Strict Quotas or Tariffs? Implications for Product Quality and Consumer Welfare in Differentiated Product Supply Chains

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2019 INFORMS Annual Meeting, Seattle, WA

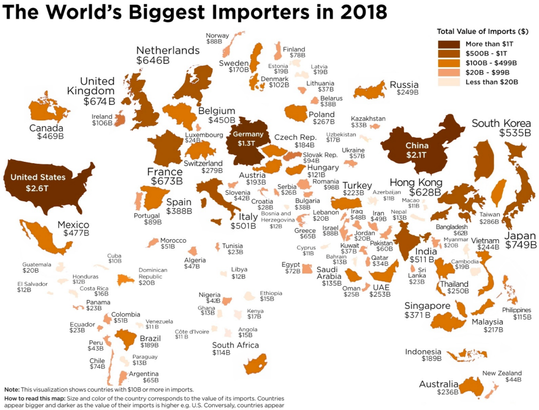
This presentation is based on the paper:

Nagurney, A., Besik, D., Li, D., 2019. Strict Quotas or Tariffs? Implications for Product Quality and Consumer Welfare in Differentiated Product Supply Chains. *Transportation Research - Part E*, 29, 136-161.

Outline

- Background and Motivation
- The Differentiated Product Supply Chain Network Equilibrium Models with Quality
- Algorithm
- Numerical Examples
- Summary

Due to the importance of global trade to both producers and consumers, a variety of products have been subject to **trade policy instruments** imposed by governments.



Background and Motivation

- The United States has imposed **tariffs** on steel. The response from the European Union was to impose **quotas** (cf. Meyer (2019)).
- Numerous **tariffs** were imposed by the United States on goods from China in 2018 including: food, toilet paper, hats, backpacks, beauty care products, sporting goods, home improvement items, and pet products, valued at $200 billion in Chinese imports (Shively (2018)).
- China then retaliated with their government deciding to impose **tariffs** of 5% to 10% on $60 billion worth of U.S. products. The tariffs apply to 5,207 items (Kuhn (2018)).

Background and Motivation

The determination of the effects of trade instruments on **product quality** and **consumer welfare**, however, has been less-researched and has been the subject of debates.

- As noted in Hallak (2006), growing evidence reveals that there are large differences across countries in terms of the quality of products that they produce and export.
- A rich theoretical literature predicts the important role of product quality in global trade.

Background and Motivation - Research Questions

- Is there any correlation between the **strict quota and the unit tariff schemes**? Are they equivalent under certain conditions?
- Do **firms benefit** from the imposition of a specific strict quota or unit tariff?
- What are the **impacts on demands, prices, and product quality** as the imposed strict quota or unit tariff changes?
- Do consumers at different demand markets gain more welfare from the imposition of a strict quota or a unit tariff? What is the impact on **consumer welfare** as the quota or tariff changes?
- Under the imposition of a strict quota or unit tariff, in order to be more profitable in competition with other firms, how should firms adjust the **locations of production facilities and demand markets** in their supply chain networks?

Background and Motivation - Literature Review

There have been studies conducted to assess the interrelationships between **a spectrum of trade policies and product quality** as in cheese (cf. Macieira and Grant (2014)), the steel industry (Boorstein and Feenstra (1991)), the footwear industry (Aw and Roberts (1986)), and the automobile industry (cf. Feenstra (1988) and Goldberg (1993)).

- These works have focused on a **monopoly** (Krishna (1987)), or on a **duopoly** (Das and Donnenfeld (1989) and Herguera, Kujal, and Petrakis (2000)), or on **perfect competition** (Falvey (1979)).
- Researchers have, typically, assumed exogenously **fixed product qualities** or **homogeneous** goods (Leland (1979), Shapiro (1983), and Deneckere, Kovenock, and Sohn (2000)).

Background and Motivation - Overview

- We formulate a competitive supply chain network model in which producers have **multiple production sites** and seek to determine both the **product flows and the quality levels** of the product at the production sites so as to maximize profits.
- The consumers, in turn, reflect their preferences for the firms' **differentiated products** through the **prices** that they are willing to pay at the demand markets.
- We then add trade policy instruments in the form of a **strict quota or a tariff** on a specific product in a group consisting of production sites in a country, imposed by another country.
- We also provide constructs for quantifying **consumer welfare in the presence or absence of tariffs or quotas** in differentiated product supply chain networks with quality.
- We propose an effective algorithm, which is then applied to a series of numerical examples that are focused on the agricultural product of **soybeans**.

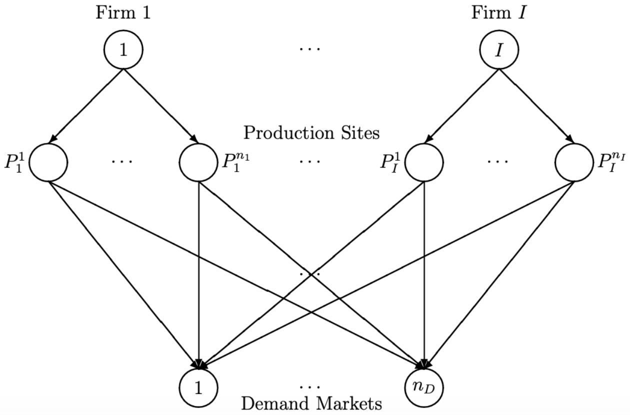


Figure: The Differentiated Product Supply Chain Network Topology

Conservation of Flows Equations

$$s_{ij} = \sum_{k=1}^{n_D} Q_{ijk}, \quad i = 1, \ldots, I; j = 1, \ldots, n_i, \tag{1}$$

$$d_{ik} = \sum_{j=1}^{n_i} Q_{ijk}, \quad k = 1, \ldots, n_D. \tag{2}$$

Nonnegative Quantities

$$Q_{ijk} \geq 0, \quad i = 1, \ldots, I; j = 1, \ldots, n_i; k = 1, \ldots, n_D. \tag{3}$$

Quality Levels

$$\bar{q}_{ij} \geq q_{ij} \geq \underline{q}_{ij}, \quad i = 1, \ldots, I; j = 1, \ldots, n_i. \tag{4}$$

Production Cost

$$\hat{f}_{ij} = \hat{f}_{ij}(Q, q) \equiv f_{ij}(s, q), \quad i = 1, \ldots, I; j = 1, \ldots, n_i, \tag{5}$$

Demand Price

$$\hat{\rho}_{ik} = \hat{\rho}_{ik}(Q, q) \equiv \rho_{ik}(d, \hat{q}), \quad k = 1, \ldots, n_D. \tag{6}$$

Utility of Firm i

$$U_i = \sum_{k=1}^{n_D} \hat{\rho}_{ik}(Q,q) \sum_{j=1}^{n_i} Q_{ijk} - \sum_{j=1}^{n_i} \hat{f}_{ij}(Q,q) - \sum_{k=1}^{n_D} \sum_{j=1}^{n_i} \hat{c}_{ijk}(Q,q). \tag{7}$$

Definition 1

A product shipment and quality level pattern $(Q^*, q^*) \in K$ *is said to constitute a differentiated product supply chain network equilibrium with quality if for each firm* i*;* $i = 1, \ldots, I$*,*

$$U_i(Q_i^*, Q_{-i}^*, q_i^*, q_{-i}^*) \geq U_i(Q_i, Q_{-i}^*, q_i, q_{-i}^*), \quad \forall (Q_i, q_i) \in K^i, \tag{9}$$

where

$$Q_{-i}^* \equiv (Q_1^*, \ldots, Q_{i-1}^*, Q_{i+1}^*, \ldots, Q_I^*) \quad \textit{and}$$
$$q_{-i}^* \equiv (q_1^*, \ldots, q_{i-1}^*, q_{i+1}^*, \ldots, q_I^*).$$

Theorem 1

Assume that for each firm i; $i = 1, \ldots, I$, the profit function $U_i(Q, q)$ is concave with respect to the variables in Q_i and q_i, and is continuous and continuously differentiable. Then the product shipment and quality pattern $(Q^*, q^*) \in K$ is a differentiated product supply chain network equilibrium with quality according to Definition 1 if and only if it satisfies the variational inequality

$$-\sum_{i=1}^{I}\sum_{j=1}^{n_i}\sum_{k=1}^{n_D}\frac{\partial U_i(Q^*,q^*)}{\partial Q_{ijk}}\times(Q_{ijk}-Q^*_{ijk})-\sum_{i=1}^{I}\sum_{j=1}^{n_i}\frac{\partial U_i(Q^*,q^*)}{\partial q_{ij}}\times(q_{ij}-q^*_{ij})\geq 0,\forall(Q,q)\in K, \quad (10)$$

that is,

$$\sum_{i=1}^{I}\sum_{j=1}^{n_i}\sum_{k=1}^{n_D}\left[-\hat{\rho}_{ik}(Q^*,q^*)-\sum_{l=1}^{n_D}\frac{\partial\hat{\rho}_{il}(Q^*,q^*)}{\partial Q_{ijk}}\sum_{h=1}^{n_i}Q^*_{ihl}+\sum_{h=1}^{n_i}\frac{\partial\hat{f}_{ih}(Q^*,q^*)}{\partial Q_{ijk}}\right.$$

$$\left.+\sum_{h=1}^{n_i}\sum_{l=1}^{n_D}\frac{\partial\hat{c}_{ihl}(Q^*,q^*)}{\partial Q_{ijk}}\right]\times(Q_{ijk}-Q^*_{ijk})$$

$$+\sum_{i=1}^{I}\sum_{j=1}^{n_i}\left[-\sum_{k=1}^{n_D}\frac{\partial\hat{\rho}_{ik}(Q^*,q^*)}{\partial q_{ij}}\sum_{h=1}^{n_i}Q^*_{ihk}+\sum_{h=1}^{n_i}\frac{\partial\hat{f}_{ih}(Q^*,q^*)}{\partial q_{ij}}+\sum_{h=1}^{n_i}\sum_{k=1}^{n_D}\frac{\partial\hat{c}_{ihk}(Q^*,q^*)}{\partial q_{ij}}\right]$$

$$\times(q_{ij}-q^*_{ij})\geq 0,\quad\forall(Q,q)\in K. \quad (11)$$

Strict Quota Regime

$$\sum_{i=1}^{I} \sum_{(j,k)\in\mathcal{G}} Q_{ijk} \leq \bar{Q}. \tag{12}$$

The Differentiated Product Supply Chain Network Equilibrium Model with a Strict Quota - GNE

Definition 2

A product shipment and quality level pattern $(Q^*, q^*) \in K \cap \mathcal{S}$ *is a differentiated product supply chain Generalized Nash Network Equilibrium with quality if for each firm* i*;* $i = 1, \ldots, I$,

$$U_i(Q_i^*, Q_{-i}^*, q_i^*, q_{-i}^*) \geq U_i(Q_i, Q_{-i}^*, q_i, q_{-i}^*), \quad \forall (Q_i, q_i) \in K^i \cap \mathcal{S}. \tag{14}$$

Corollary 1

A vector $(Q^*, q^*) \in K \cap \mathcal{S}$ *is said to be a variational equilibrium of the above Generalized Nash Network Equilibrium if it is a solution of the variational inequality*

$$-\sum_{i=1}^{I}\sum_{(j,k)\notin\mathcal{G}}\frac{\partial U_i(Q^*,q^*)}{\partial Q_{ijk}}\times(Q_{ijk}-Q^*_{ijk})+\sum_{i=1}^{I}\sum_{(j,k)\in\mathcal{G}}\left(-\frac{\partial U_i(Q^*,q^*)}{\partial Q_{ijk}}+\lambda^*\right)$$

$$\times(Q_{ijk}-Q^*_{ijk})-\sum_{i=1}^{I}\sum_{j=1}^{n_i}\frac{\partial U_i(Q^*,q^*)}{\partial q_{ij}}\times(q_{ij}-q^*_{ij})$$

$$+(\bar{Q}-\sum_{i=1}^{I}\sum_{(j,k)\in\mathcal{G}}Q^*_{ijk})\times(\lambda-\lambda^*)\geq 0,\quad \forall(Q,q,\lambda)\in\mathcal{K}, \tag{16}$$

where $(Q^*, q^*, \lambda^*) \in \mathcal{K}$.

Unit Tariff Scheme

$$\hat{U}_i = U_i - \sum_{i=1}^{I} \sum_{(j,k)\in\mathcal{G}} \tau^* Q_{ijk}, \qquad (17)$$

with U_i; $i = 1, \ldots, I$, as in (7).

Theorem 2

A product shipment and quality pattern $(Q^*, q^*) \in K$ is a differentiated product supply chain network equilibrium according to Definition 1 with $\hat{U}_i$ replacing U_i for $i = 1, \ldots, I$, if and only if it satisfies the variational inequality:

$$-\sum_{i=1}^{I} \sum_{(j,k) \notin \mathcal{G}} \frac{\partial U_i(Q^*, q^*)}{\partial Q_{ijk}} \times (Q_{ijk} - Q^*_{ijk}) + \sum_{i=1}^{I} \sum_{(j,k) \in \mathcal{G}} \left(-\frac{\partial U_i(Q^*, q^*)}{\partial Q_{ijk}} + \tau^*\right)$$

$$\times (Q_{ijk} - Q^*_{ijk}) - \sum_{i=1}^{I} \sum_{j=1}^{n_i} \frac{\partial U_i(Q^*, q^*)}{\partial q_{ij}} \times (q_{ij} - q^*_{ij}) \geq 0, \forall (Q, q) \in K. \quad (18)$$

We have established the following equivalence.

- When the strict quota constraint (i.e., (12)) is **tight**, the equilibrium pattern of the VI with the strict quota also satisfies the one with a tariff. This result requires that the tariff be imposed on the same product shipment group as the strict quota and set to the equilibrium Lagrange multiplier associated with the strict quota constraint.

- The above relationship also provides a nice interpretation for the **Lagrange multiplier** associated with the strict quota in that it is a price or, in effect, a tariff.

Consumer Welfare Measure

$$CW_{ik} = \int_0^{d_{ik}^*} \rho_{ik}(d_{-ik}^*, d_{ik}, \hat{q}^*)\,\mathrm{d}(d_{ik}) - \rho_{ik}(d^*, \hat{q}^*)d_{ik}^*,$$

$$i = 1, \ldots, I;\ k = 1, \ldots, n_D, \tag{24}$$

where $d_{-ij}^* \equiv (d_{11}^*, \ldots, d_{i,j-1}^*, d_{i,j+1}^*, \ldots, d_{mn}^*)$ (cf. Spence (1975) and Wildman (1984)).

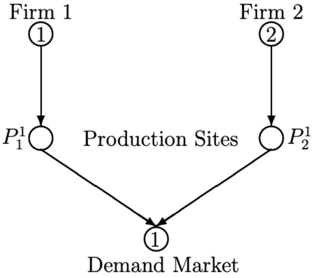


Figure: The Differentiated Product Supply Chain Network Topology for the Illustrative Examples

The conservation of flow equations are:

$$s_{11} = d_{11} = Q_{111}, \quad s_{21} = d_{21} = Q_{211}.$$

The production costs of Firm 1 and Firm 2 are:

$$\hat{f}_{11}(Q,q) = Q_{111}^2 + 3Q_{111} + q_{11}, \quad \hat{f}_{21}(Q,q) = Q_{211}^2 + Q_{211} + 0.5q_{21}^2.$$

The transportation cost functions are:

$$\hat{c}_{111}(Q,q) = Q_{111}^2 + 0.5Q_{111} + q_{11}, \quad \hat{c}_{211}(Q,q) = Q_{211}^2 + Q_{211} + 2q_{21}.$$

The average quality level expressions are:

$$\hat{q}_{11} = \frac{q_{11}Q_{111}}{Q_{111}} = q_{11}, \quad \hat{q}_{21} = \frac{q_{21}Q_{211}}{Q_{211}} = q_{21}.$$

We set the quality upper bounds as: $\bar{q}_{11} = \bar{q}_{21} = 100$. The minimum quality standards are: $\underline{q}_{11} = \underline{q}_{21} = 0.8$. The demand price functions for the products of Firm 1 and Firm 2 at the demand market are:

$$\hat{\rho}_{11}(Q,q) = -(Q_{111} + Q_{211}) + 0.5q_{11} + 20, \quad \hat{\rho}_{21}(Q,q) = -(Q_{211} + Q_{111}) + q_{21} + 25.$$

$$Q^*_{111} = 4.00, \quad Q^*_{211} = 3.40, \quad q^*_{11} = \hat{q}_{11} = 21.80, \quad q^*_{21} = \hat{q}_{21} = 1.40.$$

The demand prices at equilibrium, in dollars, are: $\rho_{11} = 23.50$ and $\rho_{21} = 19.00$. The profits of the firms, in dollars, are: $U_1 = 4.40$ and $U_2 = 30.90$.

The consumer welfare associated with the two firms' products is, respectively, $CW_{11} = 8.00$ and $CW_{21} = 5.78$.

$$Q_{211} \leq 3.$$

$$Q^*_{111} = 4.00, \quad Q^*_{211} = 3.00, \quad q^*_{11} = \hat{q}_{11} = 21.00, \quad q^*_{21} = \hat{q}_{21} = 1.00.$$

The demand prices at equilibrium of Firm 1 and Firm 2 are: $\rho_{11} = 23.50$ and $\rho_{21} = 19.00$. The profits of the firms are now: $U_1 = 6.00$ and $U_2 = 24.50$. In addition, the consumer welfare associated with the firms' products is now: $CW_{11} = 8.00$ and $CW_{21} = 4.50$.

$$\lambda^* = 2.00.$$

$$Q^*_{111} = 4.00, \quad Q^*_{211} = 3.00, \quad q^*_{11} = \hat{q}_{11} = 21.00, \quad q^*_{21} = \hat{q}_{21} = 1.00.$$

The demand prices at equilibrium of Firm 1 and Firm 2 are: $\rho_{11} = 23.50$ and $\rho_{21} = 19.00$. The profits of the firms are now: $U_1 = 6.00$ and $U_2 = 24.50$. In addition, the consumer welfare associated with the firms' products is now: $CW_{11} = 8.00$ and $CW_{21} = 4.50$.

The Algorithm

The Modified Projection Method

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

Step 1: Computation
Compute $\bar{X}^t$ by solving the variational inequality subproblem:

$$\langle \bar{X}^t + \beta F(X^{t-1}) - X^{t-1}, X - \bar{X}^t \rangle \geq 0, \quad \forall X \in \mathcal{K}. \tag{35}$$

Step 2: Adaptation
Compute X^t by solving the variational inequality subproblem:

$$\langle X^t + \beta F(\bar{X}^t) - X^{t-1}, X - X^t \rangle \geq 0, \quad \forall X \in \mathcal{K}. \tag{36}$$

Step 3: Convergence Verification
If $|X^t - X^{t-1}| \leq \epsilon$, with $\epsilon > 0$, a pre-specified tolerance, then stop; otherwise, set $t := t + 1$ and go to Step 1.

Numerical Examples - Background

- The US is a leader in producing, consuming, and exporting soybeans globally (Song, Xu, and Marchant (2004)). In the US, soybean **production and export** have become essential parts of the agricultural economy. In 2018, soybean production in the United States reached 5.11 billion bushels with an export of 2.13 billion bushels (Lundgren (2018)).
- China is the **largest importer** of soybeans due to its population size (Brown (2012)). The consumption of soybeans in China, in 2017, was reported to be 112.18 million tons, but the domestic production volume was only 13 million tons (Wood (2018)).
- In 2018, the Chinese government imposed **quotas and tariffs** on the soybeans exported from the United States (Wong and Koty (2019)). This created an opportunity for other large soybean exporters, such as **Brazil and Argentina**. In 2017, Brazil exported 53.8 million tons of soybeans to China, corresponding to **75%** of its production volume (Zhou et al. (2018)). Shane (2018) claims that the Chinese importer, Hebei Power Sea Feed Technology, bought thousands of tons of soybeans for animal feed from Brazil instead of the United States in 2018.

- Example 1
- Example 2 (Example 1 with a Strict Quota)
  - Sensitivity analysis
    - Changes of Quality Coefficient in a Cost Functions
    - Changes in the Strict Quota
- Example 3 (Example 1 with Tariffs)
  - Sensitivity analysis
    - Changes in Tariffs
- Example 4 (Example 2 with one Production Site Shutdown)
- Example 5 (Example 1 with a New Demand Market)
- Example 6 (Example 5 with a Strict Quota)

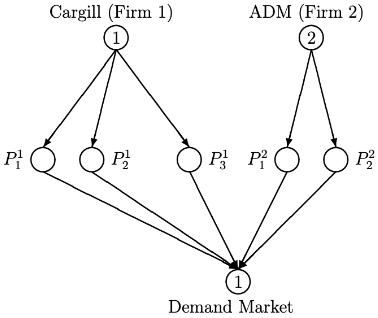


Figure: The Differentiated Product Supply Chain Network Topology for Example 1

The production cost functions of Cargill at its production sites, P_1^1, P_2^1, and P_3^1 are:

$$\hat{f}_{11}(Q_{111}, q_{11}) = 0.04Q_{111}^2 + 0.35Q_{111} + 0.4Q_{111}q_{11} + 0.6q_{11}^2,$$

$$\hat{f}_{12}(Q_{121}, q_{12}) = 0.05Q_{121}^2 + 0.35Q_{121} + 0.4Q_{121}q_{12} + 0.4q_{12}^2,$$

$$\hat{f}_{13}(Q_{131}, q_{13}) = 0.05Q_{131}^2 + 0.8Q_{131} + 0.4Q_{131}q_{13} + 0.4q_{13}^2.$$

The production cost functions faced by ADM at its production sites, P_1^2 and P_2^2, are:

$$\hat{f}_{21}(Q_{211}, q_{21}) = 0.06Q_{211}^2 + 0.5Q_{211} + 1.2Q_{211}q_{21} + q_{21}^2,$$

$$\hat{f}_{22}(Q_{221}, q_{22}) = 0.07Q_{221}^2 + 0.3Q_{221} + 1.3Q_{221}q_{22} + 1.5q_{22}^2.$$

The total transportation cost functions associated with Cargill for shipping its soybeans to Demand Market 1 are:

$$\hat{c}_{111}(Q_{111}, q_{11}) = 0.02Q_{111}^2 + 0.2Q_{111} + 0.5q_{11}^2, \quad \hat{c}_{121}(Q_{121}, q_{12}) = 0.02Q_{121}^2 + 0.4Q_{121} + 0.8q_{12}^2,$$

$$\hat{c}_{131}(Q_{131}, q_{13}) = 0.02Q_{131}^2 + 0.5Q_{131} + 0.8q_{13}^2,$$

and ADM's total transportation cost functions are:

$$\hat{c}_{211}(Q_{211}, q_{21}) = 0.02Q_{211}^2 + 0.5Q_{211} + 0.6q_{21}^2, \quad \hat{c}_{221}(Q_{221}, q_{22}) = 0.02Q_{221}^2 + 0.4Q_{221} + 0.8q_{22}^2.$$

The demand price functions for the soybeans of Cargill and ADM at Demand Market 1 are:

$$\rho_{11}(d, \hat{q}) = 1500 - (0.3d_{11} + 0.2d_{21}) + 0.7\hat{q}_{11},$$

$$\rho_{21}(d, \hat{q}) = 1600 - (0.35d_{21} + 0.3d_{11}) + 2\hat{q}_{21},$$

with the average quality $\hat{q}_{11}$ and $\hat{q}_{21}$ being:

$$\hat{q}_{11} = \frac{Q_{111}q_{11} + Q_{121}q_{12} + Q_{131}q_{13}}{Q_{111} + Q_{121} + Q_{131}}, \quad \hat{q}_{21} = \frac{Q_{211}q_{21} + Q_{221}q_{22}}{Q_{211} + Q_{221}}.$$

Furthermore, the upper and lower bounds of quality levels are:

$$\bar{q}_{11} = \bar{q}_{12} = \bar{q}_{13} = \bar{q}_{21} = \bar{q}_{22} = 100,$$

$$\underline{q}_{11} = \underline{q}_{12} = \underline{q}_{13} = \underline{q}_{21} = \underline{q}_{22} = 10.$$

Equilibrium Flows	Results	Equilibrium Quality	Results
Q^*_{111}	756.70	q^*_{11}	100.00
Q^*_{121}	591.26	q^*_{12}	73.91
Q^*_{131}	585.90	q^*_{13}	73.24
Q^*_{211}	779.32	q^*_{21}	100.00
Q^*_{221}	612.32	q^*_{22}	93.18

Demand	Results	Average Quality	Results
d^*_{11}	1,933.86	$\hat{q}_{11}$	83.91
d^*_{21}	1,391.64	$\hat{q}_{21}$	97.00

Demand Price	Results	Consumer Welfare	Results	Profits	Results
ρ_{11}	700.25	CW_{11}	560,973.35	U_1	1,180,812.05
ρ_{21}	726.76	CW_{21}	338,916.81	U_2	724,196.08

Table: Results for Example 1

This example considers the same differentiated product supply chain network problem as in Example 1, but with the imposition of a strict quota of $\bar{Q} = 1200$ by the Chinese government on imports from US production sites, that is, the production site P_1^1 of Cargill and the production site P_1^2 of ADM. The equivalent tariff, is $\lambda^* = 29.91$.

Equilibrium Flows	Results	Equilibrium Quality	Results
Q_{111}^*	528.96	q_{11}^*	72.13
Q_{121}^*	697.99	q_{12}^*	87.25
Q_{131}^*	692.63	q_{13}^*	86.58
Q_{211}^*	671.04	q_{21}^*	100.00
Q_{221}^*	708.75	q_{22}^*	100.00

Demand	Results	Average Quality	Results
d_{11}^*	1,919.58	$\hat{q}_{11}$	82.84
d_{21}^*	1,379.79	$\hat{q}_{21}$	100.00

Demand Price	Results	Consumer Welfare	Results	Profits	Results
ρ_{11}	706.16	CW_{11}	552,718.33	U_1	1,181,876.72
ρ_{21}	741.20	CW_{21}	333,167.37	U_2	728,637.06

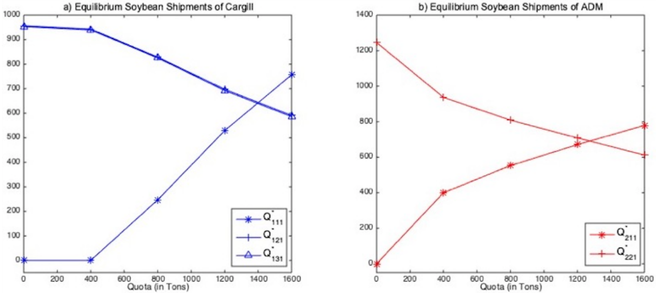
Table: Results for Example 2

Coeff. of q_{12}^2 in $\hat{f}_{12}$	**Quota**	Q_{111}^*	Q_{121}^*	Q_{131}^*	Q_{211}^*	Q_{221}^*	q_{11}^*	q_{12}^*	q_{13}^*	q_{21}^*	q_{22}^*
0.2	with	525.90	716.00	679.90	674.10	705.56	71.71	100.00	84.99	100.00	100.00
0.2	without	743.97	621.85	570.98	778.96	611.51	100	93.28	71.37	100.00	93.06
0.4	with	528.96	697.99	692.63	671.04	708.75	72.13	87.25	86.58	100.00	100.00
0.4	without	756.70	591.26	585.9	779.32	612.32	100.00	73.91	73.24	100.00	93.18
0.6	with	532.48	677.26	707.29	667.52	712.42	72.61	72.56	88.41	100.00	100.00
0.6	without	765.06	571.19	595.68	779.57	612.85	100.00	61.2	74.46	100.00	93.26
0.8	with	534.99	662.5	717.72	665.01	715.03	72.95	62.11	89.72	100.00	100.00
0.8	without	770.96	557.01	602.59	779.74	613.22	100.00	52.22	75.32	100.00	93.32
1.0	with	536.86	651.45	725.53	663.14	716.99	73.21	54.29	90.69	100.00	100.00
1.0	without	775.36	546.46	607.74	779.87	613.5	100.00	45.54	75.97	10.000	93.36

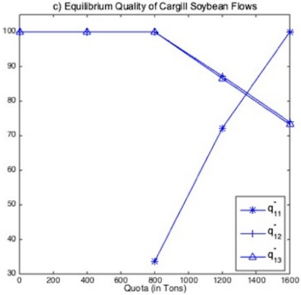
Table 8: Equilibrium Soybean Flows and Equilibrium Quality Levels with a Varying Quality Coefficient in $\hat{f}_{12}$ with and without the Strict Quota

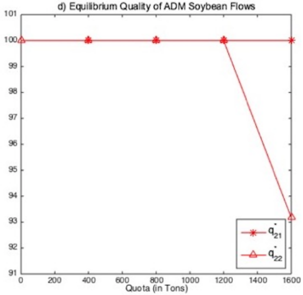
Coeff. of q_{12}^2 in $\hat{f}_{12}$	**Quota**	ρ_{11}	ρ_{21}	CW_{11}	CW_{21}	U_1	U_2
0.2	with	708.39	740.58	553996.44	333104.16	1183676.53	727808.73
0.2	without	703.45	726.19	562679.86	338344.67	1182645.7	722969.50
0.4	with	706.16	741.20	552718.33	333167.37	1181876.72	728637.06
0.4	without	700.25	726.76	560973.35	338916.81	1180812.05	724196.08
0.6	with	703.80	741.91	551248.08	333240.18	1180660.12	729587.16
0.6	without	698.39	727.14	559855.12	339292.45	1179609.38	725001.41
0.8	with	702.27	742.42	550202.67	333292.02	1179796.75	730260.94
0.8	without	697.20	727.41	559065.70	339557.98	1178759.8	725570.68
1.0	with	701.20	742.80	549421.21	333330.80	1179152.28	730763.64
1.0	without	696.36	727.61	558478.65	339755.64	1178127.73	725994.42

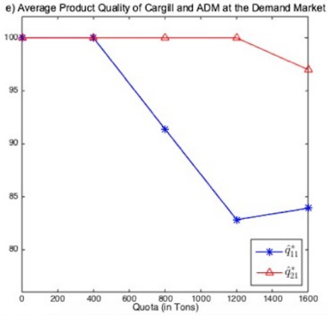
Table 9: Equilibrium Demand Prices, Consumer Welfare, and Profits with a Varying Quality Coefficient in $\hat{f}_{12}$ with and without the Strict Quota


a) Equilibrium Soybean Shipments of Cargill
Quota (in Tons)
b) Equilibrium Soybean Shipments of ADM
Quota (in Tons)

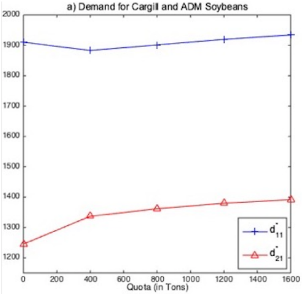
Sensitivity Analysis: Impacts of Changes in the Strict Quota

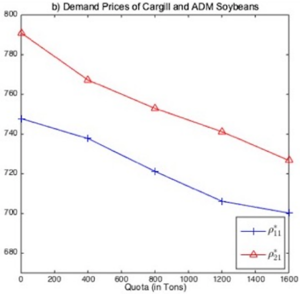




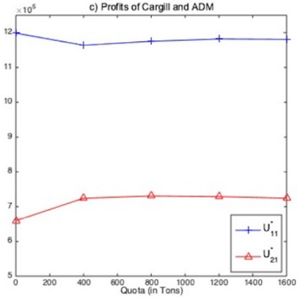

e) Average Product Quality of Cargill and ADM at the Demand Market
100
95
90
85
80
0
200
400
600
800
1000
1200
1400
1600
Quota (in Tons)
$\hat{q}^*_{11}$
$\hat{q}^*_{21}$

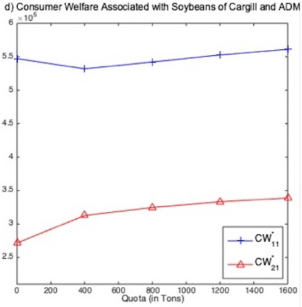
Sensitivity Analysis: Impacts of Changes in the Strict Quota



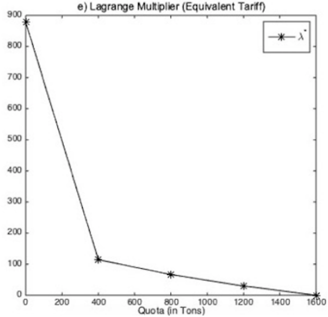


Sensitivity Analysis: Impacts of Changes in the Strict Quota





Sensitivity Analysis: Impacts of Changes in the Strict Quota



Numerical Examples - Example 3 (Example 1 with Tariffs on Soybeans from the United States)

In Example 3, we investigate numerically the impacts of tariffs imposed by China on soybeans from the United States. We consider the same supply chain topology and the same data as in Example 1. The tariff is $\tau^* = 10.00$ dollars on imports of soybeans from the United States.

Equilibrium Flows	Results	Equilibrium Quality	Results
Q^*_{111}	685.38	q^*_{11}	93.46
Q^*_{121}	624.46	q^*_{12}	78.06
Q^*_{131}	619.09	q^*_{13}	77.39
Q^*_{211}	735.79	q^*_{21}	100.00
Q^*_{221}	653.62	q^*_{22}	99.46

Demand	Results	Average Quality	Results
d^*_{11}	1,928.93	$\hat{q}_{11}$	83.32
d^*_{21}	1,389.42	$\hat{q}_{21}$	99.75

Demand Price	Results	Consumer Welfare	Results	Profits	Results
ρ_{11}	701.76	CW_{11}	558,116.66	U_1	1,174,437.42
ρ_{21}	734.52	CW_{21}	337,834.91	U_2	718,677.19

Table: Results for Example 3

τ^*	Q^*_{111}	Q^*_{121}	Q^*_{131}	Q^*_{211}	Q^*_{221}
20.00	606.79	661.38	656.02	702.79	681.92
29.90	528.96	697.99	692.63	671.04	708.75
40.00	449.69	735.28	729.91	638.70	736.07

τ^*	q^*_{11}	q^*_{12}	q^*_{13}	q^*_{21}	q^*_{22}	$\hat{q}_{11}$	$\hat{q}_{21}$
20.00	82.74	82.67	82.00	100.00	100.00	82.47	100.00
29.90	72.13	87.25	86.58	100.00	100.00	82.84	100.00
40.00	61.32	91.10	91.24	100.00	100.00	84.74	100.00

τ^*	d^*_{11}	d^*_{21}	ρ_{11}	ρ_{21}	CW_{11}	CW_{21}	U_1	U_2
20.00	1,924.19	1,384.71	703.53	738.09	555,378.50	335,548.02	1,169,791.64	713,460.32
29.90	1,919.58	1,379.79	706.16	741.20	552,718.33	333,167.37	1,166,059.22	708,571.37
40.00	1,914.88	1,374.78	709.71	744.36	550,015.49	330,751.37	1,163,040.11	703,900.27

Table: Sensitivity Analysis: Impact of Changes in Tariffs

Numerical Examples - Example 4 (Example 2 with Cargill's Production Site in the United States Shut Down)

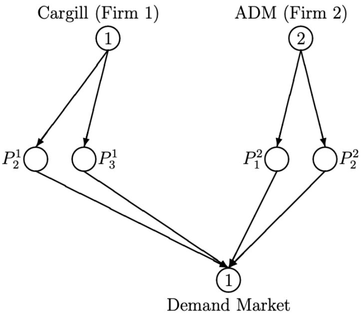


Figure: The Differentiated Product Supply Chain Network Topology for Example 4

Numerical Examples - Example 4 (Example 2 with Cargill's Production Site in the United States Shut Down)

Equilibrium Flows	Results	Equilibrium Quality	Results
Q^*_{111}	-	q^*_{11}	-
Q^*_{121}	930.73	q^*_{12}	100.00
Q^*_{131}	926.80	q^*_{13}	100.00
Q^*_{211}	788.93	q^*_{21}	100.00
Q^*_{221}	633.23	q^*_{22}	99.36

Demand	Results	Average Quality	Results
d^*_{11}	1,857.53	$\hat{q}_{11}$	100.00
d^*_{21}	1,422.16	$\hat{q}_{21}$	98.38

Demand Price	Results	Consumer Welfare	Results	Profits	Results
ρ_{11}	728.31	CW_{11}	517,560.59	U_1	1,131,885.86
ρ_{21}	741.75	CW_{21}	353,945.28	U_2	756,415.15

Table: Results for Example 4

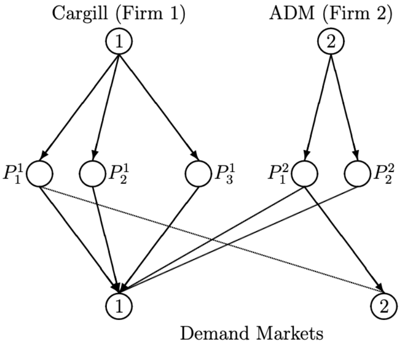


Figure: The Differentiated Product Supply Chain Network Topology for Example 5

Numerical Examples - Example 5 (Example 1 with a New Demand Market in the United States)

The total soybean production outputs:

$$s_{11} = Q_{111} + Q_{112}, \; s_{12} = Q_{121}, \; s_{13} = Q_{131}, \; s_{21} = Q_{211} + Q_{212}, \; s_{22} = Q_{221}.$$

The updated production cost functions of Cargill and ADM are:

$$f_{11}(s_{11}, q_{11}) = 0.04s_{11}^2 + 0.35s_{11} + 0.4s_{11}q_{11} + 0.6q_{11}^2, f_{12}(s_{12}, q_{12}) = 0.05s_{12}^2 + 0.35s_{12} + 0.4s_{12}q_{12} + 0.4q_{12}^2,$$

$$f_{13}(s_{13}, q_{13}) = 0.05s_{13}^2 + 0.8s_{13} + 0.4s_{13}q_{13} + 0.4q_{13}^2, f_{21}(s_{21}, q_{21}) = 0.06s_{21}^2 + 0.5s_{21} + 1.2s_{21}q_{21} + q_{21}^2,$$

$$f_{22}(s_{22}, q_{22}) = 0.07s_{22}^2 + 0.3s_{22} + 1.3s_{22}q_{22} + 1.5q_{22}^2.$$

The two additional total transportation cost functions are:

$$\hat{c}_{112}(Q_{112}, q_{11}) = 0.002Q_{112}^2 + 0.02Q_{112} + 0.8q_{11}^2, \qquad \hat{c}_{212}(Q_{212}, q_{21}) = 0.002Q_{212}^2 + 0.04Q_{212} + q_{21}^2.$$

The additional demand price functions for the soybeans of Cargill and ADM at Demand Market 2 are:

$$\rho_{12}(d, \hat{q}) = 1100 - (0.25d_{12} + 0.2d_{22}) + 0.9\hat{q}_{12}, \rho_{22}(d, \hat{q}) = 1400 - (0.3d_{22} + 0.25d_{12}) + 1.4\hat{q}_{22},$$

Numerical Examples - Example 5 (Example 1 with a New Demand Market in the United States)

Equilibrium Flows	Results	Equilibrium Quality	Results
Q^*_{111}	87.50	q^*_{11}	100.00
Q^*_{121}	913.30	q^*_{12}	100.00
Q^*_{131}	909.37	q^*_{13}	100.00
Q^*_{211}	150.11	q^*_{21}	77.79
Q^*_{221}	1,126.34	q^*_{22}	100.00
Q^*_{112}	1,469.53	-	-
Q^*_{212}	1,422.13	-	-

Demand	Results	Average Quality	Results
d^*_{11}	1,910.17	$\hat{q}_{11}$	100.00
d^*_{21}	1,276.44	$\hat{q}_{21}$	97.39
d^*_{12}	1,469.53	$\hat{q}_{12}$	100.00
d^*_{22}	1,422.13	$\hat{q}_{22}$	77.79

Demand Price	Results	Consumer Welfare	Results	Profits	Results
ρ_{11}	741.66	CW_{11}	547,310.17	U_1	1,809,217.78
ρ_{21}	774.97	CW_{21}	285,128.51	U_2	1,405,249.62
ρ_{12}	538.19	CW_{12}	269,938.75	-	-
ρ_{22}	714.89	CW_{22}	303,368.87	-	-

Table: Results for Example 5

In Example 6, we consider the same supply chain topology and the data as in Example 5, but we assume that China now imposes a strict quota of $\bar{Q} = 100$ on its imports from the United States.

Equilibrium Flows	Results	Equilibrium Quality	Results
Q^*_{111}	19.30	q^*_{11}	100.00
Q^*_{121}	945.79	q^*_{12}	100.00
Q^*_{131}	941.86	q^*_{13}	100.00
Q^*_{211}	80.70	q^*_{21}	67.35
Q^*_{221}	1,182.64	q^*_{22}	100.00
Q^*_{112}	1,476.77	-	-
Q^*_{212}	1,428.25	-	-

Demand	Results	Average Quality	Results
d^*_{11}	1,906.95	$\hat{q}_{11}$	100.00
d^*_{21}	1,263.34	$\hat{q}_{21}$	97.91
d^*_{12}	1,476.77	$\hat{q}_{12}$	100.00
d^*_{22}	1,428.25	$\hat{q}_{22}$	67.35

Demand Price	Results	Consumer Welfare	Results	Profits	Results
ρ_{11}	745.25	CW_{11}	545,470.00	U_1	1,812,002.21
ρ_{21}	781.57	CW_{21}	279,305.28	U_2	1,403,470.22
ρ_{12}	535.16	CW_{12}	272,607.69	-	-
ρ_{22}	696.62	CW_{22}	305,984.29	-	-

Table: Results for Example 6

- The results consistently and unanimously show that **consumer welfare declines** for consumers in the country imposing a strict quota or tariff on an imported product. Hence, a government may wish to loosen a quota (equivalently, reduce a tariff) so as not to adversely affect its own consumers.
- Producing firms should **expand their demand markets** within their own countries. This allows for a basic, but, effective, redesign of the supply chain network under a tariff or quota and results in higher profits for the firms. Also, firms should **expand the number of production sites** to countries not under a tariff or quota to maintain or improve upon their profits if some of their production sites are in countries subject to such trade policy instruments.
- Finally, the examples numerically support our theoretical finding that a tariff has the **equivalent impact** on product flows and product quality as a strict quota, provided that the constraint is tight. Hence, governments have the flexibility of imposing either a tariff or a quota to obtain equivalent trade flows and product quality levels. The imposition of a tariff may be more advisable/favored by a government, since it requires **less "policing"** and also yields **financial rewards**.

Summary - Practical Insights

- Governments should be cautious in imposing trade policy instruments in the form of tariffs or quotas on products in competitive, that is, oligopolistic, supply chain networks, since the **consumer welfare** of consumers in their own country can decrease as a result.

- Governments, by imposing a tariff or quota, may help firms in their country garner **enhanced profits** but at the expense of consumers.

- Producers should expand the **geographic dispersion** of their production sites to reduce the impact of imposed tariffs or quotas.

- Producers should actively expand their **demand markets** in countries not under trade policy instrument regimes, since doing so can lead to higher profits.

Future Research

- The investigation of tariffs and quotas in more complex, **multitiered** supply chain networks, in which there is assembly, etc., clearly merits study.
- It would be very worthwhile to model a government that is interested in enforcing a trade policy that **maximizes total consumer welfare** in its own country.
- It would be very interesting to consider the **redesign of supply chain networks** in the presence of trade policy instruments such as quotas or tariffs. We leave such work for future research.

Thank You!