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

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Managing Disaster Risk: A Way to Sustainability Nepal Germany Academic Association (NEGAAS) November 21-22, 2021



#### Acknowledgments

Thanks to Professors Tanka Nath Dhamala and Urmila Pyakurel and to Er. Ravi Khanal, the organizers of this exciting event, and to the Nepal German Academic Association (NEGAAS) and its Program on Migration and Diaspora for the invitation to speak.



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
- Game Theory and Supply Chain Network Models Inspired by the COVID-19 Pandemic
  - Food and Labor Disruptions
  - • Cooperation in the COVID-19 Pandemic
- Impacting Policy

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#### **Background and Motivation**

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The COVID-19 pandemic, declared by the World Health Organization (WHO) on March 11, 2020, is a healthcare disaster not limited to time or location.

Hence, the response to this disaster requires the harnessing of appropriate resources to mitigate its impacts, which have affected people across the globe.

Working together as academics with decision-makers and policy-makers can accomplish much good and can relieve suffering. A forum such as this is excellent in disseminating ideas and knowledge.

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#### I Work on the Modeling of Network Systems



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#### Much of My Recent Research Has Been on Supply Chains



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### 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.



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 cross cannot be scheder DPE cannot be aroupused and distributed; and produce taken the delivered to our hom

### 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:

- captures the deterioration of fresh food along the entire supply chain from a network perspective;
- handles the time decay through the introduction of arc multipliers;
- formulates oligopolistic competition with product differentiation;
- includes the disposal of the spoiled food products, along with the associated costs;
- 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



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### 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:

- it handles the perishability of the pharmaceutical product through the introduction of arc multipliers;
- it allows each firm to minimize the discarding cost of waste / perished medicine;
- 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.



#### Blood Supply Chains for the Red Cross

Our research on blood supply chains, a topic I teach in my Humanitarian Logistics and Healthcare class, has also been influential in the pandemic.



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### **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

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### 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.

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#### 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 and globally.

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#### Food Supply Chain Disruptions Due to COVID-19



### 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 International Publishing Switzerland, 2021, pp 173-193.



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• 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.

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# Perishable Food Supply Chain Network Model with Labor



Our findings include:

- The lack of labor on a single link, even a freight one, may significantly negatively impact a food firm.
- Preserving productivity in all utilized supply chain network economic activities is critical since the impact of a drastic reduction can severely reduce profits.
- Adding more direct sales, whether at farmers' markets or nearby farm stands, may help a food firm in a pandemic.
- 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.

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#### 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

TIME

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

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



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.



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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."

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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.

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#### Labor and Supply Chain Networks

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.

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

- 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.
- 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.
- 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.

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Our findings include:

- 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.
- Preduction in labor availability can result in a significant increase in product prices at the consumer level.
- Even in the case of reduced labor availability, electronic commerce can result in increased profits.
- Having the flexibility of labor being able to be reallocated across supply chain network activities can enable enhanced profits.

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

#### Game Theory Supply Chain Network Model with Labor

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.



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#### Labor and Supply Chain Networks

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.

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# Game Theory Supply Chain Network Model with Labor



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

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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.

- Disruptions in labor on a supply chain network link;
- Addition of a competitor;
- Modifications in demand price functions;
- Sensitivity analysis in terms of labor availability under Scenario 3.

**The full input and out data are available in our paper in the** *European Journal of Operational Research.* 

Farmers should do everything possible to secure the health of the workers at his production/harvesting 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!

#### Some Additional Research

In a recent paper of ours, **"Wage-Dependent Labor and Supply Chain Networks,"** in press in *Analysis, Geometry, Nonlinear Optimization and Applications,* P.M. Pardalos and T. M. Rassias, Editors, World Scientific Publishing, Singapore, we introduced a supply chain network game theory model without wage bounds on links and one with wage bounds on links and with labor availability that depended on wages.

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.

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# **Cooperation in the COVID-19 Pandemic**

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We recognize the great competition now for a spectrum of medical supplies, vaccines, etc., as well as labor in multiple sectors of the economy, including healthcare, but there are also opportunities for cooperation among stakeholders.

There is also great promise in the COVID-19 pandemic of enhanced partnerships and these even may be between private companies, including pharmaceutical ones, as well as private and nonprofit organizations.

Lessons learned from disaster management are potentially of great benefit to pandemic preparedness, response, and even recovery since we are in the midst of a healthcare disaster.

#### Cooperation in Disaster Relief

Our paper, **"Quantifying Supply Chain Network Synergy for Humanitarian Organizations,"** A. Nagurney and Q. Qiang, *IBM Journal of Research and Development*, **64(1/2)**, 2020, pp. 12:1-12:16, identifies potential synergy of cooperation.



**Disaster Response and Management** 

The models capture the uncertainties associated with costs and demands.

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### Case Without Cooperation



Figure: Supply Chains of Organizations 1 through *m* Prior to Cooperation

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#### Case with Cooperation



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We denote the synergy by  $S^{TGC}$ . It is the percentage difference between the total generalized cost without *vs*. with the horizontal cooperation (evaluated at the respective optimal solutions):

$$S^{TGC} \equiv [\frac{TGC^{0*} - TGC^{1*}}{TGC^{0*}}] \times 100\%.$$

The lower the total generalized cost  $TGC^{1*}$ , the higher the synergy associated with the supply chain network cooperation and, therefore, the greater the total cost savings resulting from the cooperation.

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The total generalized costs include not only the monetary costs, but also the risks and uncertainties involved in the supply chain as well as the associated penalties of shortages and surpluses.

In specific disaster relief operations, including in the pandemic, one may evaluate the integration of supply chain networks with only a subset of the links connecting the original supply chain networks.

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# **Impacting Policy**

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#### Writing OpEds in the Pandemic

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

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



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

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

### Writing OpEds in the Pandemic

On January 8, 2021, my article,

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



On September 21, 2021, I published the article,

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

### Writing OpEds in the Pandemic



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

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### Some of the Media Coverage During the Pandemic



#### Many of the Media Interviews Have Been Fascinating



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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.

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State of California Office of the Attorney General Xavier Becerra Arronney 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 Attr: ACBTS/AB/APAHPAIA Sec. 209 ACBTS/AB/MS.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 Alterneys General frem California, Colerada, Connecticat, Delavaras, the District of Columbia, Havini, Illinois, Joux, Maine, Masachusetta, Kheighan, Minnesota, Nevada, New Jeney, New Mexico, New York, Oregon, Pennylvania, Vermont, and Vigrinai submit hist letter in response to the folcard government" "Solicitation for Public Comments on Section 209 of the Pandemis and All-Hazards Preparedness and Advancing Innovation Act, "Q5 Fed. Reg. [15:27]. We support the Office of the Assistant Secteratry for Health in the U.S. Department of Health and Human Services' (HIR) sylferst and work in maintaining an adequent antional Nodo 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.<sup>1</sup> Every day, the United States needs approximately 36,000 units of red blood cells, nearly 7,000

<sup>&</sup>lt;sup>1</sup> Anna Nagumey, How Coronavirus is Upsetting the Blood Supply Chain, Live Science (Mar. 13, 2020), https://www.livescience.com/coronavirus-blood-supply-chain.html/.

#### Impacting Policy

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

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#### Thank You!



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

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The Virtual Center for Supernetworks is an interdisciplinary center at the Isenberg School of Management that advances knowledge on large-scale networks and integrates operations research and management science, engineering, and economics. Its Director is Dr. Anna Nagurney, the John F. Smith Memorial Professor of Operations Management.

Mission: The Virtual Center for Supernetworks fosters the study and application of supernetworks and serves as a resource on networks ranging from transportation and logistics, including supply chains, and the Internet, to a spectrum of economic networks.

The Applications of Supernetworks Include: decision-making, optimization, and game theory; supply chain management; critical infrastructure from transportation to electric power networks; financial networks; knowledge and social networks; energy, the environment, and sustainability; cybersecurity; Future Internet Architectures; risk management; network vulnerability, resiliency, and performance metrics; humanitarian logistics and healthcare.

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Announcements and Notes	Photos of Center Activities	Photos of Network Innovators	Friends of the Center	Course Lectures	Fulbright Lectures	UMass Amherst INFORMS Student Chapter	
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#### For more information: https://supernet.isenberg.umass.edu/