Modeling of COVID-19 Trade Measures on Essential Products: A Multiproduct, Multicountry Spatial Price Equilibrium Framework

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Abstract

In this paper, we develop a unified variational inequality framework in the context of spatial price network equilibrium problems that handles multiple products with multiple demand and supply markets in multiple countries as well as multiple transportation routes. The model incorporates a plethora of distinct trade measures, which is particularly important in the pandemic, as PPEs and other essential products are in high demand, but short in supply globally. In the model, product flows as well as prices at the supply markets and the demand markets in different countries are variables that allows us to seamlessly introduce various trade measures, including tariffs, quotas, as well as price floors and ceilings. Qualitative properties are analyzed. Numerical examples are provided to illustrate the impacts of the trade measures on equilibrium product path and link flows, and on prices, and demand and supply quantities. Given the relevance of the trade measures in the world today and discussions concerning the impacts, the framework constructed in this paper is especially timely.

Keywords: Covid-19; essential supplies; trade measures; spatial price equilibrium; networks

Outline

Introduction

- On **March 11, 2020**, the World Health Organization declared the novel coronavirus outbreak a pandemic.

- The **COVID-19 pandemic** plunged almost all countries into crisis quickly.

(FABRICE COFFRINI / Getty Images)

—AFP via Getty Images

(ABC News)

(AFP - Cindy Ord)

Introduction

- The pandemic has endangered and disrupted the lives of **billions around the world**.
- As of April 9, 2022, there have been more than **80 million cases** and **985,000 deaths** in the United States alone.

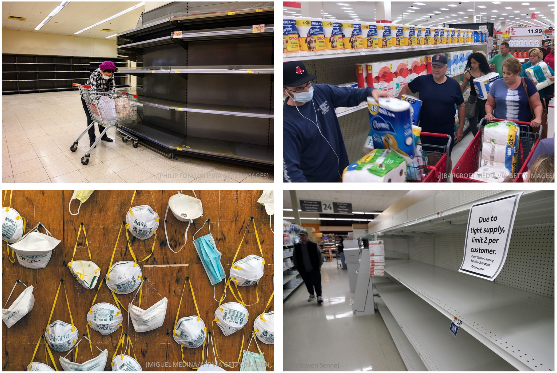
- The International Monetary Fund (IMF) warned about the severe impacts of the COVID-19 pandemic on **low-income families** and the fight against **poverty**.

Introduction

- One of the most effective ways in decreasing the spread of the virus is to use **Personal Protective Equipment (PPE)**.
- There has been a **sharp increase in demand** for medical supplies worldwide.
- **Intense competition** over items that had never before experienced such demand.
- The price of N95 masks grew from \$0.38 to \$5.75 each (a 1,413% increase).

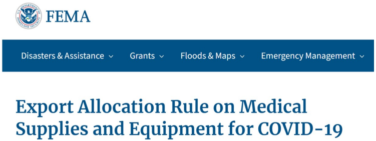
Introduction

- The WHO estimated that **production** of these items would have to **increase by 40 percent** to meet the demand.
- China historically has produced **half of the world's face masks**.
- To **increase production capacity**, Ford, General Motors, and Tesla dedicated their manufacturing facilities and capability to this effort.



Introduction

- Many **governments** instituted different **trade policies and measures** in order to **reduce** the risk of essential/vital product **shortages**.
- New **export bans** in more than 75 countries were issued on **medical supplies** such as antibiotics, face masks, and ventilators.



Introduction

- China **decreased import tariffs** on several types of products such as **medical supplies, raw materials, agricultural products, and meat**.
- The United States **excluded certain products** from the additional duty of 25% on a list of 19 products from China. Put **restrictions on exports** of five types of PPEs.
- Germany **banned the export** of PPEs.
- The European Competition Network issued a joint statement highlighting that it is very important that the **prices of the goods that are necessary** for the health of the people, **remain within the competitive range**.
- In India, the government tried to **control the price** of life-saving oxygen gas, but this policy was accompanied by shortcomings that led to the **emergence of the oxygen black market**.

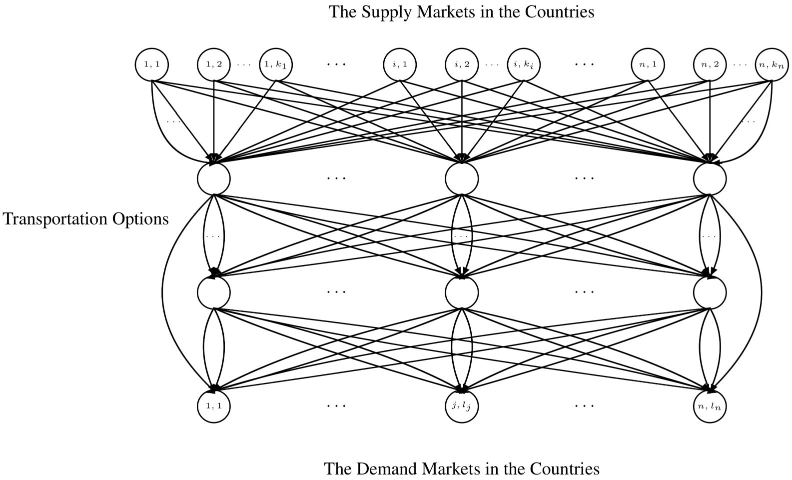
Literature Review

- Queiroz et al. (2020) mapped out a research agenda by providing a **structured literature review**.
- Ivanov (2020) conducted **simulation-based research** to investigate the possible impact of the COVID-19 pandemic on global supply chains.
- Baldwin and Evenett (2020) suggested that the **governments should not turn inward** in response to the COVID-19 pandemic because national trade obstacles would make the **production** of medical supplies **harder** for countries.
- Shingal (2020) stated that, although the pandemic is a health crisis, with **proper trade measures**, **secondary financial crises** can be prevented.
- Nagurney, Besik, and Nagurney (2019), provided a modeling and computational framework for **competitive global supply chain networks**, operating as an oligopoly, where **trade instruments** are imposed in the form of **tariff-rate quotas**.

Our Contributions

- With **so much competition** over essential commodities at the **international level** in the pandemic, governments have **a variety of tools** to use.
- Governments utilize **trade policy measures** to achieve their goals in this competition.
- We developed a **multiproduct, multicountry spatial price equilibrium model** that integrates a **plethora of trade measures** that different countries can impose (and have been imposing) on **essential products**.
- The work builds on the work of Nagurney, Besik, and Dong (2019) but with the following significant extensions/modifications:
    - Multiple essential products
    - Multiple supply markets and multiple demand markets in each country
    - Prices and product flows as variables
    - Multiplicity of trade measures including price floors and ceilings
    - Special relevance to the COVID-19 pandemic.

The Multiproduct, Multicountry Spatial Price Equilibrium Model with Trade Measures



Notation	Definition
x_p^h	the flow of essential product h on path p. We group the path flows into the vector $x \in R_+^{Hn_P}$.
f_a^h	the flow of essential product h on link a. We group the product link flows into the vector $f \in R_+^{Hn_L}$.
$\pi_{(i,k)}^h$	the supply price of product h at supply market k in country i. We group all the supply market prices into the vector $\pi \in R^{Hn_k}$.
$\rho_{(j,l)}^h$	the demand price of product h at demand market l in country j. We group all the demand market prices into the vector $\rho \in R^{Hn_l}$.
$c_a^h(f)$	the unit cost of transportation of product h on link a.
$C_p^h(x)$	the unit cost of transportation of product h on path p. We group all the path costs into the vector $C \in R^{Hn_P}$.
$s_{(i,k)}^h(\pi)$	the supply of product h at supply market k of country i. We group all the supply functions into the vector $s(\pi) \in R^{Hn_k}$.
$d_{(j,l)}^h(\rho)$	the demand for product h at demand market l of country j. We group all the demand functions into the vector $d(\rho) \in R^{Hn_l}$.
τ_{ij}^h	the unit tariff imposed by country j on product h from country i.
$\underline{\pi}_{(i,k)}^h$	the supply price lower bound on product h imposed on supply market k of country i by country i.
$\bar{\pi}_{(i,k)}^h$	the supply price upper bound on product h imposed on supply market k of country i by country i.
$\bar{\rho}_{(j,l)}^h$	the demand price upper bound on product h imposed on demand market l of country j by country j.
G_g^h	the group consisting of all the countries i and j comprising the group and the supply markets of i and demand markets of j for which a strict quota of $\bar{Q}_g^h$ on product h is imposed. There is a total of n_G quotas imposed, with n_{G^h} denoting the number of quotas imposed on product h.

The essential product path flows must be nonnegative, that is:

$$x_p^h \geq 0, \quad \forall p \in P, \forall h. \tag{1}$$

The product link flows, in turn, are related to the product path flows thus:

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

The unit transportation cost on a path associated with the transportation of an essential product:

$$C_p^h(x) = \sum_{a \in L} c_a^h(f) \delta_{ap}, \quad \forall p \in P, \tag{3}$$

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

Feasible Set

We define the feasible set

$$K \equiv \{(x,\lambda,\pi,\rho) \in R_+^{H(n_P+n_G+n_k+n_l)}, \text{ and } \underline{\pi}^h_{(i,k)} \leq \pi^h_{(i,k)} \leq \bar{\pi}^h_{(i,k)}, \forall h,i,k, \text{ and}$$

$$0 \leq \rho^h_{(j,l)} \leq \bar{\rho}^h_{(j,l)}, \forall h,j,l\}.$$

Definition 1:Multiproduct, Multicountry Spatial Price Equilibrium Conditions Under Trade Measures

A multiproduct, multicountry product flow, quota Lagrange multiplier, supply price, and demand price pattern $(x^*, \lambda^*, \pi^*, \rho^*) \in K$ *is an essential product spatial price equilibrium under trade measures of tariffs, quotas, supply price floors and ceilings, and demand price ceilings, if the following conditions hold: For all essential products h and for all groups* G_g^h *for all* g, h*, and for all pairs of supply and demand markets in the countries:* $(i,j),(k,l) \in G_g^h$*, and all paths* $p \in P_{(j,l)}^{(i,k)}$*, for all* i, j, k, l*:*

$$\pi_{(i,k)}^{h*} + C_p^h(x^*) + \tau_{ij}^h + \lambda_{G_g^h}^* \begin{cases} = \rho_{(j,l)}^{h*}, & \text{if} \quad x_p^{h*} > 0, \\ \geq \rho_{(j,l)}^{h*}, & \text{if} \quad x_p^{h*} = 0, \end{cases} \tag{4}$$

$$\lambda_{G_g^h}^* \begin{cases} \geq 0, & \text{if} \quad \sum_{p \in P_{G_g^h}} x_p^{h*} = \bar{Q}_{G_g^h}, \\ = 0, & \text{if} \quad \sum_{p \in P_{G_g^h}} x_p^{h*} < \bar{Q}_{G_g^h}; \end{cases} \tag{5}$$

Definition 1:Multiproduct, Multicountry Spatial Price Equilibrium Conditions Under Trade Measures

for all products h and all supply markets k in the countries i:

$$s^h_{(i,k)}(\pi^*) \begin{cases} \leq \sum_{p\in P^{(i,k)}} x^{h*}_p, & \text{if} \quad \pi^{h*}_{(i,k)} = \bar{\pi}^h_{(i,k)}, \\ = \sum_{p\in P^{(i,k)}} x^{h*}_p, & \text{if} \quad \underline{\pi}^h_{(i,k)} < \pi^{h*}_{(i,k)} < \bar{\pi}^h_{(i,k)}, \\ \geq \sum_{p\in P^{(i,k)}} x^{h*}_p, & \text{if} \quad \pi^{h*}_{(i,k)} = \underline{\pi}^h_{(i,k)}, \end{cases} \tag{6}$$

plus, for all products h and all demand markets l in the countries j:

$$d^h_{(j,l)}(\rho^*) \begin{cases} \geq \sum_{p\in P_{(j,l)}} x^{h*}_p, & \text{if} \quad \rho^{h*}_{(j,l)} = \bar{\rho}^h_{(j,l)}, \\ = \sum_{p\in P_{(j,l)}} x^{h*}_p, & \text{if} \quad 0 < \rho^{h*}_{(j,l)} < \bar{\rho}^h_{(j,l)}, \\ \leq \sum_{p\in P_{(j,l)}} x^{h*}_p, & \text{if} \quad \rho^{h*}_{(j,l)} = 0. \end{cases} \tag{7}$$

For paths not belonging to any group associated with a quota, we have that (4) holds with the quota Lagrange multiplier removed and (5) also excised.

The above **spatial price equilibrium framework** enables **decision-makers** and policy-makers to evaluate the **impacts of different trade measures** on **product prices and product flows**.

Theorem 1: Variational Inequality Formulation of the Multiproduct, Multicountry Essential Product Spatial Equilibrium Conditions Under Trade Measures

A multiproduct, multicountry product flow, quota Lagrange multiplier, supply price, and demand price pattern $(x^*, \lambda^*, \pi^*, \rho^*) \in K$ *is an essential product spatial price equilibrium under trade measures of tariffs, quotas, supply price floors and ceilings, and demand price ceilings, according to Definition 1, if and only if it satisfies the variational inequality problem:*

Theorem 1: Variational Inequality Formulation of the Multiproduct, Multicountry Essential Product Spatial Equilibrium Conditions Under Trade Measures

$$\sum_{h=1}^{H}\sum_{g=1}^{n_{G^h}}\sum_{(i,j)\in G_g^h}\sum_{k\in O_i}\sum_{l\in D_j}\sum_{p\in P_{(j,l)}^{(i,k)}}\left[\pi_{(i,k)}^{h*}+C_p^h(x^*)+\tau_{ij}^h+\lambda_{G_g^h}^*-\rho_{(j,l)}^{h*}\right]\times\left[x_p^h-x_p^{h*}\right]$$

$$+\sum_{h=1}^{H}\sum_{g=1}^{n_{G^h}}\sum_{(i,j)\notin G_g^h}\sum_{k\in O_i}\sum_{l\in D_j}\sum_{p\in P_{(j,l)}^{(i,k)}}\left[\pi_{(i,k)}^{h*}+C_p^h(x^*)+\tau_{ij}^h-\rho_{(j,l)}^{h*}\right]\times\left[x_p^h-x_p^{h*}\right]$$

$$+\sum_{h=1}^{H}\sum_{g=1}^{n_{G^h}}\left[\bar{Q}_{G_g^h}-\sum_{p\in P_{G_g^h}}x_p^{h*}\right]\times\left[\lambda_{G_g^h}-\lambda_{G_g^h}^*\right]$$

$$+\sum_{h=1}^{H}\sum_{i=1}^{n}\sum_{k=1}^{k_i}\left[s_{(i,k)}^h(\pi^*)-\sum_{p\in P^{(i,k)}}x_p^{h*}\right]\times\left[\pi_{(i,k)}^h-\pi_{(i,k)}^{h*}\right]$$

$$+\sum_{h=1}^{H}\sum_{j=1}^{n}\sum_{l=1}^{l_j}\left[\sum_{p\in P_{(j,l)}}x_p^{h*}-d_{(j,l)}^h(\rho^*)\right]\times\left[\rho_{(j,l)}^h-\rho_{(j,l)}^{h*}\right]\geq 0,\quad\forall(x,\lambda,\pi,\rho)\in K. \qquad (8)$$

Standard Form

We now put variational inequality (8) into standard variational inequality form (cf. Nagurney (1999)): determine $X^* \in \mathcal{K}$, such that:

$$\langle F(X^*), X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{K}, \tag{9}$$

where $\langle \cdot, \cdot \rangle$ denotes the inner product in $\mathcal{N}$-dimensional Euclidean space, F is a given continuous function from $\mathcal{K}$ to $\mathcal{R}^{\mathcal{N}}$, and $\mathcal{K}$ is a given closed, convex set. $\mathcal{N} = H(n_P + n_G + n_k + n_l)$ for our model.

Algorithm

Modified Projection Method (Korpelevich (1977))

Step 0: Initialization

Initialize with $X^0 \in \mathcal{K}$. Set the iteration counter $\tau := 1$ and let β be a scalar such that $0 < \beta \leq \frac{1}{L}$, where L is the Lipschitz constant.

Step 1: Computation

Compute $\bar{X}^\tau$ by solving the variational inequality subproblem:

$$\langle \hat{X}^\tau + \eta F(X^{\tau-1}) - X^{\tau-1}, X - \hat{X}^\tau \rangle \geq 0, \quad \forall X \in \mathcal{K}. \tag{10}$$

Step 2: Adaptation

Compute X^τ by solving the variational inequality subproblem:

$$\langle X^\tau + (\eta F(\hat{X}^\tau) - X^{\tau-1}), X - X^\tau \rangle \geq 0, \quad \forall X \in \mathcal{K}. \tag{11}$$

Step 3: Convergence Verification

If $|X^\tau - X^{\tau-1}| \leq \epsilon$, with $\epsilon > 0$, a pre-specified tolerance, then stop; otherwise, set $\tau := \tau + 1$ and go to Step 1.

Algorithm

Explicit Formulae for Step 1 for the Essential Product Flows on Paths with Quotas

For all h, g, for all $(i,j) \in G^h_g$, and for all (k,l), for each path $p \in P^{(i,k)}_{(j,l)}$, compute:

$$\hat{x}^{\tau}_p = \max\{0, x^{\tau-1}_p - \eta(\pi^{h(\tau-1)}_{(i,k)} + C^h_p(x^{\tau-1}) + \tau^h_{ij} + \lambda^{\tau-1}_{G^h_g} - \rho^{h(\tau-1)}_{(j,l)})\}; \quad (12)$$

Explicit Formulae for Step 1 for the Essential Product Flows on Paths without Quotas

For all h, g, for all $(i,j) \notin \cup_g G^h_g$, and for all (k,l), for each path $p \in P^{(i,k)}_{(j,l)}$, compute:

$$\hat{x}^{h\tau}_p = \max\{0, x^{h\tau-1}_p - \eta(\pi^{h(\tau-1)}_{(i,k)} + C^h_p(x^{\tau-1}) + \tau^h_{ij} - \rho^{h(\tau-1)}_{(j,l)})\}; \quad (13)$$

Algorithm

Explicit Formulae for Step 1 for the Quota Lagrange Multipliers

For all h and for all g, for each group G_g^h, compute:

$$\hat{\lambda}^{\tau}_{G_g^h} = \max\{0, \lambda^{\tau-1}_{G_g^h} - \eta(\bar{Q}_{G_g^h} - \sum_{p \in P_{G_g^h}} x_p^{h(\tau-1)})\}; \quad (14)$$

Explicit Formulae for Step 1 for the Supply Prices

For all h, for all i, and for all $\forall k$, for each h, i, k, compute:

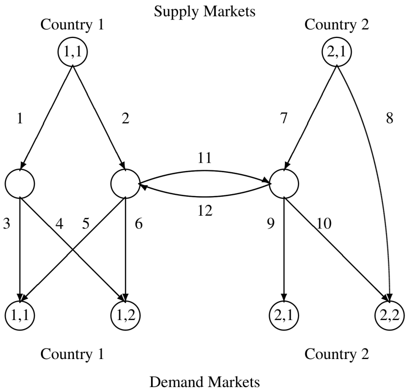
$$\hat{\pi}^{h\tau}_{(i,k)} = \max\{\underline{\pi}^h_{(i,k)}, \min\{\pi^{h(\tau-1)}_{(i,k)} - \eta(s^h_{(i,k)}(\pi^{\tau-1}) - \sum_{p \in P_{G_g^h}} x_p^{h(\tau-1)}), \bar{\pi}^h_{(i,k)}\}\}; \quad (15)$$

Explicit Formulae for Step 1 for the Demand Price

For all h, for all j, and for all l, for each h, j, l, compute:

$$\hat{\rho}^{h\tau}_{(j,l)} = \max\{0, \min\{\rho^{h(\tau-1)}_{(j,l)} - \eta(\sum_{p \in P_{G_g^h}} x_p^{h(\tau-1)} - d^h_{(j,l)}(\rho^{\tau-1})), \bar{\rho}^h_{(j,l)}\}\}. \quad (16)$$

- Two countries, with a single supply market in each country and with two demand markets in each country.
- The product being produced, shipped, and demanded is that of N95 masks.
- The prices, the price floors, and the price ceilings are in a common currency.



- These numerical examples are stylized but, nevertheless, are grounded in realistic data.
- Country 1, for example, is inspired by China and Country 2 by the United States.
- The unit of flow is a kilogram of N95 masks with a kilogram corresponding to 100-150 masks.
- Air cargo shipping cost ranges from $2 to $4 per kilogram.
- We assume links 1, 2, 7, 8, 11, and 12 are air freight links. Links 11 and 12 are international long distance air shipping links between the two countries.

The data for this example are as follows. The paths are:

$$p_1 = (1,3), \quad p_2 = (2,5), \quad p_3 = (7,12,5), \quad p_4 = (1,4), \quad p_5 = (2,6), \quad p_6 = (7,12,6),$$

$$p_7 = (2,11,9), \quad p_8 = (7,9), \quad p_9 = (2,11,10), \quad p_{10} = (7,10), \quad p_{11} = (8).$$

The supply functions at the supply markets are:

$$s^1_{(1,1)}(\pi) = 25\pi^1_{(1,1)} + 3000, \quad s^1_{(2,1)}(\pi) = 22\pi^1_{(2,1)} + 1000.$$

The demand functions at the demand markets are:

$$d^1_{(1,1)}(\rho) = -0.5\rho^1_{(1,1)} + 1800, \quad d^1_{(1,2)}(\rho) = -0.5\rho^1_{(1,2)} + 1500,$$

$$d^1_{(2,1)}(\rho) = -1.5\rho^1_{(2,1)} + 1000, \quad d^1_{(2,2)}(\rho) = -1.0\rho^1_{(2,2)} + 2500.$$

The link unit transportation cost functions are:

$$c^1_1(f) = .01f^1_1 + 3, \quad c^1_2(f) = .02f^1_2 + 2, \quad c^1_3(f) = .03f^1_3 + 2, \quad c^1_4(f) = .06f^1_4 + 1, \quad c^1_5(f) = .5f^1_5 + 1,$$

$$c^1_6(f) = .02f^1_6 + 2, \quad c^1_7(f) = .4f^1_7 + 4, \quad c^1_8(f) = .1f^1_8 + 3, \quad c^1_9(f) = .5f^1_9 + 1, \quad c^1_{10}(f) = .05f^1_{10} + 1,$$

$$c^1_{11}(f) = .2f^1_{11} + .1f^1_{12} + 4, \quad c^1_{12}(f) = .3f^1_{12} + .20f^1_{11} + 5.$$

Country 2 exports no N95 masks to Country 1, since the equilibrium link flow on link 12 is equal to 0.00.

The computed equilibrium supply market prices are:

$$\pi^{1*}_{(1,1)} = 32.55, \quad \pi^{1*}_{(2,1)} = 48.57,$$

and the computed equilibrium demand market prices are:

$$\rho^{1*}_{(1,1)} = 109.16, \quad \rho^{1*}_{(1,2)} = 88.50, \quad \rho^{1*}_{(2,1)} = 397.14, \quad \rho^{1*}_{(2,2)} = 223.08.$$

- The **supply market price** in **Country 1** is **lower** than that at the supply market in Country 2; the same for the demand market prices in Country 1 as opposed to those in Country 2.
- All the supply market prices and all the demand markets prices are positive and none are at a value of 0.

Data as in Example 1 but with a **Tariff Imposed by Country 2 on Imports of N95 Masks** from Country 1 ($\tau_{12}^1 = 2$)

The computed equilibrium supply market prices are now:

$$\pi_{(1,1)}^{1*} = 32.35, \quad \pi_{(2,1)}^{1*} = 48.76,$$

and the equilibrium demand market prices are:

$$\rho_{(1,1)}^{1*} = 108.95, \quad \rho_{(1,2)}^{1*} = 88.24, \quad \rho_{(2,1)}^{1*} = 397.52, \quad \rho_{(2,2)}^{1*} = 223.57.$$

Clearly, **under the imposed tariff**, **consumers** at the two demand markets **in Country 2** experience a **higher price for the N95 masks** than they did in Example 1, whereas **consumers** at demand markets **in Country 1** experience **reduced prices**, as compared to the values in Example 1.

Sensitivity analysis:

When the tariff τ^1_{12} was 234 or higher the flow on link 11 was zero. Furthermore, under a unit tariff of 234, the computed equilibrium supply market prices were

$$\pi^{1*}_{(1,1)} = 9.15, \quad \pi^{1*}_{(2,1)} = 70.79,$$

and the computed equilibrium demand market prices were:

$$\rho^{1*}_{(1,1)} = 84.56, \quad \rho^{1*}_{(1,2)} = 57.89, \quad \rho^{1*}_{(2,1)} = 441.50, \quad \rho^{1*}_{(2,2)} = 280.34.$$

One can see that consumers in **Country 2** suffer, in that, **the higher the tariff** that is levied by their country's government, **the higher the demand market prices** for the N95 masks.

The government of **Country 1** institutes an **export quota for the N95 masks** of 100.

The **quota of 100 is met**, since the sum of the path flows on paths p_7 and p_9 is equal to 100; equivalently, one can see that, given the network topology for this set of problems, the equilibrium link flow on link 11 is 100.00. The associated computed Lagrange multiplier is $\lambda^{1*} = 21.11$, when we suppress the group notation.

The computed equilibrium supply market prices are now:

$$\pi^{1*}_{(1,1)} = 20.00, \quad \pi^{1*}_{(2,1)} = 5.65,$$

and the equilibrium demand market prices are:

$$\rho^{1*}_{(1,1)} = 95.47, \quad \rho^{1*}_{(1,2)} = 69.80, \quad \rho^{1*}_{(2,1)} = 200.00, \quad \rho^{1*}_{(2,2)} = 100.00.$$

Example 5

- **The supply flows** of the N95 masks in both countries now **decrease**, which is **detrimental** to the health of those who require them as well as to the containment of contagion.
- These numerical examples **illustrate the impacts of trade measures** not only on the country imposing the trade measure(s) but also on other countries.
- Interestingly, it may so happen that a **trade measure imposed by a country**, hoping to help its citizens, **may actually adversely affect its consumers**, but may positively affect those in another country.

- Many governments of different countries have **instituted a variety of trade measures** such as **tariffs, quotas**, as well as **price supports in the form of price floors and ceilings** on **essential products in the pandemic**.
- We introduce a **multiproduct, multicountry spatial price equilibrium model**, which has both product flows, as well as supply market prices and demand market prices as variables.
- We state the **governing equilibrium conditions**, in the presence of the **trade measures**, and derive a **variational inequality formulation**, which is then used to obtain solutions to illustrative examples and numerical examples, with the latter solved via an **implemented algorithm**.

- The modeling and algorithmic framework enables **policy makers and decision-makers** to **quantify the impacts of different trade measures**, both individually or jointly, and to ascertain who may benefit and who may lose.
- For example, the computed solutions to numerical examples reveal that **unexpected results may occur**.
- A country may think that it is benefiting its own consumers, but actually helps those in another country and not its own.
- This work has enriched the portfolio of **spatial price equilibrium models** which incorporate relevant policies in the form of **trade measures**, and which are being actively imposed now by **governments** around the world **in the pandemic**.

- This paper is dedicated to all essential workers, including healthcare workers, grocery workers, farmers, emergency services, freight service providers, and tech workers, who have sacrificed so much in the COVID-19 pandemic.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The Virtual Center for Supernetworks is an interdisciplinary center at the Isenberg School of Management that advances knowledge on large-scale networks and integrates operations research and management science, engineering, and economics. Its Director is Dr. Anna Nagurney, the John F. Smith Memorial Professor of Operations Management.
Mission: The Virtual Center for Supernetworks fosters the study and application of supernetworks and serves as a resource on networks ranging from transportation and logistics, including supply chains, and the Internet, to a spectrum of economic networks.
The Applications of Supernetworks Include: decision-making, optimization, and game theory; supply chain management; critical infrastructure from transportation to electric power networks; financial networks; knowledge and social networks; energy, the environment, and sustainability; cybersecurity; Future Internet Architectures; risk management; network vulnerability, resiliency, and performance metrics; humanitarian logistics and healthcare.
Announcements and Notes
Photos of Center Activities
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Friends of the Center
Course Lectures
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UMass Amherst INFORMS Student Chapter
Professor Anna Nagurney's Blog
Network Classics
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Thank you!