Quantification of International Trade Network Performance Under Disruptions to Supply, Transportation, and Demand Capacity, and Exchange Rates in Disasters

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- **Robustness Measurement**
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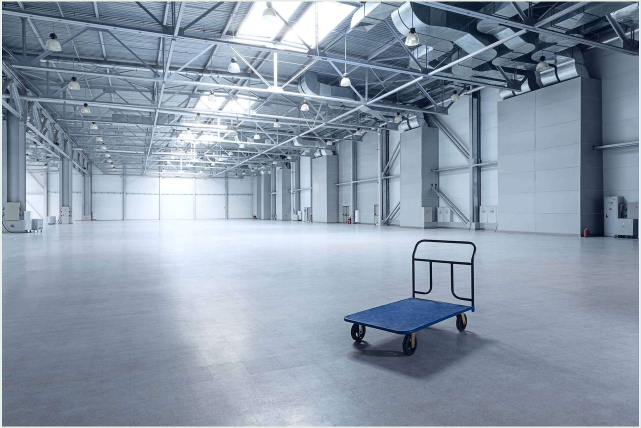
Background and Motivation

Introduction

Disasters, both sudden-onset and slow-onset ones, are transforming the landscapes for global trade, generating shocks on the supply side, on transportation, as well as on the demand side.

Introduction

The COVID-19 pandemic vividly demonstrated the impacts of the shutdowns of production plants and the challenges associated with the harvesting of agricultural products, plus the changes in the demand for many products.



Introduction

The Horn of Africa is experiencing its worst ever recorded drought, pushing more than 3 million of the area's residents to extreme levels of food insecurity and also resulting in the displacement of millions of people.

In the US, the recent California wildfires, further exacerbated by climate change and droughts, have resulted in billions of dollars of yearly damage to the agricultural industry.

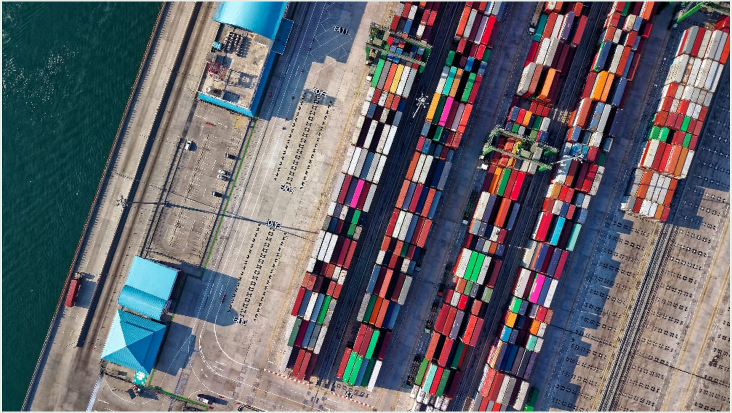
Introduction

Earthquakes in early February 2023 devastated parts of Turkey, including agricultural lands, and have affected the country's GDP.

Increasing global strife and violence, notably the full-scale invasion of Ukraine by Russia on February 24, 2022, have led to growing suffering and loss of life, as well as major impacts on economies and trade.

Introduction

Disasters have caused and will continue to cause, in an era of climate change and global uncertainty, disruptions to the production, transportation, and consumption of many commodities that are needed for the sustenance and sustainability of humanity.



Literature Review

• The intellectual foundations for our modeling framework are based on the classical work of Samuelson (1952) and Takayama and Judge (1964, 1971) in spatial price equilibrium modeling but with the benefit of the variational inequality methodology (cf. Nagurney (1999)).

• We build upon the works of Nagurney et al. (2023, 2024), which introduced exchange rates in general multicommodity spatial price equilibrium models for international trade. A relevant paper is also the one by Passacantando and Raciti (2024), also in press in the new Dynamics of Disasters volume.

• The research in this paper adds to the growing, broad literature on network vulnerability. For a summary of network robustness and resilience measures please refer to Sharkey et al. (2020).

• The work in this paper also adds to the literature on disaster management in terms of mitigation and recovery. A plethora of papers on the dynamics of disasters, relevant models, algorithms, and applications can be found in the edited volumes of Kotsireas, Nagurney, and Pardalos (2018) and Kotsireas et al. (2021).

Our Contributions

- **We allow for not only capacities on the supplies and the transportation routes but also at the demand markets.**
- **We introduce distinct disaster scenarios, with associated probabilities and capacities, as well as disruptions to exchange rates.**
- **We construct a network performance measure under each specific disaster scenario disruption and propose a unified network performance measure.**
- **A robustness measure is constructed using the unified network performance measure and the performance of the network in the absence of disruptions.**
- **An importance indicator is proposed to allow for the quantification of network components and their ranking.**
- **The framework is applied to Russia's war on Ukraine under different scenarios.**

The Multicommodity International Trade Model

The Multicommodity International Trade Model

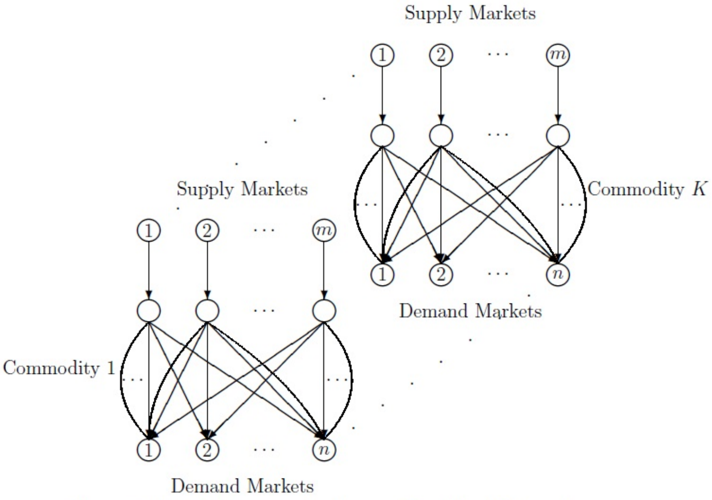


Figure 1: The Multicommodity International Trade Network

Parameters

Notation	Parameter Definition
$u_i^{s^k\xi_l}$	upper bound on supply of commodity k; $k = 1, \ldots, K$ at supply market i; $i = 1, \ldots, m$ under disaster scenario ξ_l; $l = 1, \ldots, \omega$.
$u_{ijr}^{Q^k\xi_l}$	upper bound on transport of commodity k; $k = 1, \ldots, K$ from supply market i; $i = 1, \ldots, m$ to demand market j; $j = 1, \ldots, n$ on route r; $r = 1, \ldots, P$ under disaster scenario ξ_l; $l = 1, \ldots, \omega$.
$u_j^{d^k\xi_l}$	upper bound on the demand of commodity k; $k = 1, \ldots, K$ at demand market j; $j = 1, \ldots, n$, under disaster scenario ξ_l; $l = 1, \ldots, \omega$. We group all the upper bounds for all the disaster scenarios into the vector u.
$e_{ij}^{\xi_l}$	exchange rate from supply market i; $i = 1, \ldots, m$ to demand market j; $j = 1, \ldots, n$ and disaster scenario ξ_l; $l = 1, \ldots, \omega$. We group the exchange rates for disaster scenario ξ_l; $l = 1, \ldots, \omega$ into the vector $e^{\xi_l} \in R_+^{mn}$ and then group all the exchange rates for all the disaster scenarios into the vector $e \in R_+^{mn\omega}$.

Variables

Notation	Variable Definition
$s_i^{k\xi_l}$	the supply of the commodity k; $k = 1, \ldots, K$, at supply market i; $i = 1, \ldots, m$ under disaster scenario ξ_l; $l = 1, \ldots, \omega$. We group all the supplies at disaster scenario ξ_l; $l = 1, \ldots, \omega$ into the vector $s^{\xi_l} \in R_+^{Km}$, and then group all the supplies for all the disaster scenarios into the vector $s \in R_+^{Km\omega}$.
$d_j^{k\xi_l}$	the demand for the commodity k; $k = 1, \ldots, K$ at demand market j; $j = 1, \ldots, n$ under disaster scenario ξ_l; $l = 1, \ldots, \omega$. We group all the demands at disaster scenario ξ_l; $l = 1, \ldots, \omega$ into the vector $d^{\xi_l} \in R_+^{Kn}$, and then group all the demands for all the disaster scenarios into the vector $d \in R_+^{Kn\omega}$.
$Q_{ijr}^{k\xi_l}$	the shipment of the commodity k; $k = 1, \ldots, K$, from supply market i; $i = 1, \ldots, m$, to demand market j; $j = 1, \ldots, n$, on route r; $r = 1, \ldots, P$ under disaster scenario ξ_l; $l = 1, \ldots, \omega$. We group all the commodity shipments at disaster scenario ξ_l; $l = 1, \ldots, \omega$ into the vector $Q^{\xi_l} \in R_+^{KmnP}$, and then group all the commodity shipments into the vector $Q \in R_+^{KmnP\omega}$.

Functions

Notation	Function Definition
$\pi_i^k(s^{\xi_l})$	the supply price function for commodity k; $k = 1, \ldots, K$, at supply market i; $i = 1, \ldots, m$ under disaster scenario ξ_l; $l = 1, \ldots, \omega$.
$\rho_j^k(d^{\xi_l})$	the demand price function for commodity k; $k = 1, \ldots, K$ at demand market j; $j = 1, \ldots, n$ under disaster scenario ξ_l; $l = 1, \ldots, \omega$.
$c_{ijr}^k(Q^{\xi_l})$	the unit transportation cost associated with shipping the commodity k; $k = 1, \ldots, K$, from supply market i; $i = 1, \ldots, m$, to demand market j; $j = 1, \ldots, n$ via route r; $r = 1, \ldots, P$ under disaster scenario ξ_l; $l = 1, \ldots, \omega$.

Equilibrium Conditions

Definition 1: The Multicommodity International Trade Network Equilibrium Conditions Under Capacity Disruptions in Disasters

A shipment and Lagrange pattern $(Q^{\xi_l *}, \lambda^{s\xi_l *}, \lambda^{Q\xi_l *}, \lambda^{d\xi_l *}) \in \mathcal{K}^{\xi_l}$, *where*

$$\mathcal{K}^{\xi_l} \equiv \{(Q^{\xi_l}, \lambda^{s\xi_l}, \lambda^{Q\xi_l}, \lambda^{d\xi_l}) | (Q^{\xi_l}, \lambda^{s\xi_l}, \lambda^{Q\xi_l}, \lambda^{d\xi_l}) \in R_+^{KmnP+Km+KmnP+Kn}\}$$

is a multicommodity international trade network equilibrium under disaster scenario ξ_l; $l = 1, \ldots, \omega$, *if the following conditions hold: for all commodities* k; $k = 1, \ldots, K$; *for all supply and demand market pairs:* (i, j); $i = 1, \ldots, m$; $j = 1, \ldots, n$, *and for all routes* r; $r = 1, \ldots, P$:

$$(\tilde{\pi}_i^k(Q^{\xi_l *}) + c_{ijr}^k(Q^{\xi_l *}))e_{ij}^{\xi_l} + \lambda_i^{s^k \xi_l *} + \lambda_{ijr}^{Q^k \xi_l *} + \lambda_j^{d^k \xi_l *} \begin{cases} = \tilde{\rho}_j^k(Q^{\xi_l *}), & \text{if } Q_{ijr}^{k\xi_l *} > 0, \\ \geq \tilde{\rho}_j^k(Q^{\xi_l *}), & \text{if } Q_{ijr}^{k\xi_l *} = 0; \end{cases} \quad (1)$$

Equilibrium Conditions

For all commodities k*;* $k = 1, \ldots, K$*, and for all supply markets* i*;* $i = 1, \ldots, m$*:*

$$u_i^{s^k \xi_l} \begin{cases} = \sum_{j=1}^{n} \sum_{r=1}^{P} Q_{ijr}^{k\xi_l *}, & \text{if } \lambda_i^{s^k \xi_l *} > 0, \\ \geq \sum_{j=1}^{n} \sum_{r=1}^{P} Q_{ijr}^{k\xi_l *}, & \text{if } \lambda_i^{s^k \xi_l *} = 0; \end{cases} \tag{2}$$

for all commodities k*;* $k = 1, \ldots, K$*, and for all supply and demand markets* (i, j)*;* $i = 1, \ldots, m$*;* $j = 1, \ldots, n$*, and for all routes* r*;* $r = 1, \ldots, P$*:*

$$u_{ijr}^{Q^k \xi_l} \begin{cases} = Q_{ijr}^{k\xi_l *}, & \text{if } \lambda_{ijr}^{Q^k \xi_l *} > 0, \\ \geq Q_{ijr}^{k\xi_l *}, & \text{if } \lambda_{ijr}^{Q^k \xi_l *} = 0; \end{cases} \tag{3}$$

and for all commodities k*;* $k = 1, \ldots, K$*, and for all demand markets* j*;* $j = 1, \ldots, n$*, and for all routes* r*;* $r = 1, \ldots, P$*:*

$$u_j^{d^k \xi_l} \begin{cases} = \sum_{i=1}^{m} \sum_{r=1}^{P} Q_{ijr}^{k\xi_l *}, & \text{if } \lambda_j^{d^k \xi_l *} > 0, \\ \geq \sum_{i=1}^{m} \sum_{r=1}^{P} Q_{ijr}^{k\xi_l *}, & \text{if } \lambda_j^{d^k \xi_l *} = 0. \end{cases} \tag{4}$$

Variational Inequality Formulation

Theorem 1

A multicommodity shipment and Lagrange multiplier pattern $(Q^{\xi_l *}, \lambda^{s\xi_l *}, \lambda^{Q\xi_l *}, \lambda^{d\xi_l *}) \in \mathcal{K}^{\xi_l}$ is a multicommodity international trade network equilibrium under capacity disruptions in disasters, according to Definition 1, if and only if it satisfies the variational inequality:

$$\sum_{k=1}^{K}\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{r=1}^{P}\Big[(\tilde{\pi}_i^k(Q^{\xi_l *})+c_{ijr}^k(Q^{\xi_l *}))e_{ij}^{\xi_l}+\lambda_i^{s^k\xi_l *}+\lambda_{ijr}^{Q^k\xi_l *}+\lambda_j^{d^k\xi_l *}-\tilde{\rho}_j^k(Q^{\xi_l *})\Big]\times(Q_{ijr}^{k\xi_l}-Q_{ijr}^{k\xi_l *})$$

$$+\sum_{k=1}^{K}\sum_{i=1}^{m}\Big[u_i^{s^k\xi_l}-\sum_{j=1}^{n}\sum_{r=1}^{P}Q_{ijr}^{k\xi_l *}\Big]\times(\lambda_i^{s^k\xi_l}-\lambda_i^{s^k\xi_l *})$$

$$+\sum_{k=1}^{K}\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{r=1}^{P}\Big[u_{ijr}^{Q^k\xi_l}-Q_{ijr}^{k\xi_l *}\Big]\times(\lambda_{ijr}^{Q^k\xi_l}-\lambda_{ijr}^{Q^k\xi_l *})$$

$$+\sum_{k=1}^{K}\sum_{j=1}^{n}\Big[u_j^{d^k\xi_l}-\sum_{i=1}^{m}\sum_{r=1}^{P}Q_{ijr}^{k\xi_l *}\Big]\times(\lambda_j^{d^k\xi_l}-\lambda_j^{d^k\xi_l *})\geq 0, \quad \forall (Q^{\xi_l}, \lambda^{s\xi_l}, \lambda^{Q\xi_l}, \lambda^{d\xi_l}) \in \mathcal{K}^{\xi_l}. \quad (5)$$

International Trade Network Performance Indicator

Definition 2: International Trade Network Performance Indicator Under Capacity and Exchange Rate Disruption ξ_l

For an international trade network $G = [N, L]$, where N is the set of nodes and L is the set of links, as depicted in Figure 1, and, given the underlying multicommodity supply price, unit transportation cost, and demand price functions, and exchange rates and capacities associated with disaster scenario ξ_l, we define the performance $\mathcal{E}^{\xi_l}$ as follows:

$$\mathcal{E}^{\xi_l}(G, \tilde{\pi}, c, \tilde{\rho}, u^{\xi_l}, e^{\xi_l}) = \frac{1}{Kn} \sum_{k=1}^{K} \sum_{j=1}^{n} \frac{d_j^{k\xi_l *}}{\hat{\rho}_j^k(Q^{\xi_l *})}, \tag{6}$$

where the demands and the incurred demand market prices are obtained through the solution of variational inequality (5) for the problem.

Unified International Trade Network Performance Measure

Assessing Performance of International Trade Networks

Definition 3: Unified International Trade Network Performance Measure

The performance indicator $\mathcal{E}$ for an international trade network under disruption set Ξ and with associated probabilities $p_{\xi_1}, p_{\xi_2}, \ldots, p_{\xi_\omega}$, respectively, is defined as:

$$\mathcal{E} = \sum_{l=1}^{\omega} \mathcal{E}^{\xi_l} p_{\xi_l}. \tag{7}$$

We let $\mathcal{E}^0$ be the performance of the international trade network under its original (not disrupted) upper bounds/capacities and original exchange rates, such that:

$$\mathcal{E}^0(G, \tilde{\pi}, c, \tilde{\rho}, u^0, e^0) = \frac{1}{Kn} \sum_{k=1}^{K} \sum_{j=1}^{n} \frac{d_j^{k*}}{\hat{\rho}_j^k(Q^*)}, \tag{8}$$

where u^0 denotes the vector of original capacities not under disruptions and e^0 denotes the vector of exchange rates, also, not under disruptions. We can also refer to both the expressions in (7) and (8) as "efficiency" measures.

Robustness Measurement

Assessing Performance of International Trade Networks

Definition 4: Robustness of an International Trade Network Under Disruptions

The robustness, $\mathcal{R}$, of an international trade network under capacity and exchange rate disruptions is calculated as:

$$\mathcal{R} = \mathcal{E}^0 - \mathcal{E}. \tag{9}$$

According to the above definition, an international trade network is more robust if, under disruptions, its performance lies close to its performance in the absence of disruptions; that is, the closer the value of $\mathcal{R}$ is to 0.00, the more robust to disruptions the international trade network is.

Importance Indicator of an International Trade Network Component

Assessing Performance of International Trade Networks

Definition 5: Importance Indicator of an International Trade Network Component

The importance indicator of an international trade network component g where g can correspond to a supply market, a demand market, or a transportation route, or a combination thereof is defined as:

$$I(g) \equiv \frac{\mathcal{E}(G, \tilde{\pi}, c, \tilde{\rho}, u^0, e^0) - \mathcal{E}(G - g, \tilde{\pi}, c, \tilde{\rho}, u^0, e^0)}{\mathcal{E}(G, \tilde{\pi}, c, \tilde{\rho}, u^0, e^0)}, \tag{10}$$

where $G - g$ denotes the graph with the component g no longer functioning.

Note that the international trade network component importance indicator (10) quantifies the relative efficiency/performance drop of the trade network when the component is no longer available.

Numerical Examples

Numerical Examples

The data for the examples are based on Russia's war on Ukraine.

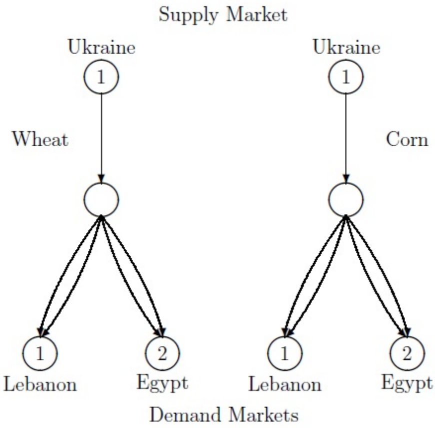


Figure 2: The International Trade Network for the Numerical Examples

Baseline Example

• First, we present a baseline example (without disruptions) that is a slightly altered version of Example 6 in Nagurney et al. (2024).

• There are two transportation routes connecting Ukraine with Lebanon and two transportation routes connecting Ukraine with Egypt.

• We denote the wheat commodity by 1 and that of corn by 2.

• The time horizon is one year, and the unit for the commodity shipments is tons with prices and costs associated with a ton of the specific commodity.

• The Modified Projection Method (Korpelevich (1977)) is the algorithm used to solve the examples.

Baseline Example

As reported in Nagurney et al. (2024), where different notation was used, the modified projection method converges to the following equilibrium commodity shipment pattern:

$$Q^{1*}_{111} = 477,085.5938, \quad Q^{1*}_{121} = 1,605,672.5000, \quad Q^{1*}_{112} = 0.0000, \quad Q^{1*}_{122} = 0.0000,$$

$$Q^{2*}_{111} = 79,128.0781, \quad Q^{2*}_{121} = 560,130.3750, \quad Q^{2*}_{112} = 0.0000, \quad Q^{2*}_{122} = 0.0000.$$

All the Lagrange multipliers are equal to 0.0000. **Only the maritime routes are used. This commodity flow pattern is quite close to Ukraine's actual wheat and corn exports to Lebanon and Egypt in 2021 and the projected amounts in 2022, with the assumption that the invasion would have never occurred.**

The equilibrium commodity supplies are:

$$s^{1*}_1 = 2,082,758.1250, \quad s^{2*}_1 = 639,258.4375.$$

The equilibrium commodity demands are:

$$d^{1*}_1 = 477,085.5938, \; d^{2*}_1 = 79,128.0781, \; d^{1*}_2 = 1,605,672.5000, \; d^{2*}_2 = 560,130.3750.$$

Baseline Example

The incurred supply prices in Ukraine in hryvnia and in US dollars at the equilibrium are:

$$\pi_1^1(s^*) = 7,328.3252 = \$266.8542, \quad \pi_1^2(s^*) = 6,971.0166 = \$253.8432.$$

The incurred demand prices at the equilibrium in Lebanon in Lebanese pounds and in US dollars are:

$$\rho_1^1(d^*) = 530,781.1875 = \$351.0457, \quad \rho_1^2(d^*) = 520,752.9063 = \$344.4132.$$

The demand prices in Egypt in Egyptian pounds and in US dollars are:

$$\rho_2^1(d^*) = 5,527.3057 = \$351.3862, \quad \rho_2^2(d^*) = 5,555.4214 = \$353.1736.$$

These results closely resemble the actual prices in these countries before the full-scale invasion. Ukrainian farmers earned around \$270 per ton of grain at the time. The demand prices in Lebanon and Egypt were also quite similar to the results.

Network Performance and the Importance of Routes

• Calculation of the performance/efficiency of the international trade network yields $\mathcal{E}^0 = 1,936.08$.

• The efficiency of the international trade network without the first transportation route joining Ukraine to Lebanon, is: 1,599.44, and, the importance of that transportation route is: .17.

• The efficiency of the network without the second route joining Ukraine with Lebanon is 1,936.08, and, the importance of that route is 0.00.

• The efficiency of the international trade network without the first route joining Ukraine with Egypt is 467.70, and, its importance is .76.

• The efficiency of the international trade network without the second route joining Ukraine with Egypt is: 1,936.08 and, its importance is 0.00.

The above results reinforce the importance of the maritime routes for the efficiency of this international trade network. For example, pre-war, Ukraine used to export more than 90% of its grains via maritime freight through its Black Sea ports.

Disruption Scenarios

We now consider several disruptions, as in wartime. We retain the same exchange rates in all the scenarios.

• Scenario ξ_1 corresponds to supply capacities being reduced, as in the case of the destruction of land through mining, bombing, etc.

• The second scenario ξ_2 corresponds to the disruption of the maritime transportation routes.

• The third disruption scenario ξ_3 integrates the data of scenarios ξ_1 and ξ_2 in terms of capacity reductions in production and transportation, but now the supply capacities are further disrupted.

Equilibrium Results Under Disruption Scenarios

Equilibrium	Scenario		
Commodity Shipment	ξ_1	ξ_2	ξ_3
$Q_{111}^{1\xi_l}$	480,127.50000	481,216.7500	517,281.0625
$Q_{121}^{1\xi_l}$	1,519,873.1250	1,500,000.0000	482,719.0000
$Q_{121}^{1\xi_l}$	0.0000	0.0000	0.0000
$Q_{122}^{1\xi_l}$	0.0000	0.0000	0.0000
$Q_{111}^{2\xi_l}$	79,433.9766	79,509.8125	83,296.5781
$Q_{121}^{2\xi_l}$	563,800.2500	563,800.2500	586,686.3125
$Q_{121}^{2\xi_l}$	0.0000	0.0000	0.0000
$Q_{122}^{2\xi_l}$	0.0000	0.0000	0.0000

Table 2: Equilibrium Commodity Shipments Under the Disruption Scenarios

Under scenario ξ_1, all the Lagrange multipliers are equal to 0.0000 except that $\lambda_1^{s^1\xi_1*} = 53.7601$. Under scenario ξ_2, all the Lagrange multipliers are equal to 0.0000. Under scenario ξ_3, all the Lagrange multipliers are equal to 0.0000 except that $\lambda_1^{s^1\xi_3*} = 734.1813$. From the size and positivity of the Lagrange multiplier associated with the supply of wheat in Ukraine, we see the importance of preserving Ukraine's capacity for wheat production.

Insights from Disruption Scenarios

Under scenario ξ_1:

• Both wheat and corn shipments to Lebanon and that of corn to Egypt decrease but are still quite close to those under scenario ξ_0.

• The wheat commodity flow to Egypt decreases relatively much more.

• The disruption to the supply of corn is not impactful since Lebanon and Egypt primarily depend on wheat.

• The limited production of wheat essentially causes Lebanon and Egypt to compete over Ukrainian wheat, and it comes at the cost of Egypt's share.

Insights from Disruption Scenarios

Under scenario ξ_2:

• The disrupted transportation capacities are still high enough to satisfy the demands almost to the pre-war levels.

• The wheat flow to Egypt, which has a much higher demand than Lebanon, is almost at the bound.

Under scenario ξ_3:

• The further disruption to the supply of wheat in Ukraine, again, comes at the price of Egypt's share of Ukrainian wheat.

• Lebanon imports more wheat and corn, while Egypt shifts towards replacing part of its lost wheat shipment by importing more Ukrainian corn.

Network Performance and Robustness

- We now calculate $\mathcal{E}$ with the assumption of the following probabilities: $p_{\xi_1} = p_{\xi_2} = .25$ and $p_{\xi_3} = .50$, where: $\mathcal{E}^{\xi_1} = 1,872.62$, $\mathcal{E}^{\xi_2} = 1,857.74$, and $\mathcal{E}^{\xi_3} = 1,163.43$.

- Under the consideration of the three disruption scenarios, and the associated probabilities, $\mathcal{E} = 1,514.30$.

- Hence, the robustness $\mathcal{R}$ is equal to 421.78 for this international trade network under such disruptions and probabilities.

Clearly, under these disruption scenarios, which are quite representative of the actual scenarios as the war on Ukraine by Russia has progressed over more than two years, the international trade network considered here is not robust since the value of $\mathcal{R}$ is not close to 0.00.

Summary and Conclusions

• We constructed a multicommodity international trade network equilibrium model under capacity disruptions in disasters to the production and transportation of commodities, the demand in the consuming markets, and the exchange rates.

• The governing equilibrium conditions of the international trade network were presented under each specific disaster scenario and then formulated as a variational inequality problem.

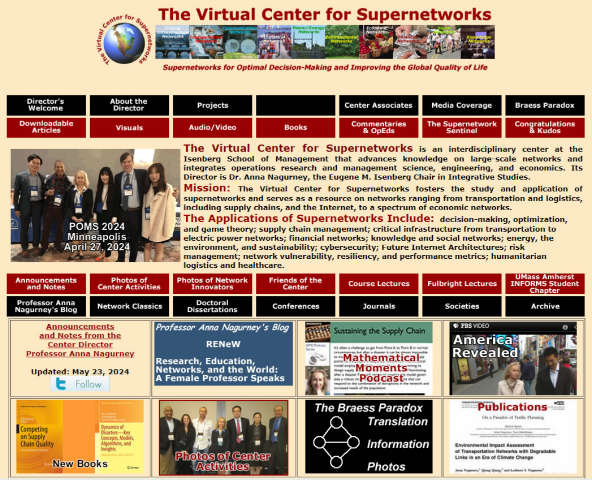
• An international trade network performance measure for each specific disaster scenario was proposed and a unified international trade network performance measure. In addition, a robustness measure was introduced.

• An international trade network importance indicator was identified. The importance indicator enables a decision-maker to rank the network components in terms of their criticality to the international trade network's performance.

• Numerical examples, drawn from the consequences of Russia's war on Ukraine, and focused on the agricultural trade of wheat and corn from Ukraine to MENA (Middle East and North Africa) countries, were presented.

• The framework is highly relevant to the challenges facing international trade.

Thank You Very Much!



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