Operations Research for Food Supply Chains in the Pandemic and Beyond

Professor Anna Nagurney

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

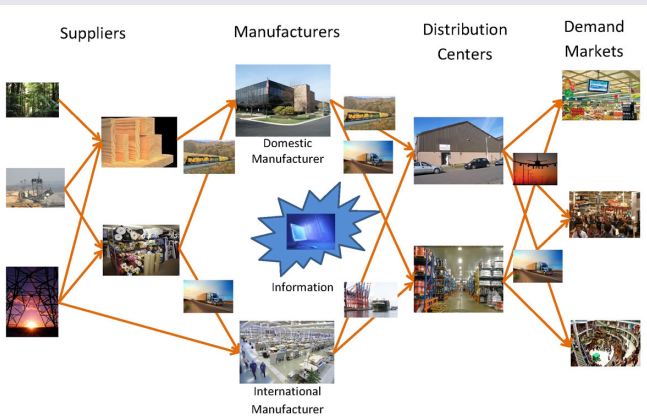
OR Capacity Building Project (CREST-OR) in Southeast Asia, July, 2021

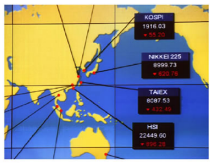
Acknowledgments

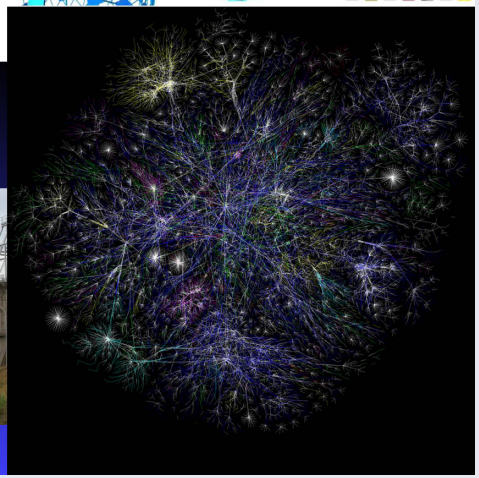
Many thanks to Professor Paola Scaparra for the opportunity to present to you.

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.

I Work on the Modeling of Network Systems





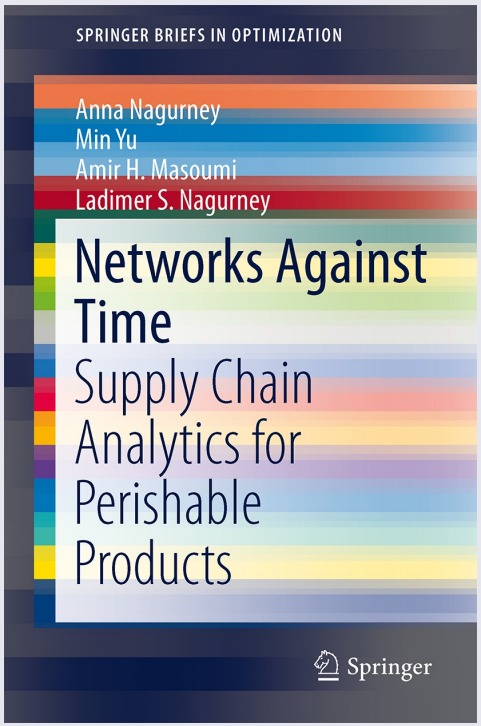


Much of My Recent Research Has Been on Supply Chains

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 for sustaining life, and maintaining a healthy diet requires physical and economic access to nutritious, sufficient, and safe food.

• A food-insecure household is one that cannot provide enough food for every person to maintain a healthy and active lifestyle.

• "Hunger" is defined as a consequence of food insecurity, referring to feelings of discomfort, sickness, and uneasiness due to prolonged and involuntary lack of food, according to the United States Department of Agriculture (USDA).

Food Supply Chains

A year before the declaration of the global COVID-19 pandemic by the World Health Organization in March 2020, the USDA noted that 10.5 % of US households, about 13.7 million (1 in 9 people), experienced food insecurity in 2019.

Beyond the impacts of Covid-19, in the form of sickness and death, and its possible long-term impact on the wealth of nations, one of the very crucial issues still pending to be addressed is food insecurity in the United States and other parts of the world.

To be able to address the issue of hunger in the United States and around the globe, the first step is to identify: who is food insecure, where do they live, and then we can suggest possible solutions.

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.

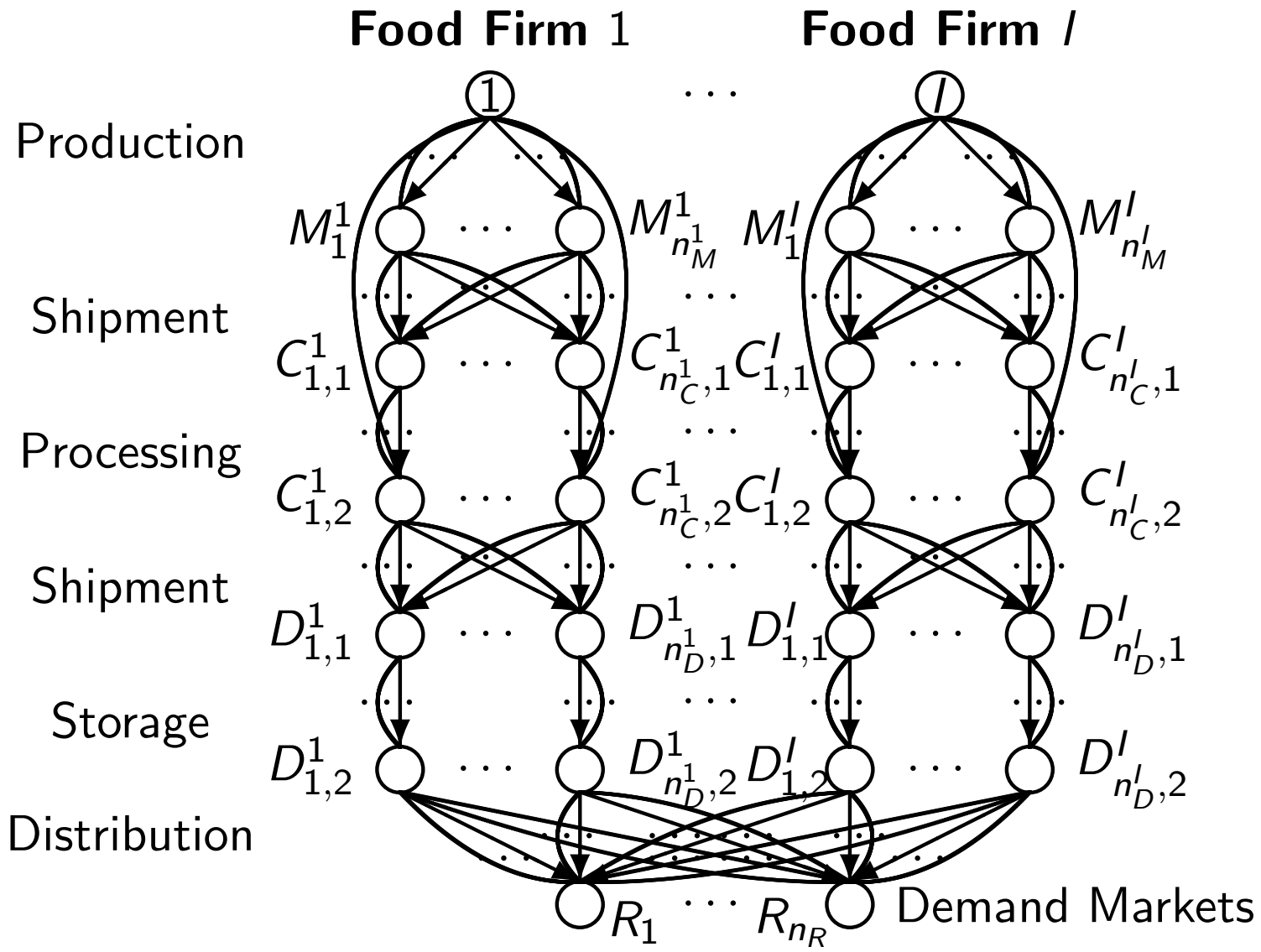
Fresh Produce Food Supply Chains

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.**

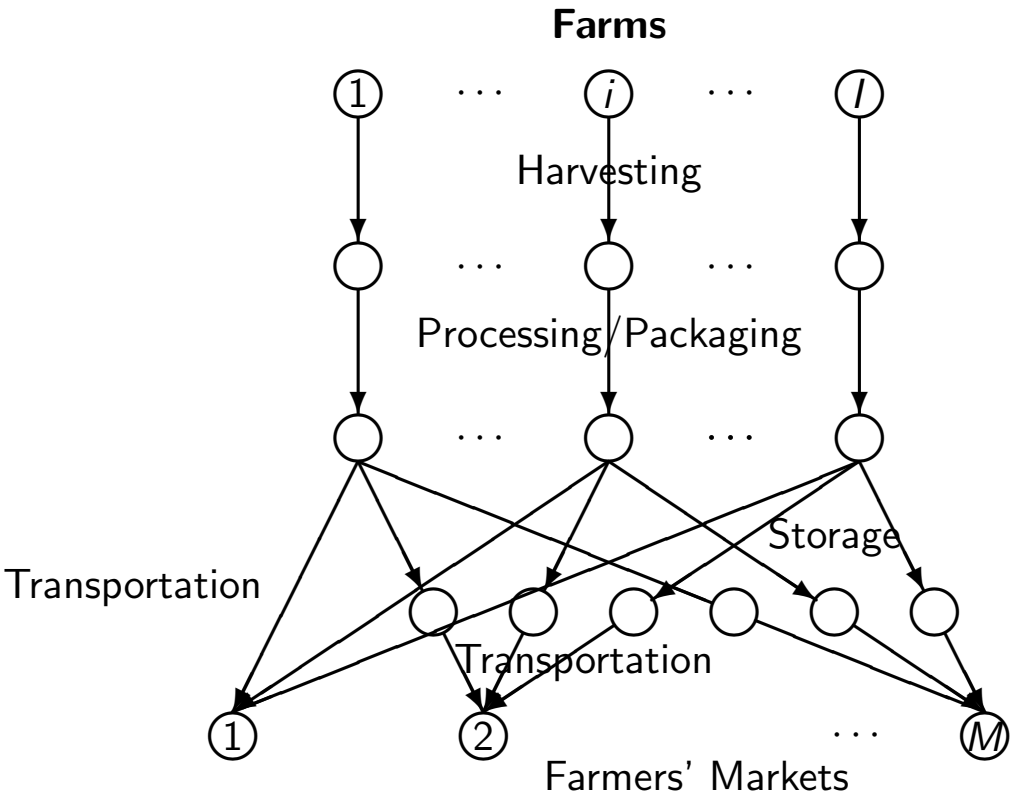
Fresh Produce Food Supply Chains

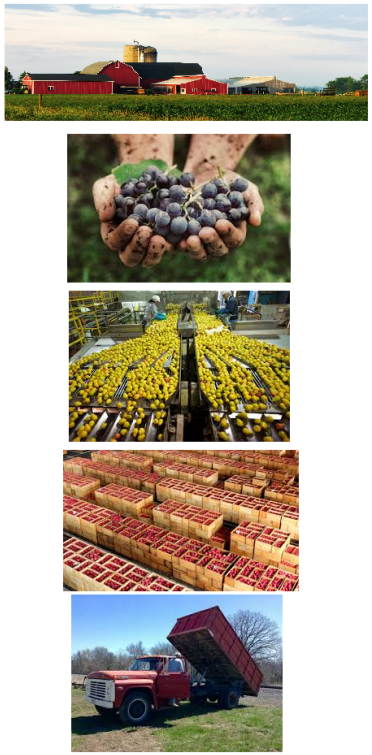


The Fresh Produce Supply Chain Network Topology

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.**

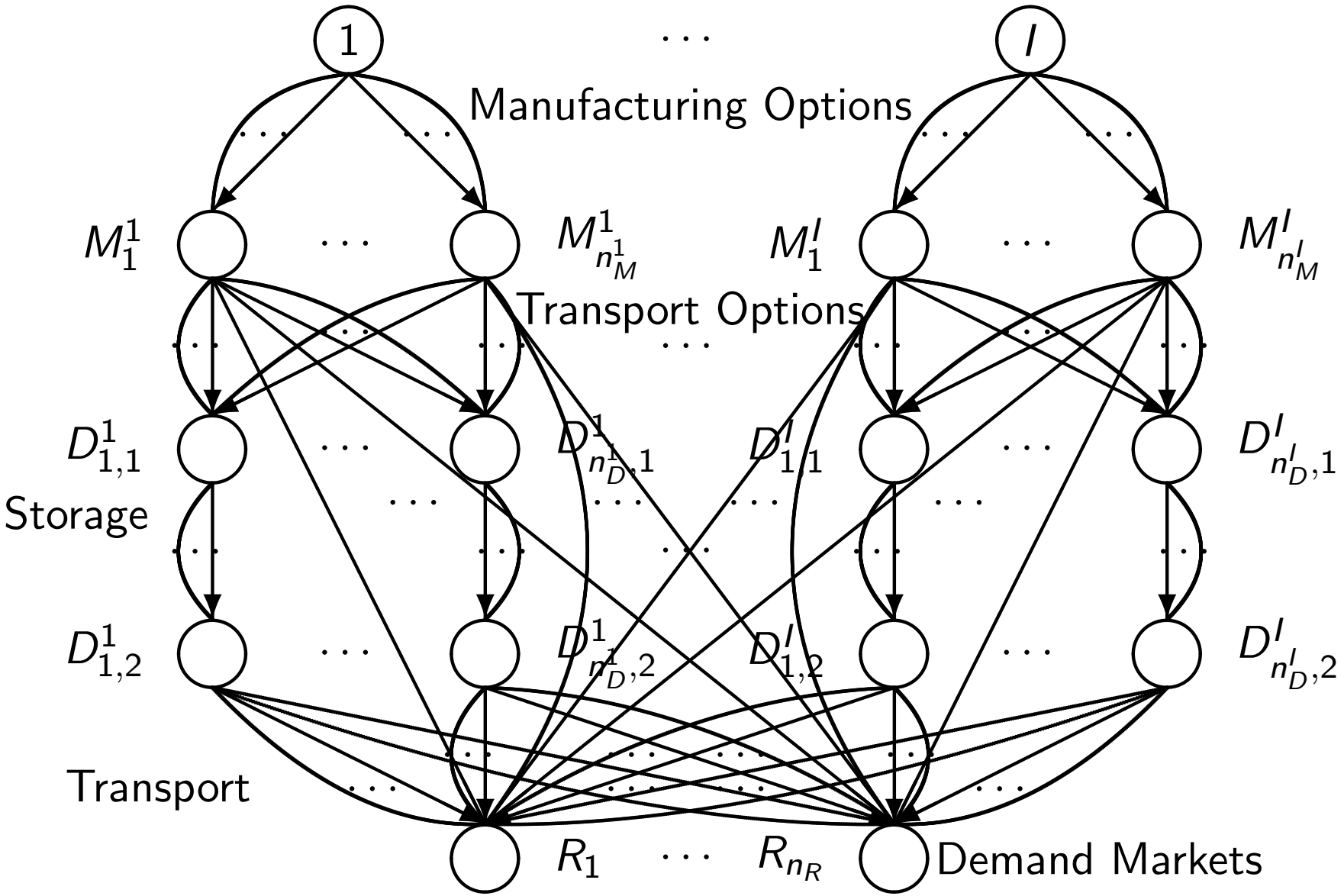


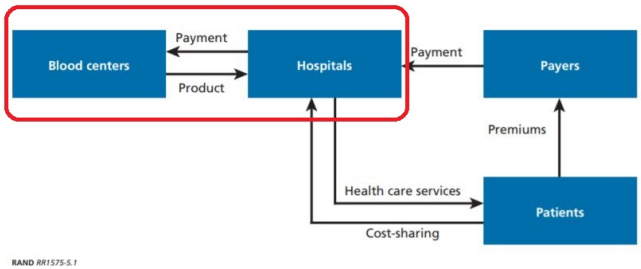
Figure: The Pharmaceutical Supply Chain Network Topology

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.**

Food Supply Chain Disruptions Due to Covid-19

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

1. **As of January 26, 2021, at least 239 meatpacking workers had died in the United States and 45,000 had contracted the coronavirus since the start of the pandemic.**
2. **Shortages of many types of meats, even organic chicken, were experienced this past spring, with price increases**. It was 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. There were shortages in the past summer 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 reenvisioned 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 (more than 42 million people, including 13 million children) 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

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

THEDENVER CHANNEL.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

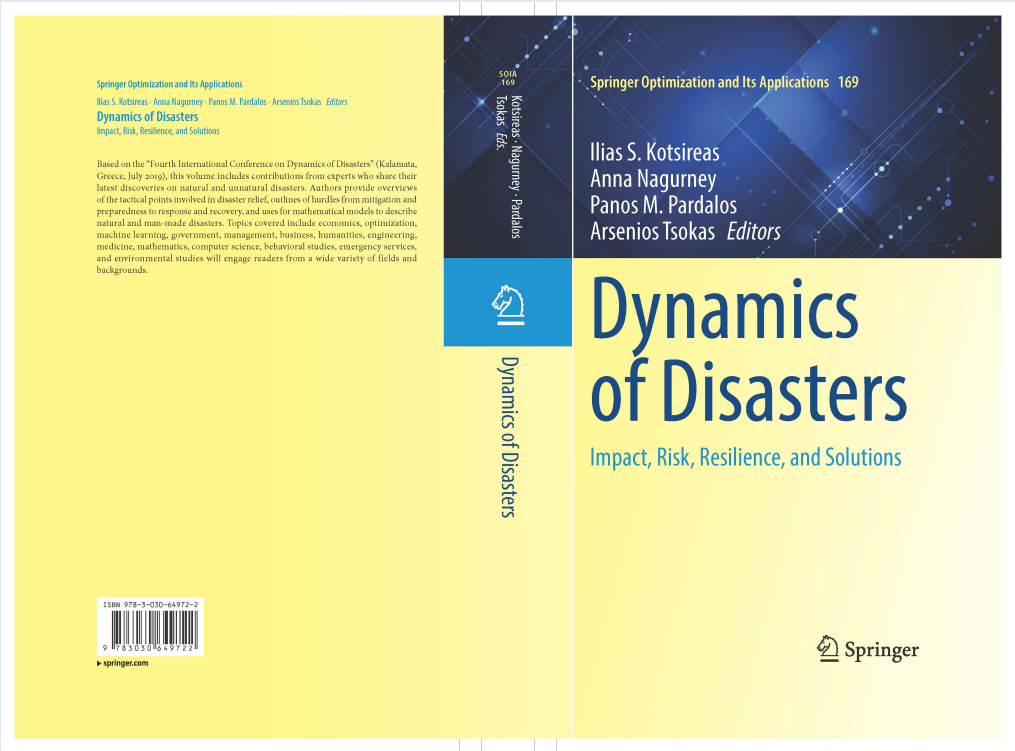
May 20, 2020 · 10:58 AM ET

ROB SCHMITZ

npr

Perishable Food Supply Chain Network Model with Labor

"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

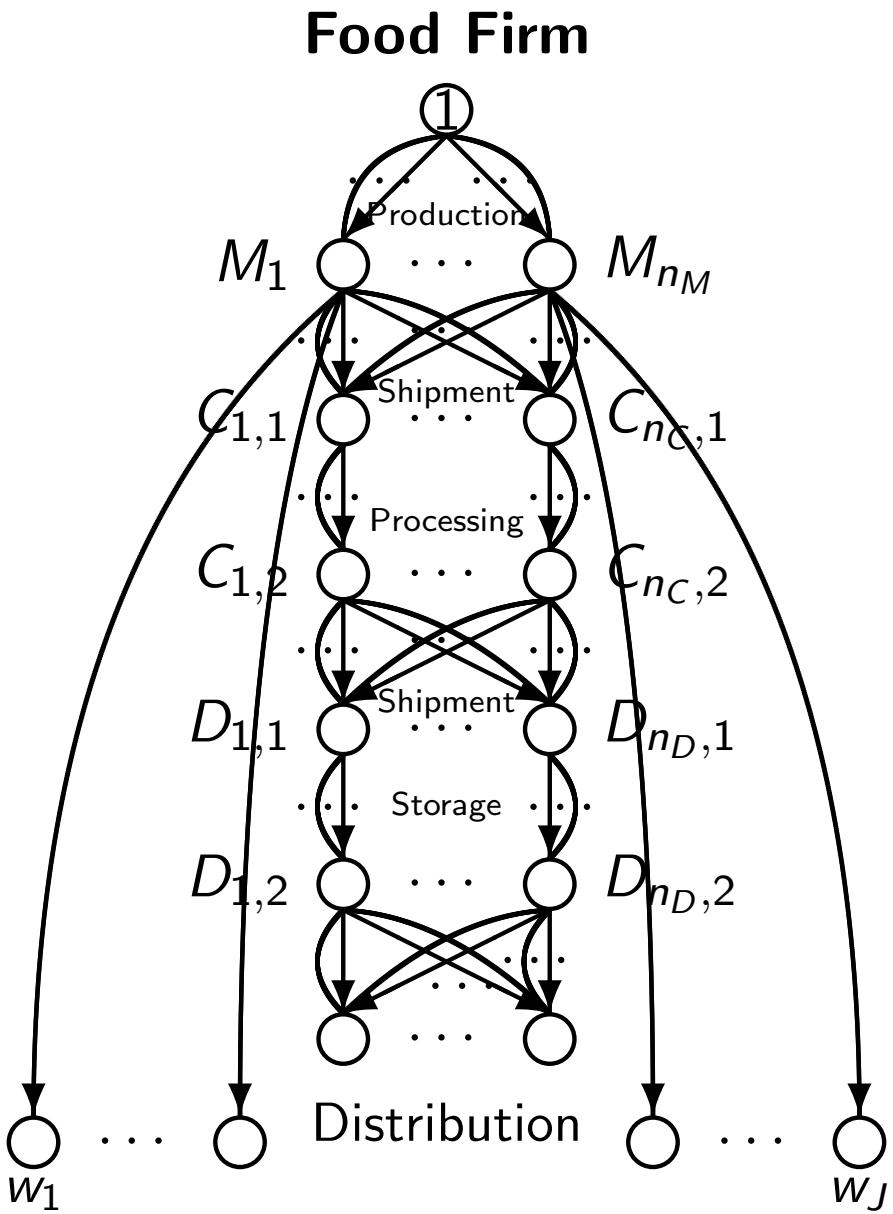


Figure: The Perishable Food Supply Chain Network Topology

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**.

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 (2021)**, in *European Journal of Operational Research*, 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

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

ARTICLE IN PRESS

JID: EOR [m5G;January 15, 2021;14:17]

European Journal of Operational Research xxx (xxxx) xxx

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Production, Manufacturing, Transportation and Logistics

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

Anna Nagurney

Department of Operations and Information Management, Isenberg School of Management, University of Massachusetts, Amherst, MA 01003, USA

ARTICLE INFO

Article history:
Received 17 August 2020
Accepted 23 December 2020
Available online xxx

Keywords:
Supply chain management
Labor
Game theory
Pandemic
Variational inequalities

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.

E-mail address: nagurney@isenberg.umass.edu

https://doi.org/10.1016/j.ejor.2020.12.054
0377-2217/

Please cite this article as: A. Nagurney, Supply chain game theory network modeling under labor constraints: Applications to the Covid-19 pandemic, European Journal of Operational Research, https://doi.org/10.1016/j.ejor.2020.12.054

Game Theory Supply Chain Network Model with Labor

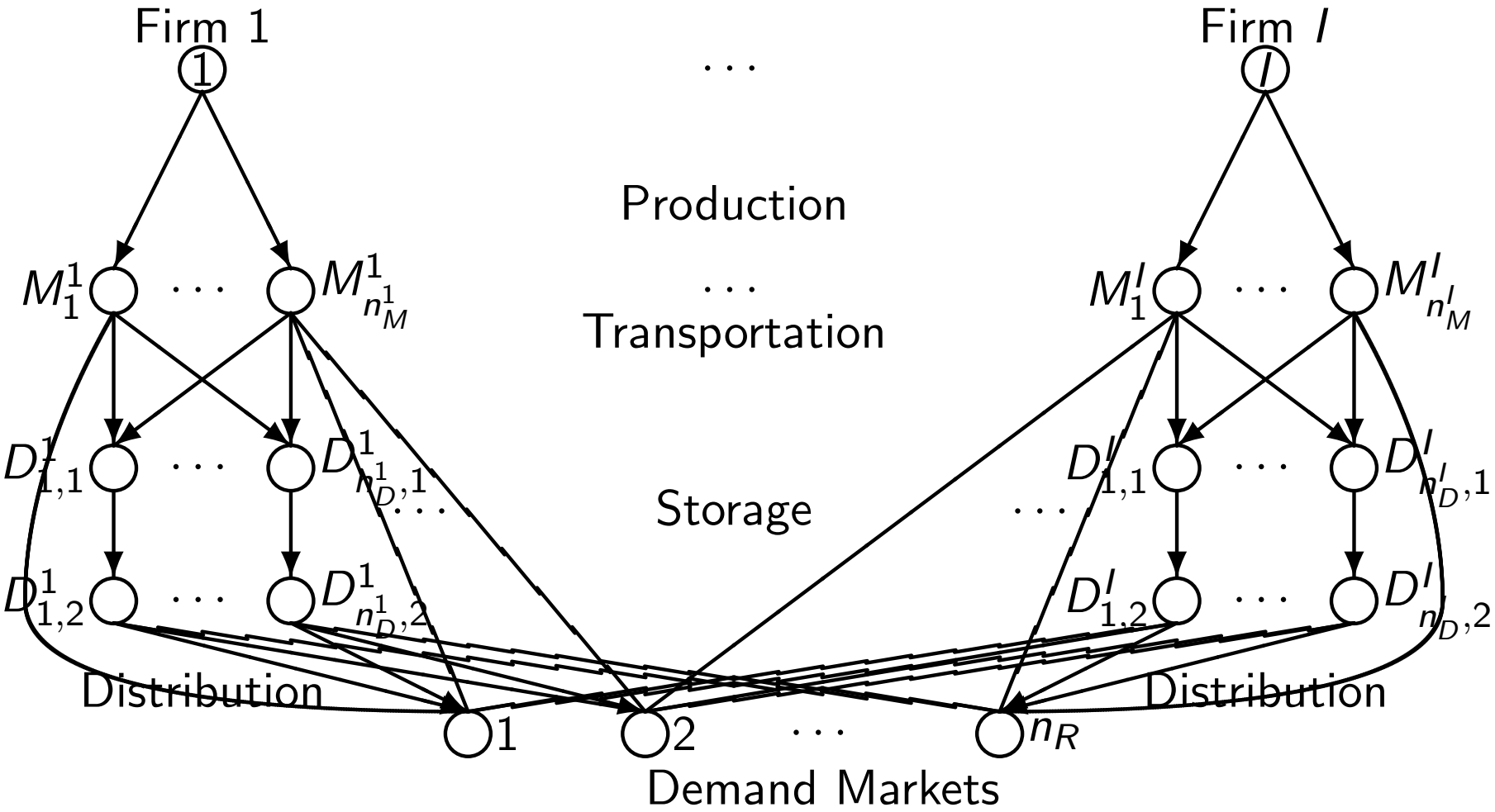


Figure: The Supply Chain Network Topology of the Game Theory Model with Labor

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.

- 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.

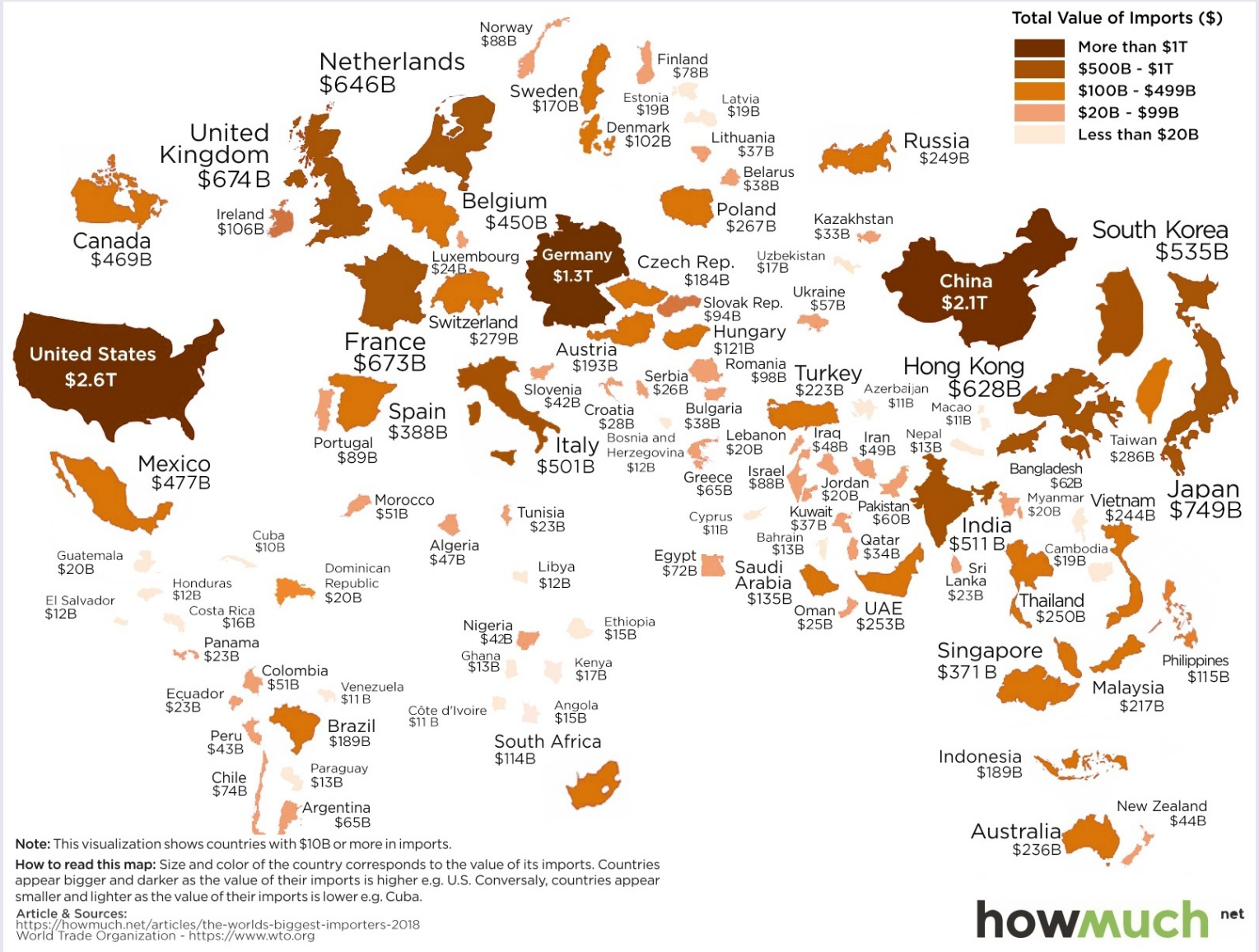
The full input and out data are available in our paper in the *European Journal of Operational Research.*

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!

Supply Chains Are Essential to Global Trade

- **Global supply chain networks** have made possible the wide distribution of goods, from agricultural products to textiles and apparel as well as aluminum and steel.
- Nations engage in trade to increase their productivity levels, employment rates, and general economic welfare.
- The increased level of world trade has also garnered **the attention of government policy makers**.
- Governments may attempt to protect their domestic firms from the possible effects of the **highly competitive** global arena.

World's Biggest Importers



Note: This visualization shows countries with $10B or more in imports.

How to read this map: Size and color of the country corresponds to the value of its imports. Countries appear bigger and darker as the value of their imports is higher e.g. U.S. Conversaly, countries appear smaller and lighter as the value of their imports is lower e.g. Cuba.

Article & Sources:
https://howmuch.net/articles/the-worlds-biggest-importers-2018
World Trade Organization - https://www.wto.org

Global Trade Policies

Examples of policy instruments that have been applied by governments to modify trade patterns included: **tariffs**, **quotas**, and a combination thereof - **tariff rate quotas**.

Tariffs Are Regularly in the News!

The imposition of tariffs by certain countries is leading to retaliation by other countries with ramifications across multiple supply chains, and a **trade war**.

With Higher Tariffs, China Retaliates Against the U.S.

The Yangshan Deep Water Port in Shanghai, China. The Chinese government said on Monday that it would raise tariffs on goods from the United States as of June 1, giving negotiators from the two countries time to strike a deal. Aly Song/Reuters

The New York Times, May 13, 2019

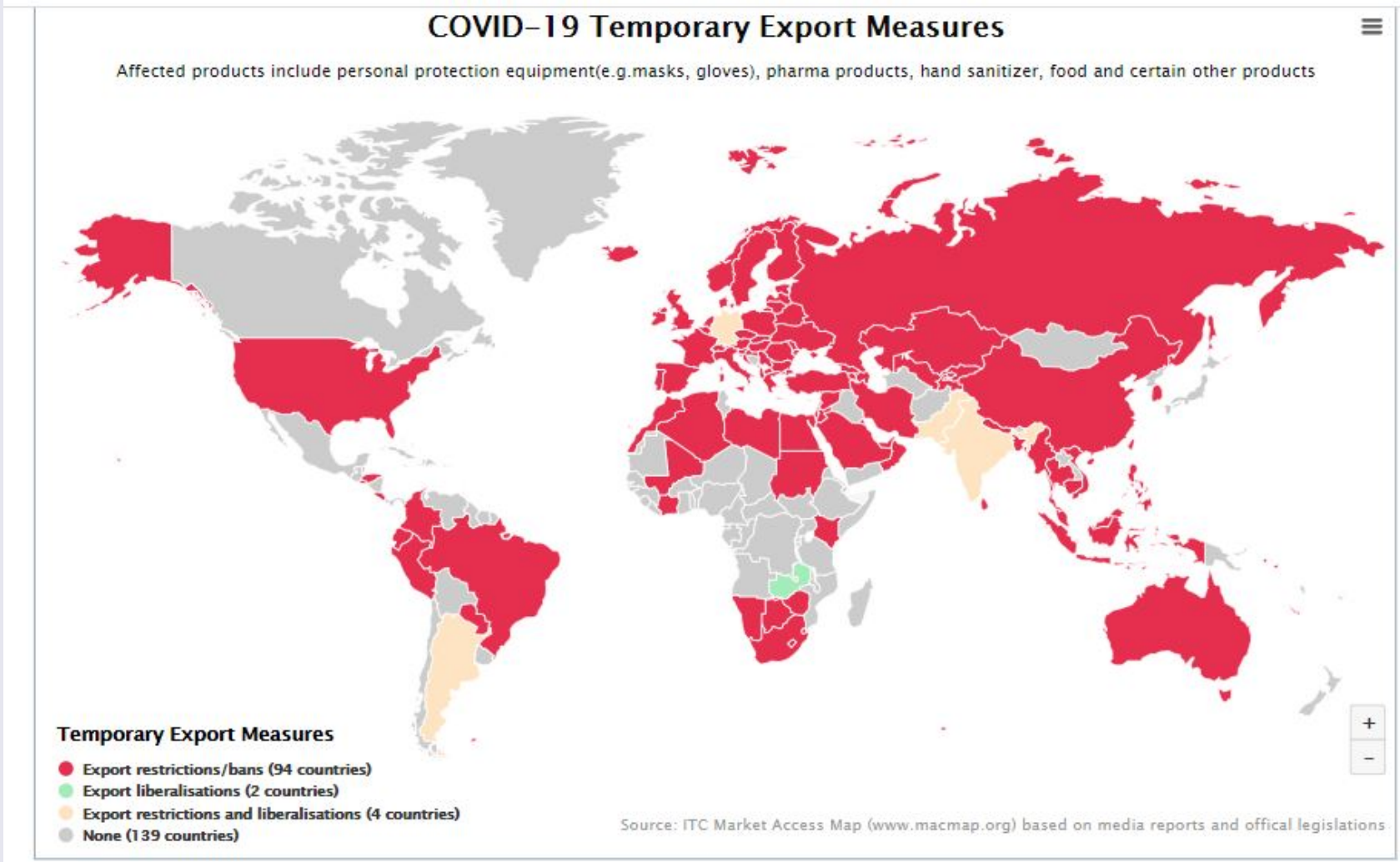
Trade Instruments in the Covid-19 Pandemic

• When the Covid-19 pandemic hit one country after another, some countries, which were among the few exporters of PPEs, faced a very high demand within their own national boundaries and, therefore, prioritized meeting their needs first. **Hence, they banned the export of medical products**.

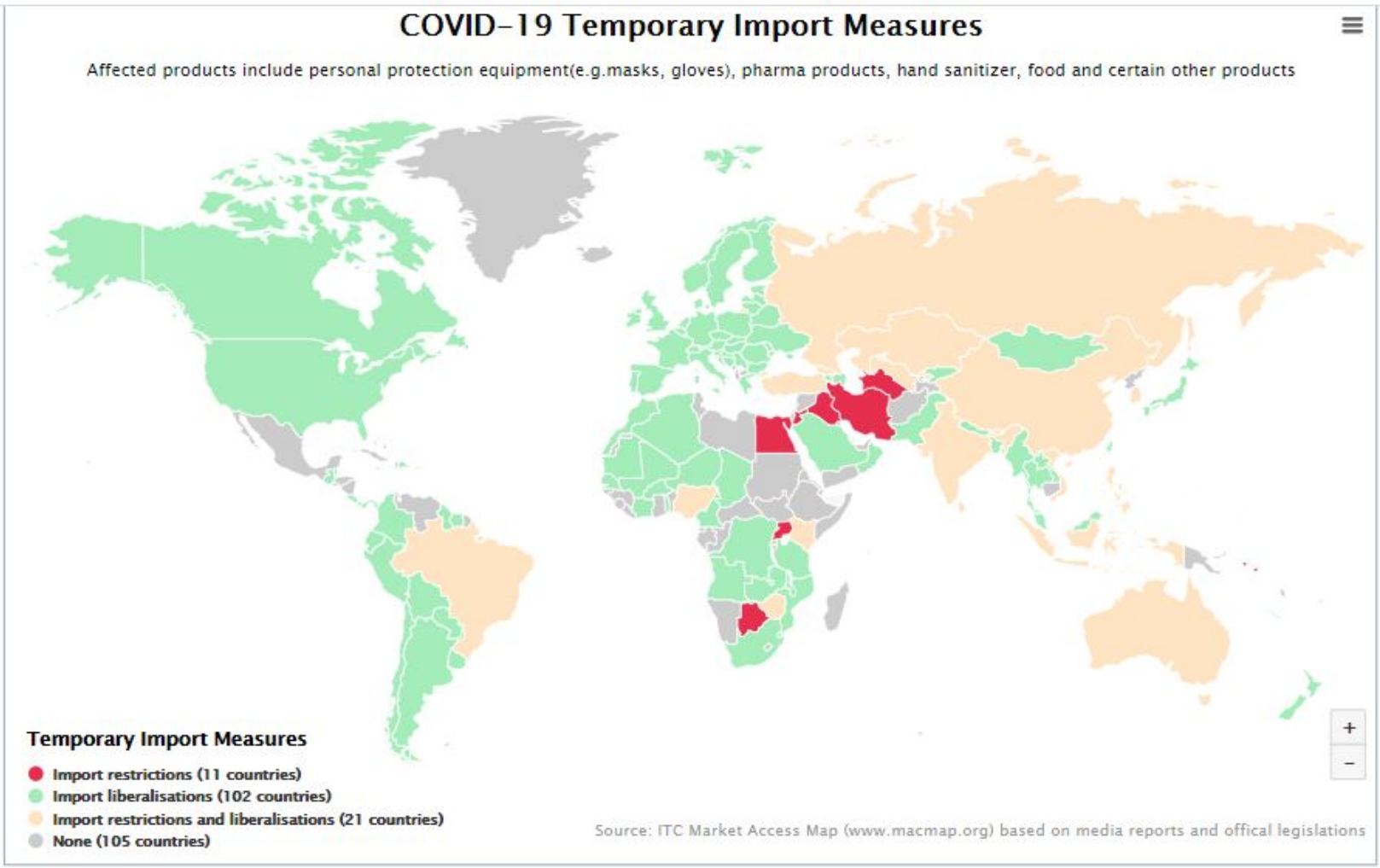
• According to Global Trade Alert, as of 25 April 2020, **122 new export bans in more than 75 countries including the US, China, and the EU were issued on medical supplies such as antibiotics, face masks, and ventilators**. Belarus imposed **restrictions on exports of food products such as onions and garlic** due to the pandemic crisis.

• **There is also a large number of countries that reduced the tariffs on essential goods to accelerate the import of such products.** China decreased import tariffs on several types of products such as medical supplies, raw materials, agricultural products, and meat. The US is temporarily excluding certain products from the additional duty of 25% on a list of 19 products from China and is putting restrictions on exports of 5 types of PPEs.

Trade Instruments in the Covid-19 Pandemic



Trade Instruments in the Covid-19 Pandemic

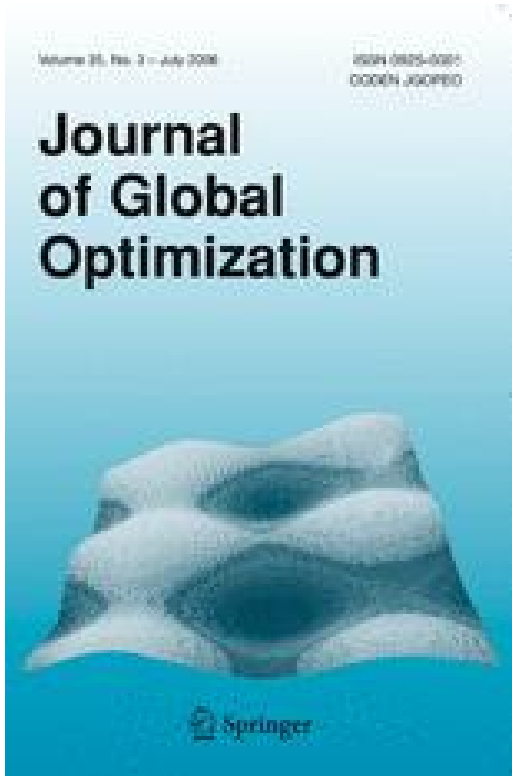


Global Trade Policies

We have been constructing **computable operational mathematical models** that enable the assessment of the impacts of trade policy instruments such as tariffs, quotas, and also tariff rate quotas on consumer prices, trade flows, as well as on the profits of producers/firms.

- A tariff rate quota (TRQ) is a **two-tiered tariff**, in which a lower **in-quota tariff** is applied to imports until a quota is attained and then a higher **over-quota tariff** is applied to all subsequent imports.
- The Uruguay Round in 1996 induced the creation of more than 1,300 new TRQs.
- **The world's four most important food crops: rice, wheat, corn, and bananas have all been subject to tariff rate quotas.**

A. Nagurney, D. Besik, and L.S. Nagurney, "Global Supply Chain Networks and Tariff Rate Quotas: Equilibrium Analysis with Application to Agricultural Products, *Journal of Global Optimization* **75 (2019), pp 439-460.**



A. Nagurney, D. Besik, and J. Dong, "Tariffs and Quotas in World Trade: A Unified Variational Inequality Framework," *European Journal of Operational Research* **275(1) (2019), pp 347-360.**

Summary

• **Operations Research is extremely useful in the construction, analysis, and solution of food supply chain network models.**

• Furthermore, the impacts of the incorporation of trade policies on both producers and consumers (as well as other policies) can be quantifiably assessed.

• Ongoing research includes the study of different food supply chain network structures, and identifying the provision of improved nutrition under budget and other constraints.

By cooperating, collaborating, and working together, we can make the world a better place and reduce food insecurity and suffering.

Thank You!

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