

# Agricultural Supply Chain Networks: Trade, Policies, and Resilience

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# Acknowledgments

**I'd like to thank Austin Iglesias Saragih for the invitation to present in your seminar series.**



**Special acknowledgments and thanks to my students and collaborators who have made research and teaching always stimulating and rewarding.**



# Outline of This Presentation

- **Background and Motivation**
- **Food Supply Chains and Disruptions**
- **International Agricultural Trade and Disasters**
- **Trade Policies and Exchange Rates**
- **The Multicommodity International Trade Model**
- **Making a Positive Impact**

# Background and Motivation

# I Work on the Modeling of Network Systems



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



# Some of My Books



# International Trade

**International trade provides us with commodities throughout the year and has benefits for producers and consumers alike.**



# 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.



# International Agricultural Trade

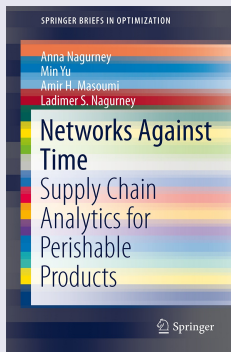
**International agricultural trade provides us with essential agri-food commodities throughout the year, ensuring our food security and simultaneously benefiting the farmers.**





# 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 and Disruptions

# 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 suffered major disruptions. Various disruptions continue because of climate change, Russia's war on Ukraine, and other disasters.



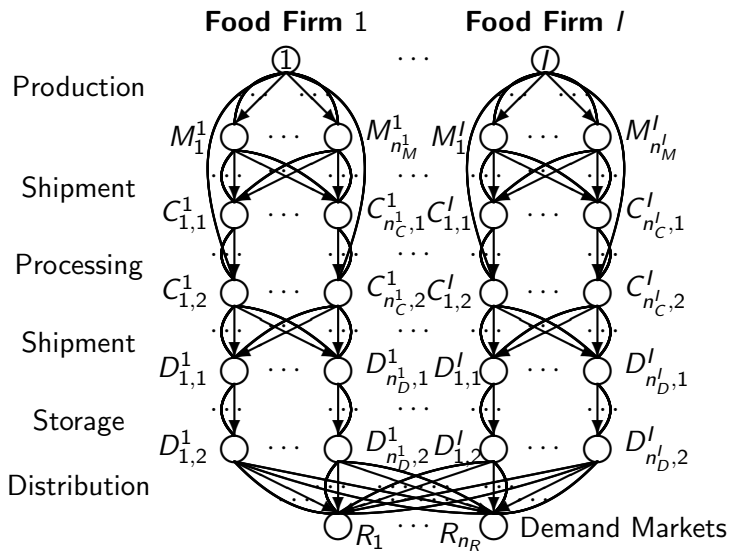
# Fresh Produce Food Supply Chains

## 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.

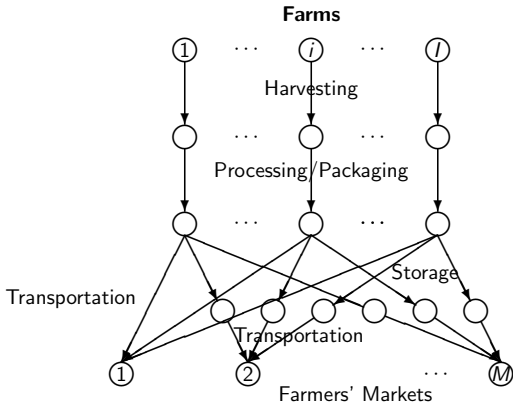
# Fresh Produce Food Supply Chains



The Fresh Produce Supply Chain Network Topology

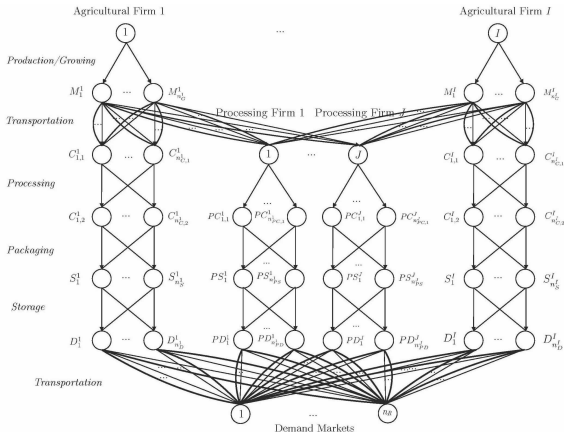
# Farmers' Markets and Fresh Produce Supply Chains

- 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.

# Integrated Supply Chain Network Model



**D. Besik, A. Nagurney, and P. Dutta, "An Integrated Multitiered Supply Chain Network Model of Competing Agricultural Firms and Processing Firms: The Case of Fresh Produce and Quality,"**  
*European Journal of Operational Research* 307(1) (2023), pp 364-381.

# Food Supply Chain Disruptions Due to COVID-19



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

QW

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



## 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

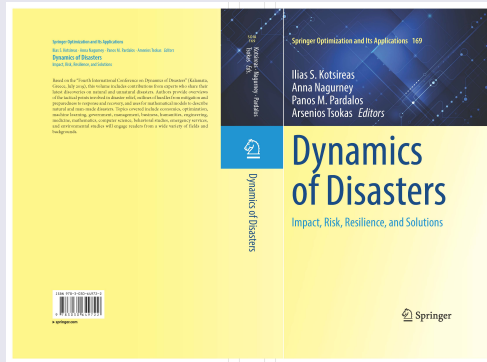


ROB SCHMITZ

n p r



**“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.

## 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.

In “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.



Journal of Operational Research

Editors' Award

2021

Presented to

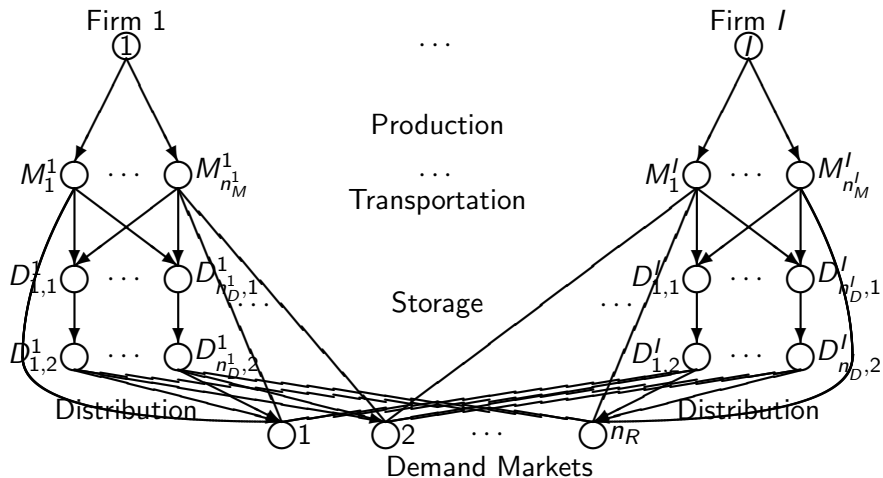
Anna Nagurney

*in recognition of an outstanding contribution to the quality of the Journal  
with sincere thanks and very best wishes from the Editors of  
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*R. Shevchik*  
Prof. Rossitza Shevchik  
Co-editing Editor of EJOR

*S. Law*  
Simon Law  
Publisher, Elsevier B.V.

# Game Theory Supply Chain Network Model with Labor



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

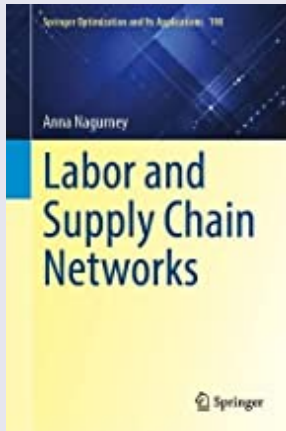
# Numerical Experiments

**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.

**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!**



# International Agricultural Trade and Disasters



# International Agricultural Trade and Disasters

- Our planet and people are being faced with immense challenges brought about by disasters, including man-made ones.
- Disasters can have an immense impact on nations, regions, businesses, organizations, and individuals. A multiplicity of disasters can also impact food security.



# Disasters and Food Security

- Climate change and COVID-19 impacted the affordability and accessibility of agri-food products around the globe.
- With the added disruptions of Russia's full-scale invasion of Ukraine, around 47 million people are estimated to have been added to the more than 276 million who were already facing food insecurity.



# Disasters and Food Security

- The FAO of the United Nations reports that between 20 and 30 percent of the Ukrainian land previously used for cultivating winter crops will probably remain unsown due to the ongoing war.
- In addition, there have been immense challenges in getting the exports of agricultural products out of Ukraine with the blockade of the Black Sea in wartime and various bottlenecks.



# Trade Policies and Exchange Rates

# Global Trade Policies

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



- 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.**



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

**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.

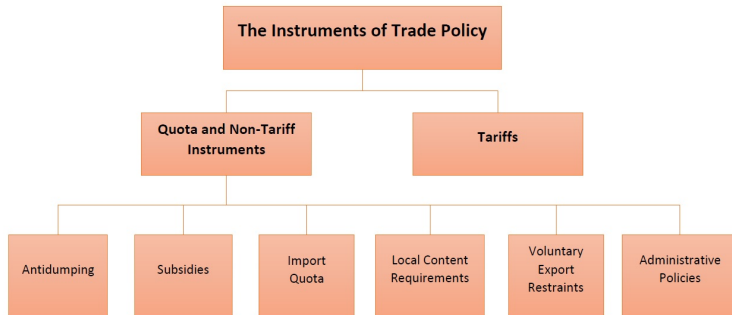


**A. Nagurney, M. Salarpour, and J. Dong, “Modeling of Covid-19 Trade Measures on Essential Products: A Multiproduct, Multicountry Spatial Price Equilibrium Framework,”** *International Transactions in Operational Research* 29(1) (2022), pp 226-258.



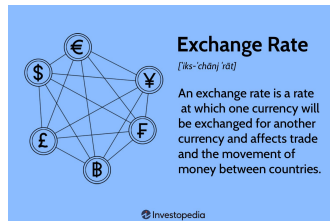
# International Trade, Policies, and Exchange Rates

Identifying quantitatively the **impacts of trade policies and exchange rates** on international trade can provide trade and regulatory bodies with valuable information on product trade volumes and producer and consumer prices.



# Exchange Rates

Exchange rates represent the value (price) of one currency relative to another currency.



They are important economic parameters in international trade, with changes in the exchange rate affecting the decision-making of individuals, businesses, and governments.

# Exchange Rates

- In August 2022, the dollar reached parity with the euro ( $\$1 = 1$  euro). For a short time, it took less than \$1 to purchase one euro. In later 2022, the dollar began giving up some ground, and by the end of 2023, the exchange rate was \$1.1062 to the euro. The dollar gained some strength in early 2024.
- In contrast, during the first year of the COVID-19 pandemic, the dollar weakened with respect to the euro, the British pound, and the yen.



# The Multicommodity International Trade Model

# The Multicommodity International Trade Model

A. Nagurney, D. Hassani, O. Nivievskiy, and P. Martyshev,  
“Exchange Rates and Multicommodity International Trade:  
Insights from Spatial Price Equilibrium Modeling with Policy  
Instruments via Variational Inequalities,” *Journal of Global  
Optimization* 87 (2023), pp 1-30.



# The Multicommodity International Trade Model

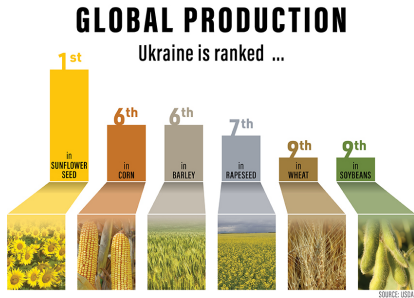
In this paper, we harness the powerful theory of variational inequalities to construct a model with the following features:

- **Multiple commodities;**
- **Multiple routes from origin nodes to destination nodes** in the same or different countries;
- **Exchange rates** and the formula for their computation along trade routes;
- Inclusion of policies in the form of **tariffs, subsidies, and quotas;**
- The underlying **economic functions can be nonlinear and asymmetric**. Hence, our **transportation cost functions capture congestion**.



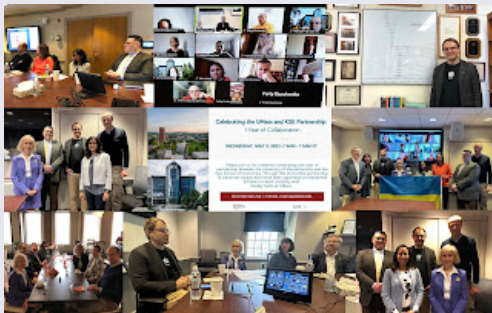
# Additional Motivation

This work is inspired by Russia's war on Ukraine and the need to assess its impacts on agricultural trade as well as on food insecurity and the need to provide more general computable models for assessing the impacts of trade policies and exchange rates on international trade.

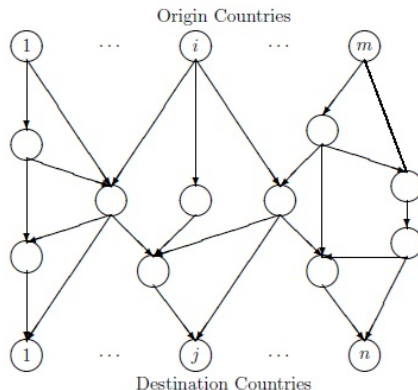


# An Acknowledgment

I acknowledge the partnership established between the University of Massachusetts Amherst and the Kyiv School of Economics, which provided support for this collaboration.



# The Multicommodity International Trade Model



The network topology is denoted by the graph  $G = [N, L]$ , where  $N$  is the set of nodes,  $L$  is the set of links, and  $P$  is the set of paths. There are  $H$  commodities, with a typical one denoted by  $h$ .

# The Multicommodity International Trade Model

Each path  $p$  represents a trade route. Intermediate nodes in the network, which are transit points, also correspond to countries.

Let  $P_{ij}$  denote the set of paths connecting the pair of origin/destination country nodes  $(i, j)$ . The paths are acyclic.

A typical link is denoted by  $a$  and represents transport from a country node at which the link originates to the node denoting the country at which the link terminates.

**A trade route can entail transportation through multiple countries, depending on the application, and via different modes, such as rail, truck, air, or water (sea, river, etc.).**

# The Exchange Rates

Associated with each link  $a \in L$  is an exchange rate  $e_a$ , reflecting the exchange rate from the country (node) that the link emanates from to the country (node) that it terminates in.

Also, associated with each pair of origin/destination countries  $(i, j)$  is the exchange rate  $e_{ij}$  for  $i = 1, \dots, m; j = 1, \dots, n$ .

# The Trade Policies

There is a nonnegative subsidy associated with commodity  $h$  and imposed by the government in country  $i$ , which is denoted by  $sub_i^h$  for  $h = 1, \dots, H$ ;  $i = 1, \dots, m$ .

The unit tariff levied by country  $j$  on commodity  $h$  from country  $i$  is denoted by  $\tau_{ij}^h$  for  $h = 1, \dots, H$ ;  $i = 1, \dots, m$ ;  $j = 1, \dots, n$ .

Tariffs within a country are not imposed; hence,  $\tau_{ii}^h = 0$ ,  $\forall i$ ,  $\forall h$ .

In addition, there are capacities, which can represent quotas, where  $\bar{Q}_p^h$ ;  $h = 1, \dots, H$ ;  $p \in P$ , denotes the bound on the commodity shipment of commodity  $h$  on path  $p$ .

# Variables and Constraints

All commodity path flows, for all commodities  $h$ , and all paths  $p$ , must be nonnegative:

$$Q_p^h \geq 0, \quad \forall h, \forall p \in P. \quad (1)$$

The flow on a link  $a$  of commodity  $h$ , in turn, is equal to the sum of the path flows of the commodity  $h$  that use the link:

$$f_a^h = \sum_{p \in P} Q_p^h \delta_{ap}, \quad \forall h, \forall a \in L. \quad (2)$$

where  $\delta_{ap} = 1$ , if link  $a$  is contained in path  $p$ , and is 0, otherwise.

# Variables and Constraints

The supply of commodity  $h$  produced in country  $i$ ,  $s_i^h$ , is equal to the shipments of the commodity from the country to all destination countries:

$$s_i^h = \sum_{p \in P^i} Q_p^h, \quad h = 1, \dots, H; i = 1, \dots, m, \quad (3)$$

whereas the demand for commodity  $h$  in country  $j$ ,  $d_j^h$ , is equal to the shipments of the commodity from all origin countries to that country:

$$d_j^h = \sum_{p \in P_j} Q_p^h, \quad h = 1, \dots, H; j = 1, \dots, n. \quad (4)$$

$Q \in R_+^{np}$  is the vector of commodity shipments with  $s \in R_+^{Hm}$  being the vector of commodity supplies and  $d \in R_+^{Hn}$  being the vector of commodity demands.



# Supply Price Functions

The supply price function for commodity  $h$  of country  $i$  is denoted by  $\pi_i^h$  and we have that:

$$\pi_i^h = \pi_i^h(s), \quad h = 1, \dots, H; i = 1, \dots, m. \quad (5a)$$

With notice of the conservation of flow equations (3), we may define new supply price functions  $\tilde{\pi}_i^h$ ;  $h = 1, \dots, H$ ;  $i = 1, \dots, m$ , such that

$$\tilde{\pi}_i^h(Q) \equiv \pi_i^h(s). \quad (5b)$$

# Demand Price Functions

The demand price functions, in turn, are:

$$\rho_j^h = \rho_j^h(d), \quad h = 1, \dots, H; j = 1, \dots, n, \quad (6a)$$

where  $\rho_j^h$  denotes the demand price for commodity  $h$  in country  $j$ . Making use now of conservation of flow equations (4), we construct equivalent demand price functions  $\tilde{\rho}_j^h$ ;  $h = 1, \dots, H$ ;  $j = 1, \dots, n$ , as follows:

$$\tilde{\rho}_j^h(Q) \equiv \rho_j^h(d). \quad (6b)$$

# Transportation Cost Functions

With each link  $a \in L$ , and commodity  $h$ , we associate a unit transportation cost  $c_a^h$  such that

$$c_a^h = c_a^h(f), \quad \forall h, \forall a \in L. \quad (7a)$$

Because of the conservation of flow equations (2), we can define link unit transportation cost functions  $\tilde{c}_a^h(Q)$ ,  $\forall a \in L$ ,  $\forall h$ , as:

$$\tilde{c}_a^h(Q) \equiv c_a^h(f). \quad (7b)$$

# The Effective Exchange Rate

Observe that, in order to appropriately quantify the effective transportation cost on a link  $a$  for a commodity  $h$ , if a commodity makes use of the link on a path from an origin country node to a destination country node, one needs to calculate the effective exchange rate associated with the commodity on link  $a$  being transported onward on path  $p$ , which is denoted by  $e_a^p$ . Note that  $e_a^p$  is the product of the exchange rates on the links on path  $p$  that include and follow link  $a$  on that path, and is given by:

$$e_a^p \equiv \begin{cases} \prod_{b \in \{a' \geq a\}_p} e_b, & \text{if } \{a' \geq a\}_p \neq \emptyset, \\ 0, & \text{if } \{a' \geq a\}_p = \emptyset, \end{cases} \quad (8)$$

where  $\{a' \geq a\}_p$  denotes the set of the links including and following link  $a$  in path  $p$ , and  $\emptyset$  denotes the null set.

# The Effective Transportation Cost

The true transportation cost then on link  $a$ ,  $a \in L$ , for commodity  $h$ ;  $h = 1, \dots, H$ , when it is used in a path  $p$ , is given by the expression:

$$\tilde{c}_a^{hp} = \tilde{c}_a^h(Q) e_a^p. \quad (9)$$

The effective transportation cost on a path,  $\tilde{C}_p^h$ ,  $\forall p \in P$ , for commodity  $h$ ;  $h = 1, \dots, H$ , is then calculated as:

$$\tilde{C}_p^h = \sum_{a \in L} \tilde{c}_a^{hp} \delta_{ap}; \quad (10)$$

that is, the effective transportation cost on a path, which represents a trade route, is equal to the sum of the effective transportation costs for the commodity on links that make up the path.

# Equilibrium Conditions

## Definition 1: The Multicommodity International Trade Equilibrium Conditions

*A multicommodity path trade flow pattern  $Q^* \in R_+^{nP}$  is an international trade spatial price network equilibrium pattern under subsidies and tariffs with explicit exchange rates and capacities if the following conditions hold: For all pairs of country origin and destination nodes:  $(i, j)$ ;  $i = 1, \dots, m$ ;  $j = 1, \dots, n$ , and all paths  $p \in P_{ij}$  as well as all commodities  $h$ ;  $h = 1, \dots, H$ :*

$$(\tilde{\pi}_i^h(Q^*) - \text{sub}_i^h + \tau_{ij}^h) e_{ij} + \tilde{C}_p^h(Q^*) \begin{cases} \leq \tilde{\rho}_j^h(Q^*), & \text{if } Q_p^{h*} = \bar{Q}_p^h, \\ = \tilde{\rho}_j^h(Q^*), & \text{if } 0 < Q_p^{h*} < \bar{Q}_p^h, \\ \geq \tilde{\rho}_j^h(Q^*), & \text{if } Q_p^{h*} = 0. \end{cases} \quad (11)$$

# Variational Inequality Formulation and Existence

## Theorem 1: Variational Inequality Formulation of the Multicommodity International Trade Equilibrium Conditions

*A multicommodity path trade flow pattern  $Q^* \in K$ , where  $K \equiv \{Q | 0 \leq Q \leq \bar{Q}\}$  is a multicommodity international trade spatial price network equilibrium pattern with exchange rates and under subsidies and tariffs and capacities, according to Definition 1, if and only if it satisfies the variational inequality:*

$$\sum_{h=1}^H \sum_{i=1}^m \sum_{j=1}^n \sum_{p \in P_{ij}} \left[ (\tilde{\pi}_i^h(Q^*) - \text{sub}_i^h + \tau_{ij}^h) e_{ij} + \tilde{C}_p^h(Q^*) - \tilde{\rho}_j^h(Q^*) \right] \times \left[ Q_p^h - Q_p^{h*} \right] \geq 0, \quad \forall Q \in K. \quad (12)$$

**Existence of an equilibrium solution  $Q^*$  is guaranteed since the feasible set  $K$  is compact.**

# Variational Inequality Formulation

## Standard Form

Variational inequality (12) is now put into standard form (cf. Nagurney (1999)),  $VI(F, \mathcal{K})$ , where one seeks to determine a vector  $X^* \in \mathcal{K} \subset R^{\mathcal{N}}$ , such that

$$\langle F(X^*), X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{K}, \quad (13)$$

where  $F$  is a given continuous function from  $\mathcal{K}$  to  $R^{\mathcal{N}}$ ,  $\mathcal{K}$  is a given closed, convex set, and  $\langle \cdot, \cdot \rangle$  denotes the inner product in  $\mathcal{N}$ -dimensional Euclidean space.

Specifically, we define  $X \equiv Q$ ,  $\mathcal{K} \equiv K$ , and  $\mathcal{N} = Hn_P$ . Plus,  $F(X)$  consists of the elements

$F_p^h(X) \equiv \left[ (\tilde{\pi}_i^h(Q) - \text{sub}_i^h + \tau_{ij}^h) e_{ij} + \tilde{C}_p^h(Q) - \tilde{\rho}_j^h(Q) \right], \forall h, \forall i, j,$   
 $\forall p \in P_{ij}$ . Clearly, VI (12) can be put into standard form (13).

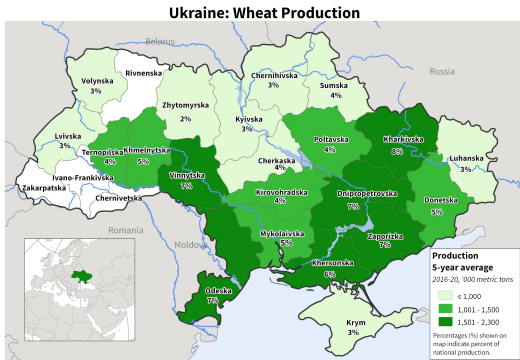


## Illustrative Examples

# Illustrative Examples

The examples focus on wheat commodity flows from Ukraine to Lebanon before and after the invasion of Ukraine by Russia on February 24, 2022.

The local currency codes are: UAH for Ukrainian hryvnia, MDL for the Moldovan leu, RON for the Romanian leu, LBP for the Lebanese pound, and USD for the United States dollar.



# Illustrative Examples

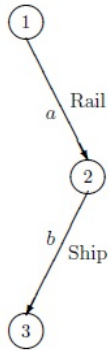
The unit of flow is a ton of wheat.

In these examples, there are no commodity path flow capacities.

These illustrative examples are stylized but, nevertheless, are grounded in real data.



# Example 1 - Pre-Invasion Scenario



The network topology for Illustrative Example 1 with nodes 1 and 2 representing Ukraine and node 3 corresponding to Lebanon. There is a single path  $p_1 = (a, b)$ , where link  $a$  corresponds to transport to the Black Sea ports via rail inside Ukraine, and link  $b$  represents maritime transport from the Black Sea ports to Lebanon.

## Example 1 - Pre-Invasion Scenario

The exchange rate data for Example 1 is drawn from early January 2022:

$$e_{13} = 55.0581, \quad e_a = 1.0000, \quad e_b = 55.0581.$$

The supply price function in Ukraine in hryvnia is:

$$\pi_1 = \pi_1(s_1) = .000136s_1 + 7,001.60.$$

The transportation cost functions in local currencies are:

$$c_a = c_a(f_a) = .000278f_a + 954.80, \quad c_b = c_b(f_b) = .000278f_b + 1,091.20.$$

The demand price function in Lebanon in Lebanese pounds is:

$$\rho_3 = \rho_3(d_3) = -.15d_3 + 602,344.00.$$

The effective exchange rates and the effective link costs are:

$$e_a^{p1} = e_a e_b = 55.0581, \quad e_b^{p1} = 55.0581,$$

$$\tilde{c}_a^{p1} = e_a^{p1} \tilde{c}_a = 55.0581 \tilde{c}_a, \quad \tilde{c}_b^{p1} = e_b^{p1} \tilde{c}_b = 55.0581 \tilde{c}_b.$$

## Example 1 - Pre-Invasion Scenario

The effective path cost on path  $p_1$  is:

$$\tilde{C}_{p_1} = \tilde{c}_a^{p_1} + \tilde{c}_b^{p_1}.$$

Applying the international trade spatial price equilibrium conditions (11), under the assumption of no tariff and no subsidy, and no quota, and assuming that  $Q_{p_1}^* > 0$ , we have that:

$$\tilde{\pi}_1(Q_{p_1}^*)e_{13} + \tilde{C}_{p_1}(Q_{p_1}^*) = \tilde{\rho}_3(Q_{p_1}^*),$$

which, in turn, reduces to:

$$.1881Q_{p_1}^* = 104,200.3344,$$

with solution:

$$Q_{p_1}^* = 553,962.4370.$$

**The 553,962.4370 tons of wheat flow is quite reasonable, since, in 2021, Lebanon imported 520,000 tons of wheat from Ukraine, and an even greater harvest was expected in 2022.**

## Example 1 - Pre-Invasion Scenario

The above wheat commodity flow pattern results in a supply and a demand of:

$$s_1^* = d_3^* = Q_{p_1}^* = 553,962.4370.$$

The supply and demand prices are:

$$\pi_1(s_1^*) = \tilde{\pi}_1(Q_{p_1}^*) = 7,076.9388 \text{ UAH} = \$257.7002,$$

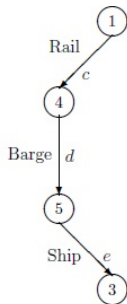
$$\rho_3(d_3^*) = \tilde{\rho}_3(Q_{p_1}^*) = 519,249.6344 \text{ LBP} = \$343.4190.$$

The incurred transportation costs are:

$$\tilde{c}_a = 1,108.8015 \text{ UAH} = \$40.3759, \quad \tilde{c}_b = 1,245.2015 \text{ UAH} = \$45.3428.$$

**The supply price of \$257.7002 per ton of wheat in Ukraine (at the farmer level) and the demand price of \$343.4190 in Lebanon are close to the reported prices in 2021. Farmers in Ukraine could get about \$270 per ton of wheat before the invasion. The transportation cost pre-invasion for a ton of wheat in Ukraine to a port was about \$40, as is the result in this example**

## Example 2 - Invasion Scenario



**In Example 2, we consider the invasion scenario after February 24, 2022, but before the Black Sea Grain Initiative, which took effect in late July.** During this period, essentially no grain was shipped from Ukraine using a Black Sea route as in Example 1. There is a single path  $p_2 = (c, d, e)$ . Nodes 1, 3, 4, and 5 denote Ukraine, Lebanon, Moldova, and Romania, respectively.



## Example 2 - Invasion Scenario

The exchange rates for Example 2 are obtained from early July; that is, after the invasion but before the Black Sea Grain Initiative:

$$e_{13} = 51.6836, \quad e_c = .6528, \quad e_d = .2523, \quad e_e = 313.6980,$$

The exchange rates were essentially the same on July 20, 2022.

The supply price function in Ukraine in hryvnia is:

$$\pi_1(s) = \pi_1(s_1) = .002673s_1 + 2,806.30.$$

**The difference in supply price function compared to the function in Example 1 is due to the damages because of the war.**

## Example 2 - Invasion Scenario

The transportation cost functions in local currencies are:

$$c_c = .002768f_c + 6,546.50, \quad c_d = .002172f_d + 2,324.60, \quad c_e = .000257f_e + 345.40.$$

**The difference in the cost function on link  $c$  in this example and the cost function on link  $a$  in Example 1, with both entailing rail transportation in Ukraine, is due to the different rail gauges used in Ukraine and Moldova, which necessitates including loading and unloading costs. Loading and unloading costs are also accounted for in the cost function on link  $d$ .**

The demand price function in Lebanon in Lebanese pounds is:

$$\rho_3(d) = \rho_3(d_3) = -.17d_3 + 793,747.50.$$

**Note that due to the food security issues in Lebanon and concerns over the availability of Ukrainian wheat because of the war, the demand price function is different from the one in Example 1.**

## Example 2 - Invasion Scenario

According to the international trade spatial price equilibrium conditions (11), and assuming that  $Q_{p_2}^* > 0$ , we have that:

$$\tilde{\pi}_1(Q_{p_2}^*)e_{13} + \tilde{C}_{p_2}(Q_{p_2}^*) = \tilde{\rho}_3(Q_{p_2}^*),$$

the solution of which yields:

$$Q_{p_2}^* = 25,780.2589.$$

**The wheat flow of 25,780.2589 tons is reasonable since, without access to deep-sea ports on the Black Sea, Ukraine can, at most, export around 10% of what it used to.**

This commodity flow results in a supply and a demand of:

$$s_1^* = d_3^* = Q_{p_2}^* = 25,780.2589.$$

## Example 2 - Invasion Scenario

The supply and demand prices are:

$$\pi_1(s_1^*) = \tilde{\pi}_1(Q^*) = 2,875.2106 \text{ UAH} = \$98.2813,$$

$$\rho_3(d_3^*) = \tilde{\rho}_3(Q^*) = 789,364.8559 \text{ LBP} = \$522.0667.$$

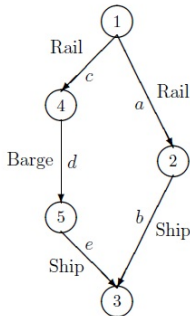
The incurred transportation link costs are:

$$\tilde{c}_c = 6,617.8597 \text{ UAH} = \$226.2137, \quad \tilde{c}_d = 2,380.5947 \text{ MDL} = \$124.6358$$

$$\tilde{c}_e = 352.0255 \text{ RON} = \$73.0358.$$

**The transportation cost of grain inside Ukraine has jumped to about \$200. Furthermore, because of the ongoing war, Ukrainian farmers are earning approximately \$100 per ton of wheat, which is similar to the supply price of \$98.2813 in this example. Moreover, with the continuing food crisis in Lebanon, and, as a result of the war, the price of wheat in Lebanon has gone up to more than \$500 per ton.**

## Example 3 - Black Sea Grain Initiative in Place



**The network topology for Example 3, where we consider the post-July 22 Black Sea Grain Initiative scenario with maritime transportation from several of the Ukrainian Black Sea ports being, again, possible.** In the network above, the nodes and the links correspond to the same countries and modes of transportation as in Examples 1 and 2.

## Example 3 - Black Sea Grain Initiative in Place

The exchange rates on links are from late August; that is, after the Black Sea Grain Initiative:

$$e_a = 1.0000, \quad e_b = 41.3469, \quad e_c = .5291,$$

$$e_d = .2521, \quad e_e = 309.8670, \quad e_{13} = 41.3469.$$

The exchange rates were essentially the same on July 22, 2022.

The supply price function in Ukrainian hryvnia is now:

$$\pi_1(s) = \pi_1(s_1) = .000167s_1 + 3,364.60.$$

**Observe that due to the damages by the ongoing war, the supply price function, again, changes from the ones in Examples 1 and 2.**

## Example 3 - Black Sea Grain Initiative in Place

The transportation cost functions in local currencies are:

$$c_a = .000217f_a + 7,144.80, \quad c_b = .000246f_b + 7,423.10,$$

$$c_c = .003284f_c + 8,304.80, \quad c_d = .003097f_d + 2,397.50,$$

$$c_e = .000428f_e + 361.20.$$

**The damages to the transportation infrastructure, and the congestion associated with products to be exported after the placement of the Black Sea Grain Initiative, result in different transportation cost functions from the previous examples.**

The demand price function in Lebanese pounds is:

$$\rho_3(d) = \rho_3(d_3) = -.082d_3 + 796,162.50.$$

**The demand price function is different from Example 2, which is in correspondence to the food security issues in Lebanon.**

## Example 3 - Black Sea Grain Initiative in Place

The equilibrium conditions (11) are, for this example, assuming positive commodity shipments:

$$\tilde{\pi}_1(Q^*)e_{13} + \tilde{C}_{p_1}(Q_{p_1}^*) = \tilde{\rho}_3(Q^*), \quad \tilde{\pi}_1(Q^*)e_{13} + \tilde{C}_{p_2}(Q_{p_2}^*) = \tilde{\rho}_3(Q^*).$$

The solution of the above system of equations yields a negative path flow on path  $p_2$ , which is infeasible. Therefore, path  $p_2$  is not used. Then, one has that:  $Q_{p_1}^* = 506,566.8120$  and  $Q_{p_2}^* = 0.0000$ , with the commodity flows, again, in tons.

**The supply is similar to what Ukraine used to export to Lebanon pre-war. With the availability of maritime transportation from Ukraine on the Black Sea, the wheat flow on path  $p_2$  is at 0.0000, which is due to the inefficiency of transporting the grain to a Middle Eastern country by such a route and composition of modes.**



## Example 3 - Black Sea Grain Initiative in Place

This wheat commodity flow pattern results in the following supply and demand:

$$s_1^* = d_3^* = Q_{p_1}^* + Q_{p_2}^* = 506,566.8120,$$

with the supply and demand prices per ton now being:

$$\pi_1(s_1^*) = \tilde{\pi}_1(Q^*) = 3,449.1966 \text{ UAH} = \$94.3212,$$

$$\rho_3(d_3^*) = \tilde{\rho}_3(Q^*) = 754,624.0214 \text{ LBP} = \$499.0899.$$

The incurred transportation costs are:

$$\tilde{c}_a = 7,254.7249 \text{ UAH} = \$198.3867, \quad \tilde{c}_b = 7,547.7154 \text{ UAH} = \$206.3988,$$

$$\tilde{c}_c = 8,304.8000 \text{ UAH} = \$227.1019, \quad \tilde{c}_d = 2,397.5000 \text{ MDL} = \$123.9018,$$

$$\tilde{c}_e = 361.2000 \text{ RON} = \$74.0245.$$

**Although the initiative has facilitated the transportation of wheat, the war, and nearly full storage have kept the prices high. The supply price at \$94.3212 and the demand price at \$499.0899, along with the \$206.3988 transportation cost on link *b*, reflect these issues and are preventing the demand**

## Example 4 - Example 3 Data with Subsidy

In Example 4, we, again, consider the post-July 22 Black Sea Grain Initiative scenario with maritime transportation via the Black Sea from Ukraine possible; however, a subsidy is introduced in this example, and the impact is quantified. We consider the effect of the subsidy  $sub_1 = 1,000.00$  in hryvnia on Ukrainian wheat shipped to Lebanon:

**In the solution of this example, again, only path  $p_1$  is used, and one has that:  $Q_{p_1}^* = 889,408.4787$  and  $Q_{p_2}^* = 0.0000$ .**

This wheat commodity flow pattern results in the following supply and demand:

$$s_1^* = d_3^* = Q_{p_1}^* + Q_{p_2}^* = 889,408.4787,$$

with the following supply and demand prices:

$$\pi_1(s_1^*) = \tilde{\pi}_1(Q^*) = 3,513.1312 \text{ UAH} = \$96.0696,$$

$$\rho_3(d_3^*) = \tilde{\rho}_3(Q^*) = 723,231.0047 \text{ LBP} = \$478.3273.$$

## Example 4 - Example 3 Data with Subsidy

The incurred transportation costs are:

$$\tilde{c}_a = 7,337.8016 \text{ UAH} = \$200.6585, \tilde{c}_b = 7,641.8944 \text{ UAH} = \$208.9742,$$

$$\tilde{c}_c = 8,304.8000 \text{ UAH} = \$227.1019, \tilde{c}_d = 2,397.5000 \text{ MDL} = \$123.9018$$

$$\tilde{c}_e = 361.2000 \text{ RON} = \$74.0245.$$

**The subsidy increases the quantity of wheat shipment, and increases the price that farmers can expect to get for a ton of wheat to \$96.0696, which is of value as the current low supply prices threaten the farmers' ability to buy seed and equipment for the next harvest season.**

**The subsidy also helps to reduce the demand price to \$478.3273, which can be of significant importance in countering the food crisis and associated food insecurity in Lebanon.**

- **The importance of having alternative routes in countering disruptions and congestion** is evident in our examples.
- The results strongly confirm **the need for efficient transportation routes for trade**, as, for example, for the export of grain via maritime transport from the Black Sea ports in the case of Ukraine.
- The examples show the **benefits of subsidies for agricultural trade for both farmers and consumers**.
- **The impact of the exchange rates on the grain commodity flows and on producer and consumer prices are revealed** in the examples for different periods: pre-invasion, following the invasion, and after the Black Sea Grain Initiative.
- **The examples demonstrate the importance of the Ukrainian grain, and its relevance to global food security.**

**A. Nagurney and E. Besedina, “A Multicommodity Spatial Price Equilibrium Model with Exchange Rate and Non-Tariff Measures,”** *Operations Research Forum* 4, Article number 84 (2023).

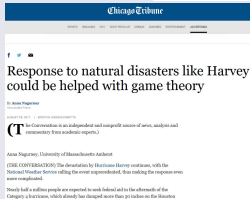
**A. Nagurney, “Food Security and Multicommodity Agricultural International Trade: Quantifying Optimal Consumer Subsidies for Nutritional Needs,”** *International Transactions in Operations Research* 31(3) (2024), pp 1375-1396.

**A. Nagurney, D. Hassani, O. Nivievskiy, and P. Martyshev, “Multicommodity International Agricultural Trade Network Equilibrium: Competition for Limited Production and Transportation Capacity under Disaster Scenarios with Implications for Food Security,”** *European Journal of Operational Research* 314(1) (2024), pp 1127-1142.

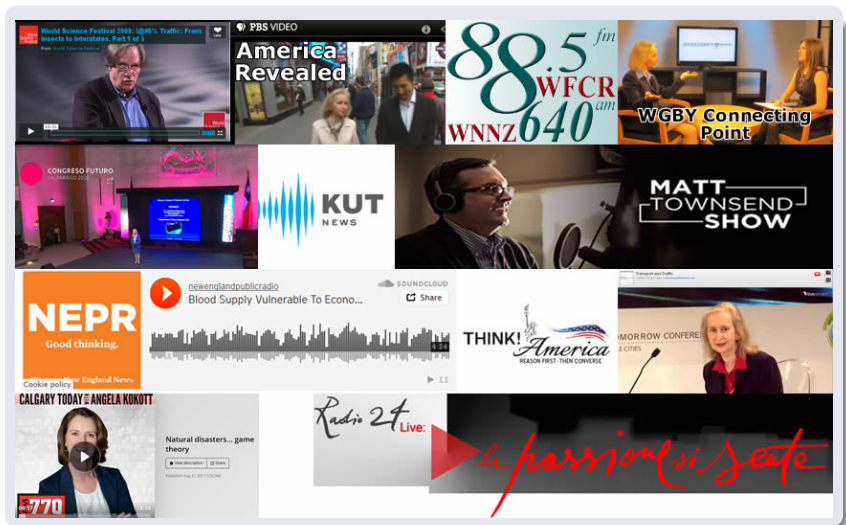
**O. Nivievskiy and A. Nagurney, “Ukraine – Addressing the domestic humanitarian crisis and the effects of the war on global food systems,”** in *Food and Humanitarian Crises: Science and Policies for Prevention and Mitigation Proceedings of the Working Group*, J. von Braun, B. Iseli, M. Torero, P. Turkson, Editors, Scripta Varia 154, LEV, Vatican City, 2024.

# Making a Positive Impact

# Writing OpEds



# 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 6:00am EDT



Read  
Twitter  
Facebook  
LinkedIn  
Print

The coronavirus, which causes the disease COVID-19, has created enormous anxiety, uncertainty, and disruption to our lives. Much has already been written about potential shortages of medicines and face masks, but little has been said about something only you and I can provide – lifesaving blood.

Our nation's blood supply is essential to our health care security. Blood transfusions are integral parts of major surgeries. Blood is used in the treatment of diseases, particularly sickle cell anemia and some cancers. Blood is needed for victims who have injuries caused by accidents or natural disasters. Every day, the U.S. needs 36,000 units of red blood cells, 7,000 units of platelets, and 10,000 units of plasma.

I am a professor and director of the Virtual Center for Supernetworks at the University of Massachusetts Amherst. Because of the escalating coronavirus health care crisis, I am deeply concerned the U.S. blood supply chain is under stress. The timing could hardly be worse; the COVID-19 outbreak coincides with our seasonal flu and colds.

Patients need blood in many states

Analytics  
INFORMS

March 24, 2020 in Coronavirus Chronicles

## The COVID-19 Pandemic and the Stressed Blood Supply Chain

By Anna Nagurney

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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 (OR) because it requires

# Writing OpEds in the Pandemic

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

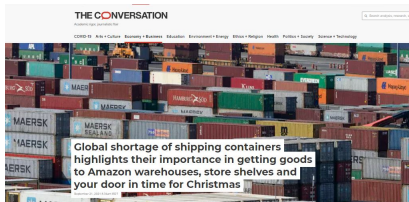
**“The Raging Competition for Medical Supplies is not a Game, but Game Theory Can Help.”**



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 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*.

On September 21, 2021, my article,

**“Global Shortage of Shipping Containers Highlights Their Importance in Getting Goods to Amazon Warehouses, Store Shelves and Your Door in Time for Christmas,”** appeared in *The Conversation*. It has had over 330,000 reads.

# Writings After the Full-Scale Invasion



## Ukraine's Students

TO THE EDITOR:

Re "For Children of War, a Time for Play" (news article and photo essay, Aug. 8):

As children, their families and teachers get excited about the new school year throughout the world, it is imperative



OTHER VIEWS COMMENTARY

## Ukraine will need 'Marshall Plan' to address human toll of war

C6 | THURSDAY, MAY 11, 2023

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### OPINION

#### LETTERS TO THE EDITOR

## Scholars from Ukraine, UMass find common ground

# Some of My Media Interviews in the Pandemic



# Some of the Media Interviews on the War on Ukraine

## Economic dangers from Russia's invasion ripple across globe

By PAUL WISEMAN and DAVID MCHUGH March 2, 2022



Feedstuffs went live.

March 16 at 2:00 p.m.

The war in Ukraine is no longer just a story about a conflict between nations. It's having an immedi...

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Anna Nagurney with John Moore



The John Batchelor Show

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## Russian war in world's 'breadbasket' threatens food supply

By JOSEPH WILSON, SAMY MAGDOY, AYA BATRAWY and CHINEDU ASADU March 6, 2022

## 'I fear a cultural genocide'; Ukrainians in Western Mass. watch, worry and help

Published: Feb. 28, 2022, 5:55 p.m.

## Threat of Russian cyber attacks likely for not just Ukraine, but also in the US

## No Ikea Shelves, No Levis: The Retail Exodus From Russia Is On

Since the invasion of Ukraine began, the increasing financial and reputational risks of doing business in Russia are leading Western brands to halt operations.

## Russian Sanctions Snarl Shipping Even as Pandemic Pressure Eases

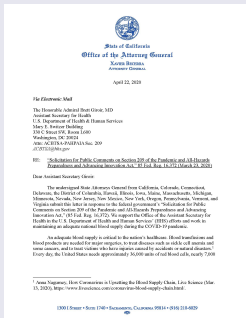


March 11, 2022

Liz Alderman and Jerry Gross

**On April 22, 2020, a letter from California Attorney General Xavier Becerra to 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 March 2020 article in *The Conversation*, which was reprinted in LiveScience, was the first reference and was cited on the first page.**




Xavier Becerra, then CA Attorney General, is now Secretary of Health and Human Services in the United States!


Plus, Maura Healey, who was then the MA Attorney General is now the Governor of Massachusetts



# Thank You Very Much!




## The Virtual Center for Supernetworks



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

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Student Chapter Event with KSE  
Exchange Students from Ukraine**

**The Virtual Center for Supernetworks** is an interdisciplinary center at the Isenberg School of Management that advances knowledge on large-scale networks and integrates operations research and management science, engineering, and economics. Its Director is Dr. Anna Nagurney, the Eugene M. Isenberg Chair in Integrative Studies.


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

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**Professor Anna Nagurney**

Updated: March 16, 2024

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