Labor and Supply Chain Networks: Insights from Models Inspired by the COVID-19 Pandemic

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Acknowledgments

Many thanks to the organizers of the NETGCOOP Conference for the opportunity to speak to you today! I wish that we could all be together in Corsica.

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 have helped 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
- **Methodology - The Variational Inequality Problem**
- **Game Theory and Supply Chain Network Models Inspired by the COVID-19 Pandemic**
  - Food and Labor Disruptions
- **Impacting Policy**

Background and Motivation

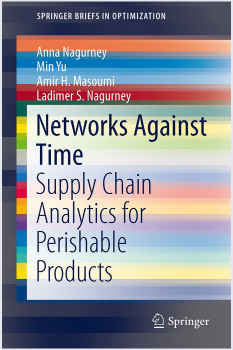
I Work on the Modeling of Network Systems

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.



It's All About People

A major research theme of ours in the COVID-19 pandemic is the inclusion of labor in supply chains, using optimization and game theory.

ORMS TODAY informs membership magazine

NEWS FEATURES PODCASTS

January 29, 2021 in Supply Chain Networks

In the End, It's All About People

COVID-19 vaccine production reveals dependency on supply chains, labor workforce in the U.S.

By Anna Nagurney

SHARE: PRINT ARTICLE: https://doi.org/10.1287/orms.2021.01.17

The COVID-19 pandemic has dramatically revealed how dependent we are on supply chains and the availability of labor. Without the human element, meatpacking plants cannot function; fresh produce cannot be picked; grocery stores cannot be shelved; PPEs cannot be produced and distributed; and products cannot be delivered to our homes

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.

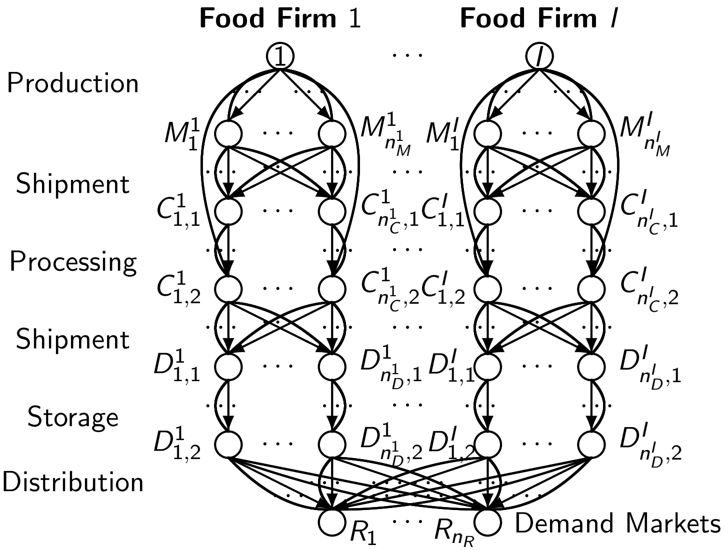
Fresh Produce Food Supply Chains

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.**

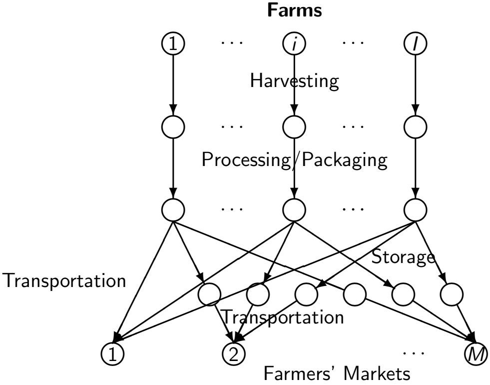
Fresh Produce Food Supply Chains

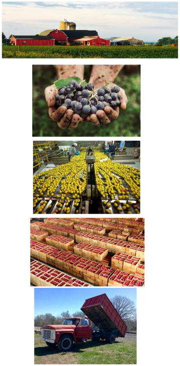


The Fresh Produce Supply Chain Network Topology

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.**

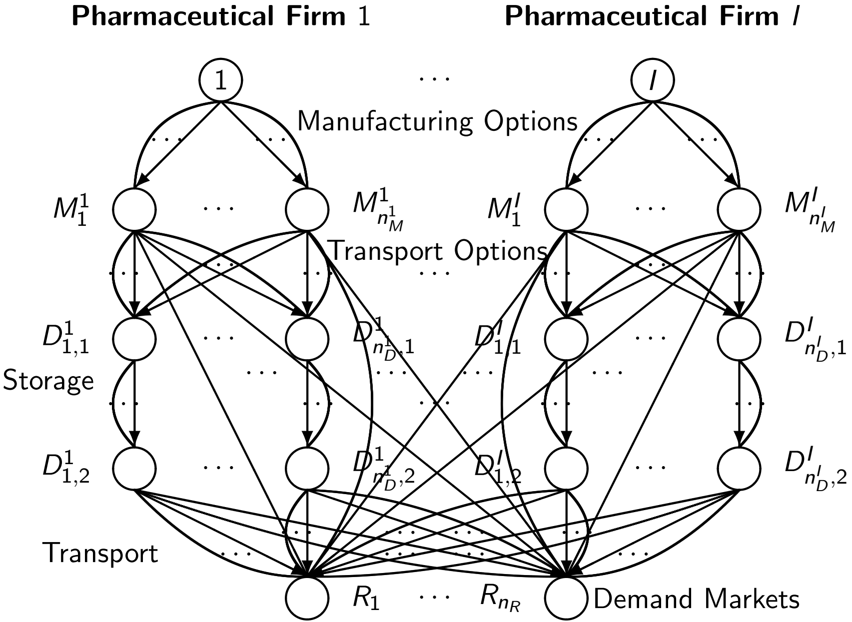


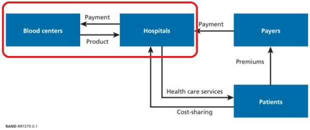
Figure: The Pharmaceutical Supply Chain Network Topology

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 impacted food supply chains in a dramatic and sustained manner.

- Infections at three of the nation's largest meat processors were significant in 2020. At Tysons Foods, the largest meat processor in the US, **the number of Tyson employees with the coronavirus exploded from less than 1,600 in April 2020 to more than 7,000 by May 25, 2020.**
- **Millions of farm animals had to be culled** because of the shutdown of several big meat processing plants. Enhanced cleaning, redesign, and emphasis on social distancing was slowing down the processing, causing additional delays.
- **Shortages of many types of meats, even organic chicken, were experienced, with price increases**.

Food Supply Chain Disruptions Due to COVID-19

- **Fresh produce (oranges, potatoes, strawberries, etc.) on some farms, had to be discarded** because of lack of timely processing capabilities at food processing plants.
- **Labor needed to pick ripened produce was less available due to migrant labor restrictions, illnesses, etc.**
- With the closures of schools, restaurants, businesses, etc., during part of the pandemic outlets for perishable food changed dramatically. **Distribution channels were being reinvisioned and redesigned.**
- **Food insecurity was rising nationally.**

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

The Christian Science Monitor

Lacking seasonal workers, Italy elevates its long-shunned migrants

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

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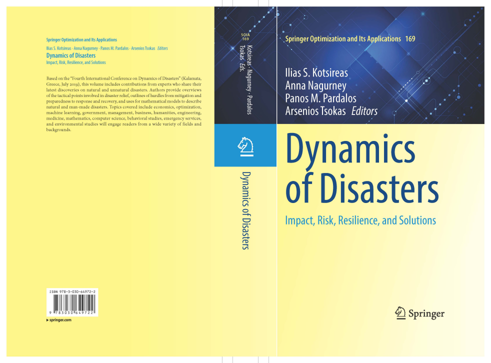
npr

Perishable Food Supply Chain Network Model with Labor

"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, P.M. Pardalos, and A. Tsokas, Editors, Springer Nature Switzerland AG, 2021, pp 173-193.**



Perishable Food Supply Chain Network Model with Labor

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

- **There are bounds on labor availability on each link as well as a productivity factor relating product flow to labor**.

- **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

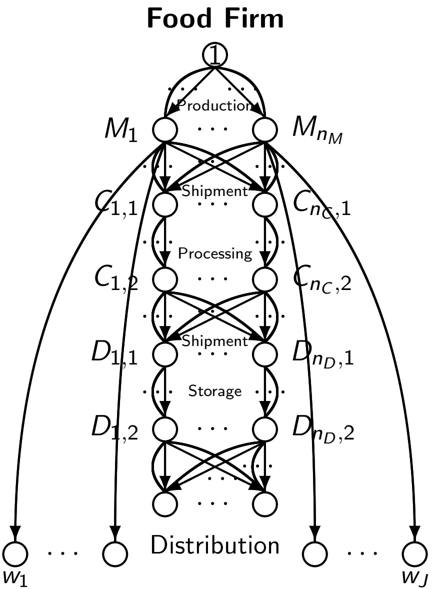


Figure: The Perishable Food Supply Chain Network Topology

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 2020, 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

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

The New York Times

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

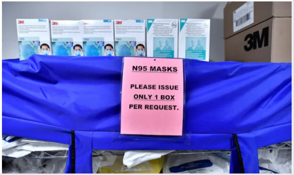
Vox

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:

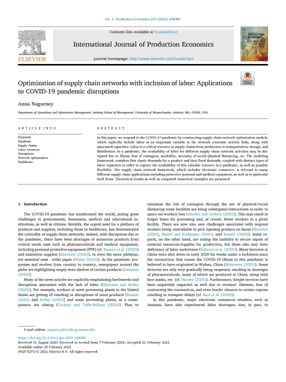
• **"It is hard to believe that our nation finds itself dealing with the same shortfalls in PPE witnessed during the first few weeks that SARS-CoV-2 began its unrelenting spread ..."**

• **"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

A. Nagurney, "Optimization of Supply Chain Networks with Inclusion of Labor: Applications to Covid-19 Pandemic Disruptions," *International Journal of Production Economics* **235 (2021), 108074.**



Int. J. Production Economics 235 (2021) 108080

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journal homepage: http://www.elsevier.com/locate/ijpe

Optimization of supply chain networks with inclusion of labor: Applications to COVID-19 pandemic disruptions

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Labor resources
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Healthcare

ABSTRACT

In this paper, we respond to the COVID-19 pandemic by constructing supply chain network optimization models, which explicitly include labor as an important variable in the network economic activity links, along with associated capacities. Labor is a critical resource in supply chains from production to transportation, storage, and distribution. In a pandemic, the availability of labor for different supply chain network activities may be disrupted due to illness, fear of contagion, morbidity, necessity of social/physical distancing, etc. 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, which includes electronic commerce, is relevant to many different supply chain applications including protective personal and medical equipment, as well as to particular food items. Theoretical results as well as computed numerical examples are presented.

1. Introduction

The COVID-19 pandemic has transformed the world, posing great challenges to governments, businesses, medical and educational institutions, as well as citizens. Notably, the urgent need for a plethora of products and supplies, including those in healthcare, has demonstrated the criticality of supply chain networks. Indeed, with disruptions due to the pandemic, there have been shortages of numerous products from critical needs ones such as pharmaceuticals and medical equipment, including personal protective equipment (PPE) (cf. Ranney et al. (2020)) and sanitation supplies (Morrison (2020)), to even the more plebeian, yet essential ones - toilet paper (Fisher (2020)). As the pandemic progresses and evolves from country to country, newspapers around the globe are highlighting empty store shelves of certain products (Swanson (2020)).

Many of the news articles are explicitly emphasizing bottlenecks and disruptions associated with the lack of labor (Bhattarai and Reiley (2020)). For example, workers at meat processing plants in the United States are getting ill resulting in disruptions of meat products (Rosane (2020) and Reiley (2020)) and some processing plants, as a consequence, are closing (Corkery and Yaffe-Bellany (2020)). Plus, to minimize the risk of contagion through the use of physical/social distancing some facilities are being redesigned/restructures in order to space out workers (see Scheiber and Corkery (2020)). This may result in longer times for processing and, of course, fewer workers in a given facility. There are now also new challenges associated with migrant workers being unavailable to pick ripening produce on farms (Shoichet (2020), Nickel and Walljasper (2020), and Russell (2020)). Some reports, on the other hand, are noting the inability to secure inputs of material resources/supplies for production, but these also may have deficiency of labor undertones (Rabouin et al. (2020)). Many factories in China were shut down in early 2020 for weeks under a lockdown since the coronavirus that causes the COVID-19 illness in this pandemic is believed to have originated in Wuhan, China (Mistreanu (2020)). Some factories are only very gradually being reopened, resulting in shortages of pharmaceuticals, many of which are produced in China, along with face masks, etc. (cf. Harney (2020)). Furthermore, freight services have been negatively impacted as well due to workers' illnesses, fear of contracting the coronavirus, and even border closures in certain regions resulting in transport delays (cf. Saul et al. (2020)).

In this pandemic, major electronic commerce retailers, such as Amazon, have also experienced labor shortages, due, in part, to

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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.

Supply Chain Model with Different Labor Constraints

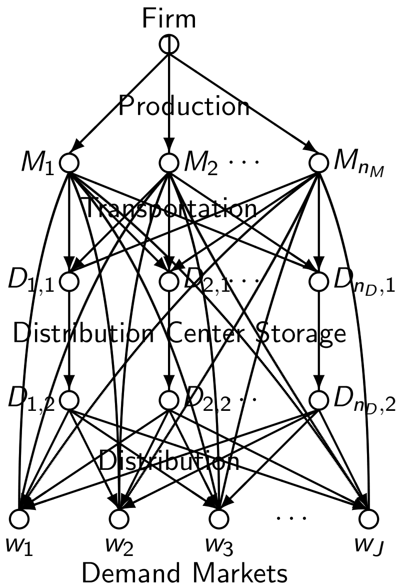


Figure: The Supply Chain Network Topology

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.**

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

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.**

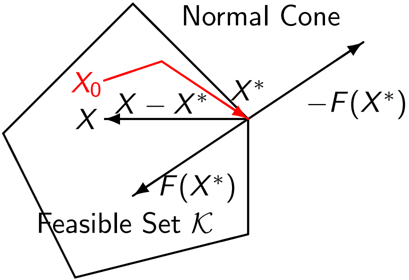
The variational inequality problem contains, as special cases, such mathematical programming problems as:

- 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)).

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

This part of the presentation is based on the paper, **"Supply Chain Game Theory Network Modeling Under Labor Constraints: Applications to the Covid-19 Pandemic,"** A. Nagurney, *European Journal of Operational Research* **293(3)** (2021), pp 880-891, in which a game theory model for supply chains with labor was constructed, under three different sets of constraints, building on our previous work.

European Journal of Operational Research 293 (2021) 880–891

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Production, Manufacturing, Transportation and Logistics

Supply chain game theory network modeling under labor constraints: Applications to the Covid-19 pandemic

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ABSTRACT

The Covid-19 pandemic has brought attention to supply chain networks due to disruptions for many reasons, including that of labor shortages as a consequences of illnesses, death, risk mitigation, as well as travel restrictions. Many sectors of the economy from food to healthcare have been competing for workers, as a consequence. In this paper, we construct a supply chain game theory network framework that captures labor constraints under three different scenarios. The appropriate equilibrium constructs are defined, along with their variational inequality formulations. Computed solutions to numerical examples inspired by shortages of migrant labor to harvest fresh produce; specifically, blueberries, in the United States, reveal the impacts of a spectrum of disruptions to labor on the product flows and the profits of the firms in the supply chain network economy. This research adds to the literature in both economics and operations research.

1. Introduction

The Covid-19 pandemic, officially declared by the World Health Organization on March 11, 2020, has demonstrated dramatically the importance of the health of workers to the global economy (Organization, 2020). Product supply chains as varied as those for Personal Protective Equipment (PPEs) (Burki, 2020) and other medical supplies (Ranney, Griffieth, & Jha, 2020), toilet paper and cleaning supplies (Gao, 2020), meat (Corkery & Yaffe-Bellany, 2020) and fresh produce (Knight, 2020; Laborde, Martin, Swinnen, & Vos, 2020), and even blood (Nagurney, 2020a), have been disrupted for reasons including that of the reduction of labor availability because of illnesses and death of workers, along with workers' fear of contracting the disease. Some workers have not been able to travel for seasonal employment because of travel restrictions to mitigate the spread of the coronavirus that causes the Covid-19 disease, resulting in both economic and personal losses (IHS-Markit, 2020). According to Elflein (2020), as of August 14, 2020, Covid-19 had spread to six continents, with over 750,000 succumbing to the coronavirus that causes the Covid-19 disease. Just over 2 months after, as of October 27, 2020, there were 1,160,421 documented deaths globally due to Covid-19 (JHU-CSSE2020, 2020). The negative impact of this global healthcare and economic crisis has affected different tiers of supply chains and associated network economic activities of production, transportation, storage, and distribution.

Labor has emerged as an essential factor in the functioning of supply chains in the pandemic. Without farmers, food cannot be produced. Without workers to harvest, food may end up rotting in the fields or be discarded (see Associated Press, 2020); without freight service provision food cannot be delivered to food processors; without food processors food cannot be processed, resulting in additional waste (see Polansek & Huffstutter, 2020). Ultimately, freight service provision is also essential for deliveries to retail outlets for purchase by consumers or even for direct transport to consumers using, for example, electronic commerce. Freight service workers have also been impacted by Covid-19 (Parker, 2020). Employees at distribution centers have been felled by Covid-19 (Daniels, 2020), as well, and Covid-19 has further exacerbated worker shortages at a time of greater demand because of electronic commerce (see Hardwick, 2020). Shortages of labor in manufacturing facilities were an issue even earlier on in February 2020 in China, since that country was impacted first by the coronavirus, which was to have originated in Wuhan, with implications for global supply chains (see Bloomberg, 2020). Labor shortages arose due to illnesses, need for social distancing in facilities, as well as adherence to quarantines. Each link of a product supply chain requires labor, and, therefore, reduction in labor capacity can propagate through paths of a supply chain network, affecting product flows as well as prices (see, e.g., OECD, 2020). Furthermore, unhealthy workers cannot be fully productive.

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Game Theory Supply Chain Network Model with Labor

Two sets of constraints have labor being shared among the competing supply chain networks of firms/organizations, in which case the governing concept is that of a **Generalized Nash Equilibrium** (rather than a Nash Equilibrium).

The research adds to modeling methodology as well as applications.

Game Theory Supply Chain Network Model with Labor

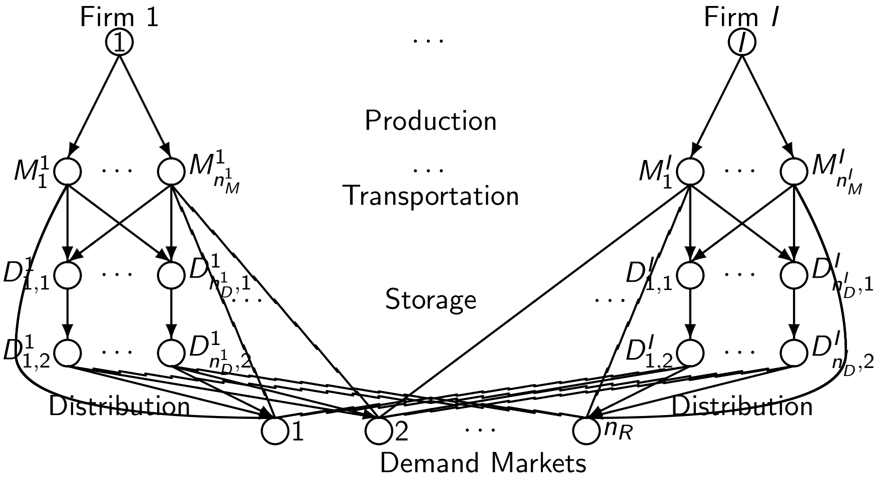

Figure: The Supply Chain Network Topology of the Game Theory Model with Labor

Table: Game Theory Supply Chain Network Model Notation

Notation	Definition
L^i	The set of links in firm i's supply chain network, with L being all the links.
$G = [N, L]$	the graph of the supply chain network consisting of all nodes N and all links L.
P^i_k	set of paths in firm i's supply chain network terminating in demand market k; $\forall i, k$.
P^i	set of all n_{P^i} paths of firm i; $i = 1, \ldots, I$.
P	set of all n_P paths in the supply chain network economy.
x_p; $p \in P^i_k$	nonnegative flow on path p originating at firm node i and terminating at k; $\forall i, k$. Group firm i's path flows into vector $x^i \in R_+^{n_{P^i}}$. Then group all firms' path flows into vector $x \in R_+^{n_P}$.
f_a	nonnegative flow of the product on link a, $\forall a \in L$. Group all link flows into vector $f \in R_+^{n_L}$.
l_a	labor on link a (usually denoted in person hours).
α_a	positive factor relating input of labor to output of product flow on link a, $\forall a \in L$.
$\bar{l}_a$	bound on the availability of labor on link a under Scenario 1, $\forall a \in L$
$\bar{l}^t$	bound on labor availability for tier t activities under Scenario 2. $T+1$ is electronic commerce tier.
$\bar{l}$	bound on labor availability under Scenario 3.
d_{ik}	demand for the product of firm i at demand market k; $\forall i, k$. Group $\{d_{ik}\}$ elements for firm i into vector $d^i \in R_+^{n_R}$ and all demands into vector $d \in R_+^{I \times n_R}$.
$\hat{c}_a(f)$	total operational cost associated with link a, $\forall a \in L$.
π_a	cost of a unit of labor on link a, $\forall a$.
$\rho_{ik}(d)$	demand price function for the product of firm i at demand market k; $\forall i, k$.

Game Theory Supply Chain Network Model with Labor

For each firm i; $i = 1, \dots, I$, we must have that:

$$\sum_{p \in P_k^i} x_p = d_{ik}, \quad k = 1, \dots, n_R. \qquad (1)$$

The path flows must be nonnegative; that is, for each firm i; $i = 1, \dots, I$:

$$x_p \geq 0, \quad \forall p \in P^i. \qquad (2)$$

The link flows of each firm i; $i = 1, \dots, I$, are related to the path flows as:

$$f_a = \sum_{p \in P} x_p \delta_{ap}, \quad \forall a \in L^i, \qquad (3)$$

where $\delta_{ap} = 1$, if link a is contained in path p, and 0, otherwise. We now discuss how labor is related to product flow.

$$f_a = \alpha_a l_a, \quad \forall a \in L^i, \quad i = 1, \dots, I. \qquad (4)$$

Game Theory Supply Chain Network Model with Labor

The utility function of firm i, U^i; $i = 1, \ldots, I$, is the profit, given by the difference between its revenue and its total costs:

$$U^i = \sum_{k=1}^{n_R} \rho_{ik}(d)d_{ik} - \sum_{a \in L^i} \hat{c}_a(f) - \sum_{a \in L^i} \pi_a l_a. \tag{5a}$$

The functions U_i; $i = 1, \ldots, I$, are assumed to be concave, with the demand price functions being monotone decreasing and continuously differentiable and the total link cost functions being convex and also continuously differentiable.

The Optimization Problem of Each Firm

The optimization problem of each firm i; $i = 1, \ldots, I$, is:

$$\text{Maximize} \quad \sum_{k=1}^{n_R} \rho_{ik}(d)d_{ik} - \sum_{a \in L^i} \hat{c}_a(f) - \sum_{a \in L^i} \pi_a l_a, \tag{5b}$$

subject to: (1), (2), (3), and (4).

Game Theory Supply Chain Network Model with Labor

Labor Scenario 1 – A Bound on Labor on Each Supply Chain Network Link

In Scenario 1, the additional constraints on the fundamental model are:

$$l_a \leq \bar{l}_a, \quad \forall a \in L. \tag{6}$$

Labor Scenario 2 – A Bound on Labor on Each Tier of Links in the Supply Chain Network

In Scenario 2, firms are faced with the ff. additional constraints:

$$\sum_{a \in L^1} l_a \leq \bar{l}^1, \tag{7,1}$$

$$\sum_{a \in L^2} l_a \leq \bar{l}^2, \tag{7,2}$$

and so on, until

$$\sum_{a \in L^{T+1}} l_a \leq l^{T+1}. \tag{7, T+1}$$

Labor Scenario 3 – A Single Labor Bound on Labor for All the Links in the Supply Chain Network

Scenario 3 may be interpreted as being the least restrictive of the scenarios considered here in that labor can be transferable across different activities of production, transportation, storage, and distribution. In Scenario 3, in addition to constraints (1) through (4), the firms are now faced with the following single constraint:

$$\sum_{a \in L} l_a \leq \bar{l}. \tag{8}$$

Game Theory Supply Chain Network Model with Labor

Recall that x^i denotes the vector of strategies, which are the path flows, for each firm i; $i = 1, \ldots, I$. We can redefine the utility/profit functions $\tilde{U}^i(x) \equiv U^i$; $i = 1 \ldots, I$ and group the profits of all the firms into an I-dimensional vector $\tilde{U}$, such that

$$\tilde{U} = \tilde{U}(x). \tag{9}$$

Objective function (5b), in lieu of the above, can now be expressed as:

$$\text{Maximize} \quad \tilde{U}^i(x) = \sum_{k=1}^{n_R} \tilde{\rho}_{ik}(x) \sum_{p \in P_k^i} x_p - \sum_{a \in L^i} \tilde{c}_a(x) - \sum_{a \in L^i} \frac{\pi_a}{\alpha_a} \sum_{p \in P} x_p \delta_{ap}. \tag{10}$$

Scenario 1 Nash Equilibrium Conditions

We define the feasible set K_i for firm i:

$K_i \equiv \{x^i | x^i \in R_+^{n_{P^i}}, \frac{\sum_{p \in P^i} x_p \delta_{ap}}{\alpha_a} \leq \bar{l}_a, \forall a \in L^i\}$, for $i = 1, \ldots, I$.

Also, we define $K \equiv \prod_{i=1}^{I} K_i$.

In Scenario 1, each firm competes noncooperatively until the following equilibrium is achieved.

Definition: Supply Chain Network Nash Equilibrium for Scenario 1

A path flow pattern $x^* \in K$ is a supply chain network Nash Equilibrium if for each firm i; $i = 1, \ldots, I$:

$$\tilde{U}^i(x^{i*}, \hat{x}^{i*}) \geq \tilde{U}^i(x^i, \hat{x}^{i*}), \quad \forall x^i \in K_i, \tag{11}$$

where $\hat{x}^{i*} \equiv (x^{1*}, \ldots, x^{i-1*}, x^{i+1*}, \ldots, x^{I*})$.

Variational Inequality Formulations

Applying the classical theory of Nash equilibria and variational inequalities, under our imposed assumptions on the underlying functions, it follows that (cf. Gabay and Moulin (1980) and Nagurney (1999)) the solution to the above Nash Equilibrium problem (see Nash (1950, 1951)) coincides with the solution of the variational inequality problem: determine $x^* \in K$, such that

$$-\sum_{i=1}^{I} \langle \nabla_{x^i} \tilde{U}^i(x^*), x^i - x^{i*} \rangle \geq 0, \quad \forall x \in K, \qquad (12)$$

where $\langle \cdot, \cdot \rangle$ represents the inner product in the corresponding Euclidean space, which here is of dimension n_P, and $\nabla_{x^i} \tilde{U}^i(x)$ is the gradient of $\tilde{U}^i(x)$ with respect to x^i.

We introduce Lagrange multipliers λ_a associated with constraint (6), $\forall a \in L$ and group the Lagrange multipliers for each firm i's network L^i into the vector λ^i. Group all such vectors for firms into vector $\lambda \in R_+^{n_L}$. Define feasible sets: $K_i^1 \equiv \{(x^i, \lambda^i) | (x^i, \lambda^i) \in R_+^{n_{P^i} + n_{L^i}}\}$; $i = 1, \ldots, I$, and $K^1 \equiv \prod_{i=1}^{I} K_i^1$.

Theorem: Alternative VI of Nash Equilibrium for Scenario 1

The supply chain network Nash Equilibrium satisfying the Definition 3.1 is equivalent to the solution of the variational inequality: determine vectors of path flows and Lagrange multipliers, $(x^*, \lambda^*) \in K^1$*, where:*

$$\sum_{i=1}^{m}\sum_{k=1}^{n_R}\sum_{p\in P_k^i}\left[\frac{\partial \tilde{C}_p(x^*)}{\partial x_p}+\sum_{a\in L^i}\frac{\lambda_a^*}{\alpha_a}\delta_{ap}+\sum_{a\in L^i}\frac{\pi_a}{\alpha_a}\delta_{ap}-\tilde{\rho}_{ik}(x^*)-\sum_{l=1}^{n_R}\frac{\partial\tilde{\rho}_{il}(x^*)}{\partial x_p}\sum_{q\in P_l^i}x_q^*\right]\times[x_p-x_p^*]$$

$$+\sum_{a\in L}\left[\bar{l}_a-\frac{\sum_{p\in P}x_p^*\delta_{ap}}{\alpha_a}\right]\times[\lambda_a-\lambda_a^*]\geq 0,\quad \forall (x,\lambda)\in K^1; \tag{13}$$

where for each path p; $p\in P_k^i$; $i=1,\ldots,m$; $k=1,\ldots,n_R$:

$$\frac{\partial \tilde{C}_p(x)}{\partial x_p}\equiv\sum_{a\in L^i}\sum_{b\in L^i}\frac{\partial \hat{c}_b(f)}{\partial f_a}\delta_{ap}, \tag{14}$$

$$\frac{\partial\tilde{\rho}_{ik}(x)}{\partial x_p}\equiv\frac{\partial\rho_{il}(d)}{\partial d_{ik}}. \tag{15}$$

Scenarios 2 and 3

For both Scenarios 2 and 3, we use a refinement of the Generalized Nash Equilibrium, known as a *Variational Equilibrium* to construct variational inequality formulations.

Hence, the labor supply chain network equilibrium models, under three different scenarios of constraints, can be uniformly qualitatively studied and solution to numerical problems, quantitatively computed using rigorous algorithms!

Realization of the Modified Projection Method Computation Step for VI (13)

Specifically, at iteration τ, we compute each of the path flows $\bar{x}_p^\tau$, $\forall P_k^i$, $\forall i$, $\forall k$, according to:

$$\bar{x}_p^\tau = \max\{0, x_p^{\tau-1} - \beta(\frac{\partial \tilde{C}_p(x^{\tau-1})}{\partial x_p} + \sum_{a \in L^i} \frac{\lambda_a^{\tau-1}}{\alpha_a}\delta_{ap} + \sum_{a \in L^i} \frac{\pi_a}{\alpha_a}\delta_{ap}$$

$$-\tilde{\rho}_{ik}(x^{\tau-1}) - \sum_{l=1}^{n_R} \frac{\partial \tilde{\rho}_{il}(x^{\tau-1})}{\partial x_p} \sum_{q \in P_l^i} x_q^{\tau-1})\} \quad (16)$$

and each of the Lagrange multipliers $\bar{\lambda}_a^\tau$, $\forall a \in L$, according to:

$$\bar{\lambda}_a^\tau = \max\{0, \lambda_a^{\tau-1} - \beta(\bar{l}_a - \frac{\sum_{p \in P} x_p^{\tau-1}\delta_{ap}}{\alpha_a})\}. \quad (17)$$

Application of the Modified Projection Method

Realization of the Modified Projection Method Computation Step for VI (13)

At iteration τ, we compute each of the path flows x_p^τ, $\forall P_k^i$, $\forall i$, $\forall k$, according to:

$$x_p^\tau = \max\{0, x_p^{\tau-1} - \beta(\frac{\partial \tilde{C}_p(\bar{x}^\tau)}{\partial x_p} + \sum_{a \in L^i} \frac{\bar{\lambda}_a^\tau}{\alpha_a}\delta_{ap} + \sum_{a \in L^i} \frac{\pi_a}{\alpha_a}\delta_{ap} - \tilde{\rho}_{ik}(\bar{x}^\tau)$$

$$- \sum_{l=1}^{n_R} \frac{\partial \tilde{\rho}_{il}(\bar{x}^\tau)}{\partial x_p} \sum_{q \in P_l^i} \bar{x}_q^\tau)\} \quad (18)$$

and each of the Lagrange multipliers λ_a^τ, $\forall a \in L$, according to:

$$\lambda_a^\tau = \max\{0, \lambda_a^{\tau-1} - \beta(\bar{l}_a - \frac{\sum_{p \in P} \bar{x}_p^\tau \delta_{ap}}{\alpha_a})\}. \quad (19)$$

Numerical Experiments

Our numerical examples are based on disruptions in migrant labor in the blueberry supply chain in the Northeast of the US in the summer of 2020.


The numerical examples investigate:

- Modifications in demand price functions;
- Disruptions in labor on a supply chain network link,

with additional numerical examples presented in the EJOR paper.

Numerical Examples

Examples 1, 2, and 3 have the supply chain network topology given below. There are two competing food firms (blueberry farms), each with two production locations, and with a single distribution center. There are two demand markets. We consider Scenario 1.

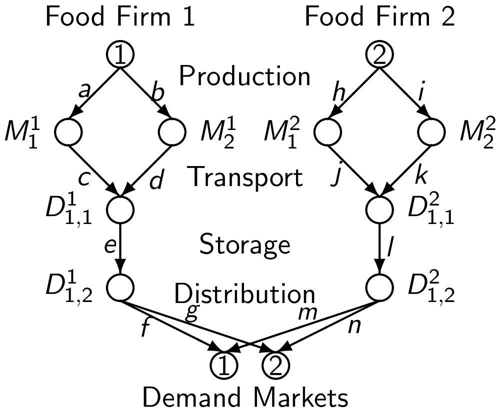

Figure: The Supply Chain Network Topology for the Numerical Examples

Example 1 - Baseline Example

The total operational cost functions for Food Firm 1 on its supply chain network L^1 are:

$$\hat{c}_a(f) = .0006 f_a^2, \quad \hat{c}_b(f) = .0007 f_b^2, \quad \hat{c}_c(f) = .001 f_c^2, \quad \hat{c}_d(f) = .001 f_d^2,$$

$$\hat{c}_e(f) = .002 f_e^2, \quad \hat{c}_f(f) = .005 f_f^2, \quad \hat{c}_g(f) = .005 f_g^2.$$

Also, the total operational costs associated with Food Firm 2's supply chain network L^2 are:

$$\hat{c}_h(f) = .00075 f_h^2, \quad \hat{c}_i(f) = .0008 f_i^2, \quad \hat{c}_j(f) = .0005 f_j^2, \quad \hat{c}_k(f) = .0005 f_k^2,$$

$$\hat{c}_l(f) = .0015 f_l^2, \quad \hat{c}_m(f) = .01 f_m^2, \quad \hat{c}_n(f) = .01 f_n^2.$$

The costs for labor (wages) for Food Firm 1 are:

$$\pi_a = 10, \quad \pi_b = 10, \quad \pi_c = 15, \quad \pi_d = 15, \quad \pi_e = 20, \quad \pi_f = 17, \quad \pi_g = 18,$$

and for Food Firm 2:

$$\pi_h = 11, \quad \pi_i = 22, \quad \pi_j = 15, \quad \pi_k = 15, \quad \pi_l = 18, \quad \pi_m = 18, \quad \pi_n = 18.$$

Example 1 - Baseline Example

The link labor productivity factors for the first firm are:

$$\alpha_a = 24,\ \alpha_b = 25,\ \alpha_c = 100,\ \alpha_d = 100,\ \alpha_e = 50,\ \alpha_f = 100,\ \alpha_g = 100,$$

and for the second firm:

$$\alpha_h = 23,\ \alpha_i = 24,\ \alpha_j = 100,\ \alpha_k = 100,\ \alpha_l = 70,\ \alpha_m = 100,\ \alpha_n = 100.$$

The bounds on labor for the first firm are:

$$\bar{l}_a = 10, \quad \bar{l}_b = 200, \quad \bar{l}_c = 300, \quad \bar{l}_d = 300, \quad \bar{l}_e = 100, \quad \bar{l}_f = 120, \quad \bar{l}_g = 120,$$

and for the second firm:

$$\bar{l}_h = 800, \quad \bar{l}_i = 90, \quad \bar{l}_j = 200, \quad \bar{l}_k = 200, \quad \bar{l}_l = 300, \quad \bar{l}_m = 100, \quad \bar{l}_n = 100.$$

Observe that the labor availability on link a is low. This is done in order to capture a disruption to labor in the pandemic.

Example 1 - Baseline Example

The demand price functions for Food Firm 1 are:

$$\rho_{11}(d) = -.0001d_{11} - .00005d_{21} + 6, \quad \rho_{12}(d) = -.0002d_{12} - .0001d_{22} + 8.$$

The demand price functions for Food Firm 2 are:

$$\rho_{21}(d) = -.0003d_{21} + 7, \quad \rho_{22}(d) = -.0002d_{22} + 7.$$

The paths are: $p_1 = (a, c, e, f)$, $p_2 = (b, d, e, f)$, $p_3 = (a, c, e, g)$, path $p_4 = (b, d, e, g)$, $p_5 = (h, j, l, m)$, $p_6 = (i, k, l, m)$, $p_7 = (h, j, l, n)$, and $p_8 = (i, k, l, n)$.

Example 1 - Baseline Example

All the Lagrange multipliers are equal to 0.00 except for $\lambda_a^* = 4.925$ with the labor equilibrium value on link a equal to its upper bound of 10.00.

The product prices at equilibrium are:

$$\rho_{11} = 5.97, \quad \rho_{12} = 7.91, \quad \rho_{21} = 6.94, \quad \rho_{22} = 6.96,$$

with equilibrium demands of:

$$d_{11}^* = 172.07, \quad d_{12}^* = 359.15, \quad \rho_{21} = 195.94, \quad \rho_{22} = 197.86.$$

The profit of Food Firm 1 is: 1,671.80 and the profit of Food Firm 2 is: 1,145.06.

Example 2 – Modification of Demand Price Functions

Example 2 has the same data as Example 1 except that we modify the demand price functions for the second firm to include a cross term, so that:

$$\rho_{21}(d) = -.0003d_{21} - .0001d_{11} + 6, \quad \rho_{22}(d) = -.0002d_{22} - .0001d_{12} + 7.$$

The Lagrange multipliers are all equal to 0.00 except for $\lambda_a^* = 4.93$.

Example 2 – Modification of Demand Price Functions

The product prices at equilibrium are now:

$$\rho_{11} = 5.97, \quad \rho_{12} = 7.91, \quad \rho_{21} = 6.92, \quad \rho_{22} = 6.92,$$

with the equilibrium demands:

$$d_{11}^* = 172.07, \quad d_{12}^* = 359.16, \quad d_{21}^* = 195.48, \quad d_{22}^* = 196.48.$$

The profit for Food Firm 1 is: 1,671.86 and the profit for Food Firm 2 is: 1,134.61. The profit for Food Firm 1 rises ever so slightly, whereas that for Food Firm 2 decreases.

Example 3 – Disruptions in Storage Facilities

Example 3 has the same data as Example 2 except that we now consider a sizable disruption in terms of the spread of COVID-19 at the distribution centers of both food firms with the bounds on labor corresponding to the associated respective links being reduced to:

$$\bar{l}_e = 5, \quad \bar{l}_l = 5.$$

All computed equilibrium Lagrange multipliers are now equal to 0 except for those associated with the distribution center links, since the equilibrium labor values attain the imposed upper bounds on links e and l, with the respective equilibrium Lagrange multiplier values being:

$$\lambda_e^* = 157.2138, \quad \lambda_l^* = 43.6537.$$

The product prices at equilibrium are now:

$$\rho_{11} = 5.99, \quad \rho_{12} = 7.94, \quad \rho_{21} = 6.94, \quad \rho_{22} = 6.94,$$

with the equilibrium demands:

$$d^*_{11} = 30.03, \quad d^*_{12} = 219.96, \quad d^*_{21} = 174.61, \quad d^*_{22} = 175.39.$$

The profit for Food Firm 1 is now dramatically reduced to 1,218.74 and the profit for Food Firm 2 also declines, but by a much smaller amount, to 1,126.73.

Equilibrium Path Flows

Table: Equilibrium Product Path Flows for Examples 1 Through 3

Equilibrium Product Path Flows	Ex. 1	Ex. 2	Ex. 3
$x^*_{p_1}$	73.23	73.22	15.65
$x^*_{p_2}$	98.85	98.85	14.38
$x^*_{p_3}$	166.77	166.78	110.60
$x^*_{p_4}$	192.38	192.38	109.35
$x^*_{p_5}$	142.85	142.62	131.97
$x^*_{p_6}$	53.08	52.86	42.63
$x^*_{p_7}$	143.81	143.12	132.36
$x^*_{p_8}$	54.04	53.36	43.02

Table: Equilibrium Link Labor Values for Examples 1 Through 3

Equilibrium Link Labor Values	Ex. 1	Ex. 2	Ex. 3
l_a^*	10.00	10.00	5.26
l_b^*	11.65	11.65	4.95
l_c^*	2.40	2.40	1.26
l_d^*	2.91	2.91	1.24
l_e^*	10.62	10.62	5.00
l_f^*	1.72	1.72	0.30
l_g^*	3.59	3.59	2.20
l_h^*	12.46	12.42	11.49
l_i^*	4.46	4.43	3.57
l_j^*	2.87	2.86	2.64
l_k^*	1.07	1.06	0.86
l_l^*	5.63	5.60	5.00
l_m^*	1.96	1.95	1.75
l_n^*	1.98	1.96	1.75

Farmers should do everything possible to secure the health of workers at their production/harvesting and other facilities, so that the blueberries can be harvested in a timely manner and so that profits do not suffer. Keeping workers healthy, through appropriate measures, impacts the bottom line!

In a recent paper of ours, **"Wage-Dependent Labor and Supply Chain Networks,"** we retained the link productivity factors, so that:

$$f_a = \alpha_a l_a, \quad \forall a \in L,$$

but had labor being wage-dependent, that is:

$$l_a = \gamma_a \pi_a, \forall a \in L.$$

We introduced a supply chain network game theory model without wage bounds on links and one with wage bounds on links:

$$\pi_a \leq \bar{\pi}_a, \quad \forall a \in L.$$

Some Additional Research

The numerical results therein clearly reveal the importance of a holistic approach to supply chain network modeling since decisions made by a specific firm can have unexpected impacts on other competing firms in the supply chain network economy.

Our results strongly suggest that having wages and labor equilibrate without any wage ceilings can be beneficial for an individual firm and also for firms engaged in competition.

Impacting Policy

Writing OpEds

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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

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

Chicago Tribune

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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

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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

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Disaster response

How disaster relief efforts could be improved with game theory

By Anna Nagurney

Published 13 March 2017

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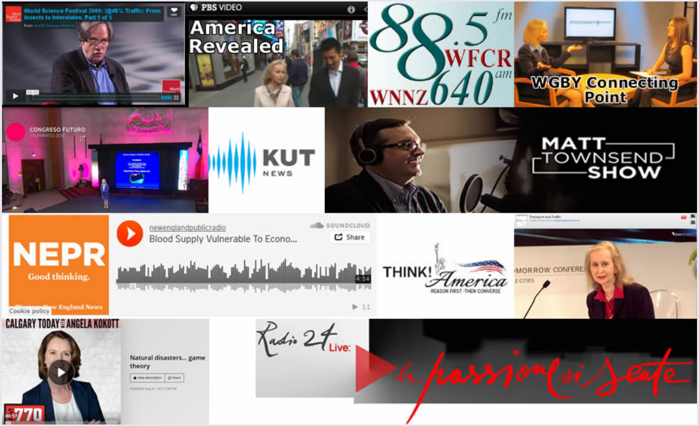
The number of disasters has doubled globally since the 1980s, with the damage and losses estimated at an average

Coverage by the Media



Writing OpEds in the Pandemic

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

Analytics

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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

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 April 5, 2021, I published the article,

"Today's Global Economy Runs on Standardized Containers, as the Ever Given Fiasco Illustrates," also in *The Conversation*.

Some of the Media Coverage of Our Work During the Pandemic

Impacting Policy

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 on blood supply chains in *The Conversation*, **which was reprinted in LiveScience, was the first reference and was cited on the first page.**

Coverage by the Media During the Pandemic

Impacting Policy

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Impacting Policy

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

Hon. Brett Giroir
April 22, 2020
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Iowa Attorney General

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Maine Attorney General

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Massachusetts Attorney General

DANA NESSEL
Michigan Attorney General

KEITH ELLISON
Minnesota Attorney General

AARON D. FORD
Nevada Attorney General

GURBIR S. GREWAL
New Jersey Attorney General

HECTOR BALDERAS
New Mexico Attorney General

LETITIA JAMES
New York Attorney General

Xavier Becerra, previously California's Attorney General, has now been confirmed as President Joe Biden's Health and Human Services Secretary!

Thank You!

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