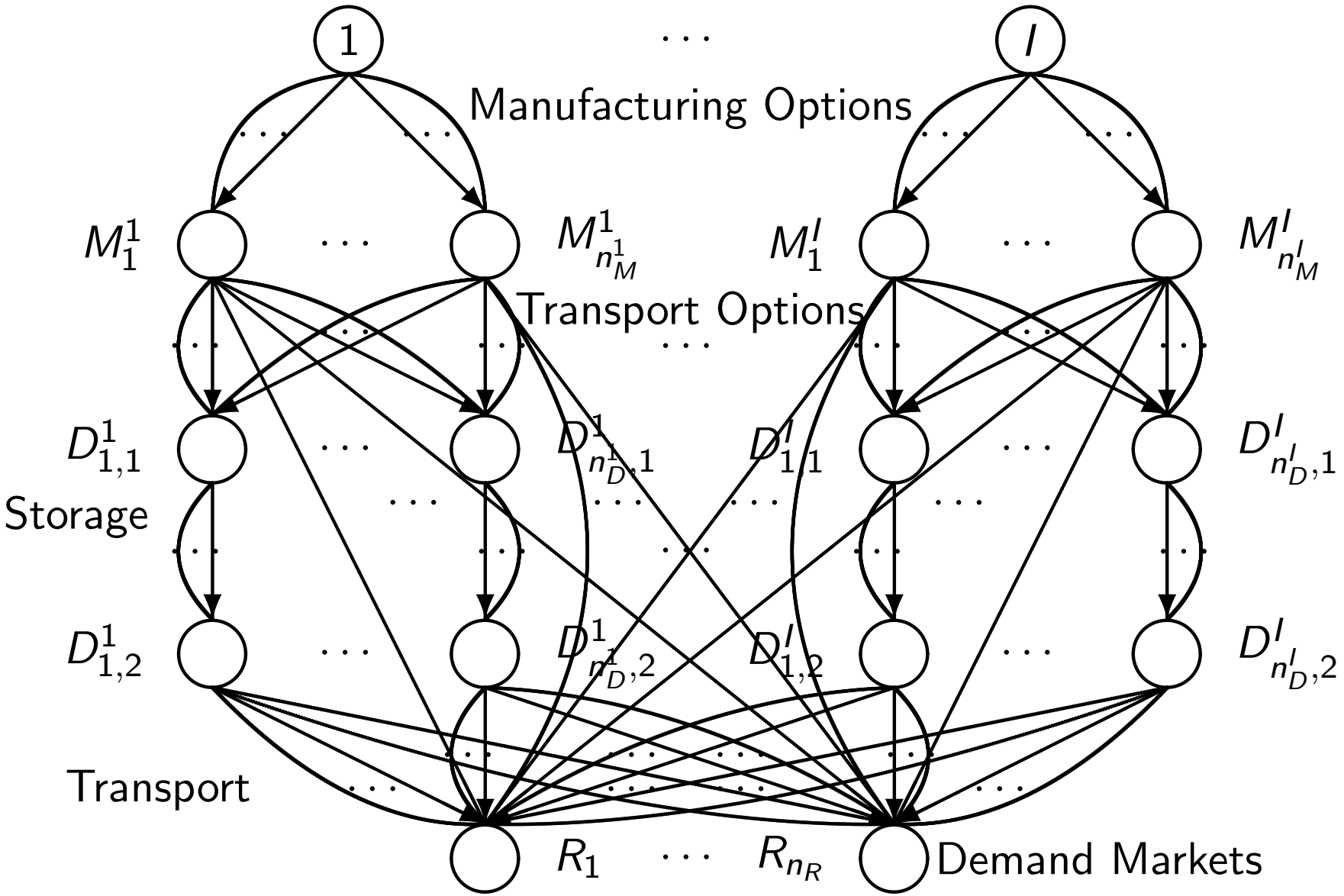


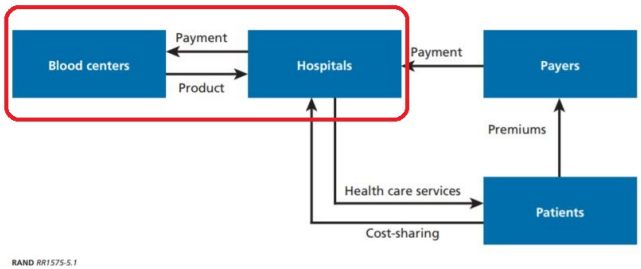
Figure: The Pharmaceutical Supply Chain Network Topology

Blood Supply Chains

Even prior to the pandemic the blood services sector was facing many challenges. This supply chain is unique in that the product cannot be produced but must be donated.

A. Nagurney and P. Dutta, "Supply Chain Network Competition Among Blood Service Organizations: A Generalized Nash Equilibrium Framework," *Annals of Operations Research* **275(2) (2019), pp 551-586.**

Operational challenges faced by blood service organizations.



A. Nagurney and P. Dutta, "Competition for Blood Donations," *Omega* **212 (2019), pp 103-114.**

Optimization and Supply Chain Network Models Inspired by the Covid-19 Pandemic

Food Supply Chain Disruptions Due to Covid-19

The Covid-19 pandemic has impacted food supply chains in a dramatic and sustained manner.

1. Infections at three of the nation's largest meat processors quadrupled in May despite new safety measures. At Tysons Foods, the largest meat processor in the US, **the number of Tyson employees with the coronavirus exploded to more than 7,000 as of May 25, 2020.**
2. **Shortages of many types of meats, even organic chicken, were experienced this past spring, with price increases**. It is projected that **meat supplies in grocery stores could shrink as much as 35%, prices could rise 20%** with even greater impact later this year.
3. **Fresh produce (oranges, potatoes, strawberries, etc.) on some farms, has had to be discarded** because of lack of timely processing capabilities at plants. Shortages now of workers for blueberry picking.

Food Supply Chain Disruptions Due to Covid-19

1. **Many farm animals have had to be culled** because of the shutdown of several big meat processing plants. Enhanced cleaning, redesign, and emphasis on social distancing is slowing down the processing, causing additional delays. **It is estimated that up to 300,000 market hogs were euthanized as of mid July**.

2. **Labor needed to pick ripened produce is less available due to migrant labor restrictions, illnesses, etc.**

3. With the closures of schools, restaurants, businesses, etc., outlets for perishable food have been changed dramatically. **Distribution channels are in need of being reinvisioned and redesigned.**

Food Insecurity

According to *The New York Times* magazine, Sept. 6, 2020:

A shadow of hunger looms over the United States. In the pandemic economy, nearly one in eight households doesn't have enough to eat. The lockdown, with its epic lines at food banks, has revealed what was hidden in plain sight: that the struggle to make food last long enough, and to get food that's healthful - what experts call 'food insecurity' - is a persistent one for millions of Americans.

Food Supply Chain Disruptions Due to Covid-19

USA TODAY

AMERICA'S FOOD CHAIN

As coronavirus pandemic spikes orange juice sales, a Florida citrus grower gets squeezed

Janine Zeitlin, USA TODAY Network - Florida
Updated 8:07 p.m. EDT May 14, 2020

CNN

An Idaho farm is giving away 2 million potatoes because coronavirus has hurt demand

By Alisha Ebrahimji, CNN
Updated 1:33 PM ET, Thu April 16, 2020

Lacking seasonal workers, Italy elevates its long-shunned migrants

The Christian Science Monitor

THEDENVERCHANNEL.COM

Farms encountering guest worker shortage amid new coronavirus restrictions

REUTERS

Piglets aborted, chickens gassed as pandemic slams meat sector

The Washington Post
Democracy Dies in Darkness

The meat industry is trying to get back to normal. But workers are still getting sick — and shortages may get worse.

There are now more than 11,000 coronavirus cases tied to Tyson Foods, Smithfield Foods and JBS

Germany Struggles To Fill Its Farm Labor Shortage After Closing Its Borders

May 20, 2020 · 10:58 AM ET

ROB SCHMITZ

npr

Perishable Food Supply Chain Network Model with Labor

New paper, "Perishable Food Supply Chain Networks with Labor in the Covid-19 Pandemic," A. Nagurney, in: *Dynamics of Disasters - Impact, Risk, Resilience, and Solutions*, **I.S. Kotsireas, A. Nagurney, and P.M. Pardalos, Editors, Springer International Publishing Switzerland, 2020.**

- With lack of availability of labor being one of the drivers of supply chain disruptions, the model that considers labor in all the supply chain network economic activities of production, transportation, processing, storage, and distribution.

- Impacts of the reduction of labor (capacities) on supply chain network links can then be quantitatively evaluated on the perishable product flows, the prices that the consumers pay, and profits of the firm.

- The framework enables a variety of sensitivity analysis exercises.

Perishable Food Supply Chain Network Model with Labor

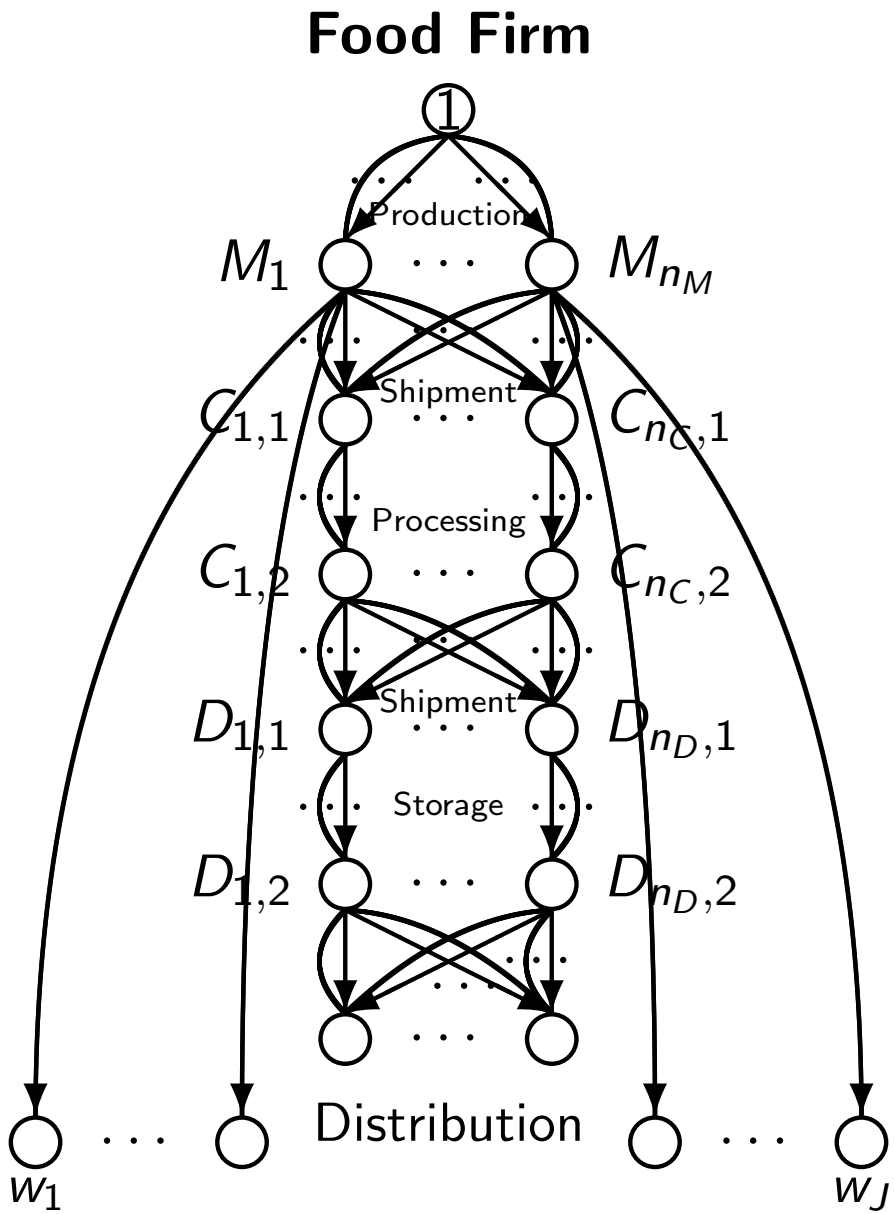


Figure: The Perishable Food Supply Chain Network Topology

Our findings include:

1. **The lack of labor on a single link, even a freight one, may significantly negatively impact a food firm.**
2. **Preserving productivity in all utilized supply chain network economic activities is critical** since the impact of a drastic reduction can severely reduce profits.
3. **Adding more direct sales, whether at farmers' markets or nearby farm stands, may help a food firm in a pandemic.**
4. Also, if a firm **enhances its marketing** so as to have consumers be willing to pay a higher price for its fresh produce, **major profit increases can occur**.

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 Press Democrat

Face masks in the national stockpile have not been substantially replenished since 2009

The New York Times

F.D.A. Bans Faulty Masks, 3 Weeks After Failed Tests

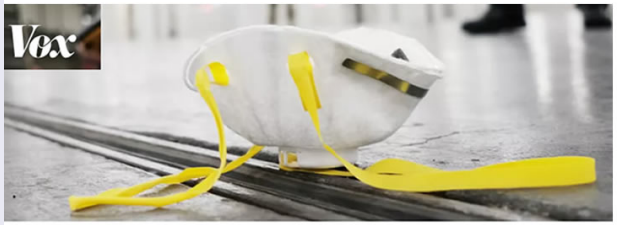
FierceHealthcare

A physician exec was trying to secure PPE for his hospital. Then the feds showed up

TIME

Begging for Thermometers, Body Bags, and Gowns: U.S. Health Care Workers Are Dangerously Ill-Equipped to Fight COVID-19

Vox

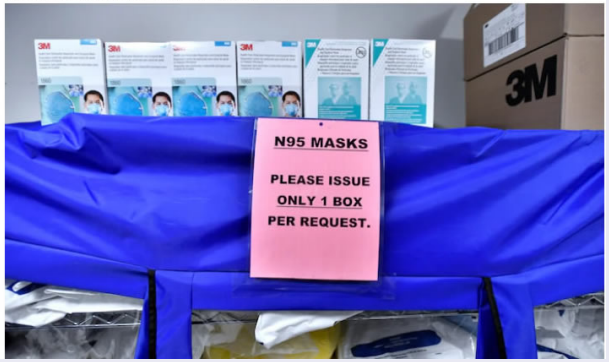


Why America ran out of protective masks — and what can be done about it

Why don't hospitals have enough masks? Because coronavirus broke the market.

The Washington Post
Democracy Dies in Darkness

Health-care supply chains are made for efficiency, not pandemics.



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."**

Supply Chain Model with Different Labor Constraints

The modeling framework considers first elastic demands for a product and then fixed demands, coupled with distinct types of labor capacities in order to capture the availability of this valuable resource in a pandemic, as well as possible flexibility.

The supply chain network framework includes electronic commerce and is relevant to many different supply chain applications including protective personal and medical equipment.

A. Nagurney, "Optimization of Supply Chain Networks with Inclusion of Labor: Applications to Covid-19 Pandemic Disruptions," 2020.

Supply Chain Model with Different Labor Constraints

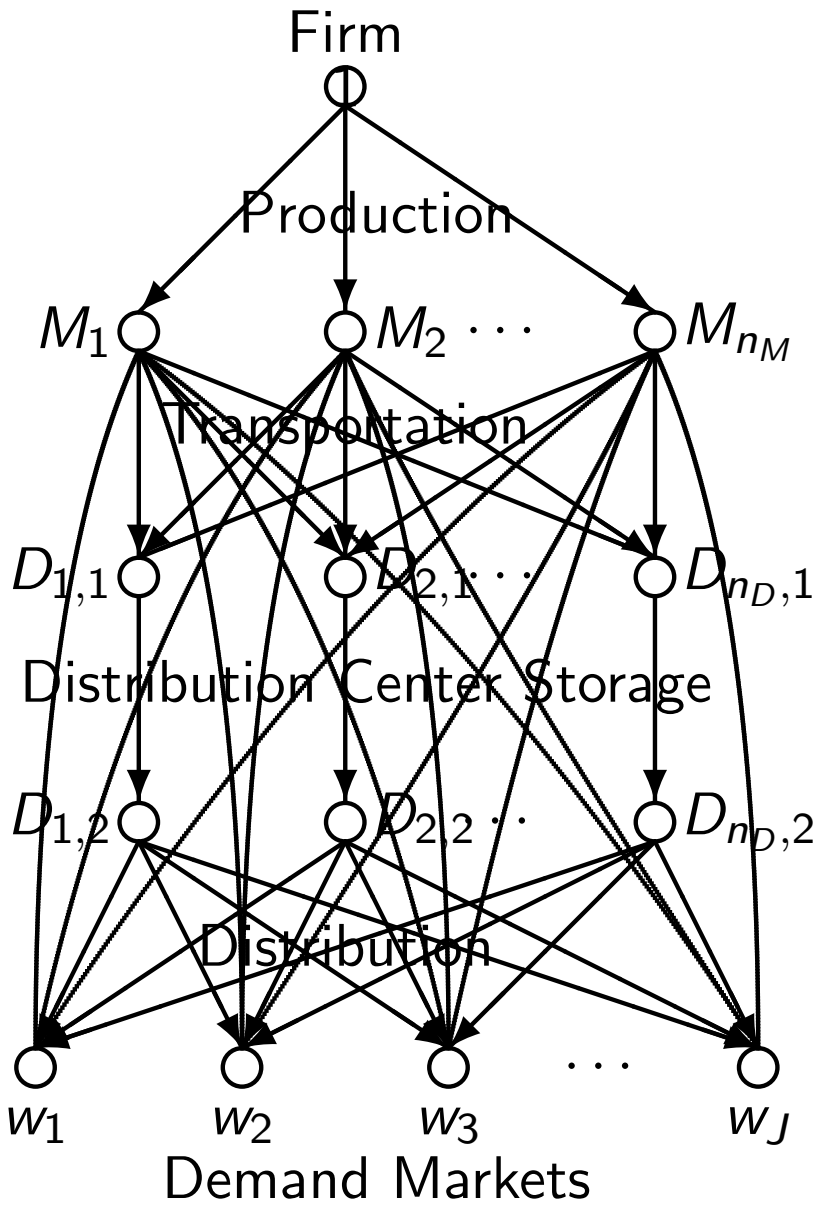


Figure: The Supply Chain Network Topology

Supply Chain Model with Different Labor Constraints

The model considers three sets of labor constraints, of increasing flexibility of movement.

1. **In the first set**, **each supply chain link has an upper bound of available labor.** Labor is is not free to move to other production sites, nor to other distribution centers, or assist in freight service provision.
2. **In the second set**, **labor is free to move across a supply chain set of network economic activities (such as production, or transportation, or storage, and, finally, distribution).** There is a capacity of labor associated with each such "tier" of supply chain links. Those who have skills in production, or in distribution, etc., may be reallocated. This has been happening in freight service provision, for example, during the Covid-19 pandemic.
3. **In the third set**, **labor is free to move across all the supply chain network economic activities, and there is a single capacity.** McKinsey & Company noted this is a means towards resilience and returning the supply chain to effectiveness while reenvisioning and reforming.

Supply Chain Model with Different Labor Constraints

Our findings include:

1. **Having appropriate healthcare pandemic mitigation processes and procedures in place is essential to continuing operations.** With even one of the two manufacturing plants closed, the can prices rise at the demand markets.
2. **Reduction in labor availability can result in a significant increase in product prices at the consumer level.**
3. **Even in the case of reduced labor availability, electronic commerce can result in increased profits.**
4. **Having the flexibility of labor being able to be reallocated across supply chain network activities can enable enhanced profits.**

Game Theory and Supply Chain Network Models Inspired by the Covid-19 Pandemic

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."

Game Theory Supply Chain Network Model with Labor

The Covid-10 pandemic has dramatically illustrated the importance of including labor (and associated possible disruptions) into the analysis of supply chain networks.

In addition, the pandemic has, in such essential sectors as food and healthcare, demonstrated the competition for labor resources!

In the paper, **"Supply Chain Game Theory Network Modeling Under Labor Constraints: Applications to the Covid-19 Pandemic," A. Nagurney (2020)**, a game theory model for supply chains with labor was constructed, under three different sets of constraints, building on our previous work.

Since, labor in this context, may be shared among the competing supply chain networks of firms/organizations, the governing concept is that of a **Generalized Nash Equilibrium** (rather than a Nash Equilibrium).

Game Theory Supply Chain Network Model with Labor

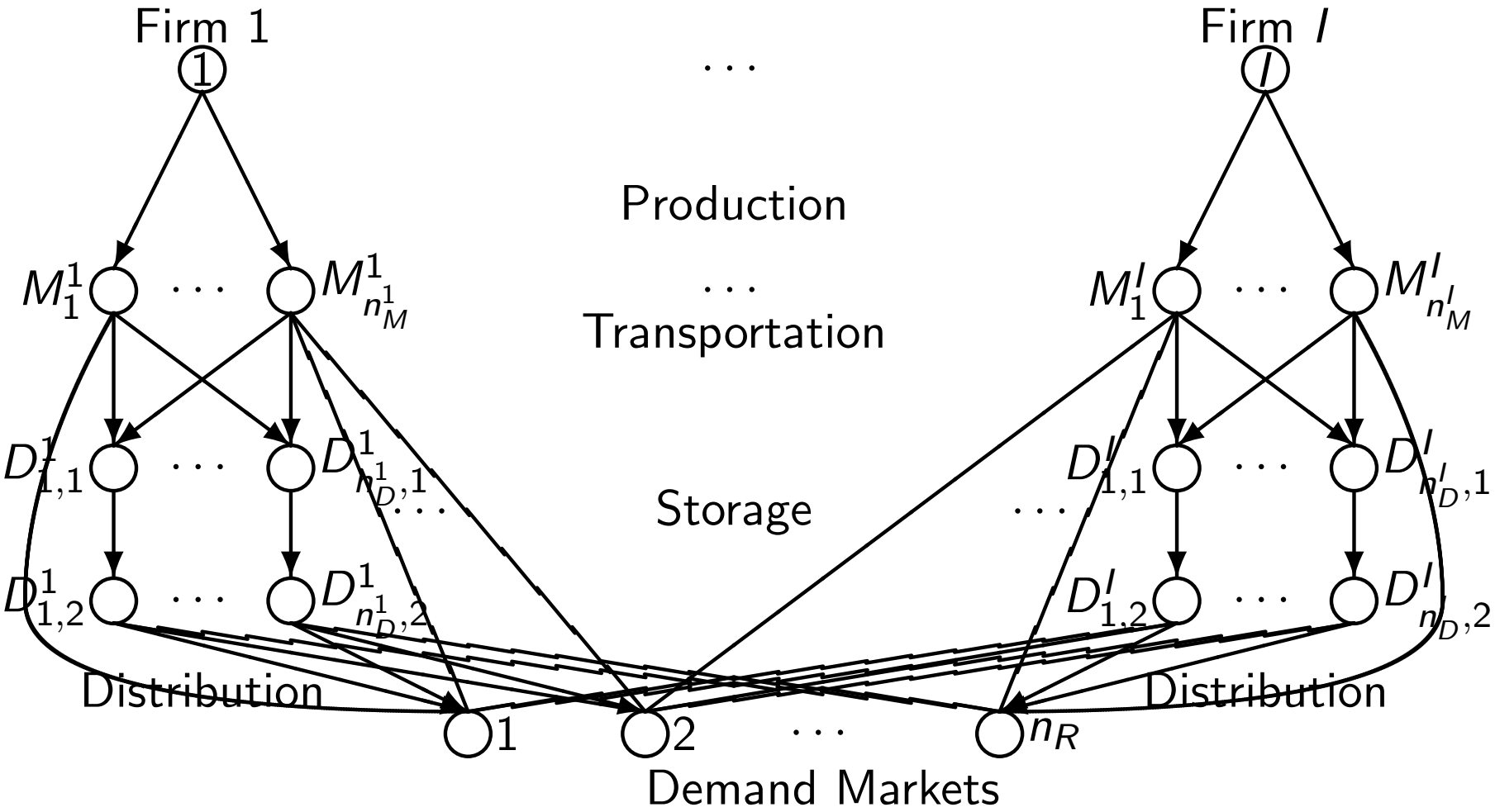


Figure: The Supply Chain Network Topology of the Game Theory Model with Labor

Game Theory Supply Chain Network Model with Labor

In the paper, we present a series of numerical examples documenting the potential impacts of labor disruptions under different scenarios.

We include results for disruptions at manufacturing plants, storage facilities; the impacts of the addition of a competitor, changes in demand price functions, as well as decreases in available labor throughout the supply chain network economy.

The research adds to modeling methodology as well as applications.

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.

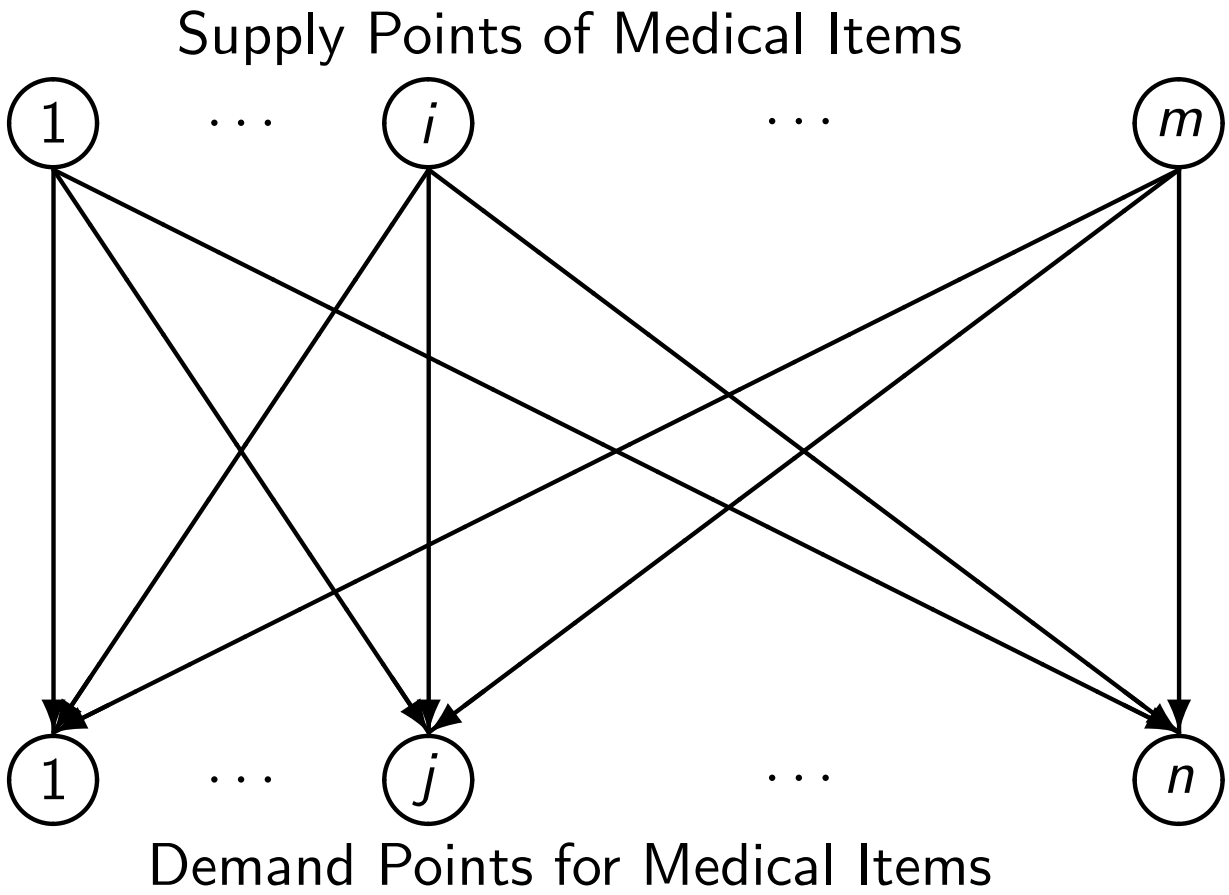


Figure: The Network Structure of the Competitive Game Theory Model for Medical Supplies with Stochastic Demands

Competition for Medical Supplies Under Stochastic Demand

The objective function of each demand point j is given by:

$$\text{Minimize} \quad \sum_{i=1}^{m} \rho_i q_{ij} + \sum_{i=1}^{m} c_{ij}(q) + \lambda_j^- E(\Delta_j^-) + \lambda_j^+ E(\Delta_j^+)$$

subject to the following constraints:

$$\sum_{j=1}^{n} q_{ij} \leq S_i, \quad i = 1, \ldots, m,$$

$$q_{ij} \geq 0, \quad i = 1, \ldots, m.$$

The model is a Generalized Nash Equilibrium one due to the competition for limited medical supplies.

Competition for Medical Supplies Under Stochastic Demand

Our findings include:

1. Our numerical results are consistent with what one can expect to observe in reality in terms of how organizations would procure critical medical supplies such as N95 masks under demand unpredictability and competition.
2. The findings confirm that more supply points with sufficient supplies are needed to ensure that organizations are not deprived of critical supplies due to competition.
3. As a result of this competition and limited local availability; in particular in the case of supplies such as masks and even coronavirus test kits, we are seeing several countries now setting up local production sites.
4. This work adds to the literature on game theory models for disaster relief with the specific features of the Covid-19 pandemic.

Impacting Policy Through Analytics

Writing OpEds

THE CONVERSATION

Academic rigor, journalistic flair

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. REUTERS/Kyodo

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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University of Massachusetts Amherst provides funding as a founding partner of The Conversation US.

Email

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

Chicago Tribune

SPORTS BREAKING HOY MOST POPULAR OPINION SUBURBS ENTERTAINMENT ADVERTISING

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

By Anna Nagurney
Associated Press

AUGUST 29, 2017 | BOSTON, MASSACHUSETTS

(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

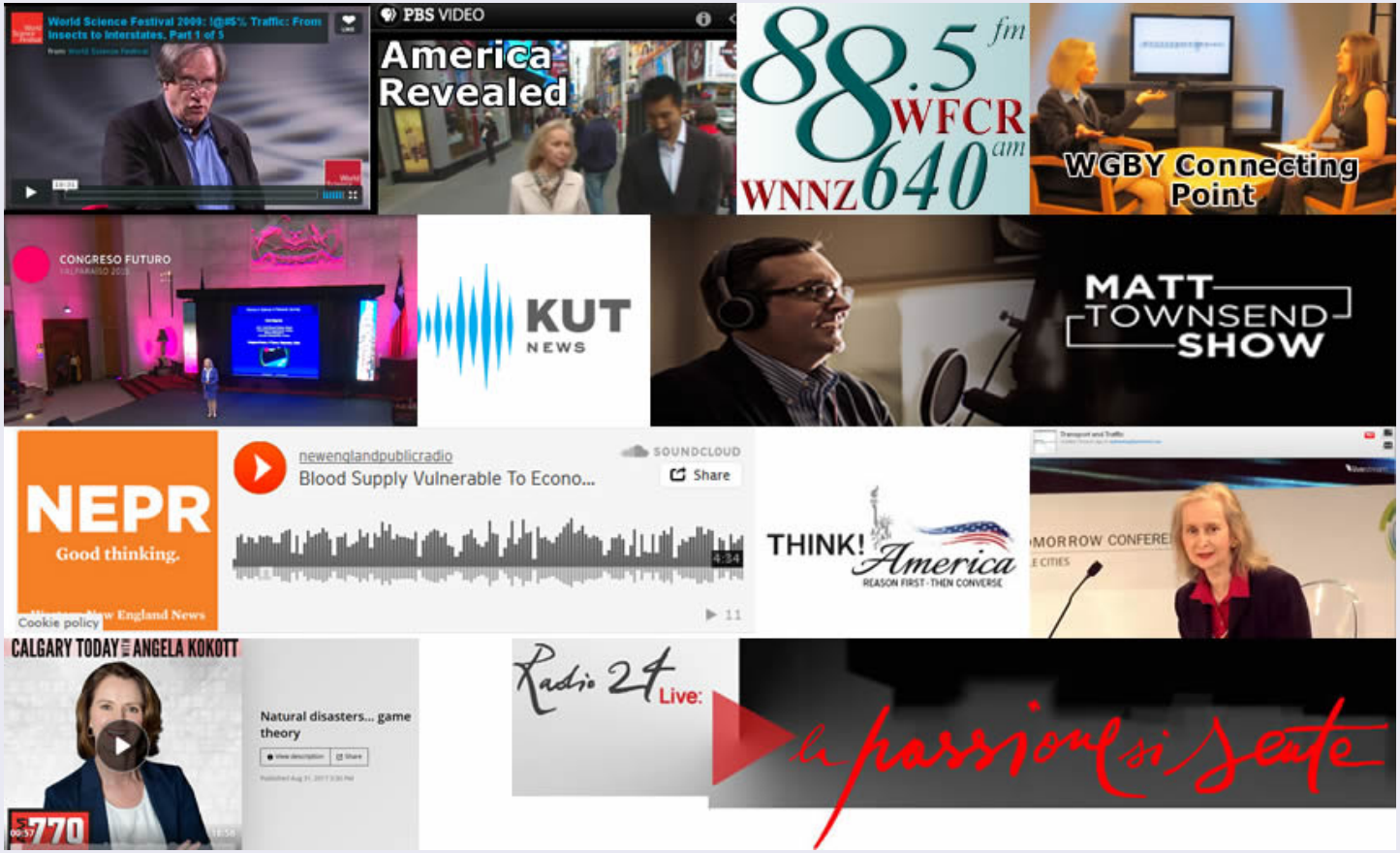
By Anna Nagurney

Published 13 March 2017

Share

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

Coverage by the Media



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

Email
Twitter 28
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Print

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

Analytics

DRIVING BETTER BUSINESS DECISIONS

informs

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

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Thank You!

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