Competitive Food Supply Chain Networks with Application to Fresh Produce

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where a full list of references can be found.

Outline

- Background and Motivation
- Literature Review
- The Fresh Produce Supply Chain Network Oligopoly Model
- Case Study
- Summary

Motivation

The fundamental difference between food supply chains and other supply chains is the **continuous and significant change in the quality** of food products throughout the entire supply chain until the points of final consumption.

Globalization of Food Supply Chains

Consumers' **expectation of year-around availability** of fresh food products has encouraged the globalization of food markets.

- The consumption of **fresh vegetables** has increased at a much faster pace than the demand for traditional crops such as wheat and other grains (USDA (2011)).

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- The consumption of **fresh vegetables** has increased at a much faster pace than the demand for traditional crops such as wheat and other grains (USDA (2011)).
- In the US alone, consumers now spend over 1.6 **trillion dollars** annually on food (Plunkett Research (2011)).
- The United States is ranked **number one as both importer and exporter** in the international trade of horticultural commodities(Cook (2002)).

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- The United States is ranked **number one as both importer and exporter** in the international trade of horticultural commodities(Cook (2002)).

The growing **global competition**, coupled with the associated **greater distances** between food production and consumption locations, creates new challenges for food supply chain management.

Food Waste/Loss

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Food Waste/Loss

- It is estimated that approximately **one third** of the global food production is wasted or lost annually (Gustavsson et al. (2011)).
- In any country, 20%–60% of the total amount of agricultural **fresh products** has been wasted or lost (Widodo et al. (2006)).
  - In developed countries, the overall average losses of fruits and vegetables during **post-production supply chain activities** are approximately 12% of the initial production.
  - The corresponding losses in developing regions are even **severer**.

Product Differentiation

Given the thin profit margins in the food industries, **product differentiation strategies** are increasingly used in food markets (Lowe and Preckel (2004), Lusk and Hudson (2004), and Ahumada and Villalobos (2009)) with **product freshness** considered one of the differentiating factors (Kärkkäinen (2003) and Lütke Entrup et al. (2005)).

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- One successful example is fresh-cut produce, including bagged salads, washed baby carrots, and fresh-cut melons (Cook (2002)).
- Retailers, such as Globus, a German retailer, are also now realizing that food freshness can be a competitive advantage (Lütke Entrup et al. (2005)).

Relevant Literature

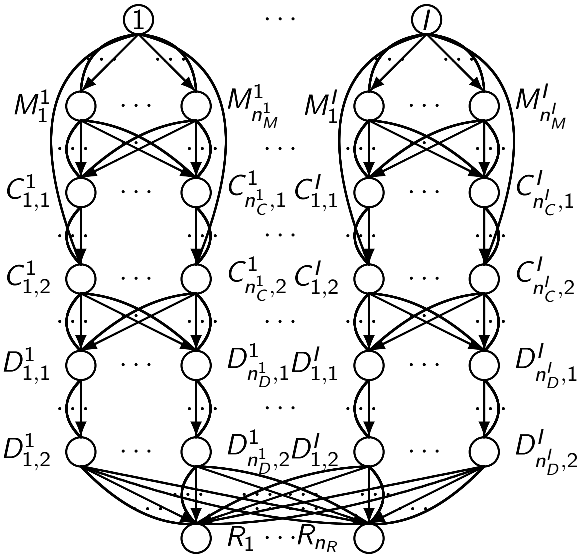
- Nahmias (1982, 2011) and Silver, Pyke, and Peterson (1998); Glen (1987) and Lowe and Preckel (2004); Lucas and Chhajed (2004); Lütke Entrup (2005); Akkerman, Farahani, and Grunow (2010); Ahumada and Villalobos (2009)
- Zhang, Habenicht, and Spieß (2003), Widodo et al. (2006), Monteiro (2007), Blackburn and Scudder (2009), Ahumada and Villalobos (2011), Rong, Akkerman, and Grunow (2011), Kopanos, Puigjaner, and Georgiadis (2012), and Liu and Nagurney (2012)
- Nagurney and Aronson (1989), Masoumi, Yu, and Nagurney (2012), Nagurney, Masoumi, and Yu (2012), Nagurney and Masoumi (2012), and Nagurney and Nagurney (2011)

The Fresh Produce Supply Chain Network Oligopoly Model

This model focuses on **fresh produce items**, such as vegetables and fruits

- They require simple or limited processing.
- The life cycle can be measured in days.

The Fresh Produce Supply Chain Network Topology



How to Handle Food Deterioration

Most of fresh produce items reach their peak quality at the time of production, and then deteriorate substantially over time (Blackburn and Scudder (2009)).

It also has been recognized that **the decay rate** varies significantly with different temperatures and under other environmental conditions (Blackburn and Scudder (2009) and Rong, Akkerman, and Grunow (2011)).

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The food products **deteriorate over time** even **under optimal conditions**.

How to Handle Food Deterioration

Microbiological decay is one of the major causes of the food quality degradation, especially for the fresh produce (Fu and Labuza (1993)). Therefore, food deterioration usually follows the first-order reactions with **exponential time decay**.

Exponential time decay has been utilized, in order to describe either **the decrease in quantity** or **the degradation in quality**.

- The decrease in quantity represents the number of units of decayed products (e.g. vegetables and fruits).
- The degradation in quality emphasizes that all the products deteriorate at the same rate simultaneously (e.g. meat, dairy, and bakery products).

How to Handle Food Deterioration

With a focus on such fresh produce items as vegetables and fruits, the model adopts exponential time decay so as to capture the discarding of spoiled products associated with **the post-production** supply chain activities.

Each unit has a probability of $e^{-\lambda t}$ to survive another t units of time, where λ is the decay rate, which is given and fixed. Let N_0 denote the quantity at the beginning of the time interval (link). Hence, the expected quantity surviving at the end of the time interval (specific link), denoted by $N(t)$, can be expressed as:

$$N(t) = N_0 e^{-\lambda t}. \tag{1}$$

How to Handle Food Deterioration

Let α_a denote the throughput factor associate with every link a in the supply chain network, which lies in the range of $(0, 1]$.

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- For a **production link**:

$$\alpha_a = 1, \tag{2a}$$

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Let α_a denote the throughput factor associate with every link a in the supply chain network, which lies in the range of $(0, 1]$.

- For a **production link**:

$$\alpha_a = 1, \tag{2a}$$

- For a **post-production link**:

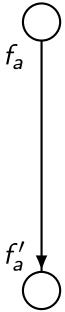
$$\alpha_a = e^{-\lambda_a t_a}, \tag{2b}$$

  where λ_a and t_a are the decay rate and the time duration associated with the link a, respectively, which are given and fixed.

How to Handle Food Deterioration

Let f_a denote the (initial) flow of product on link a; and f'_a denote the final flow on link a.

How to Handle Food Deterioration



Let f_a denote the (initial) flow of product on link a; and f'_a denote the final flow on link a.

$$f'_a = \alpha_a f_a, \quad \forall a \in L. \tag{3}$$

The Number of Units of the Spoiled Fresh Produce on Link a

$$f_a - f'_a = (1 - \alpha_a) f_a, \quad \forall a \in L. \tag{4}$$

How to Handle Food Deterioration

Total Discarding Cost Functions

$$\hat{z}_a = \hat{z}_a(f_a), \quad \forall a \in L, \tag{5}$$

which is assumed to be convex and continuously differentiable.

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- The model mainly focuses on the disposal of the decayed food products at **the processing, storage, and distribution stages** (see also Thompson (2002)).
- It is imperative to remove the spoiled fresh food products from the supply chain network.
  - For instance, fungi are the common post-production diseases of fresh fruits and vegetables, which can colonize the fruits and vegetables rapidly (Sommer, Fortlage, and Edwards (2002)).

How to Handle Food Deterioration

Multiplier α_{ap}

$$\alpha_{ap} \equiv \begin{cases} \delta_{ap} \prod_{b \in \{a' < a\}_p} \alpha_b, & \text{if } \{a' < a\}_p \neq \emptyset, \\ \\ \delta_{ap}, & \text{if } \{a' < a\}_p = \emptyset, \end{cases} \tag{6}$$

where $\{a' < a\}_p$ denotes the set of the links preceding link a in path p, and $\emptyset$ denotes the null set.

How to Handle Food Deterioration

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where $\{a' < a\}_p$ denotes the set of the links preceding link a in path p, and $\emptyset$ denotes the null set.

Relationship between Link Flows, f_a, and Path Flows, x_p

$$f_a = \sum_{i=1}^{I} \sum_{k=1}^{n_R} \sum_{p \in P_k^i} x_p \alpha_{ap}, \quad \forall a \in L. \tag{7}$$

How to Handle Food Deterioration

Path Multiplier μ_p

$$\mu_p \equiv \prod_{a \in p} \alpha_a, \quad \forall p \in P_k^i;\ i = 1, \ldots, I;\ k = 1, \ldots, n_R. \tag{8}$$

How to Handle Food Deterioration

Path Multiplier μ_p

$$\mu_p \equiv \prod_{a \in p} \alpha_a, \quad \forall p \in P_k^i;\ i = 1, \ldots, I;\ k = 1, \ldots, n_R. \tag{8}$$

Relationship between Path Flows, x_p, and demands, d_{ik}

$$\sum_{p \in P_k^i} x_p \mu_p = d_{ik}, \quad i = 1, \ldots, I;\ k = 1, \ldots, n_R. \tag{9}$$

d_{ik} can capture **production differentiation**, due to food safety and health concerns.

Demand Price Functions

$$\rho_{ik} = \rho_{ik}(d), \quad i = 1, \ldots, I; k = 1, \ldots, n_R, \tag{10}$$

which captures the demand-side competition. These demand price functions are assumed to be continuous, continuously differentiable, and monotone decreasing.

Total Operational Cost Functions

$$\hat{c}_a = \hat{c}_a(f), \quad \forall a \in L, \tag{11}$$

where f is the vector of all the link flows. Such cost functions can capture the supply-side competition. The total cost on each link is assumed to be convex and continuously differentiable.

The Profit Function of Firm i

$$U_i = \sum_{k=1}^{n_R} \rho_{ik}(d) d_{ik} - \sum_{a \in L^i} \Big(\hat{c}_a(f) + \hat{z}_a(f_a) \Big). \quad (12)$$

In this oligopoly competition problem, the strategic variables are the paths flows.

- X_i: the vector of path flows associated with firm i; $i = 1, \ldots, I$.
- X: the vector of all the firm' strategies, that is, $X \equiv \{\{X_i\} | i = 1, \ldots, I\}$.

Supply Chain Network Cournot-Nash Equilibrium

A path flow pattern $X^* \in K = \prod_{i=1}^{I} K_i$ *is said to constitute a supply chain network Cournot-Nash equilibrium if for each firm* i*;* $i = 1, \ldots, I$*:*

$$U_i(X_i^*, \hat{X}_i^*) \geq U_i(X_i, \hat{X}_i^*), \quad \forall X_i \in K_i, \tag{13}$$

where $\hat{X}_i^* \equiv (X_1^*, \ldots, X_{i-1}^*, X_{i+1}^*, \ldots, X_I^*)$ *and* $K_i \equiv \{X_i | X_i \in R_+^{n_{P^i}}\}$.

An equilibrium is established if NO firm can unilaterally improve its profit, given other firms' decisions.

Variational Inequality Formulation

Variational Inequality (Path Flows)

Determine $x^* \in K^1$ such that:

$$\sum_{i=1}^{I}\sum_{k=1}^{n_R}\sum_{p\in P_k^i}\left[\frac{\partial \hat{C}_p(x^*)}{\partial x_p}+\frac{\partial \hat{Z}_p(x^*)}{\partial x_p}-\hat{\rho}_{ik}(x^*)\mu_p\right.$$

$$\left.-\sum_{l=1}^{n_R}\frac{\partial \hat{\rho}_{il}(x^*)}{\partial x_p}\sum_{p\in P_l^i}\mu_p x_p^*\right]\times[x_p-x_p^*]\geq 0,\quad \forall x\in K^1, \tag{14}$$

where $K^1 \equiv \{x | x \in R_+^{n_P}\}$.

Variational Inequality Formulation

Variational Inequality (Link Flows)

Determine $(f^*, d^*) \in K^2$*, such that:*

$$\sum_{i=1}^{I} \sum_{a \in L^i} \left[\sum_{b \in L^i} \frac{\partial \hat{c}_b(f^*)}{\partial f_a} + \frac{\partial \hat{z}_a(f_a^*)}{\partial f_a} \right] \times [f_a - f_a^*]$$

$$+ \sum_{i=1}^{I} \sum_{k=1}^{n_R} \left[-\rho_{ik}(d^*) - \sum_{l=1}^{n_R} \frac{\partial \rho_{il}(d^*)}{\partial d_{ik}} d_{il}^* \right] \times [d_{ik} - d_{ik}^*] \geq 0,$$

$$\forall (f, d) \in K^2, \tag{15}$$

where $K^2 \equiv \{(f, d) | x \geq 0, \mathit{and}\, (7)\, \mathit{and}\, (9)\, \mathit{hold}\}$.

Existence

There exists at least one solution to variational inequality (14) (equivalently, to (15)), since there exists a $b > 0$*, such that variational inequality*

$$\langle F(X^b)^T, X - X^b \rangle \geq 0, \quad \forall X \in \mathcal{K}_b, \tag{16}$$

admits a solution in $\mathcal{K}_b$ *with*

$$x^b \leq b. \tag{17}$$

Uniqueness

With existence, variational inequality (16) and, hence, variational inequality (16) admits at least one solution. Moreover, if the function $F(X)$ of variational inequality (15) is strictly monotone on $\mathcal{K} \equiv K^2$, that is,

$$\langle (F(X^1) - F(X^2))^T, X^1 - X^2 \rangle > 0, \quad \forall X^1, X^2 \in \mathcal{K},\ X^1 \neq X^2, \tag{18}$$

then the solution to variational inequality (15) is unique, that is, the equilibrium link flow pattern and the equilibrium demand pattern are unique.

Algorithm – Euler Method

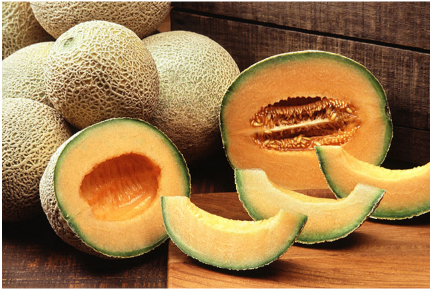
Closed Form Expression for Fresh Produce Path Flows

$$x_p^{\tau+1} = \max\{0, x_p^\tau + a_\tau(\hat{\rho}_{ik}(x^\tau)\mu_p + \sum_{l=1}^{n_R} \frac{\partial \hat{\rho}_{il}(x^\tau)}{\partial x_p} \sum_{q \in P_l^i} \mu_q x_q^\tau - \frac{\partial \hat{C}_p(x^\tau)}{\partial x_p}$$

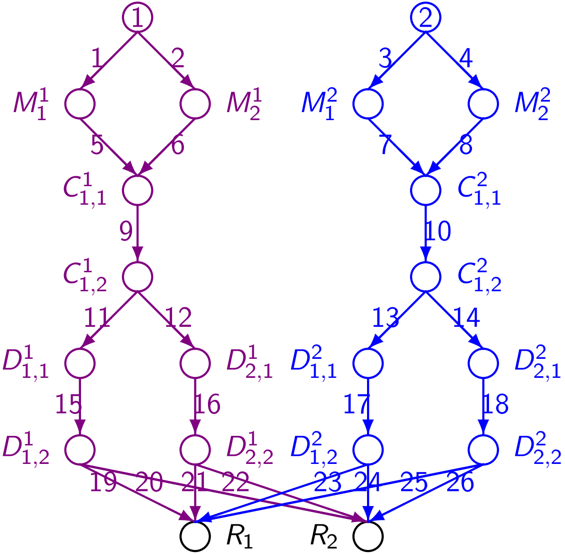
$$- \frac{\partial \hat{Z}_p(x^\tau)}{\partial x_p})\}, \quad \forall p \in P_k^i;\ i = 1, \ldots, I;\ k = 1, \ldots, n_R. \tag{19}$$

Case Study

Most of cantaloupes consumed in the United States are originally produced in California, Mexico, and in some countries in Central America.



- Typically, cantaloupes can be stored for 12–15 days at 2.2° to 5°C (36° to 41°F).
- It has been noticed that the decay of cantaloupes may result from such post-production disease, depending on the season, the region, and the handling technologies utilized between production and consumption.



- **Firm** 1 is located in California.
- **Firm** 2 is located in Central America.

Case 1

- Consumers at the demand markets were indifferent between cantaloupes of Firm 1 and Firm 2.
- Consumers at demand market R_2 were willing to pay relatively more as compared to those at demand market R_1.

The Demand Price Functions

$$\rho_{11} = -.0001d_{11} - .0001d_{21} + 4, \quad \rho_{12} = -.0001d_{12} - .0001d_{22} + 6;$$

$$\rho_{21} = -.0001d_{21} - .0001d_{11} + 4, \quad \rho_{22} = -.0001d_{22} - .0001d_{12} + 6.$$

Link a	λ_a	t_a	α_a	$\hat{c}_a(f)$	$\hat{z}_a(f_a)$	f_a^*
1	–	–	1.00	$.005f_1^2 + .03f_1$	0.00	76.32
2	–	–	1.00	$.006f_2^2 + .02f_2$	0.00	75.73
3	–	–	1.00	$.001f_3^2 + .02f_3$	0.00	103.74
4	–	–	1.00	$.001f_4^2 + .02f_4$	0.00	105.62
5	.150	0.20	.970	$.003f_5^2 + .01f_5$	0.00	76.32
6	.150	0.25	.963	$.002f_6^2 + .02f_6$	0.00	75.73
7	.150	0.30	.956	$.001f_7^2 + .02f_7$	0.00	103.74
8	.150	0.30	.956	$.001f_8^2 + .01f_8$	0.00	105.62
9	.040	0.50	.980	$.002f_9^2 + .05f_9$	$.001f_9^2 + 0.02f_9$	147.01
10	.060	0.50	.970	$.001f_{10}^2 + .02f_{10}$	$.001f_{10}^2 + 0.02f_{10}$	200.14
11	.015	1.50	.978	$.005f_{11}^2 + .01f_{11}$	0.00	65.98
12	.015	3.00	.956	$.01f_{12}^2 + .01f_{12}$	0.00	78.12
13	.025	2.00	.951	$.005f_{13}^2 + .02f_{13}$	0.00	96.47
14	.025	4.00	.905	$.01f_{14}^2 + .01f_{14}$	0.00	97.76
15	.010	3.00	.970	$.004f_{15}^2 + .01f_{15}$	$.001f_{15}^2 + 0.02f_{15}$	64.51

Link a	λ_a	t_a	α_a	$\hat{c}_a(f)$	$\hat{z}_a(f_a)$	f_a^*
16	.010	3.00	.970	$.004f_{16}^2 + .01f_{16}$	$.001f_{16}^2 + 0.02f_{16}$	74.68
17	.015	3.00	.956	$.004f_{17}^2 + .01f_{17}$	$.001f_{17}^2 + 0.02f_{17}$	91.77
18	.015	3.00	.956	$.004f_{18}^2 + .01f_{18}$	$.001f_{18}^2 + 0.02f_{18}$	88.45
19	.015	1.00	.985	$.005f_{19}^2 + .01f_{19}$	$.001f_{19}^2 + 0.02f_{19}$	7.98
20	.015	3.00	.956	$.015f_{20}^2 + .1f_{20}$	$.001f_{20}^2 + 0.02f_{20}$	54.62
21	.015	3.00	.956	$.015f_{21}^2 + .1f_{21}$	$.001f_{21}^2 + 0.02f_{21}$	0.00
22	.015	1.00	.985	$.005f_{22}^2 + .01f_{22}$	$.001f_{22}^2 + 0.02f_{22}$	72.48
23	.020	1.00	.980	$.005f_{23}^2 + .01f_{23}$	$.001f_{23}^2 + 0.02f_{23}$	27.74
24	.020	3.00	.942	$.015f_{24}^2 + .1f_{24}$	$.001f_{24}^2 + 0.02f_{24}$	59.99
25	.020	3.00	.942	$.015f_{25}^2 + .1f_{25}$	$.001f_{25}^2 + 0.02f_{25}$	0.00
26	.020	1.00	.980	$.005f_{26}^2 + .01f_{26}$	$.001f_{26}^2 + 0.02f_{26}$	84.56

The Equilibrium Demands

$$d_{11}^* = 7.86, \quad d_{12}^* = 123.62, \quad d_{21}^* = 27.19, \quad \text{and} \quad d_{22}^* = 139.38.$$

The Equilibrium Prices

$$\rho_{11} = 4.00, \quad \rho_{12} = 5.97, \quad \rho_{21} = 4.00, \quad \text{and} \quad \rho_{22} = 5.97.$$

The Profits of Two Firms

$$U_1 = 370.46 \quad \text{and} \quad U_2 = 454.72.$$

Case 2

- The CDC reported a multi-state cantaloupe-associated outbreak.
- Due to food safety and health concerns, the regular consumers of cantaloupes switched to other fresh fruits.

The Demand Price Functions

$$\rho_{11} = -.001d_{11} - .001d_{21} + .5, \quad \rho_{12} = -.001d_{12} - .001d_{22} + .5;$$

$$\rho_{21} = -.001d_{21} - .001d_{11} + .5, \quad \rho_{22} = -.001d_{22} - .001d_{12} + .5.$$

Link a	λ_a	t_a	α_a	$\hat{c}_a(f)$	$\hat{z}_a(f_a)$	f_a^*
1	–	–	1.00	$.005f_1^2 + .03f_1$	0.00	4.43
2	–	–	1.00	$.006f_2^2 + .02f_2$	0.00	4.40
3	–	–	1.00	$.001f_3^2 + .02f_3$	0.00	5.94
4	–	–	1.00	$.001f_4^2 + .02f_4$	0.00	6.94
5	.150	0.20	.970	$.003f_5^2 + .01f_5$	0.00	4.43
6	.150	0.25	.963	$.002f_6^2 + .02f_6$	0.00	4.40
7	.150	0.30	.956	$.001f_7^2 + .02f_7$	0.00	5.94
8	.150	0.30	.956	$.001f_8^2 + .01f_8$	0.00	6.94
9	.040	0.50	.980	$.002f_9^2 + .05f_9$	$.001f_9^2 + 0.02f_9$	8.53
10	.060	0.50	.970	$.001f_{10}^2 + .02f_{10}$	$.001f_{10}^2 + 0.02f_{10}$	12.31
11	.015	1.50	.978	$.005f_{11}^2 + .01f_{11}$	0.00	4.82
12	.015	3.00	.956	$.01f_{12}^2 + .01f_{12}$	0.00	3.54
13	.025	3.00	.928	$.005f_{13}^2 + .02f_{13}$	0.00	6.86
14	.025	5.00	.882	$.01f_{14}^2 + .01f_{14}$	0.00	5.09
15	.010	3.00	.970	$.004f_{15}^2 + .01f_{15}$	$.001f_{15}^2 + 0.02f_{15}$	4.72

Link a	λ_a	t_a	α_a	$\hat{c}_a(f)$	$\hat{z}_a(f_a)$	f_a^*
16	.010	3.00	.970	$.004f_{16}^2 + .01f_{16}$	$.001f_{16}^2 + 0.02f_{16}$	3.38
17	.015	3.00	.956	$.004f_{17}^2 + .01f_{17}$	$.001f_{17}^2 + 0.02f_{17}$	6.36
18	.015	3.00	.956	$.004f_{18}^2 + .01f_{18}$	$.001f_{18}^2 + 0.02f_{18}$	4.49
19	.015	1.00	.985	$.005f_{19}^2 + .01f_{19}$	$.001f_{19}^2 + 0.02f_{19}$	4.58
20	.015	3.00	.956	$.015f_{20}^2 + .1f_{20}$	$.001f_{20}^2 + 0.02f_{20}$	0.00
21	.015	3.00	.956	$.015f_{21}^2 + .1f_{21}$	$.001f_{21}^2 + 0.02f_{21}$	0.00
22	.015	1.00	.985	$.005f_{22}^2 + .01f_{22}$	$.001f_{22}^2 + 0.02f_{22}$	3.28
23	.020	1.00	.980	$.005f_{23}^2 + .01f_{23}$	$.001f_{23}^2 + 0.02f_{23}$	6.08
24	.020	3.00	.942	$.015f_{24}^2 + .1f_{24}$	$.001f_{24}^2 + 0.02f_{24}$	0.00
25	.020	3.00	.942	$.015f_{25}^2 + .1f_{25}$	$.001f_{25}^2 + 0.02f_{25}$	0.00
26	.020	1.00	.980	$.005f_{26}^2 + .01f_{26}$	$.001f_{26}^2 + 0.02f_{26}$	4.29

The Equilibrium Demands

$$d_{11}^* = 4.51, \quad d_{12}^* = 3.24, \quad d_{21}^* = 5.96, \quad \text{and} \quad d_{22}^* = 4.21.$$

The Equilibrium Prices

$$\rho_{11} = 0.49, \quad \rho_{12} = 0.49, \quad \rho_{21} = 0.49, \quad \text{and} \quad \rho_{22} = 0.49.$$

The Profits of Two Firms

$$U_1 = 1.16 \quad \text{and} \quad U_2 = 1.63.$$

Case 3

- Firm 1 would like to regain consumers' confidence in its own product after the cantaloupe-associated outbreak.
- Firm 1 had its label of cantaloupes redesigned.
  - The label incorporates the guarantee of food safety.
  - The label also causes additional expenditures associated with its processing activities.

The Demand Price Functions

$$\rho_{11} = -.001 d_{11} - .0005 d_{21} + 2.5, \quad \rho_{12} = -.0003 d_{12} - .0002 d_{22} + 3;$$

$$\rho_{21} = -.001 d_{21} - .001 d_{11} + .5, \quad \rho_{22} = -.001 d_{22} - .001 d_{12} + .5.$$

Link a	λ_a	t_a	α_a	$\hat{c}_a(f)$	$\hat{z}_a(f_a)$	f_a^*
1	–	–	1.00	$.005f_1^2 + .03f_1$	0.00	36.92
2	–	–	1.00	$.006f_2^2 + .02f_2$	0.00	36.64
3	–	–	1.00	$.001f_3^2 + .02f_3$	0.00	5.43
4	–	–	1.00	$.001f_4^2 + .02f_4$	0.00	6.44
5	.150	0.20	.970	$.003f_5^2 + .01f_5$	0.00	36.92
6	.150	0.25	.963	$.002f_6^2 + .02f_6$	0.00	36.64
7	.150	0.30	.956	$.001f_7^2 + .02f_7$	0.00	5.43
8	.150	0.30	.956	$.001f_8^2 + .01f_8$	0.00	6.44
9	.040	0.50	.980	$.003f_9^2 + .06f_9$	$.001f_9^2 + 0.02f_9$	71.11
10	.060	0.50	.970	$.001f_{10}^2 + .02f_{10}$	$.001f_{10}^2 + 0.02f_{10}$	11.35
11	.015	1.50	.978	$.005f_{11}^2 + .01f_{11}$	0.00	36.33
12	.015	3.00	.956	$.01f_{12}^2 + .01f_{12}$	0.00	33.38
13	.025	3.00	.928	$.005f_{13}^2 + .02f_{13}$	0.00	6.68
14	.025	5.00	.882	$.01f_{14}^2 + .01f_{14}$	0.00	4.33
15	.010	3.00	.970	$.004f_{15}^2 + .01f_{15}$	$.001f_{15}^2 + 0.02f_{15}$	35.52

Link a	λ_a	t_a	α_a	$\hat{c}_a(f)$	$\hat{z}_a(f_a)$	f_a^*
16	.010	3.00	.970	$.004f_{16}^2 + .01f_{16}$	$.001f_{16}^2 + 0.02f_{16}$	31.91
17	.015	3.00	.956	$.004f_{17}^2 + .01f_{17}$	$.001f_{17}^2 + 0.02f_{17}$	6.20
18	.015	3.00	.956	$.004f_{18}^2 + .01f_{18}$	$.001f_{18}^2 + 0.02f_{18}$	3.82
19	.015	1.00	.985	$.005f_{19}^2 + .01f_{19}$	$.001f_{19}^2 + 0.02f_{19}$	17.78
20	.015	3.00	.956	$.015f_{20}^2 + .1f_{20}$	$.001f_{20}^2 + 0.02f_{20}$	16.69
21	.015	3.00	.956	$.015f_{21}^2 + .1f_{21}$	$.001f_{21}^2 + 0.02f_{21}$	0.00
22	.015	1.00	.985	$.005f_{22}^2 + .01f_{22}$	$.001f_{22}^2 + 0.02f_{22}$	30.96
23	.020	1.00	.980	$.005f_{23}^2 + .01f_{23}$	$.001f_{23}^2 + 0.02f_{23}$	5.93
24	.020	3.00	.942	$.015f_{24}^2 + .1f_{24}$	$.001f_{24}^2 + 0.02f_{24}$	0.00
25	.020	3.00	.942	$.015f_{25}^2 + .1f_{25}$	$.001f_{25}^2 + 0.02f_{25}$	0.00
26	.020	1.00	.980	$.005f_{26}^2 + .01f_{26}$	$.001f_{26}^2 + 0.02f_{26}$	3.65

The Equilibrium Demands

$$d_{11}^* = 17.52, \quad d_{12}^* = 46.46, \quad d_{21}^* = 5.81, \quad \text{and} \quad d_{22}^* = 3.58.$$

The Equilibrium Prices

$$\rho_{11} = 2.48, \quad \rho_{12} = 2.99, \quad \rho_{21} = 0.48, \quad \text{and} \quad \rho_{22} = 0.45.$$

The Profits of Two Firms

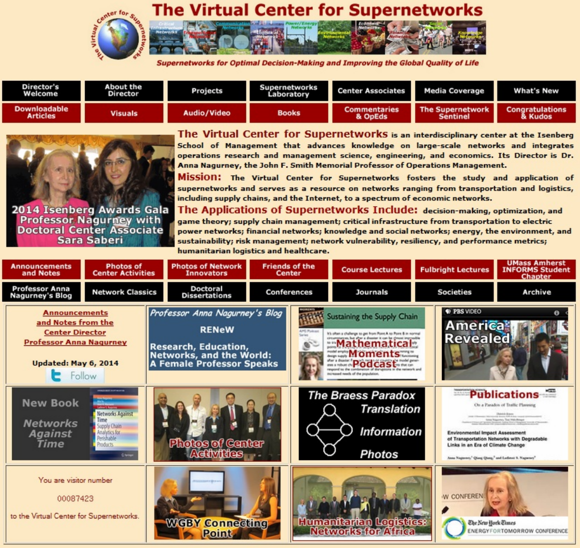
$$U_1 = 84.20 \quad \text{and} \quad U_2 = 1.38.$$

Summary

With a focus on such fresh produce items as vegetables and fruits,

- we adopted exponential time decay for the calculation of arc multipliers, so as to handle the discarding of spoiled food products associated with the post-production supply chain activities;
- we considered product differentiation due to product freshness and food safety concerns; and
- we also allowed for the assessment of alternative technologies involved in each supply chain activity, which could affect the time durations and environmental conditions associated with that activity.

Thank You!



For more information, see: http://supernet.isenberg.umass.edu