Global Supply Chain Networks and Tariff Rate Quotas: Equilibrium Analysis with Application to Agricultural Products

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Background and Motivation

- Global supply chain networks have made possible the production and wide distribution of goods, as varied as food and other agricultural products to textiles and apparel as well as aluminum and steel.
- The global product flows associated with supply chain networks underpinning world trade have also garnered the attention of government policy makers concerned with the highly competitive environment and possible effects on domestic firms.
- Examples of policy instruments that have been applied by governments to modify trade patterns included: tariffs, quotas, and a combination thereof - tariff rate quotas.

Background and Motivation

- A tariff rate quota (TRQ) is a two-tiered tariff, in which a lower in-quota tariff is applied to the units of 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.
- 43 World Trade Organization members have a total of 1,425 tariff quotas in their commitments.
- The world's four most important food crops: rice, wheat, corn, and bananas have all been subject to tariff rate quotas.

Background and Motivation

- Tariffs, as well as tariff rate quotas, are garnering prominent attention in the news on world trade.
- The imposition of tariffs by certain countries, leading to retaliation by other countries with ramifications across multiple supply chains, resulting in a trade war.
- We need the research community to construct computable operational mathematical models that enable the assessment of the impacts of trade policy instruments such as tariff rate quotas on consumer prices, trade flows, as well as the profits of producers/firms.

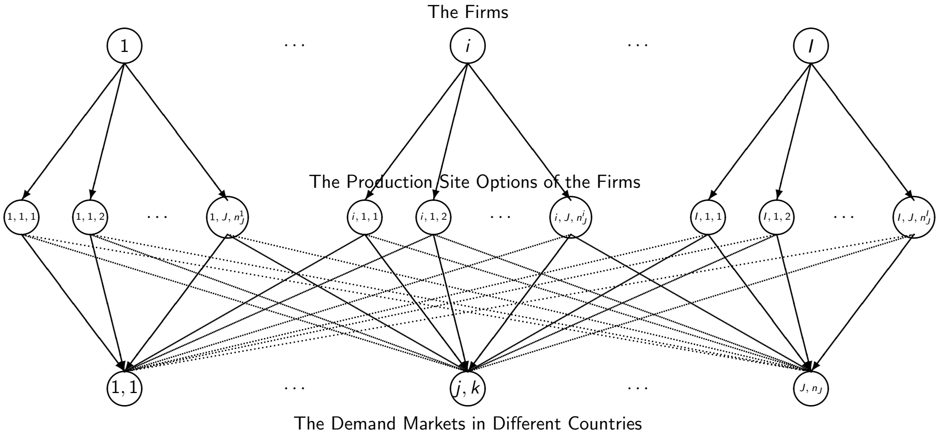
Literature Review

- **Perfect Competition**
  - Tariff rate quotas (TRQs) have been deemed challenging to formulate; models have focused almost exclusively on **spatial price equilibrium**.
  - Spatial price equilibrium models are perfectly competitive models with numerous producers (Samuelson (1964), Takayama and Judge (1964, 1971)).
  - For more recent applications of spatial price equilibrium models, utilizing variational inequality theory, see Nagurney (1999, 2006), Daniele (2004), Li, Nagurney, and Yu (2018)).
  - For the inclusion of tariff rate quotas into spatial price equilibrium models using variational inequality theory, see Nagurney, Besik, and Dong (2019).
- **Imperfect Competition**
  - In many industrial sectors, the more appropriate framework is that of imperfect competition, as in the case of **oligopolistic competition**.
  - Shono (2001) relaxed the assumption of perfect competition, and incorporated TRQs, under oligopolistic competition and that the computable framework consisted of linear functions.
  - Maeda, Suzuki, and Kaiser (2001, 2005) considered oligopolistic competition and TRQs but assumed that there is a single producer in each country.

Literature Review

- In this paper:
  - We introduce the global supply chain network model, consisting of firms that seek to maximize their profits.
  - We determine how much of the product to manufacture/produce at the production sites, which can be located in multiple countries.
  - We incorporate tariff rate quotas into the supply chain network equilibrium model.
  - A case study is provided on an agricultural application, focused on avocados, a very popular fruit in the United States, with growing consumer demand even in China.

The Global Supply Chain Network Model with TRQs



Notation Related to Tariff Rate Quotas

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

The Global Supply Chain Network Model with TRQs

- **Strategic Variables:**

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

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

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

The Global Supply Chain Network Model with TRQs

Production Cost Functions

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

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

Transportation Cost Functions

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

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

Conservation of Flow

The demand at each demand node l; $\forall l \in \mathcal{K}$, is denoted by d_l and must satisfy the following conservation of flow equation:

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

The Global Supply Chain Network Model with TRQs

Demand Price Functions

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

$$\rho_l = \rho_l(d). \tag{4a}$$

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

$$\hat{\rho}_l = \hat{\rho}_l(Q) \equiv \rho_l(d), \quad \forall l \in \mathcal{K}. \tag{4b}$$

The Global Supply Chain Network Model with TRQs

Utility Functions

For a firm i in the former category, we define the utility function U_i^G as

$$U_i^G = \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} \hat{\rho}_l(Q) Q_{ihl} - \sum_{h \in \mathcal{J}_i} f_{ih}(Q) - \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} c_{ihl}(Q) - \sum_{G_g \in \mathcal{I}^i} (\tau^u_{G_g} + \lambda^*_{G_g}) \sum_{(h,l) \in G_g} Q_{ihl}, \quad (5a)$$

where $\lambda^*_{G_g}$ is the equilibrium economic rent equivalent for group G_g and it assumes values as in Definition 1 below, and, for a firm i in the latter category, we define its utility function U_i, as

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

Definition 1: Global Supply Chain Network Equilibrium Under TRQs

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

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

where $Q_{-i}^* \equiv (Q_1^*, \ldots, Q_{i-1}^*, Q_{i+1}^*, \ldots, Q_I^*)$, and $K_i \equiv \{Q_i | Q_i \in R_+^{\sum_{j=1}^J Kn_j^i}\}$ and for all groups G_g:

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

Variational Inequality Formulation of the Governing Equilibrium Conditions

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

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

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

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

Variational Inequality Formulation of the Governing Equilibrium Conditions

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

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

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

Variants of the Model

Remark 1: Unit Tariffs

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

Variants of the Model

Remark 2: Strict Quotas

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

$$U_i^Q = \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} \hat{\rho}_l(Q) Q_{ihl} - \sum_{h \in \mathcal{J}_i} f_{ih}(Q) - \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} c_{ihl}(Q) - \sum_{G_g \in \mathcal{I}^i} \lambda^*_{G_g} \sum_{(h,l) \in G_g} Q_{ihl}, \tag{10}$$

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

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

Qualitative Properties

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

$$\langle F(X^*), X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{L}, \tag{12}$$

where X and $F(X)$ are $\mathcal{N}$-dimensional vectors, $\mathcal{L}$ is a closed, convex set, and F is a given continuous function from $\mathcal{L}$ to $R^{\mathcal{N}}$.

Qualitative Properties

Theorem 2: Existence of a Solution X^* to (12)

Existence of a solution X^* to the variational inequality governing the global supply chain network model with tariff rate quotas given by (12); equivalently, (8), is guaranteed.

Proposition 1: Monotonicity of $F(X)$ in (12)

$F(X)$ in (12) is monotone, that is,

$$\langle F(X^1) - F(X^2), X^1 - X^2 \rangle \geq 0, \quad \forall X^1, X^2 \in \mathcal{L}, \tag{13}$$

if and only if $\hat{F}(X)$ is monotone, where the (i,h,l)-component of $\hat{F}(X)$, $\forall i,h,l$, consists of

$$\left[\sum_{j \in \mathcal{J}_i} \frac{\partial f_{ij}(Q)}{\partial Q_{ihl}} + \sum_{j \in \mathcal{J}_i} \sum_{k \in \mathcal{K}} \frac{\partial c_{ijk}(Q)}{\partial Q_{ihl}} - \hat{\rho}_l(Q) - \sum_{j \in \mathcal{J}_i} \sum_{k \in \mathcal{K}} \frac{\partial \hat{\rho}_k(Q)}{\partial Q_{ihl}} Q_{ijk} \right]. \tag{14}$$

The Algorithm: The Modified Projection Method

Path Flows

For each Q_{ihl} with (h,l) **associated with a group G_g**, $\forall g$, compute:

$$\bar{Q}^t_{ihl} = \max\{0, \beta(-\sum_{j\in\mathcal{J}_i}\frac{\partial f_{ij}(Q^{t-1})}{\partial Q_{ihl}} - \sum_{j\in\mathcal{J}_i}\sum_{k\in\mathcal{K}}\frac{\partial c_{ijk}(Q^{t-1})}{\partial Q_{ihl}} + \hat{\rho}_l(Q^{t-1})$$

$$+\sum_{j\in\mathcal{J}_i}\sum_{k\in\mathcal{K}}\frac{\partial\hat{\rho}_k(Q^{t-1})}{\partial Q_{ihl}}Q^{t-1}_{ijk} - \tau^u_{G_g} - \lambda^{t-1}_{G_g}) + Q^{t-1}_{ihl}\}, \quad (15a)$$

and for each Q_{ihl} with (h,l) **not associated with a tariff rate quota group**, compute:

$$\bar{Q}^t_{ihl} = \max\{0, \beta(-\sum_{j\in\mathcal{J}_i}\frac{\partial f_{ij}(Q^{t-1})}{\partial Q_{ihl}} - \sum_{j\in\mathcal{J}_i}\sum_{k\in\mathcal{K}}\frac{\partial c_{ijk}(Q^{t-1})}{\partial Q_{ihl}} + \hat{\rho}_l(Q^{t-1})$$

$$+\sum_{j\in\mathcal{J}_i}\sum_{k\in\mathcal{K}}\frac{\partial\hat{\rho}_k(Q^{t-1})}{\partial Q_{ihl}}Q^{t-1}_{ijk}) + Q^{t-1}_{ihl}\}. \quad (15b)$$

The Quota Rent Equivalents

The closed form expression for the quota rent equivalent for group G_g; $g = 1, \ldots, n_G$, is:

$$\bar{\lambda}^t_{G_g} = \max\{0, \min\{\beta(\sum_{i=1}^{I}\sum_{(h,l)\in G_g} Q^{t-1}_{ihl} - \bar{Q}_{G_g}) + \lambda^{t-1}_{G_g}, \tau^o_{G_g} - \tau^u_{G_g}\}\}. \quad (16)$$

Case Study on Avocados

- Mexico produces more avocados than any other country in the world, about a third of the global total.
- Mexico exported more than 1.7 billion pounds of Haas avocados to the US.
- With about 90% of the avocados imported from Mexico to the United States coming from Michoacan.
- The Mexican state of Jalisco, the second-largest avocado-producing state in Mexico, accounts for about 6 percent of total Mexican production.

Case Study on Avocados

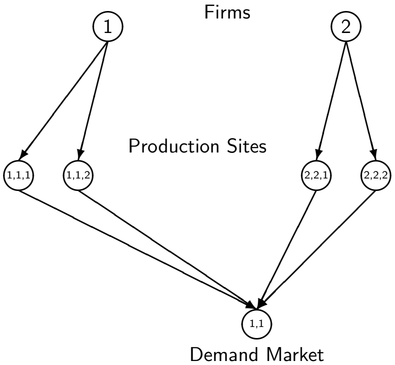
- The volume of avocado imports into the United States has surpassed even the volume by weight of bananas imported into the United States.
- US domestic avocado consumption has risen to approximately 6.5 pounds per person annually, as compared to only 1.4 in 1990.
- The United States is among the world's top ten avocado producers, producing between 160,000 and 270,000 tons of avocados a year.
- In terms of other major demand markets, Mexico was the largest supplier of avocados to China until 2017.

Case Study on Avocados

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

Example 1: Baseline Example Without Tariff Rate Quotas

- Firm 1 has two US production sites: one in San Diego county, and the other in San Luis Obispo in California.
- Firm 2 also has two production sites available, but located in Mexico, in Michoacan and Jalisco, respectively.
- There is a single demand market in this example, located in the United States.
- We are interested in determining the equilibrium avocado product flows: Q^*_{111}, Q^*_{121}, Q^*_{231}, and Q^*_{241}.



Example 1: Baseline Example Without Tariff Rate Quotas

- The production cost functions faced by Firm 1 at its two production sites are, respectively:

$$f_{11}(Q) = .005Q_{111}^2 + .8Q_{111}, \quad f_{12}(Q) = .01Q_{121}^2 + 1.1Q_{121}.$$

- The transportation cost functions associated with Firm 1 transporting the avocados to the demand market are:

$$c_{111}(Q) = .1Q_{111}^2 + .5Q_{111}, \quad c_{121}(Q) = .1Q_{121}^2 + .4Q_{121}.$$

- The production cost functions faced by Firm 2, with the production sites at the two locations in Mexico, are, respectively:

$$f_{23}(Q) = .0005Q_{231}^2 + .15Q_{231}, \quad f_{24}(Q) = .0005Q_{241}^2 + .5Q_{241},$$

and its transportation costs to the demand market are:

$$c_{231}(Q) = .04Q_{231}^2 + .5Q_{231}, \quad c_{241}(Q) = .045Q_{241}^2 + .5Q_{241}.$$

- The demand price function is:

$$\rho_1(d) = -.01d_1 + 3.$$

Equilibrium Product Flows, Demand Prices, and Profits

- The modified projection method yielded the equilibrium avocado product flow pattern:

$$Q^*_{111} = 5.63, \quad Q^*_{121} = 4.52, \quad Q^*_{231} = 20.75, \quad Q^*_{241} = 15.24.$$

- Demand price per pound of avocados is $\rho_1 = 2.54$.
- Firm 1 achieves a utility (profit) of **6.09 in millions of dollars** whereas Firm 2 enjoys a utility (profit) of **34.63 in millions** of dollars.

Example 2: Tariff Rate Quotas on Avocados from Mexico

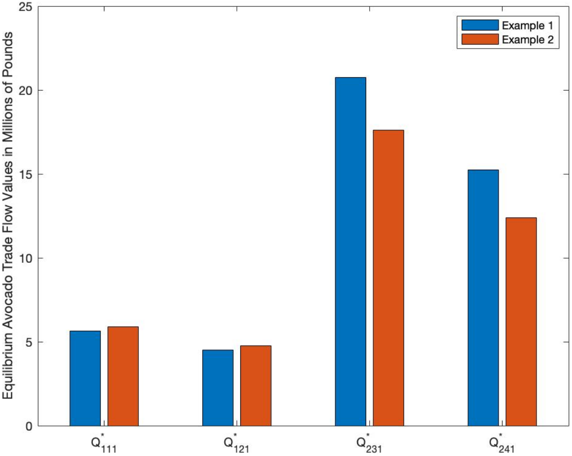
- The United States assigns the tariff rate quota on group G_1, which consists of the Mexican production sites that ship to the United States, and the demand market.
- In this example, $\bar{Q}_1 = 30$, $\tau^u_{G_1} = .25$ and $\tau^o_{G_1} = .50$.
- Equilibrium avocado product trade flow and economic rent equivalent patterns are:

$$Q^*_{111} = 5.88, \quad Q^*_{121} = 4.76, \quad Q^*_{231} = 17.60, \quad Q^*_{241} = 12.40,$$

$$\lambda^*_{G_1} = .09.$$

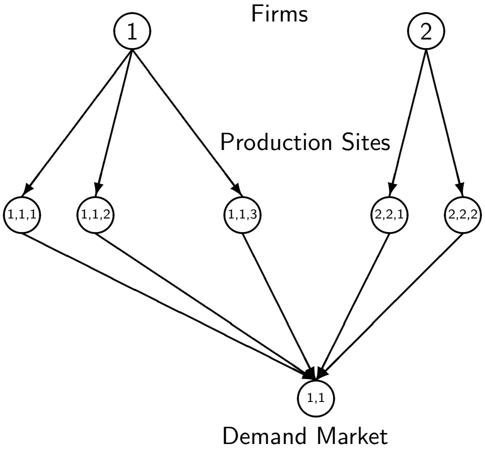
- The demand market price per pound of avocados is: $\rho_1 = 2.59$.
- The utility (profit) of Firm 1 is: 6.69 in millions of dollars and that of Firm 2: 24.18 in millions of dollars.
- The US government acquires tariff payments of 10.24 in millions of dollars.

Equilibrium Avocado Trade Flows in Example 1 and in Example 2



Example 3: Addition of a New Production Site in the United States

- Example 3 has the same data as Example 2 except that now Firm 1 has added a production site in Florida.



Example 3: Addition of a New Production Site in the United States

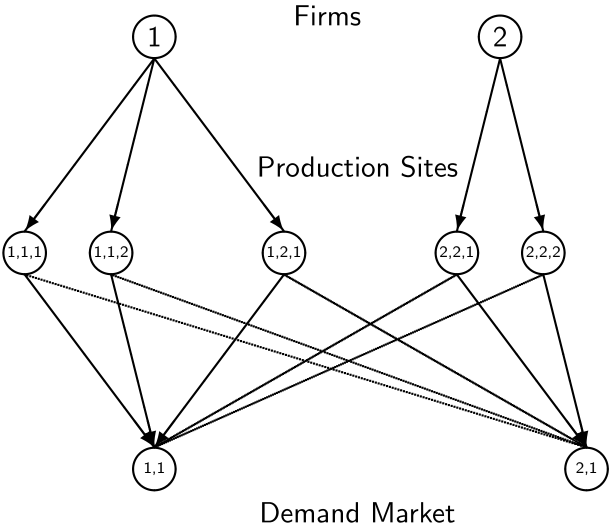
- The new computed equilibrium avocado product flow pattern is:

$$Q^*_{111} = 5.57, \quad Q^*_{121} = 4.45, \quad Q^*_{151} = 7.56, \quad Q^*_{231} = 17.60,$$
$$Q^*_{241} = 12.40.$$

- The volume of imports from Mexico remain at the quota $\bar{G}_1 = 30$ million pounds and the equilibrium $\lambda^*_{G_1} = .02$.
- The utility (profit) of Firm 1 is now 12.36 in millions of dollars and 24.18 for Firm 2 in millions of dollars.
- The US government now acquires tariff payments of 8.10 in millions of dollars.

Example 4: Addition of a New Demand Market in China

There has been growing interest among consumers in China for avocados.



Example 4: Addition of a New Demand Market in China

- The new computed equilibrium avocado product flow pattern is:

$$Q^*_{111} = 5.03, \quad Q^*_{112} = 13.33, \quad Q^*_{121} = 3.48, \quad Q^*_{122} = 11.96,$$

$$Q^*_{151} = 7.60, \quad Q^*_{152} = 1.07,$$

$$Q^*_{231} = 17.51, \quad Q^*_{232} = 40.09, \quad Q^*_{241} = 12.49, \quad Q^*_{242} = 21.82.$$

- The incurred demand market prices at the equilibrium in the United States and China are $\rho_1 = 2.54$ and $\rho_2 = 6.12$, respectively.
- The utility (profit) of Firm 1 is now 68.35 and that of Firm 2 is: 174.97.
- The imports from Mexico to the United States are at the quota with $\lambda^*_{G_1} = .01$.
- The US government income from tariff payments is now: 7.8 in millions of dollars.

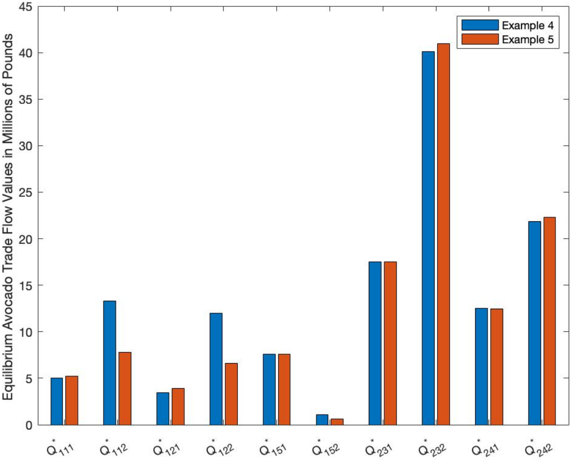
Example 5: Tariff Rate Quota Imposed by China on Imports from the United States

- G_2 consists of the production sites corresponding to the United States and the demand market in China.
- The added data are: $\bar{Q}_{G_2} = 15$, $\tau^u_{G_2} = 1$ and $\tau^o_{G_2} = 2$.
- The modified projection method yielded the following equilibrium avocado product flow pattern:

$$Q^*_{111} = 5.25, \quad Q^*_{112} = 7.80, \quad Q^*_{121} = 3.92, \quad Q^*_{122} = 6.58,$$
$$Q^*_{151} = 7.58, \quad Q^*_{152} = .63,$$
$$Q^*_{231} = 17.50, \quad Q^*_{232} = 40.99, \quad Q^*_{241} = 12.48, \quad Q^*_{242} = 22.30.$$

- The demand prices are: $\rho_1 = 2.53$ for a pound of avocados in the United States and $\rho_2 = 6.22$ for a pound of avocados in China.
- The equilibrium economic rents are: $\lambda^*_{G_1} = 0.00$ and $\lambda^*_{G_2} = .87$.
- Firm 1 now has a reduced utility (profit) of 30.60 in millions of dollars, whereas Firm 2 has a utility (profit) of 181.67 in millions of dollars.

Equilibrium Avocado Trade Flows in Example 4 and in Example 5

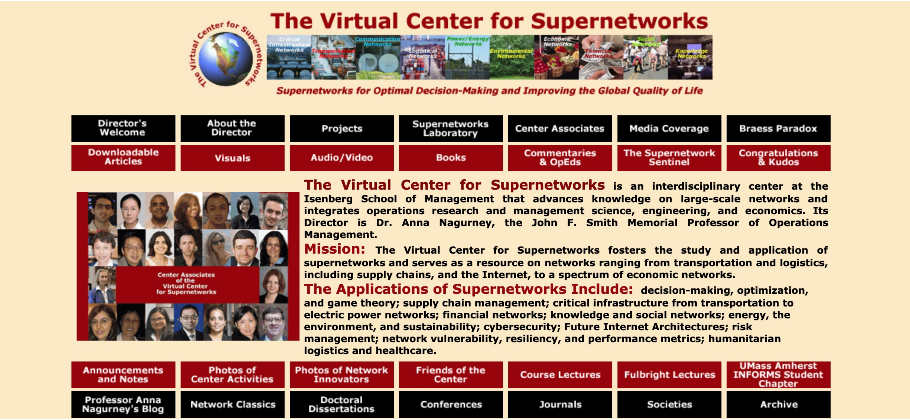


Summary and Conclusions

- We constructed a modeling and computational framework for competitive global supply chain networks in the presence of trade policies in the form of tariff rate quotas.
- To-date, there has been limited modeling work integrating oligopolistic firms, competing globally, in the presence of such trade policies, which have been challenging to model.
- The theoretical framework utilized for the formulation, analysis, and computation of the equilibrium product flow and economic rent equivalent patterns is the theory of variational inequalities.
- The numerical examples that comprise the case study quantify impacts of tariff rate quotas on consumer prices, on product flows, as well as on the firms' profits.
- The results demonstrate that TRQs can be effective in reducing product flows from countries on which they are imposed but at the expense of the consumers in terms of prices.

Questions and Comments

THANK YOU!



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