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

Professor Anna Nagurney

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

Harold Larnder Memorial Lecture
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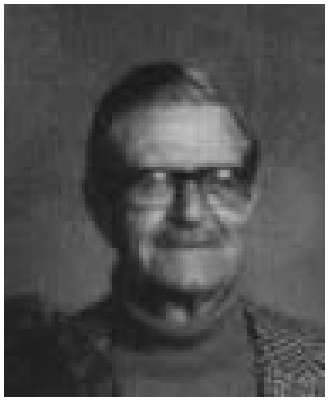
Canadian Operational Research Society
Société canadienne de recherche opérationnelle

Harold Larnder - 1902-1981



OR Forum

The Origin of Operational Research

HAROLD LARNDER

(Received and accepted December 1983)

This paper presents an account of the events in the years just preceding and during the second world war that led up to the concept and practice of operational research as it is now generally understood.

Introductory Note

Before the second world war there were widely scattered portents of the eventual emergence of a science of operations that could be applied to improving them. However, operations research did not emerge as a coherent professional field with a continuing history until the early years of the war and until its operations, present and future, were subjected to scientific inquiry.

Unlike almost all other modern fields of science and technology, operations research is remarkable in that it is possible to trace a single stream of events that led to its concept and practice. This paper by Harold Larnder, a participant in these events, gives a brief—almost too brief—personal account of his involvement in them.

Born in England in 1902, Harold Larnder was educated at Dalhousie University in Halifax, Nova Scotia. On completion of his studies in physics and engineering, he worked until 1935 as a radio engineer on long distance communications, primarily in the Caribbean and in Western Europe. When Sir Robert Watson-Watt assembled the team at Bawdsey Research Station on the coast of East Anglia to develop the first radars for the Royal Air Force, Larnder joined it as the specialist on high-powered transmitters. Larnder's paper tells how this beginning led to "operational research."

Later in the war, after the events described in his paper, Larnder worked with the RAF Coastal Command and the Allied Tactical Air Force, in this last position holding the honorary rank of Group Captain of the Royal Air Force. After the war he was awarded the OBE and shared in the prize given to Sir Robert Watson-Watt's team for the invention of radar.

Larnder returned to Canada in 1951, where he held various posts in the Defense Research Board until his retirement in 1967. He was President of the Canadian Operational Research Society in 1966. He died on July 22, 1981.

George Lindsey, a long-time friend of Larnder's, tells of the event that prompted this paper (Lindsey [1983]):

Subject classification. 460 origins of OR applications for radar, 601 origin of operational research.

Operations Research
Vol. 32, No. 2, March–April 1984

0030-364X/84/3202-0465 $01.25

When Canada was the host for the IFORS Conference of 1978, and we wanted to put on a feature for the international audience, we decided to present the founder of our profession, as if a congress of physicists could be addressed by Sir Isaac Newton in person. But Harold was too shy to agree. He feared that a history specialist would challenge him, claiming prior discovery by an American, or perhaps a Russian would tell us that Popoff had invented OR at the time of the revolution. It took all our powers of persuasion, a small contract, and several rehearsals, before he agreed to give the talk.

The hopes of the Conference's organizers were more than fulfilled: Larnder's straightforward and modest delivery of his obviously significant account prompted the large audience at a plenary session to give him a standing ovation, a response unique in the history of IFORS Conferences.

The version of the paper given at the IFORS Conference was published in its proceedings (Haley [1979], pp. 3–12). However, even before this version had appeared, Larnder had written me in my capacity as chairman of the TIMS/ORSA archives committee to send me a revised version. This newer version records, at the urging of George Lindsey, a fact that modesty had kept him from claiming in the IFORS version: that it was he who had conceived of the importance of—and constructed—the graphs for the Williams study that had played a vital role in Churchill's decision about sending RAF fighters to France. He had also made some other changes, notably in the first section of the paper.

Thus, what we have here is the paper published in the Conference proceedings as amended later that year and sent to me on December 10, 1978.

Readers who may wish to explore Larnder's involvement in wartime OR work further may consult the references that I have added at the end of his paper (Clark [1965], Cunningham et al. (to appear), Lindsey [1981], Rowe [1948], Waddington [1973], Watson-Watt [1957], Wood and Dempster [1969], and Wright [1969]).

—HUGH J. MISER

OVER the ages many famous men, Archimedes, Leonardo da Vinci, and Galileo, to name a few, have studied warlike operations and carried out analysis that might well qualify as "operational research." Who knows what help of an operational research nature Napoleon may have received from Lazare Carnot, the organizer of victory? In 1877, J. H. Poynting, the physicist, even extended operational analysis into sociology! However, none of these early efforts led to any sustained or conscious activity, no new branch of applied science was conceived, no International Federation of Operational Research Societies resulted from all their early work.

Operational research, like radar, was conceived to answer a specific military need—the defense of Britain against air attack. Its origin cannot be clearly understood without consideration of the origin of radar, especially since the pioneer Operational Research Section was composed almost entirely of scientists who had previously been engaged on technical research for the development of radar.

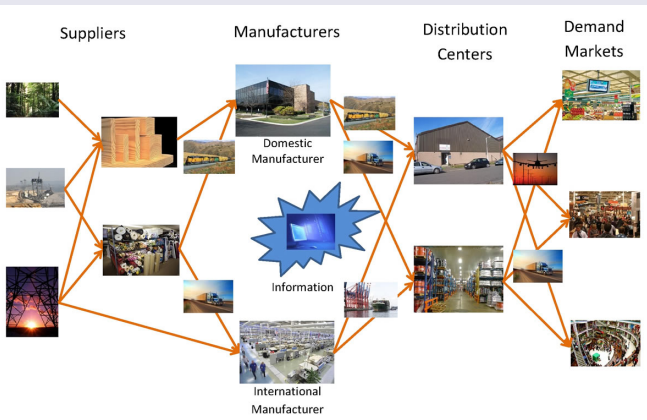
Larnder Prize Recipients

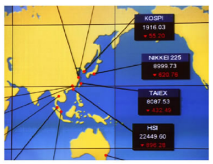
Outline of Presentation

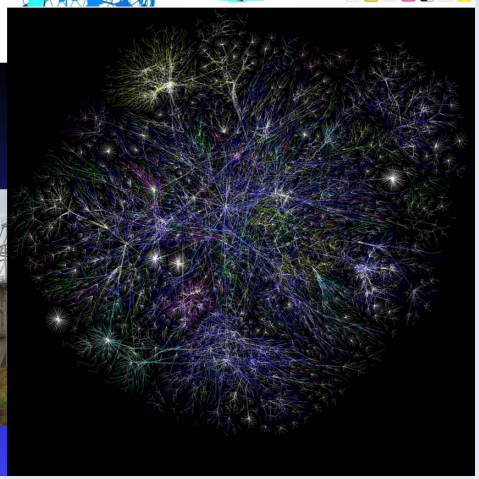
- **Motivation and Some Background**
- **Quality and Food Supply Chain Networks**
- **Relationship of the Food Models to Others, Including Pharmaceutical and Blood**
- **Methodology - The VI Problem**
- **Trade Instruments and Impacts**
- **Incorporation of Labor into Supply Chain Networks**
- **Impacting Policy Through Analytics**

Motivation and Some Background

I Work on the Modeling of Network Systems





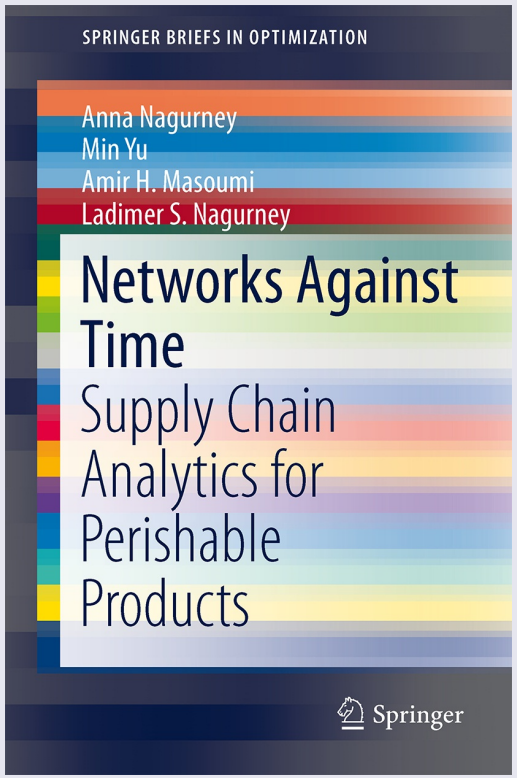


Much of My Recent Research Has Been on Supply Chains

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.



My Recent Interview in *The New York Times*

Quotes from my interview with Kim Severson, a Pulitzer Prize winning journalist, appeared in *The New York Times* on September 9, 2020.

Food
The New York Times

Seven Ways The Virus Changed Shopping

Oranges and frozen foods go fast. Shelves have fewer choices. And customers are steering their carts in new directions.

By KIM SEVERSON

7 Ways the Virus Changed Shopping

Quality and Food Supply Chain Networks

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.

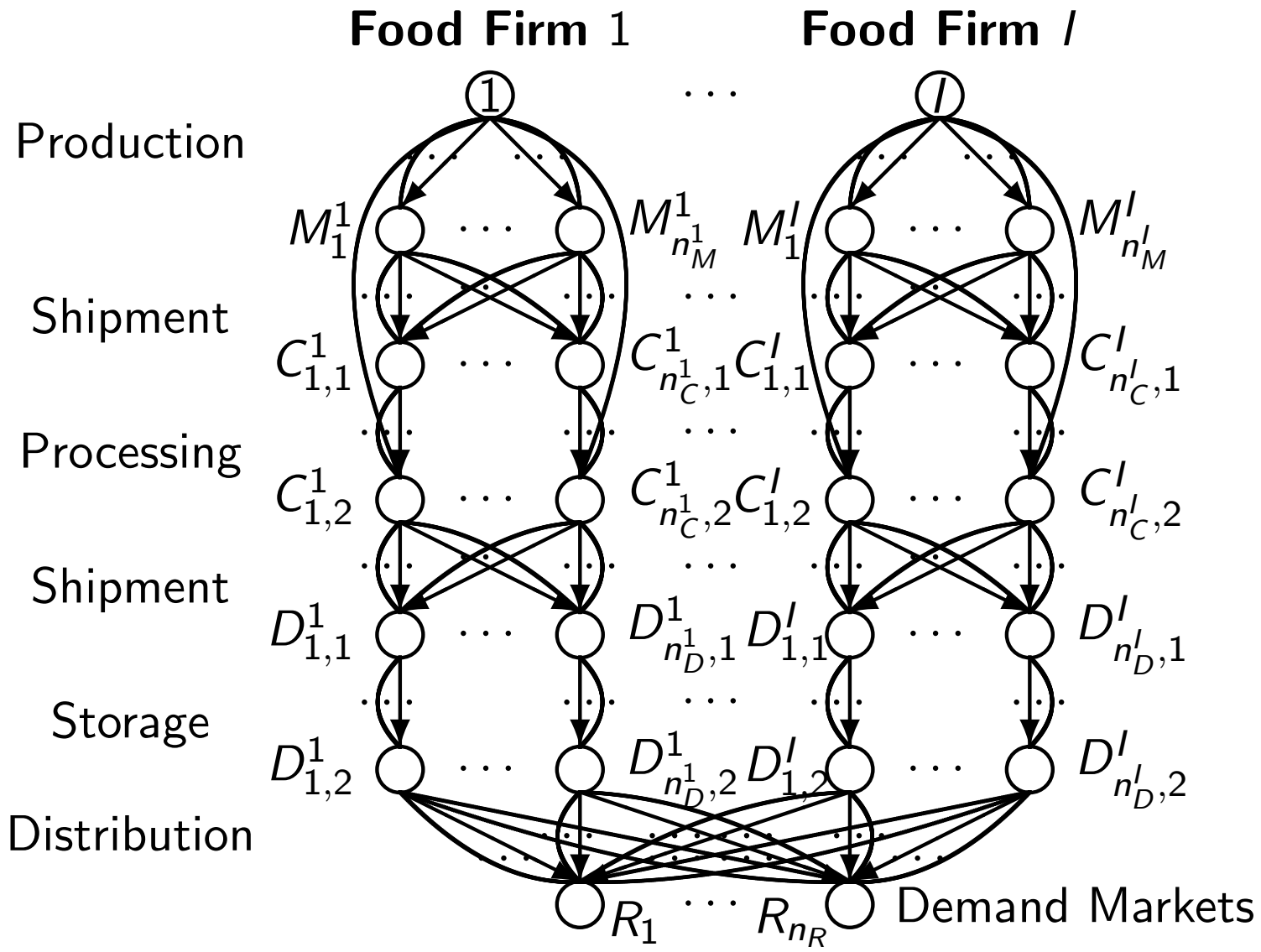
Fresh Produce Food Supply Chains

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



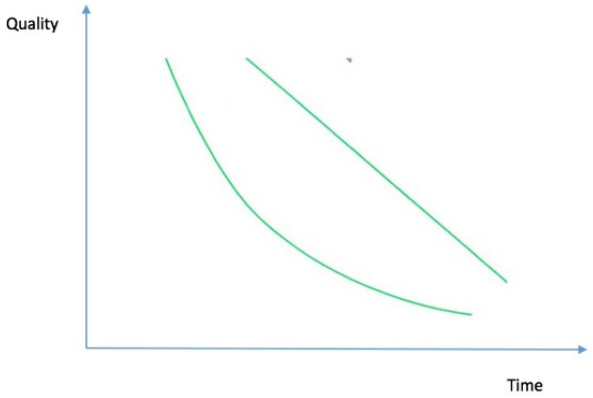
The Fresh Produce Supply Chain Network Topology

Quality and Food Supply Chain Networks

- **Food supply chains**, as noted in Yu and Nagurney (2013), are distinct from other product supply chains.
- Fresh produce is exposed to continuous and significant **change in the quality** of food products throughout the entire supply chain from the points of production/harvesting to points of demand/consumption.
- The quality of food products is **decreasing with time**, even with the use of advanced facilities and under the best **processing, handling, storage, and shipment** conditions
- .

Quality and Food Supply Chain Networks

- It has been discovered that the quality of fresh produce can be determined scientifically using **chemical formulae**, which include both **time** and **temperature**.
- The **initial quality** is also very important and food producers, such as farmers, have significant control over this important **strategic variable** at their production/harvesting sites.
- There are great opportunities for enhanced decision-making in this realm that can be supported by **appropriate models** and **methodological tools**.



Preliminaries on Quality

Fresh foods **deteriorate** since they are biological products, and, therefore, **lose quality over time**. The rate of **quality deterioration** can be represented as a function of the microenvironment, the gas composition, the relative humidity, and the temperature.

Labuza (1984) demonstrated that the quality of a food attribute, q, over time t, which can correspond, depending on the fruit or vegetable, to **the color change**, **the moisture content**, **the amount of nutrition such as vitamin C**, or **the softening of the texture**, can be formulated via the differential equation:

$$\frac{\partial q}{\partial t} = -kq^n = -Ae^{(-E/RT)}q^n,$$

where k is the reaction rate and is defined by the Arrhenius formula, $Ae^{(-E/RT)}$, A is a pre-exponential constant, T is the temperature, E is the activation energy, and R is the universal gas constant.

Preliminaries on Quality

If the reaction order n is zero, that is, $\frac{\partial q}{\partial t} = -k$, and the **initial quality** is denoted by q_0, we can quantify the **remaining quality** q_t at time t according to:

$$q_t = q_0 - kt.$$

Examples of fresh produce that follow a reaction order of zero include **watermelons** and **spinach**.

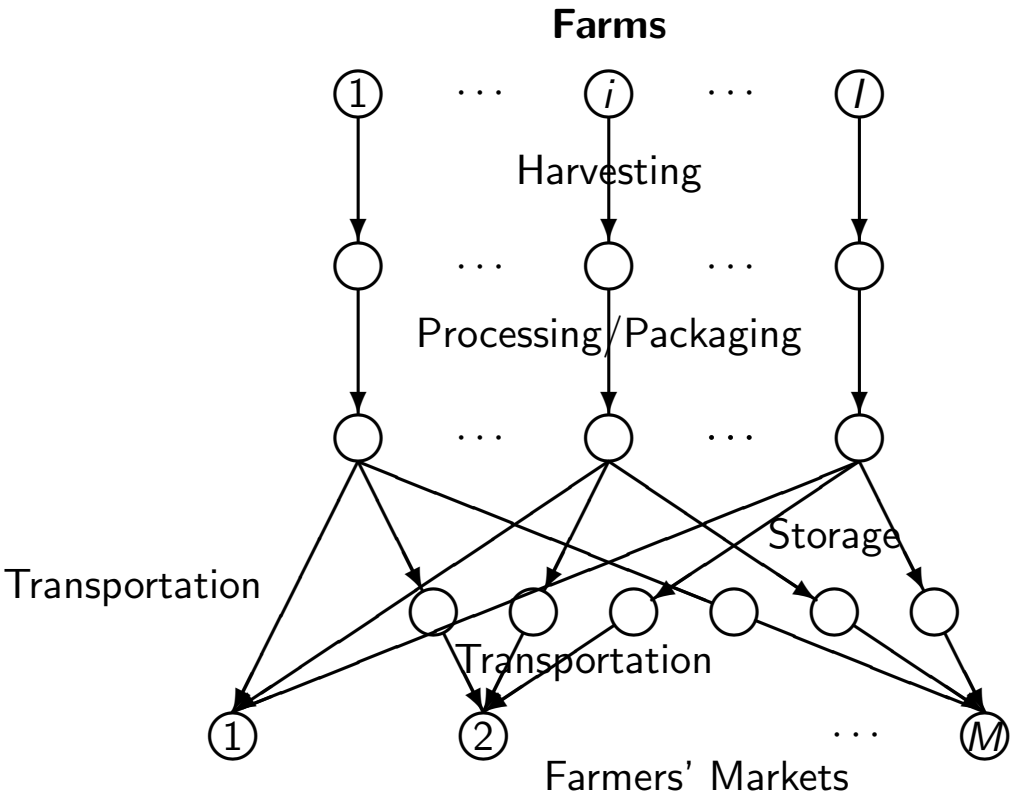
If the reaction order is 1, known as a *first order reaction*, the quality decay function is then given by the expression:

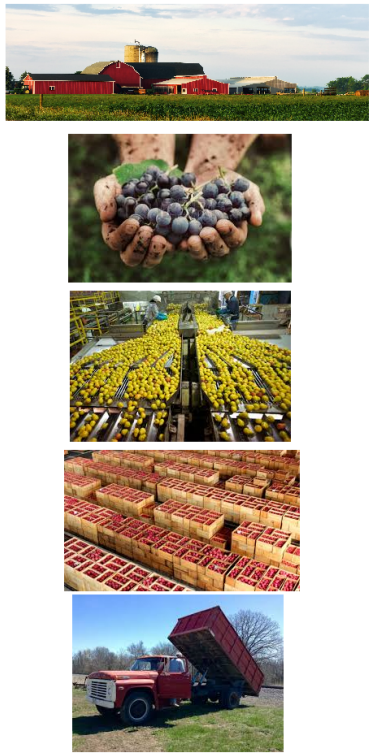
$$q_t = q_0 e^{-kt}.$$

Popular fruits that follow first order kinetics include **peaches**, and **strawberries**, as well as vegetables such as: **peas, beans**, **carrots**, **avocados**, and **tomatoes**.

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.**

A. Nagurney, D. Besik, and M. Yu, "Dynamics of Quality as a Strategic Variable in Complex Food Supply Chain Network Competition: The Case of Fresh Produce," *Chaos* **28, 043124 (2018); doi: 10.1063/1.5023683.**

• We construct a competitive supply chain network model for fresh produce under **oligopolistic competition** among the food firms, who are profit-maximizers.

• The firms have, as their **strategic variables**, not only the **product flows** on the pathways of their supply chain networks from the production/harvesting locations to the ultimate points of demand, but also the **initial quality** of the produce that they grow at their production locations.

• Consumers at the retail outlets, **differentiate the fresh produce** from the distinct firms and reflect their preferences through the **prices** that they are willing to pay which depend on quantities of the produce as well as **the average quality** of the produce associated with the firm and retail outlet pair(s).

Relationship of the Food Models to Other Models, Including Pharmaceutical and Blood

Relationship of the Food Models to Others in the Literature - 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.**

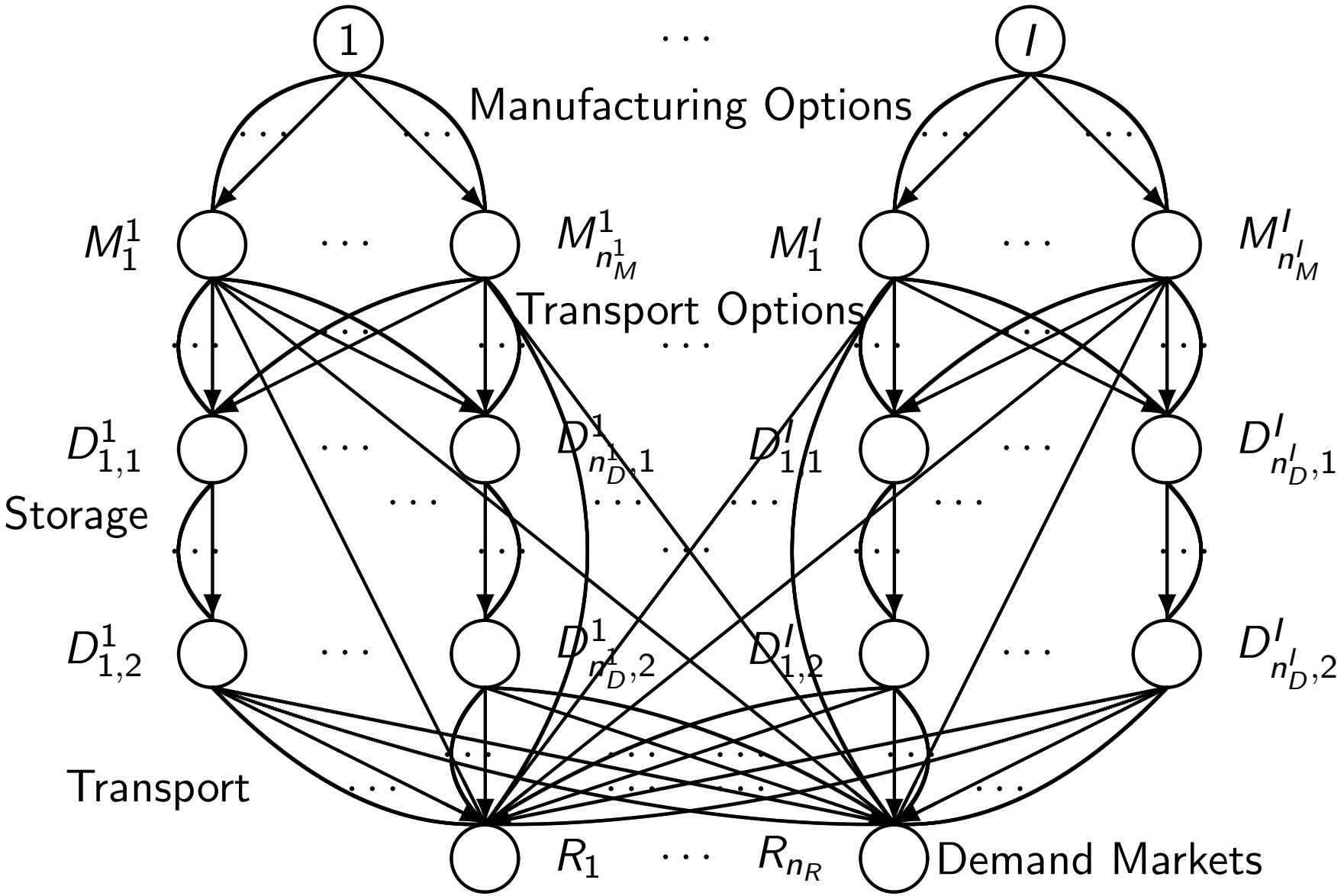


Figure: The Pharmaceutical Supply Chain Network Topology

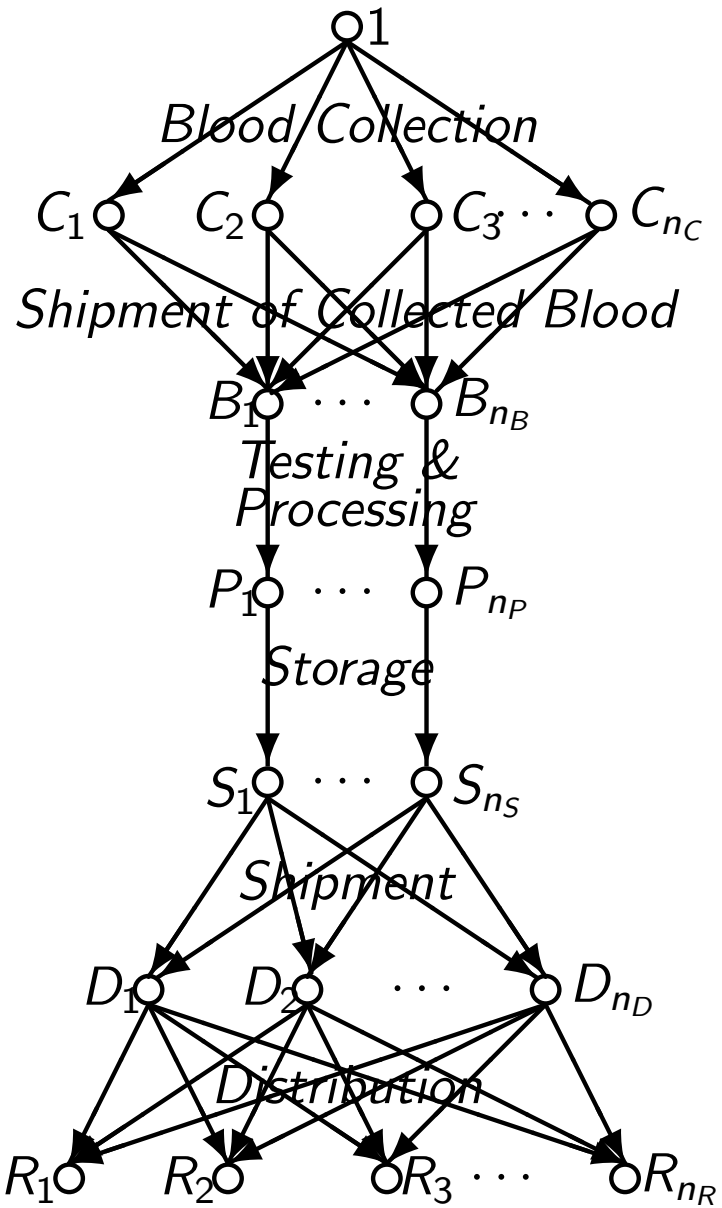
Relationship of the Food Models to Others in the Literature - Fashion

If quality is not a strategic variable and the product is not perishable, then the model is related to the **sustainable fashion supply chain network model of Nagurney and Yu in the** *International Journal of Production Economics* **135 (2012), pp 532-540**. In that model, the other criterion, in addition to the profit maximization one, is emission minimization.

Relationship of the Food Models to Others in the Literature - Blood

A. Nagurney, A.H. Masoumi, and M. Yu, "Supply Chain Network Operations Management of a Blood Banking System with Cost and Risk Minimization," *Computational Management Science* **9(2) (2012), pp 205-231.**

Relationship of the Food Models to Others in the Literature - Blood



ARC Regional Division

Blood Collection Sites

Blood Centers

Component Labs

Storage Facilities

Distribution Centers

Demand Points

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*.*

Methodology - The Variational Inequality Problem

The vector X consists of **the decision variables** – typically, the flows (products, prices, etc.).

$\mathcal{K}$ is the **feasible set representing how the decision variables are constrained** – for example, the flows may have to be nonnegative; budget constraints may have to be satisfied; similarly, quality and/or time constraints may have to be satisfied.

The function F that enters the variational inequality represents **functions that capture the behavior in the form of the functions such as costs, profits, risk, etc.**

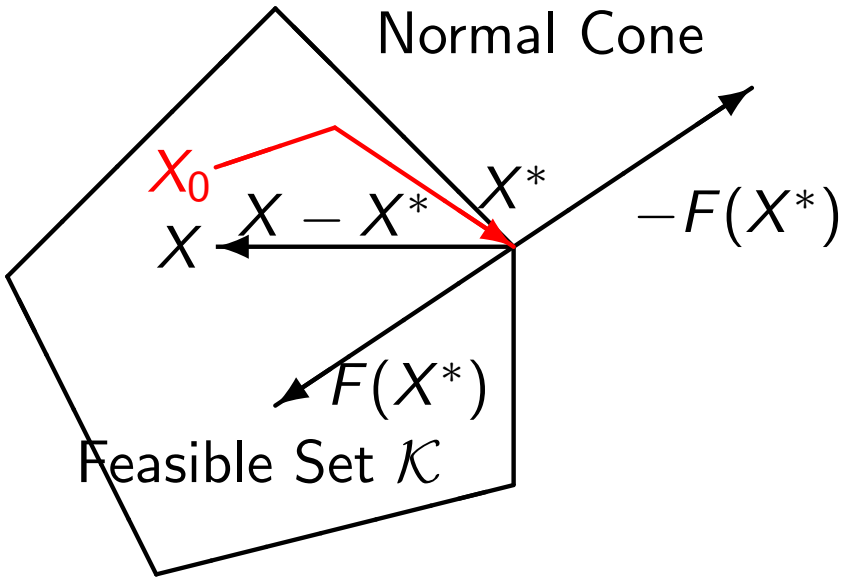
The variational inequality problem contains, as special cases, such mathematical programming problems as:

- systems of equations,
- optimization problems,
- complementarity problems,
- game theory problems, operating under Nash equilibrium,
- and is related to the fixed point problem.

Hence, it is a natural methodology for a spectrum of supply chain network problems from centralized to decentralized ones.

Geometric Interpretation of VI($F, \mathcal{K}$) and a Projected Dynamical System (Dupuis and Nagurney, Nagurney and Zhang)

In particular, $F(X^*)$ is "orthogonal" to the feasible set $\mathcal{K}$ at the point X^*.



Associated with a VI is a Projected Dynamical System, which provides the natural underlying dynamics.

To model the **dynamic behavior of complex networks**, including supply chains, we utilize *projected dynamical systems* (PDSs) advanced by Dupuis and Nagurney (1993) in *Annals of Operations Research* and by Nagurney and Zhang (1996) in our book *Projected Dynamical Systems and Variational Inequalities with Applications*.

Such nonclassical dynamical systems are now being used in:

evolutionary games (Sandholm (2005, 2011)),

ecological predator-prey networks (Nagurney and Nagurney (2011a, b)),

even **neuroscience** (Girard et al. (2008),

dynamic spectrum model for cognitive radio networks (Setoodeh, Haykin, and Moghadam (2012)),

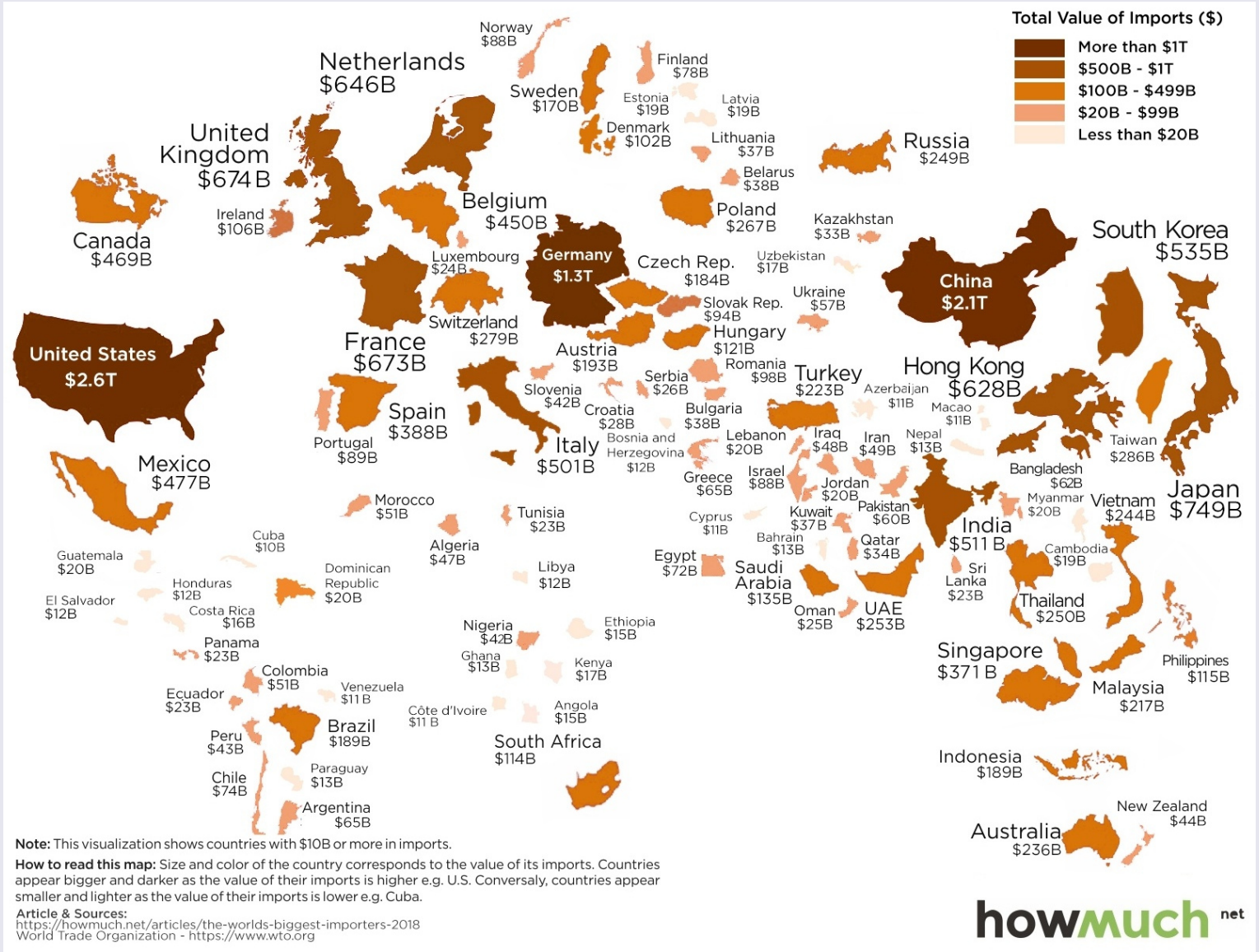
Future Internet Architectures (Saberi, Nagurney, Wolf (2014); see also Nagurney et al. (2015), Marentes et al. (2016)).

Trade Instruments and Impacts

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

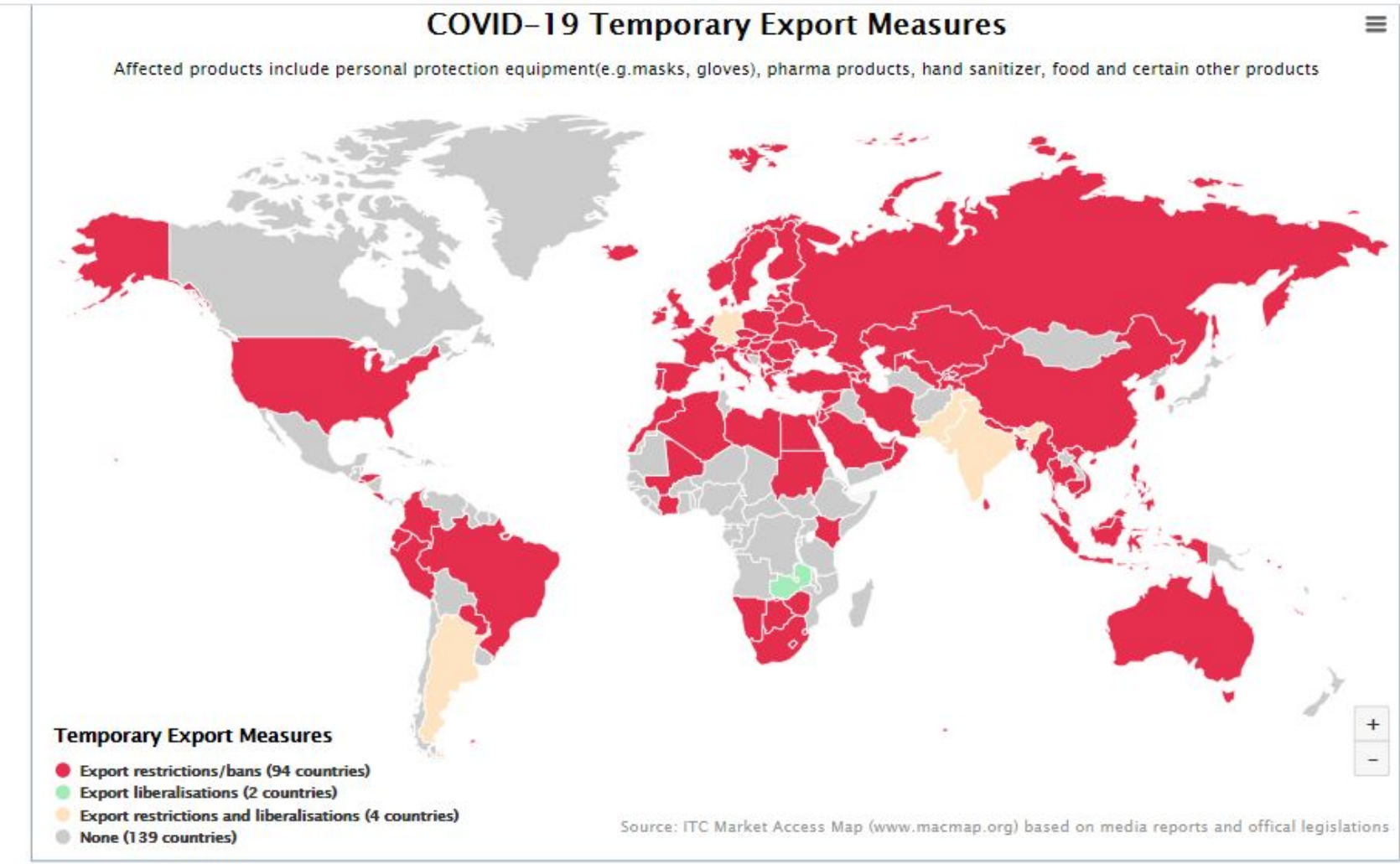
Trade Instruments in the Covid-19 Pandemic

• 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**.

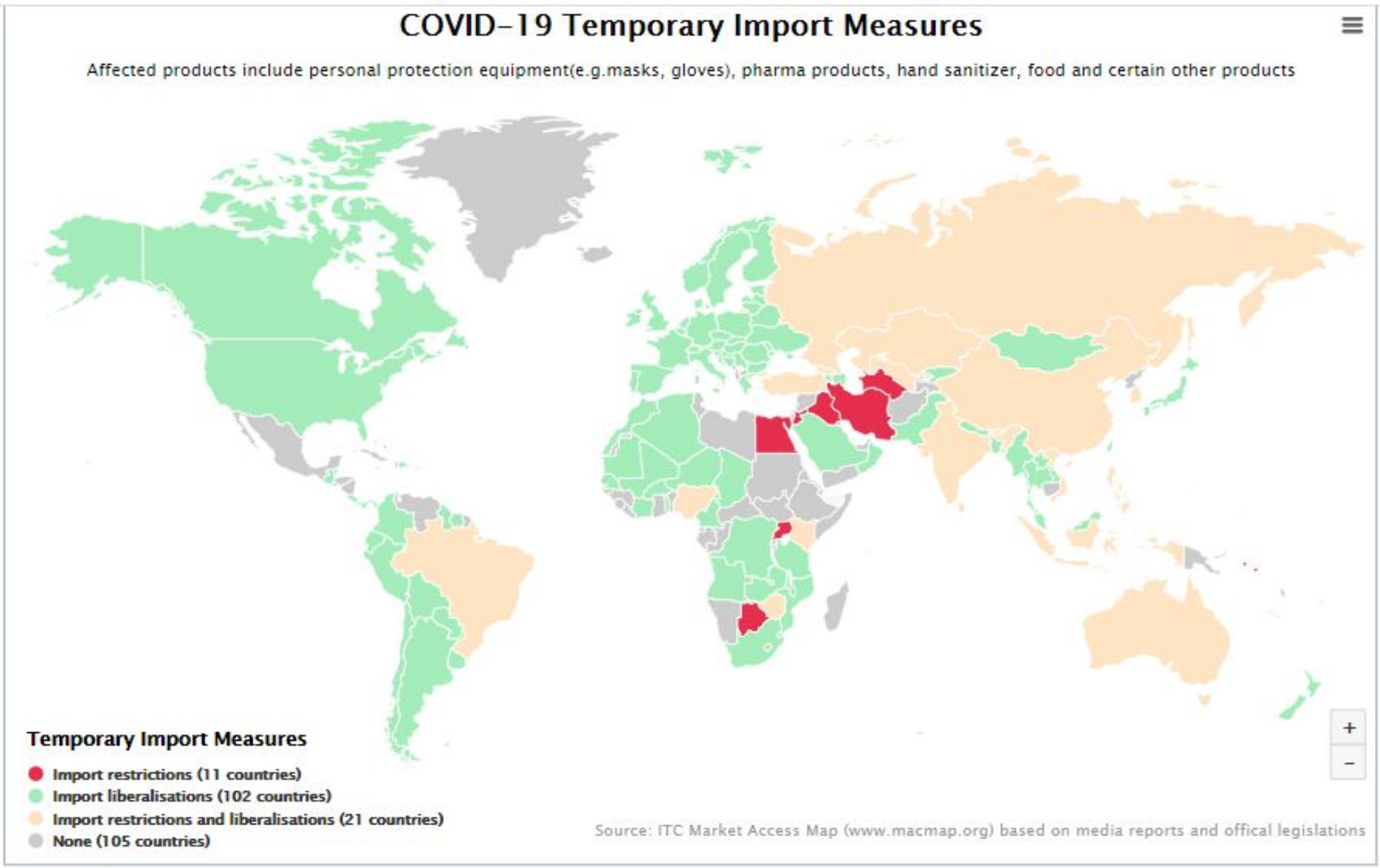
• According to Global Trade Alert, as of 25 April 2020, **122 new export bans in more than 75 countries including the US, China, and the EU were issued on medical supplies such as antibiotics, face masks, and ventilators**. Belarus imposed **restrictions on exports of food products such as onions and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



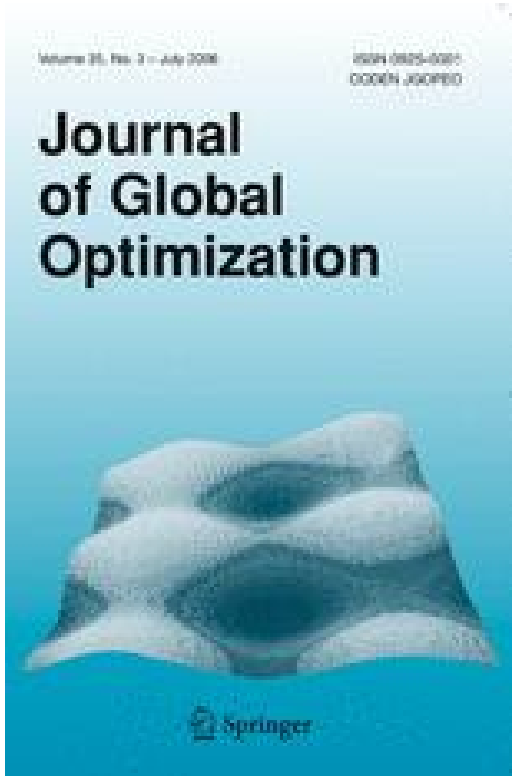
Global Trade Policies

Our research community needs to construct **computable operational mathematical models** that enable the assessment of the impacts of trade policy instruments such as tariff rate quotas on consumer prices, trade flows, as well as on the profits of producers/firms.

However, this is very challenging research!

The part of this presentation is based on the paper:

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.**



Motivation

- 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.**

Literature Review - Perfect Competition

- Tariff rate quotas (TRQs) have been deemed challenging to formulate; models have focused almost exclusively on **spatial price equilibrium**.
- Spatial price equilibrium models are perfectly competitive models with numerous producers (Samuelson (1964), Takayama and Judge (1964, 1971)).
- For more recent applications of spatial price equilibrium models, utilizing variational inequality theory, see Nagurney (1999, 2006), Daniele (2004), Li, Nagurney, and Yu (2018)).
- For the inclusion of tariff rate quotas into spatial price equilibrium models using variational inequality theory, see the EJOR paper by Nagurney, Besik, and Dong (2019).

Literature Review - Perfect Competition

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.**

Literature Review - Imperfect Competition

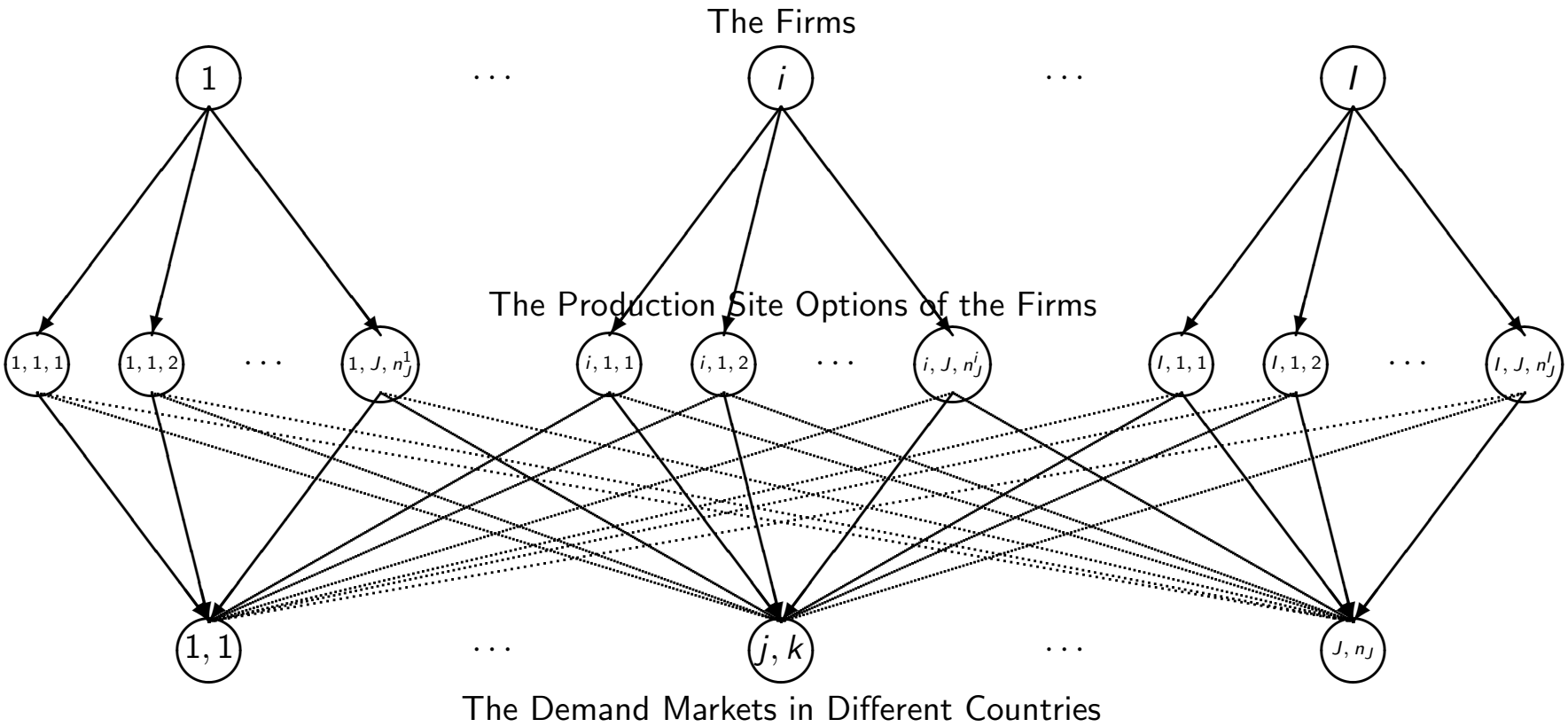
- In many industrial sectors, the more appropriate framework is that of imperfect competition, as in the case of **oligopolistic competition**.
- Shono (2001) relaxed the assumption of perfect competition, and incorporated TRQs, under oligopolistic competition and that the computable framework consisted of linear functions.
- Maeda, Suzuki, and Kaiser (2001, 2005) considered oligopolistic competition and TRQs but assumed that there is a single producer in each country.

Our Model

Specifically, we:

- Introduce **the global supply chain network model** consisting of firms that seek to maximize their profits by determining how much of the product to manufacture/produce at the production sites, which can be located in multiple countries;
- **Incorporate tariff rate quotas** into the supply chain network equilibrium model, and
- Provide **a case study on the agricultural product of avocados**, a very popular fruit in the United States, with growing consumer demand even in China.

The Global Supply Chain Network Model with TRQs



Notation Related to Tariff Rate Quotas

- The groups G_g; $g = 1, \ldots, n_G$, consist of the middle tier nodes $\{h\}$ corresponding to the production sites in the countries from which imports are to be restricted under the tariff quota regime and the demand markets $\{l\}$ in the country that is imposing the tariff rate quota.
- Associated with each group G_g is an under-quota tariff $\tau^u_{G_g}$.
- Associated with each group G_g is an over-quota tariff $\tau^o_{G_g}$, where $\tau^u_{G_g} < \tau^o_{G_g}$.

The Variables

Q_{ihl}: denotes the volume of the product manufactured/produced by firm i at production site $h \in \mathcal{J}_i$ and then shipped to demand market l for consumption.

Q_i: is the vector of nonnegative product flows, where $Q_i = \{Q_{ihl}; h \in \mathcal{J}_i, l \in \mathcal{K}\}$.

Q is then the vector of all the Q_is.

λ_{G_g}: denotes the quota rent equivalent for G_g.

The Global Supply Chain Network Model with TRQs

The Production Cost Functions

Each firm i; $i = 1, \ldots, I$, is faced with a production cost function f_{ih} associated with manufacturing the product at h:

$$f_{ih} = f_{ih}(Q), \quad \forall h \in \mathcal{J}_i. \tag{1}$$

The Transportation Cost Functions

Each firm i; $i = 1, \ldots, I$, encumbers a transportation cost c_{ihl} associated with transporting the product from production site node h to demand market node l:

$$c_{ihl} = c_{ihl}(Q), \quad \forall h \in \mathcal{J}_i, \forall l \in \mathcal{K}. \tag{2}$$

The Conservation of Flow Equations

Demand at each demand node l; $\forall l \in \mathcal{K}$, denoted by d_l, satisfies:

$$\sum_{i=1}^{I} \sum_{h \in \mathcal{J}_i} Q_{ihl} = d_l. \tag{3}$$

The Demand Price Functions

The consumers, located at the demand markets, reflect their willingness to pay for the product through the demand price functions ρ_I, $\forall I \in \mathcal{K}$, with these functions being expressed as:

$$\rho_I = \rho_I(d), \tag{4a}$$

where d is the vector of all the demands.

In view of (3), we can redefine the demand price functions (4a) as follows:

$$\hat{\rho}_I = \hat{\rho}_I(Q) \equiv \rho_I(d), \quad \forall I \in \mathcal{K}. \tag{4b}$$

The Utility Function for a Firm Under a TRQ

For a firm i affected by a TRQ, we define the utility function U_i^G as

$$U_i^G \equiv \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} \hat{\rho}_l(Q) Q_{ihl} - \sum_{h \in \mathcal{J}_i} f_{ih}(Q) - \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} c_{ihl}(Q)$$

$$- \sum_{G_g \in \mathcal{I}^i} (\tau^u_{G_g} + \lambda^*_{G_g}) \sum_{(h,l) \in G_g} Q_{ihl} \qquad (5a)$$

where $\lambda^*_{G_g}$ is the equilibrium economic rent equivalent for group G_g, assuming values as in Definition 1 below. We group the $\lambda^*_{G_g}$s into the vector λ^*.

The Utility Function for a Firm Not Under A TRQ

For any other firm i, we define its utility function U_i, as

$$U_i \equiv \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} \hat{\rho}_l(Q) Q_{ihl} - \sum_{h \in \mathcal{J}_i} f_{ih}(Q) - \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} c_{ihl}(Q). \quad (5b)$$

We then define $\hat{U}_i \equiv U_i^G$ for all firms i with plants associated with groups and $\hat{U}_i \equiv U_i$ for all firms without plants in countries subject to tariff rate quotas.

Also, we define the feasible sets: $K_i \equiv \{Q_i | Q_i \in R_+^{\sum_{j=1}^{J} Kn_j^i}\}$, $\forall i$.

We assume that the utility functions are concave and continuously differentiable.

Definition 1: Global Supply Chain Network Equilibrium Under TRQs

A product flow pattern Q^* and quota rent equivalent λ^* is a global supply chain network equilibrium under tariff rate quotas if, for each firm i; $i = 1, \ldots, I$, the following conditions hold:

$$\hat{U}_i(Q_i^*, Q_{-i}^*, \lambda^*) \geq \hat{U}_i(Q_i, Q_{-i}^*, \lambda^*), \quad \forall Q_i \in K_i, \tag{6}$$

where $Q_{-i}^* \equiv (Q_1^*, \ldots, Q_{i-1}^*, Q_{i+1}^*, \ldots, Q_I^*)$, and for all groups G_g:

$$\lambda_{G_g}^* \begin{cases} = \tau_{G_g}^o - \tau_{G_g}^u, & \text{if} \quad \sum_{i=1}^{I} \sum_{(h,l) \in G_g} Q_{ihl}^* > \bar{Q}_{G_g}, \\ \leq \tau_{G_g}^o - \tau_{G_g}^u, & \text{if} \quad \sum_{i=1}^{I} \sum_{(h,l) \in G_g} Q_{ihl}^* = \bar{Q}_{G_g}, \\ = 0, & \text{if} \quad \sum_{i=1}^{I} \sum_{(h,l) \in G_g} Q_{ihl}^* < \bar{Q}_{G_g}. \end{cases} \tag{7}$$

Theorem 1: Variational Inequality Formulation of the Global Supply Chain Network Equilibrium Under TRQs

Under the assumption that the utility functions are concave and continuously differentiable, the product flow and quota rent equivalent pattern $(Q^*, \lambda^*) \in \mathcal{H}$ *is a global supply chain network equilibrium under tariff rate quotas according to Definition 1 if and only if it satisfies the variational inequality (VI):*

$$-\sum_{i=1}^{I}\sum_{h\in\mathcal{J}_i}\sum_{l\in\mathcal{K}}\frac{\partial\hat{U}_i(Q^*,\lambda^*)}{\partial Q_{ihl}}\times(Q_{ihl}-Q^*_{ihl})$$

$$+\sum_{g}\left[\bar{Q}_{G_g}-\sum_{i=1}^{I}\sum_{(h,l)\in G_g}Q^*_{ihl}\right]\times\left[\lambda_{G_g}-\lambda^*_{G_g}\right]\geq 0,\quad\forall(Q,\lambda)\in\mathcal{H}, \tag{8}$$

where $\mathcal{H}\equiv\{(Q,\lambda)|Q\in\bar{K},\lambda\in R_+^{n_G}|0\leq\lambda_{G_g}\leq\tau^o_{G_g}-\tau^u_{G_g},\forall g\}$.

Corollary 1: Variational Inequality Formulation for the Global Supply Chain Network Without TRQs

In the absence of tariff rate quotas, the equilibrium of the resulting global supply chain network model collapses to the solution of the VI: determine $Q^* \in \bar{K}$, *satisfying:*

$$-\sum_{i=1}^{I}\sum_{h\in\mathcal{J}_i}\sum_{l\in\mathcal{K}}\frac{\partial U_i(Q^*)}{\partial Q_{ihl}}\times(Q_{ihl}-Q^*_{ihl})\geq 0,\quad \forall Q\in\bar{K}, \qquad (9)$$

where $\bar{K}\equiv\prod_{i=1}^{I}K_i$.

Variants of the Model

Unit Tariffs

The framework can be adapted to handle the simpler trade policy of unit tariffs with an appended term: $-\sum_{h\in\mathcal{J}_i}\sum_{l\in\mathcal{K}}\tau_{hl}Q_{ihl}$, where τ_{hl} denotes the unit tariff assessed on a product flow from h to l, with $\tau_{hl}=0$, if h,l corresponds to a production site and demand market pair in countries not under a tariff.

Strict Quotas

If there is a strict quota regime, for those firms i that are affected, the utility function U_i^G in (5a) is modified to U_i^Q as:

$$U_i^Q = \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} \hat{\rho}_l(Q) Q_{ihl} - \sum_{h \in \mathcal{J}_i} f_{ih}(Q) - \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} c_{ihl}(Q)$$

$$- \sum_{G_g \in \mathcal{I}^i} \lambda^*_{G_g} \sum_{(h,l) \in G_g} Q_{ihl}, \tag{10}$$

where the groups G_g, $\forall g$, now correspond to those node pairs under strict quotas. The Nash Equilibrium conditions (6) are still relevant but the system (7) is replaced with the system below: for all groups G_g:

$$\bar{Q}_{G_g} - \sum_{i=1}^{I} \sum_{(h,l) \in G_g} Q^*_{ihl} \begin{cases} = 0, & \text{if} \quad \lambda^*_{G_g} > 0, \\ \geq 0, & \text{if} \quad \lambda_{G_g} = 0. \end{cases} \tag{11}$$

A Case Study on Avocados

• The volume of avocado imports into the United States has surpassed even the volume by weight of bananas imported into the US.

• US domestic avocado consumption has risen to approximately 6.5 pounds per person annually, as compared to only 1.4 in 1990.

• The US is among the world's top ten avocado producers, producing between 160,000 and 270,000 tons of avocados a year.

• In terms of other major demand markets, Mexico was the largest supplier of avocados to China until 2017.

A Case Study on Avocados

The United States' imposition of a variety of tariffs, in turn, resulted in retaliatory tariffs by multiple countries, notably, by Mexico and China and on agricultural products produced in the US.

ailing dissidents at home, for his role
eating a humanitarian crisis in Yem-
and for backing the Saudi prince
se agents killed the dissident writer
al Khashoggi.
et under the Trump administration,
influence in Washington appears
Continued on Page 10

tem, which led to a series of design mistakes and regulatory oversights. As Boeing rushed to get the plane done, many of the employees say, they didn't recognize the importance of the decision. They described a compartmentalized approach, each of them focusing on a small part of
Continued on Page 20

A Jump in the Cost of Guacamole And a Blow to a Business Tactic

By BEN CASSELMAN

When trade tensions with China flared last year, many companies sought refuge in a country with a long, stable relationship with the United States: Mexico.

Now, that alternative for production and materials may also be in jeopardy with President Trump's threat to impose escalating tariffs on imports from Mexico, aimed at forcing action on illegal immigration.

In the short term, the tariffs would mean lower profits for American importers and higher prices for American consumers on everything from avocados to Volkswagens. In the long run, they could force companies to reconsider the continent-spanning supply chains that have made North America one of the world's most interconnected economies.

JOSE CASTANARES/A.F.P. — GETTY IMAGES

Tariffs on Mexico would ripple far beyond avocado prices.

That disruption, experts warn, could be far more damaging to the United States economy than the cost of tariffs themselves.

The United States imported more than $345 billion in goods from Mexico last year, and shipped $265 billion the other way. But if anything, those numbers understate the interdependence. American refiners process crude
Continued on Page 19

LEISURE | SUNDAY REVIEW

Figure: Front page of *The New York Times*, June 2, 2019

A Case Study on Avocados

Findings

- To-date, there has been limited modeling work of imperfectly competitive firms in supply chain networks, in the presence of trade policies such as TRQs, which have been challenging to model.
- The theory of variational inequalities is very useful for the formulation, analysis, and solution of oligopolistic supply chain network equilibrium problems under TRQs.
- The numerical examples that comprise the case study quantify impacts of tariff rate quotas on consumer prices, on product flows, as well as on the firms' profits.
- **The results demonstrate that TRQs can be effective in reducing product flows from countries on which they are imposed but at the expense of the consumers in terms of prices.**

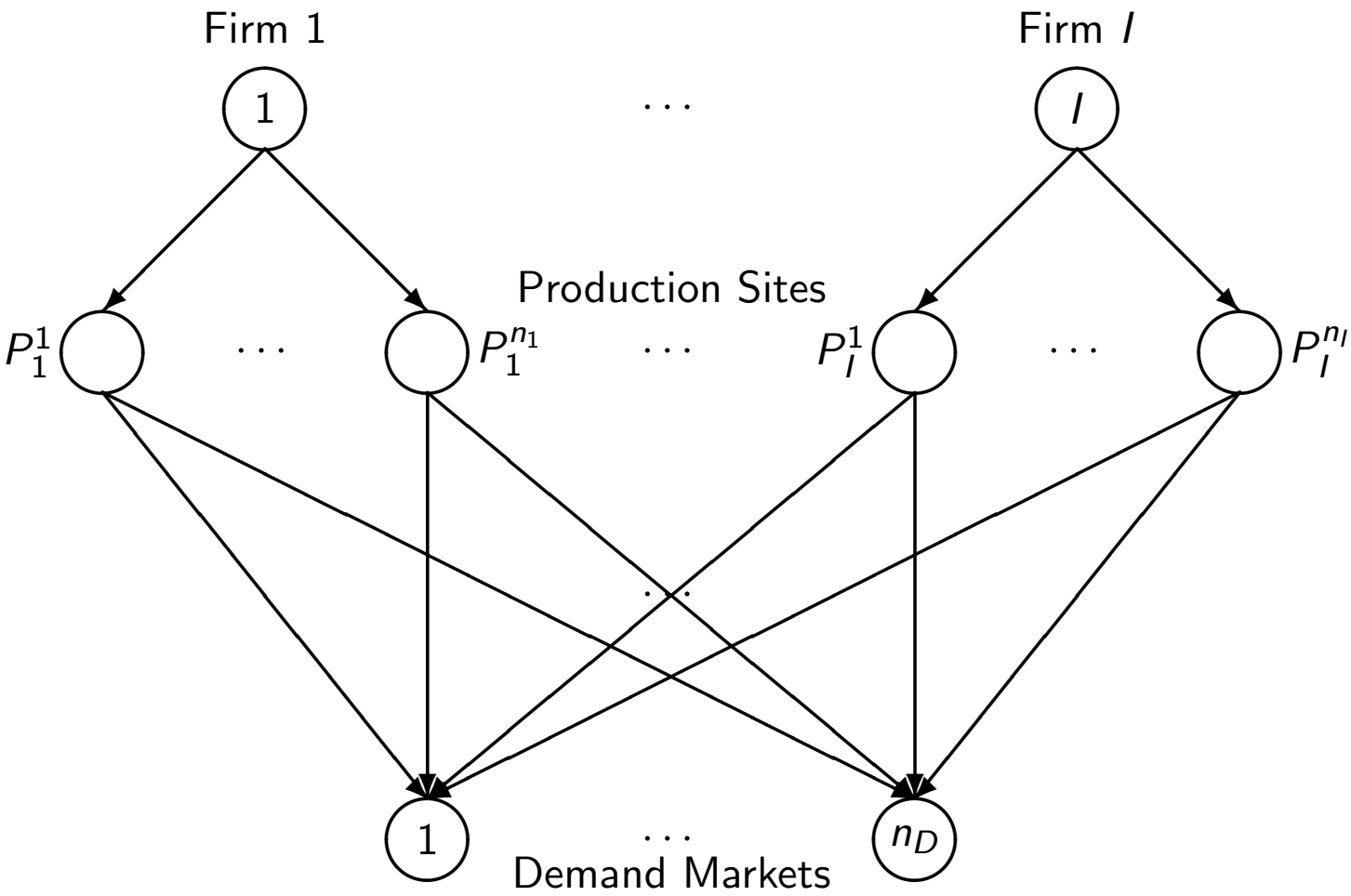
Supply Chain Network Models with Quality Under Strict Quotas or Tariffs

Now we turn to research on the incorporation of quality as a strategic variable and the exploration of the relationship between strict quotas and tariffs.

Specifically, we are interested in the impact of tariffs or strict quotas on consumer welfare.

A. Nagurney, D. Besik, and D. Li, "Strict Quotas or Tariffs? Implications for Product Quality and Consumer Welfare in Differentiated Product Supply Chains," *Transportation Research E* **29 (2019), pp 136-161.**

The Differentiated Product Supply Chain Network Equilibrium Models with Quality



Equivalence Between the Model with a Strict Quota and the Model with a Tariff

We have established theoretically (and also illustrate numerically in our paper) that if the strict quota is tight and the tariff for the same group is set to the associated Lagrange multiplier then the equilibrium product flows and quality levels of both the strict quota and the tariff models coincide.

The provides government decision makers and policy makers the the flexibility of imposing either trade policy instrument, under certain conditions.

Of course, under a tariff regime the government gets added income.

Managerial Insights

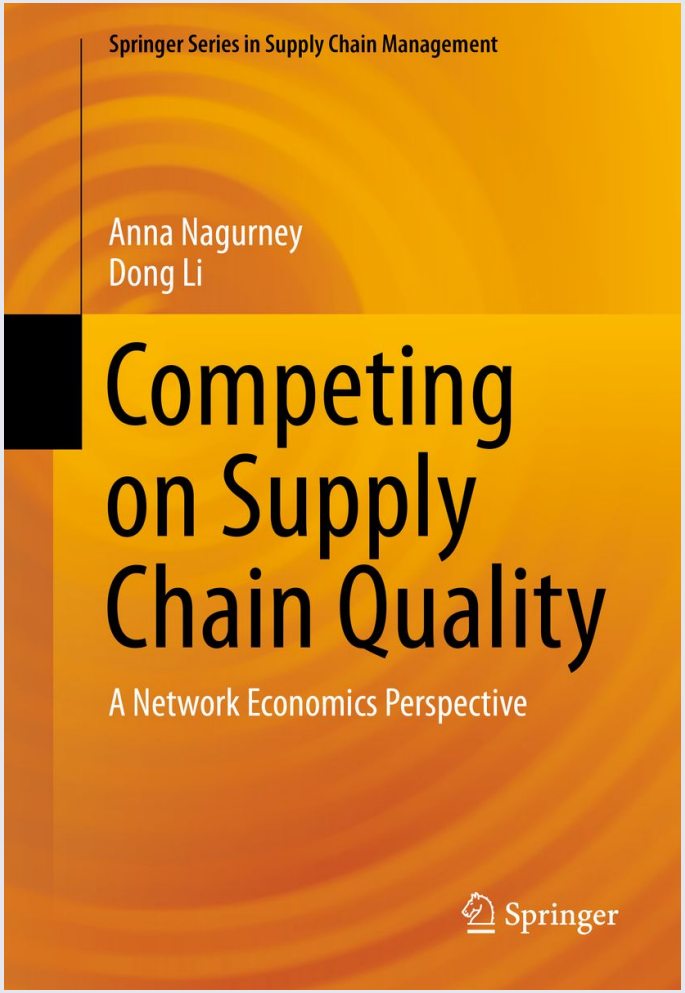
- From the consumer's perspective, **the results consistently and unanimously show that consumer welfare declines for consumers in the country imposing a strict quota or tariff on an imported product.** Hence, a government may wish to loosen a quota (equivalently, reduce a tariff) so as not to adversely affect its own consumers.

- Producing firms, as also critical stakeholders in competitive supply chain networks, **should expand their demand markets within their own countries.** This allows for a basic, but, effective, redesign of the supply chain network under a tariff or quota and results in higher profits for the firms.

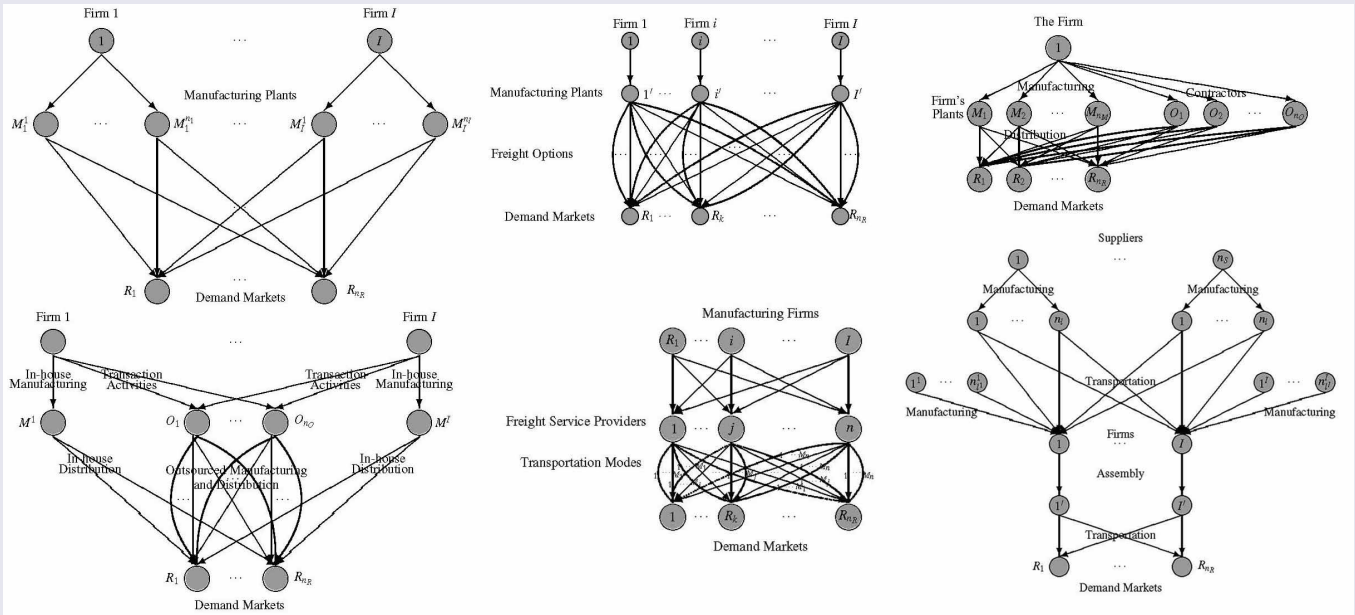
Managerial Insights

- **Also, firms should expand the number of production sites to countries not under a tariff or quota to maintain or improve upon their profits if some of their production sites are in countries subject to such trade policy instruments**.
- Governments have the flexibility of imposing either a tariff or a quota to obtain equivalent trade flows and product quality levels. **The imposition of a tariff may be more advisable/favored by a government, since it requires less "policing" and also yields financial rewards**.

Our Research on Quality



In the book, we present supply chain network models and tools to investigate information asymmetry, impacts of outsourcing on quality, minimum quality standards, applications to industries such as pharma and high tech, freight services and quality.



Incorporation of Labor into Supply Chain Networks

It's All About People

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 through e-commerce. Also, COVID-19 vaccine production may lack the human resources to ensure product quality and efficacy, as well as its distribution and ultimate administration into our arms. Without healthcare workers to administer COVID-19 vaccines, the battle against the coronavirus cannot be won. Many hospitals are already short-staffed because of the pandemic.

Food Supply Chain Disruptions Due to Covid-19

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

1. **As of January 26, 2021, at least 239 meatpacking workers had died 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 doesn't have enough to eat. The lockdown, with its epic lines at food banks, has revealed what was hidden in plain sight: that the struggle to make food last long enough, and to get food that's healthful - what experts call 'food insecurity' - is a persistent one for millions of Americans.

Food Supply Chain Disruptions Due to Covid-19

USA TODAY

AMERICA'S FOOD CHAIN

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

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

CNN

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

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

Lacking seasonal workers, Italy elevates its long-shunned migrants

The Christian Science Monitor

THEDENVERCHANNEL.COM

Farms encountering guest worker shortage amid new coronavirus restrictions

REUTERS

Piglets aborted, chickens gassed as pandemic slams meat sector

The Washington Post
Democracy Dies in Darkness

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

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

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

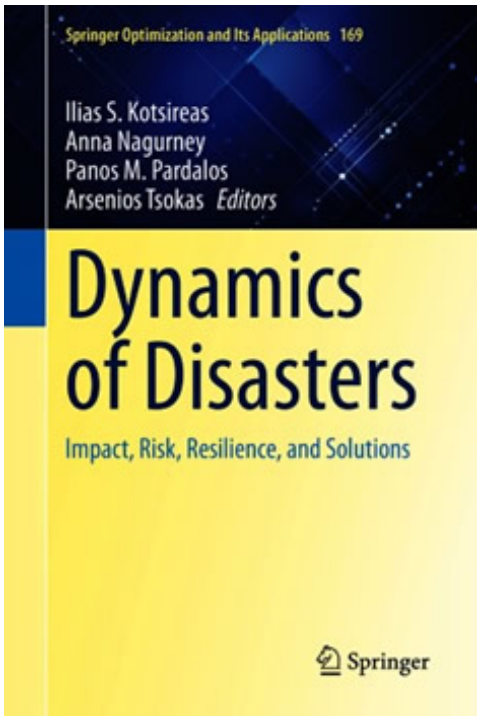
May 20, 2020 · 10:58 AM ET

ROB SCHMITZ

npr

Perishable Food Supply Chain Network Model with Labor

New paper, "Perishable Food Supply Chain Networks with Labor in the Covid-19 Pandemic," A. Nagurney, in: *Dynamics of Disasters - Impact, Risk, Resilience, and Solutions*, **I.S. Kotsireas, A. Nagurney, P.M. Pardalos, and A. Tsokas, Editors, Springer International Publishing Switzerland, 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 that considers labor in all the supply chain network economic activities of production, transportation, processing, storage, and distribution.
- Impacts of the reduction of labor (capacities) on supply chain network links can then be quantitatively evaluated on the perishable product flows, the prices that the consumers pay, and profits of the firm.
- The framework enables a variety of sensitivity analysis exercises.

Perishable Food Supply Chain Network Model with Labor

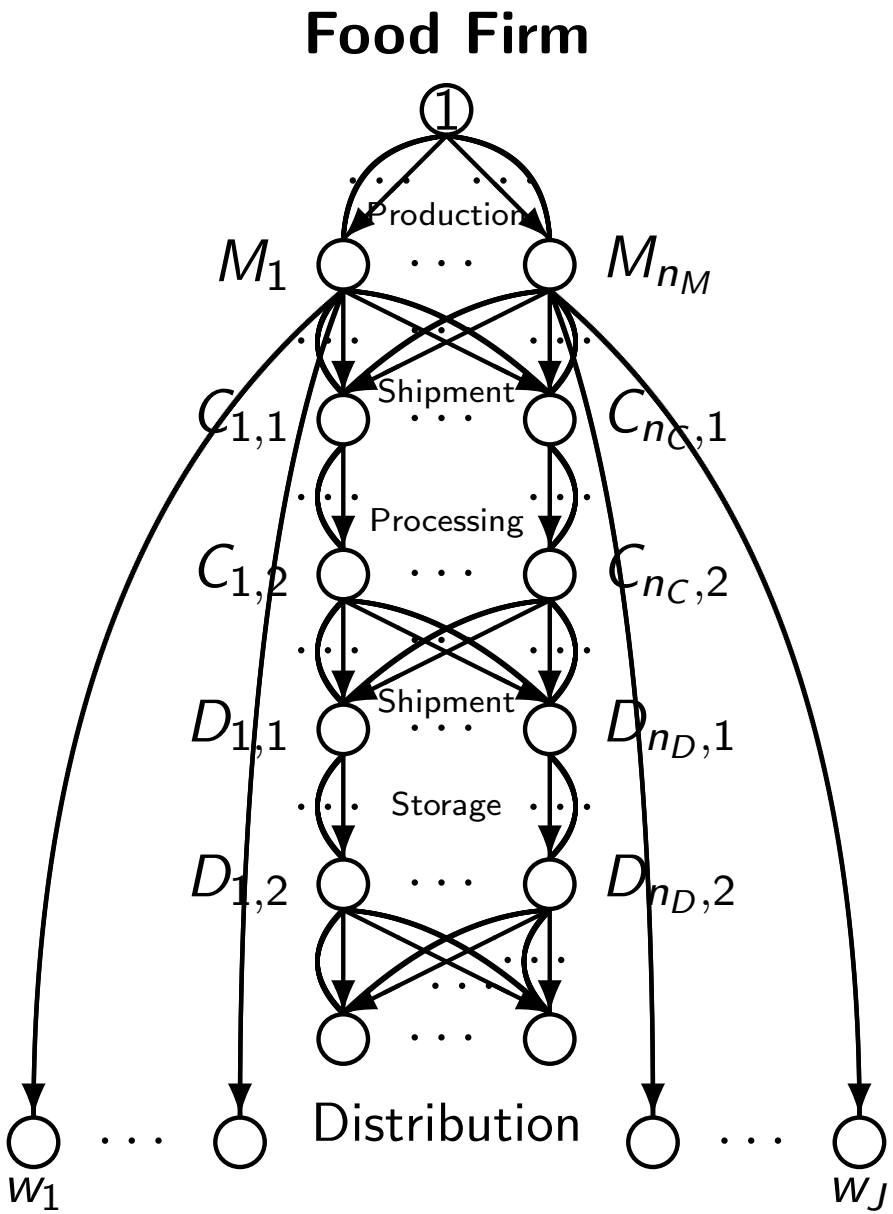


Figure: The Perishable Food Supply Chain Network Topology

Our findings include:

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

Shortages of Medical Supplies, Including PPEs

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

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

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

Where Are the PPEs?

The Press Democrat

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

The New York Times

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

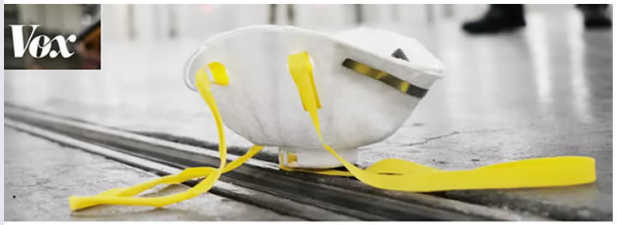
FierceHealthcare

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

TIME

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

Vox

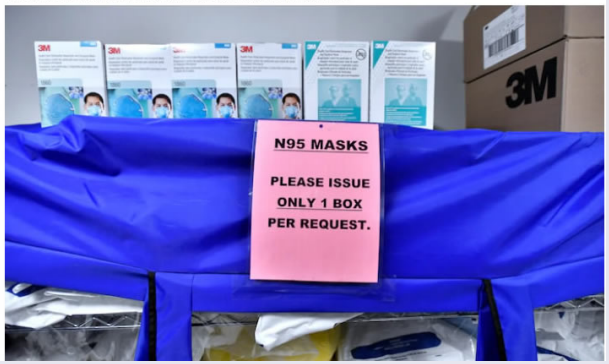


Why America ran out of protective masks — and what can be done about it

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

The Washington Post
Democracy Dies in Darkness

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



Recurring Shortages of PPEs

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

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

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

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

Supply Chain Model with Different Labor Constraints

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

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

A. Nagurney, "Optimization of Supply Chain Networks with Inclusion of Labor: Applications to Covid-19 Pandemic Disruptions," *International Journal of Production Economics* **235, 2021, 108080.**

Supply Chain Model with Different Labor Constraints

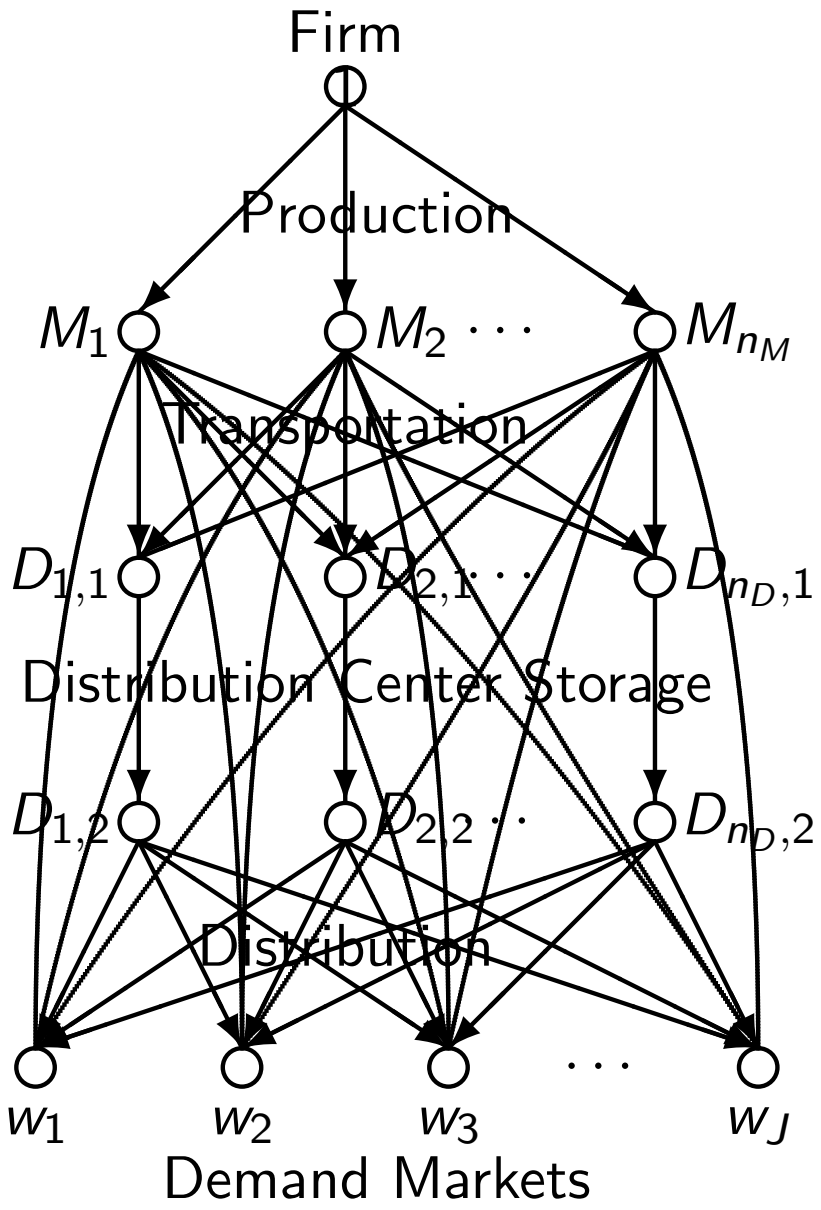


Figure: The Supply Chain Network Topology

Supply Chain Model with Different Labor Constraints

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

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

Supply Chain Model with Different Labor Constraints

Our findings include:

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

Game Theory Supply Chain Network Model with Labor

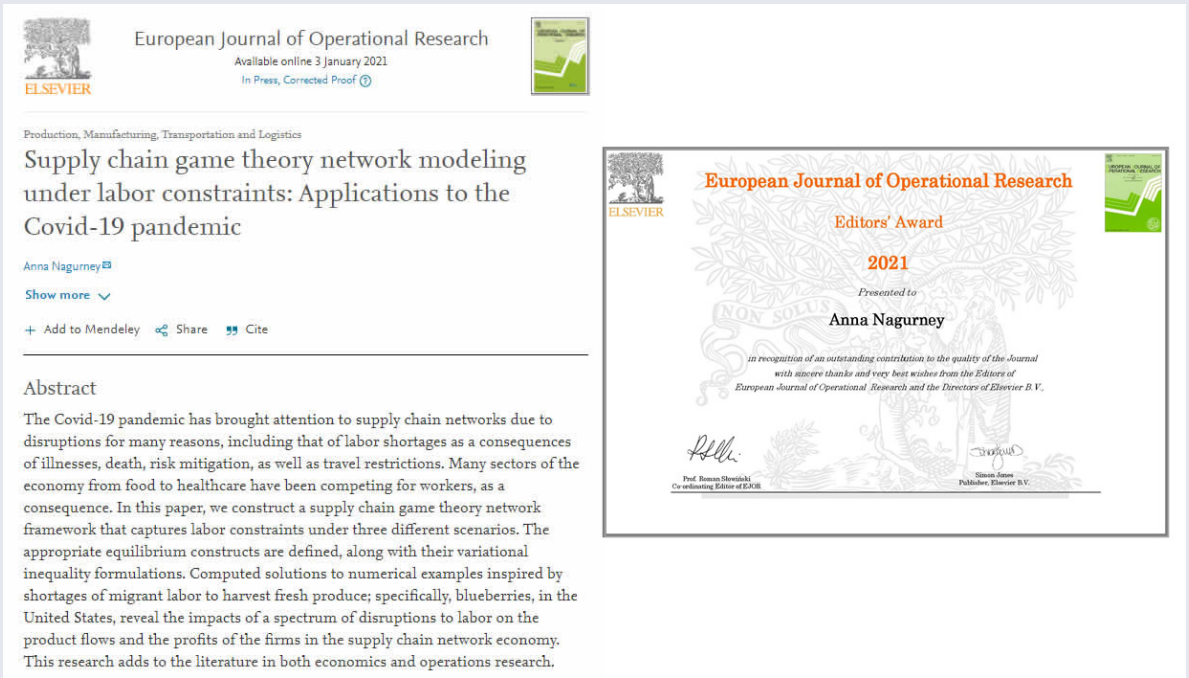
The Covid-10 pandemic has dramatically illustrated the importance of including labor (and associated possible disruptions) into the analysis of supply chain networks.

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,** *European Journal of Operational Research* **293(3) (2021), pp 880-891**, a game theory model for supply chains with labor was constructed, under three different sets of constraints, building on our previous work.

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.



European Journal of Operational Research

Available online 3 January 2021

In Press, Corrected Proof

Production, Manufacturing, Transportation and Logistics

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

Anna Nagurney

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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.

European Journal of Operational Research

Editors' Award

2021

Presented to

Anna Nagurney

in recognition of an outstanding contribution to the quality of the Journal with sincere thanks and very best wishes from the Editors of European Journal of Operational Research and the Directors of Elsevier B.V.

Prof. Roman Slowinski
Co-ordinating Editor of EJOR

Simon Jones
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Game Theory Supply Chain Network Model with Labor

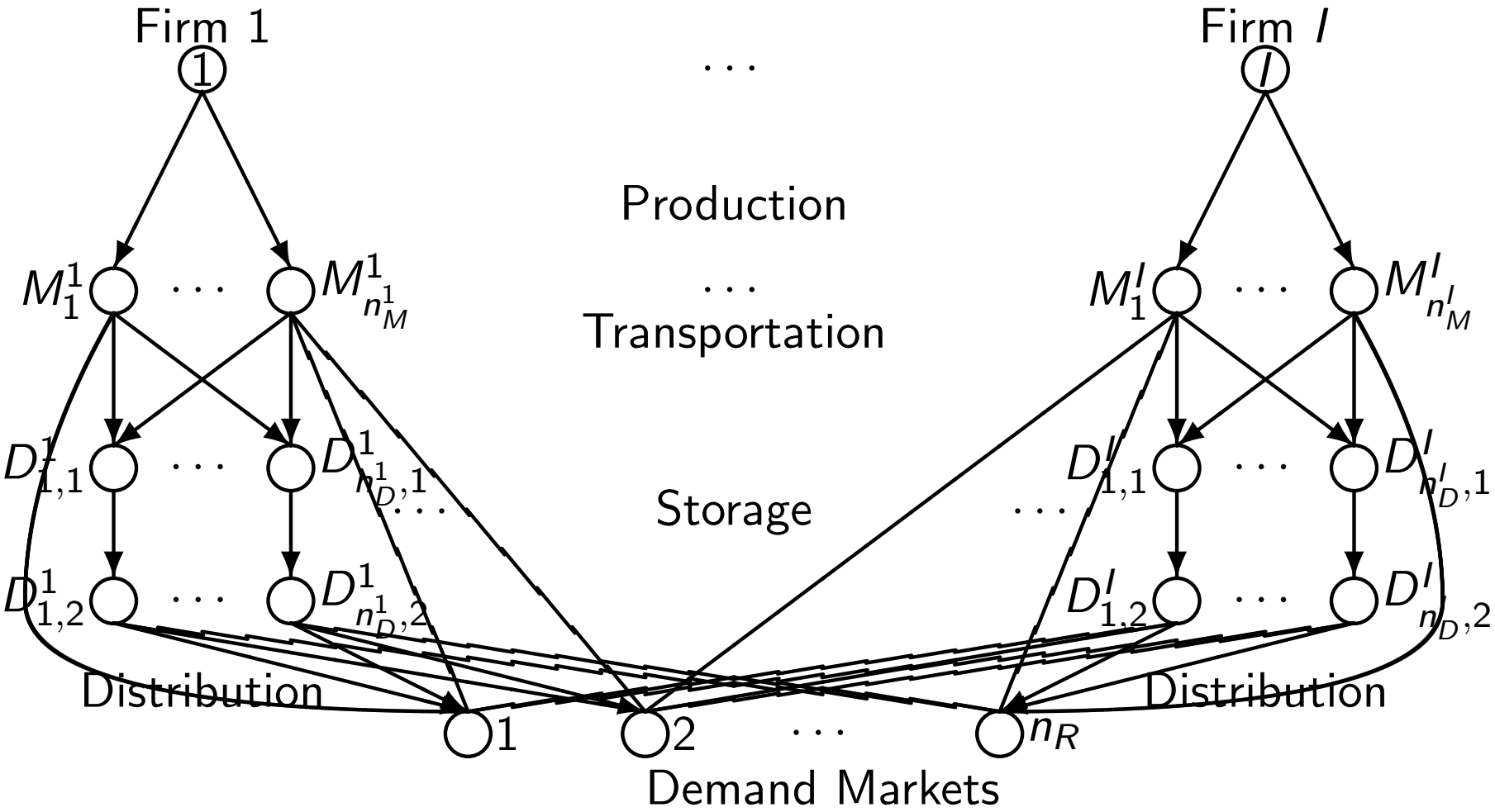

Figure: The Supply Chain Network Topology of the Game Theory Model with Labor

Game Theory Supply Chain Network Model with Labor

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.
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Game Theory Supply Chain Network Model with Labor

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

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

The research adds to modeling methodology as well as applications since two of the scenarios are Generalized Nash Equilibrium problems.

Some Additional Research

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

"Competition for Medical Supplies Under Stochastic Demand in the Covid-19 Pandemic: A Generalized Nash Equilibrium Framework," A. Nagurney, M. Salarpour, J. Dong, and P. Dutta, in: *Nonlinear Analysis and Global Optimization*, **T.M. Rassias, and P.M. Pardalos, Editors, (2021), Springer Nature Switzerland AG, pp 331-356.**

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

Some Additional Research

A. Nagurney, M. Salarpour, J. Dong, and L.S. Nagurney, "A Stochastic Disaster Relief Game Theory Network Model", *SN Operations Research Forum* 1(10) (2020), pp 1-33.

SN Operations Research Forum (2020) 1: 10
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ORIGINAL RESEARCH

SN

A Stochastic Disaster Relief Game Theory Network Model

Anna Nagurney[1] · Mojtaba Salarpour[1] · June Dong[2] · Ladimer S. Nagurney[3]

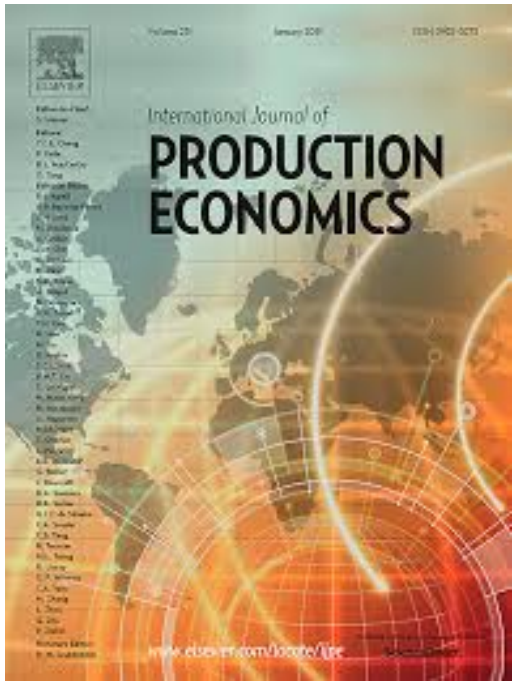
Received: 26 December 2019 / Accepted: 20 March 2020 / Published online: 11 April 2020

Abstract

In this paper, we construct a novel game theory model for multiple humanitarian organizations engaged in disaster relief. Each organization is faced with a two-stage stochastic optimization problem associated with the purchase and storage of relief items pre-disaster, subject to a budget constraint, and, if need be, additional purchases and shipments post the disaster. The model integrates logistical and financial components, in that the humanitarian organizations compete for financial donations,

Some Additional Research

M. Salarpour and A. Nagurney, 2021. A Multicountry, Multicommodity Stochastic Game Theory Network Model of Competition for Medical Supplies Inspired by the Covid-19 Pandemic, in press in the *International Journal of Production Economics.*



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Writing OpEds Prior to the Pandemic

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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

Author

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

Disclosure statement

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

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

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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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ANNA NAGURNEY, THE CONVERSATION

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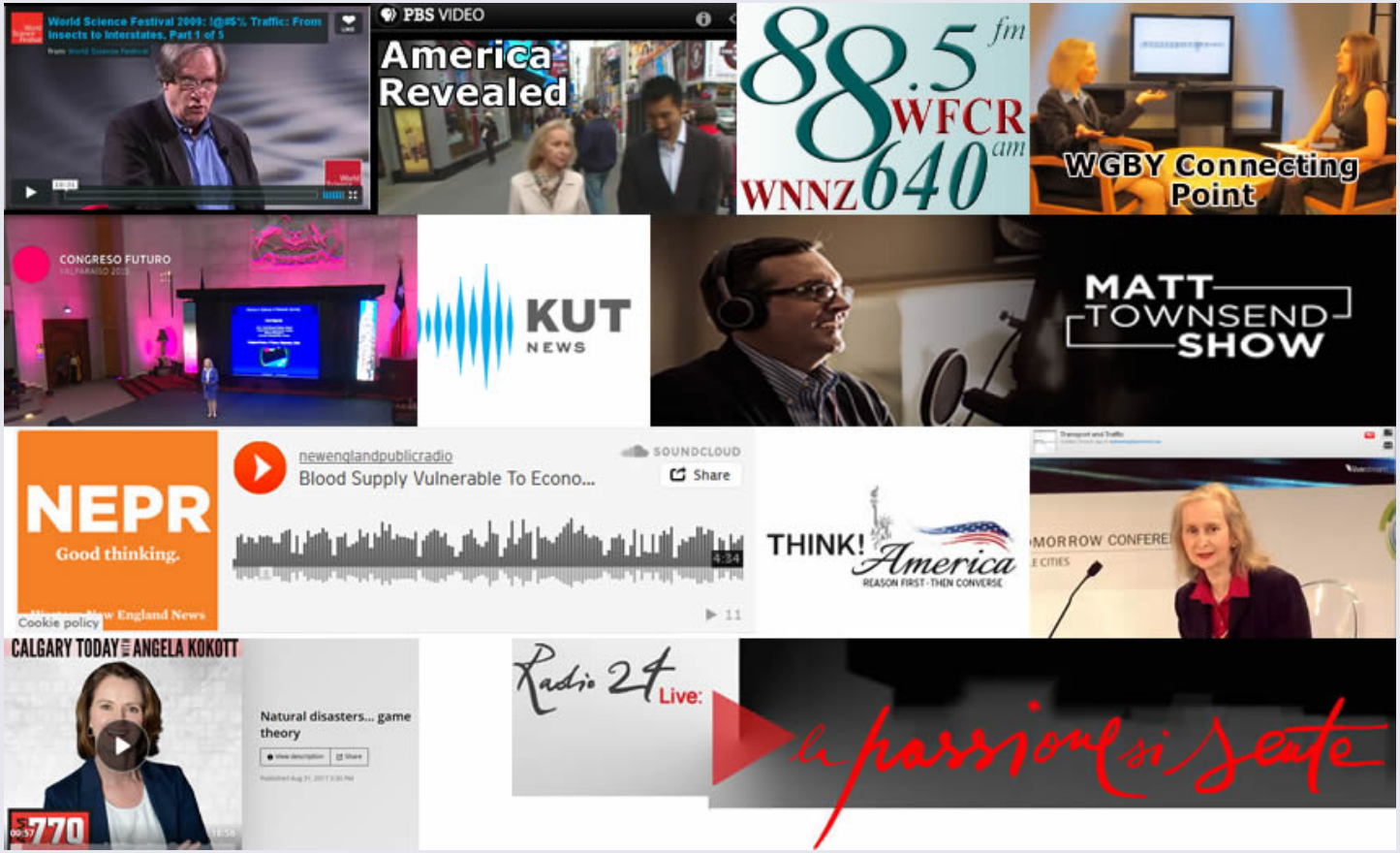
The number of disasters has doubled globally since the 1980s, with the damage and losses estimated at an average

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

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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*.

Coverage by the Media During the Pandemic

Impacting Policy Through Analytics

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

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

Impacting Policy Through Analytics

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

April 22, 2020

Via Electronic Mail

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

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

Dear Assistant Secretary Giroir:

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

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

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

Impacting Policy Through Analytics

Hon. Brett Giroir
April 22, 2020
Page 7

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Nevada Attorney General

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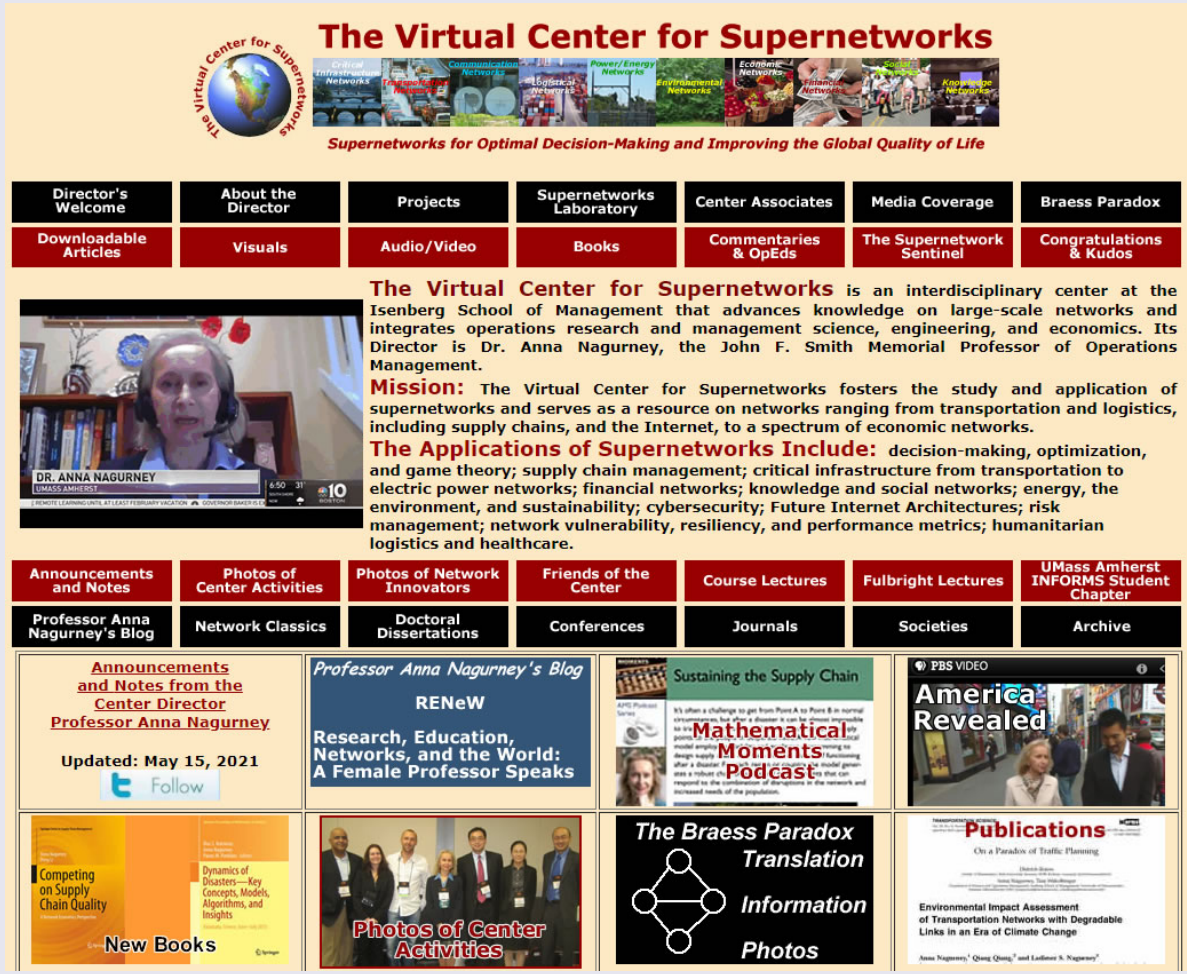
New Jersey Attorney General

HECTOR BALDERAS
New Mexico Attorney General

LETITIA JAMES
New York Attorney General

Xavier Becerra, President Biden's choice as his Secretary of the Department of Health and Human Services, was recently confirmed!

Thank You Very Much!



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