Agricultural Supply Chain Networks: From Trade to Resilience and How OR Can Help

Professor Anna Nagurney

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

IFORS 2023, July 10-14, Santiago, Chile



Professor Anna Nagurney OR a

I'd like to thank IFORS and the organizers of this conference in Santiago for the invitation to deliver this keynote.



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

周下 イヨト イヨト

= 990

Background and Motivation

Professor Anna Nagurney OR and Supply Chains

Image: A mathematical states and a mathem

< E ▶ E

I Work on the Modeling of Network Systems



Professor Anna Nagurney OR and Supply Chains

イロト イヨト イヨト イヨト

臣

Much of My Recent Research Has Been on Supply Chains



590

< A > < E

► 4 3 ×



Professor Anna Nagurney OR and Supply Chains

イロト イヨト イヨト イヨト

臣

DQC

International Trade

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



Professor Anna Nagurney

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.



Professor Anna Nagurney

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.

 SPRINGER BRIEFS IN OPTIMIZATION	
Anna Nagurney Min Yu Amir H. Macoumi	
 Ladimer S. Nagurney	
Networks Against	
 Time	
 Supply Chain	
 Analytics for	
Perishable	
 Products	
🖄 Springer	

Food Supply Chains and Disruptions

Professor Anna Nagurney OR and Supply Chains

< (10) > < 3 =

▲ 문 ▶ 문

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:

- captures the deterioration of fresh food along the entire supply chain from a network perspective;
- handles the time decay through the introduction of arc multipliers;
- formulates oligopolistic competition with product differentiation;
- includes the disposal of the spoiled food products, along with the associated costs;
- allows for the assessment of alternative technologies involved in each supply chain activity.

M. Yu and A. Nagurney, "Competitive Food Supply Chain Networks with Application to Fresh Produce," European Journal of Operational Research 224(2) (2013), pp 273-282.

DQA

Fresh Produce Food Supply Chains



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.

nan

Food Supply Chain Disruptions Due to COVID-19



Food Insecurity

According to The New York Times magazine, Sept. 6, 2020:



A shadow of hunger looms over the United States. In the pandemic economy, nearly one in eight households (more than 42 million people, including 13 million children) doesn't have enough to eat. The lockdown, with its epic lines at food banks, has revealed what was hidden in plain sight: that the struggle to make food last long enough, and to get food that's healthful - what experts call 'food insecurity' - is a persistent one for millions of Americans.

Perishable Food Supply Chain Network Model with Labor

"Perishable Food Supply Chain Networks with Labor in the Covid-19 Pandemic," A. Nagurney, in: Dynamics of Disasters -Impact, Risk, Resilience, and Solutions, I.S. Kotsireas, A. Nagurney, P.M. Pardalos, and A. Tsokas, Editors, Springer Nature Switzerland AG, 2021, pp 173-193.



Professor Anna Nagurney

• 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.

・ 同 ト ・ ヨ ト ・ ヨ ト

Our findings include:

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

Game Theory Supply Chain Network Modeling with Labor

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.



OR and Supply Chains

・ロト ・回ト ・ヨト・

Game Theory Supply Chain Network Model with Labor



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

▲□ ▶ ▲ □ ▶ ▲ □ ▶

臣

DQC

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!

< E ▶ E



◆□ ▶ ◆□ ▶ ◆ □ ▶ ◆ □ ▶ ●

Ð,

International Agricultural Trade and Disasters

Professor Anna Nagurney OR and Supply Chains

Э

< 三 ▶ …

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.



< A > < E

- 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.



OR and Supply Chains

イロン 不同 とうほどう ほどう

- 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.



Professor Anna Nagurney

- With the major earthquake and aftershock striking Turkey and Syria in February 2023, the FAO is assessing their effects on the agricultural sector in both countries.
- In Turkey, the early estimate is approximately a 1% decrease in its GDP due to the damages to the agricultural sector.
- More than 4 million people in northern parts of Syria have already been identified as being food insecure.



Professor Anna Nagurney

- The Horn of Africa is now experiencing its worst drought recorded in modern history. The ongoing dry spell has caused food insecurity for 21 million people in the region.
- From July to December 2022, the number of children facing severe food insecurity in the Horn of Africa region doubled from 10 million to more than 20 million.
- The high food prices caused by COVID-19, climate change, and the shortage of grains due to the ongoing war in Ukraine have further complicated the disastrous situation in the region.



Professor Anna Nagurney

Trade Policies and Exchange Rates

Professor Anna Nagurney OR and Supply Chains

A (10) > (10)

æ

International Trade and Policies

- Nations engage in trade to increase their productivity levels, employment rates, and general economic welfare.
- The increased level of world trade and competition has garnered the attention of government policy makers.
- Trade policy instruments such as tariffs, subsidies, and quotas have become highly relevant as the world continues to battle the impacts of the COVID-19 pandemic and millions on the planet suffer from hunger and growing food insecurity.



Examples of policy instruments that have been applied by governments to modify trade patterns included: 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.


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



・ロ・・ 日本・ キョ・・

DQC

ł

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



・ 同 ト ・ ヨ ト ・ ヨ ト

臣

590

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.



DQC

ł

イロト イポト イヨト イヨト

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.



イロト イポト イヨト イヨト

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.



イロト イポト イヨト イヨト

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.

Image: A mathematical states and a mathem

Exchange Rates

• The US dollar has gotten stronger over the past year, with the greatest rate of increase occurring since the Russian invasion of Ukraine on February 24, 2022, with the war still ongoing.

• 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

Professor Anna Nagurney OR and Supply Chains

₹ Ξ → Ξ

F 4

590

A Model, Hot Off the Press

A. Nagurney, D. Hassani, O. Nivievskyi, 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* 2023.

®		
Court to unline		
exchange rates and multicommodity international trade:		
instruments via variational inequalities		
interest of the variational integrations		
Anna Nagurney ¹ O - Dana Hassani ¹ - Oleg Nivievskyi ² - Pavlo Martyshev ²		
Received 29 December 2022 / Accepted: 2 May 2023		
 Ine Autor) j, under exclusive scance-to springer scance-futures weeks, CC, part of springer Nature 2023 		
Abstract		
In this paper, we construct a multicommodity international trade spatial price equilibrium model of spacial relevance to assistivations in which exchange rates are included above with		
policy instruments in the form of tariffs, subsidies as well as quotas. The model allows for		
multiple trade routes between country origin nodes and country destination nodes and these		
trade routes can include different modes of transportation and transport through distinct coun- triar. We continue the instructs of antibasea rotes through the definition of affective and, contr		
and identify the overring multicommodity international indestratial price equilibrium con-		
ditions, which are then formulated as a variational inequality problem in product path flows.		
Existence results are established and a computational procedure presented. The illustrative numerical ensured as one and a case and a real inertial by the instants of the nur analysis Ultraine.		
on agricultural trade flows and product prices. The modeling and algorithmic framework		
allows for the quantification of the impacts of exchange rates and various trade policies, as		
well as the addition or deletion of supply markets, demand markets and/or routes, on supply and demand markets minute in head any second and an observed and/or routes, on supply		
implications for food security.		
Keywords: Exchange rates - Spatial price equilibrium - International trade - Networks -		
Variational inequalities - Agriculture		
1 Introduction		
Eachange 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 assecting the decision-making of monvatian, businesses, and governments. A separate		
70° Anna Namanari		
ng mey @ischerg.muss.edu		
¹ Department of Operations and Information Management, Deuberg School of Management, University of Manachusette, Applevel. MA (2003), 1283.		
² Center for Food and Land Use Research, Kylv School of Economics, Mykoly Shpaka St. 3, Kylv 02000.	 _	
1000		

OR and Supply Chains

590

-> -< ≣ >

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.



The authors 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.

DQC

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.).

・ 同 ト ・ ヨ ト ・ ヨ ト

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, ..., m; j = 1, ..., n.

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, ..., H; i = 1, ..., m.

The unit tariff levied by country j on commodity h from country i is denoted by τ_{ij}^{h} for h = 1, ..., H; i = 1, ..., m; j = 1, ..., 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} ; $h = 1, \ldots, H$; $p \in P$, denotes the bound on the commodity shipment of commodity h on path p.

▲御▶ ▲ 臣▶ ▲ 臣▶

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

$$Q^h_p \ge 0, \quad \forall h, \forall p \in P.$$
 (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:

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

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

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:

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

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

 $Q \in R_+^{n_P}$ 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.

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

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

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

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

The demand price functions, in turn, are:

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

where ρ_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 $\tilde{\rho}_j^h$; $h = 1, \ldots, H$; $j = 1, \ldots, n$, as follows:

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

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

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

$$\tilde{c}^h_a(Q) \equiv c^h_a(f). \tag{7b}$$

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:

$$e_{a}^{p} \equiv \begin{cases} \prod_{b \in \{a' \ge a\}_{p}} e_{b}, & \text{if } \{a' \ge a\}_{p} \neq \emptyset, \\ 0, & \text{if } \{a' \ge a\}_{p} = \emptyset, \end{cases}$$
(8)

• (1) • (2) • (3) • (3) • (3)

æ

590

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

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

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

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

$$\tilde{C}^{h}_{\rho} = \sum_{a \in L} \tilde{c}^{hp}_{a} \delta_{ap}; \qquad (10)$$

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.

Definition 1: The Multicommodity International Trade Equilibrium Conditions

A multicommodity path trade flow pattern $Q^* \in R_+^{n_P}$ 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, ..., m; j = 1, ..., n, and all paths $p \in P_{ij}$ as well as all commodities h; h = 1, ..., H:

$$(\tilde{\pi}_{i}^{h}(Q^{*}) - sub_{i}^{h} + \tau_{ij}^{h})e_{ij} + \tilde{C}_{p}^{h}(Q^{*}) \begin{cases} \leq \tilde{\rho}_{j}^{h}(Q^{*}), & \text{if } Q_{p}^{h*} = \bar{Q}_{p}^{h}, \\ = \tilde{\rho}_{j}^{h}(Q^{*}), & \text{if } 0 < Q_{p}^{h*} < \bar{Q}_{p}^{h}, \\ \geq \tilde{\rho}_{j}^{h}(Q^{*}), & \text{if } Q_{p}^{h*} = 0. \end{cases}$$

$$(11)$$

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 $K \equiv \{Q|0 \le Q \le \overline{Q}\}$ 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:

$$\sum_{h=1}^{H} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{p \in P_{ij}} \left[(\tilde{\pi}_{i}^{h}(Q^{*}) - sub_{i}^{h} + \tau_{ij}^{h})e_{ij} + \tilde{C}_{p}^{h}(Q^{*}) - \tilde{\rho}_{j}^{h}(Q^{*}) \right]$$

$$\times \left[Q_p^h - Q_p^{h*} \right] \ge 0, \quad \forall Q \in K.$$
(12)

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

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

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

< 回 > < 三 > < 三

where F is a given continuous function from \mathcal{K} to $\mathbb{R}^{\mathcal{N}}$, \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 $F_p^h(X) \equiv \left[(\tilde{\pi}_i^h(Q) - sub_i^h + \tau_{ij}^h)e_{ij} + \tilde{C}_p^h(Q) - \tilde{\rho}_j^h(Q) \right]$, $\forall h, \forall i, j, \forall p \in P_{ii}$. Clearly, VI (12) can be put into standard form (13).

Illustrative Examples

Professor Anna Nagurney OR and Supply Chains

▶ ★ Ē ▶

æ

590

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.





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.

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:

$$e_a^{p_1} = e_a e_b = 55.0581, \quad e_b^{p_1} = 55.0581,$$

$$\tilde{c}_{a}^{P_{1}} = e_{a}^{P_{1}}\tilde{c}_{a} = 55.0581\tilde{c}_{a}, \quad \tilde{c}_{b}^{P_{1}} = e_{b}^{P_{1}}\tilde{c}_{b} = 55.0581\tilde{c}_{b} \Rightarrow \Rightarrow \circ \circ \circ$$

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:

$$ilde{\pi}_1(Q_{
ho_1}^*)e_{13}+ ilde{C}_{
ho_1}(Q_{
ho_1}^*)= ilde{
ho}_3(Q_{
ho_1}^*),$$

which, in turn, reduces to:

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

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 = -2000

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

500



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. 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.

・ 回 ト ・ ヨ ト ・ ヨ ト …

5990
Example 2 - Invasion Scenario

The transportation cost functions in local currencies are:

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

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.

DQC

Example 2 - Invasion Scenario

According to the international trade spatial price equilibrium conditions (11), and assuming that $Q_{\rho_2}^* > 0$, we have that:

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

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:

 $\tilde{c}_c = 6,617.8597$ UAH = \$226.2137, $\tilde{c}_d = 2,380.5947$ 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, and, as a result of the supply price of ton, and a supply to more than \$500 per ton.



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.

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.

向下 イヨト イヨト

The transportation cost functions in local currencies are:

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

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

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

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:

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

DQR

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

$$ilde{\pi}_1(Q^*)e_{13} + ilde{\mathcal{C}}_{
ho_1}(Q^*_{
ho_1}) = ilde{
ho}_3(Q^*), \quad ilde{\pi}_1(Q^*)e_{13} + ilde{\mathcal{C}}_{
ho_2}(Q^*_{
ho_2}) = ilde{
ho}_3(Q^*).$$

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.

(4月) トイヨト イヨト

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:

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

・回 とくほとくほとう

DQR

• 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.

イロト イヨト イヨト イヨト

• International trade of commodities is essential to both producers and consumers. Various recent events of historical significance, from the COVID-19 pandemic to Russia's war on Ukraine, have demonstrated the criticality of trade for the availability of various agricultural commodities.

• Our model allows for multiple routes for commodities from origin countries to destination countries, and these routes, in turn, can consist of multiple transportation links through different countries. We show how exchange rates affect costs on links and paths as well as supply prices, and formalize the definition of the multicommodity spatial price equilibrium with exchange rates and under policies such as tariffs, subsidies, and quotas on commodity path flows.

< ∃⇒

• The governing equilibrium conditions are formulated as a variational inequality problem in commodity path flows, and the existence of an equilibrium is established.

• The numerical examples, for which complete input and output data are reported in our paper, are drawn from Russia's war on Ukraine, both illustrative examples as well as larger-scale ones, which are solved using an implemented computational scheme.

• The flexibility of the modeling and algorithmic framework allows for quantitatively investigating the impacts of different scenarios with features of exchange rates plus various policies and the addition/deletion of markets and trade routes.

Making a Positive Impact

Professor Anna Nagurney OR and Supply Chains

イロト イヨト イヨト イヨト

æ

Writing OpEds



Professor Anna Nagurney

OR and Supply Chains

Coverage by the Media



イロト イヨト イヨト イヨト

臣

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*.



How coronavirus is upsetting the blood supply chain





- Twitter
- in anxiety, uncertainty, and disruption to our lives. Much has already been written
- a anxiety, uncertainty, and disruption to our lives. Much has aready been written
- about potential shortages of <u>medicines</u> and <u>face masks</u>, but itth about something only you and I can provide – lifesaving blood.

Our ration's blood supply is essential to our health care security. Blood transfluions are integral parts of major suggreich. Blood is used in the treatment of diseases, particularly siddle cell anemia and some cancers. Blood is needed for victims who have impuries cauced by accidents or anrantel diasaers. <u>Exercidag</u>, the U.S. needs 36,000 units of red blood cells. 7,000 units of plastets, and 10,000 units of plasters.

Lama professor and director of the Virtual Center for Supernetworks at the University of Massachusetts Amberds. Because of the scalating coronarium. health care credits I am deeply concerned the U.S. blood supply chain is under stress. The timing could landly be worse; the COVID-19 outbreak coincides with our vessional flux and colds.

Professor Anna Nagurney

Patients need blood in many states



The COVID-19 Pandemic and the Stressed Blood Supply Chain





Bloot is exercited to caracterize hardbackers executly. It is a 16-assing product that carent be meanufactured and comes salely from various data carent be assing a set of the set of the

Deen in the best of times, the complex blood supply chain in the United States is under stress. Although 20% of the U.S. populations insights to donate blood, have the trick statuly does not in a year. Parthermore, issues of associatily come into play with fu and colds exiting donations; the same for wardsarvaited events and holidays. To further complicate matters, blood is perishable, platelets last five days and red blood cells have a shell If of 42 days.

The block barries of the second secon

The critical blood supply chain is unique from others that we study in operations research (0.R.) because it requires

OR and Supply Chains

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



イロト イヨト イヨト イヨト

Some of My Media Interviews in the Pandemic



・ 同 ト ・ ヨ ト ・ ヨ ト

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





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



Anna Nagurney with John Moore

The John Batchelor Show

1/2: #Ukraine: The Kyiv School of Economics is open for business under fire. Paul Gregory @HooverInst @PaulR_Gregory. Anna Nagurney @Supernetworks University of Massachusetts. Paul Becker, Duke University

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

By JOSEPH WILSON, SAMY MAGDY, AVA 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 Jenny 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.

Impacting Policy



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

It's All About the People! Thank You to IFORS!



(1日) (1日) (1日) (1日)

DQC

ł

Thank You Very Much!



More information on our work can be found on the Supernetwork Center site: https://supernet.isenberg.umass.edu/

Professor Anna Nagurney OR and Supply Chains

Э

SOR