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 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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- 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.

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  - 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.

The immense food waste/loss, further stresses food supply chains and the associated quality and profitability.

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)).

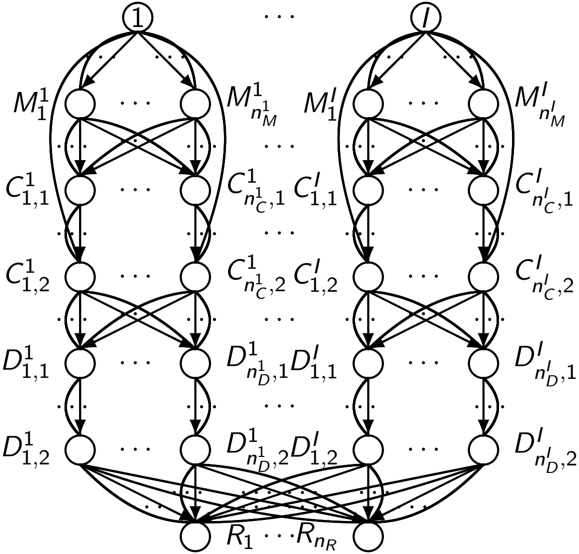
Relevant Literature

- 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, with simple or limited required processing, whose 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)).

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), while the degradation in quality emphasizes that all the products deteriorate at the same rate simultaneously, which is more relevant to 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 $(0, 1]$.

Hence, the throughput factor α_a for a post-production link a can be represented as:

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

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.

The value of α_a for a production link is set equal to 1.

In rare cases, food deterioration follows the zero order reactions with linear decay. Then, $\alpha_a = 1 - \lambda_a t_a$ for a post-production link.

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; i.e., the flow that reaches the successor node of the link after deterioration has taken place. Therefore,

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

Consequently, the number of units of the spoiled fresh produce on link a is the difference between the initial and the final flow, $f_a - f'_a$, where

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

How to Handle Food Deterioration

Associated with the food deterioration is a total discarding cost function, $\hat{z}_a$, which, in view of (5.4), is a function of flow on the link, f_a, that is,

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

which is assumed to be convex and continuously differentiable.

It is worth noting that 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)). Here, the model mainly focuses on the disposal of the decayed food products at the processing, storage, and distribution stages (see also Thompson (2002)).

How to Handle Food Deterioration

The multiplier, α_{ap}, which is the product of the multipliers of the links on path p that precede link a in that path, is defined as follows:

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

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

Hence, the relationship between the link flow, f_a, and the path flows can be expressed as:

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

How to Handle Food Deterioration

Let μ_p denote the multiplier corresponding to the throughput on path p, defined as:

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

The demand for food firm i's fresh food product; $i = 1, \ldots, I$, at demand market R_k; $k = 1, \ldots, n_R$, denoted by d_{ik}, is equal to the sum of all the final flows – subject to perishability – on paths joining (i, R_k):

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

The consumers may differentiate the fresh food products, due to food safety and health concerns.

The Demand Price Functions

The demand price of food firm i's product at demand market R_k is denoted by ρ_{ik}, which is assumed that

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

These demand price functions are assumed to be continuous, continuously differentiable, and monotone decreasing.

The Total Cost Functions

The total operational cost on link a may, in general, depend upon the product flows on all the links, that is,

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

where f is the vector of all the link flows. The total cost on each link is assumed to be convex and continuously differentiable.

The Profit Function of Firm i

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

X_i: the vector of path flows associated with firm i; $i = 1, \ldots, I$, where $X_i \equiv \{\{x_p\} | p \in P^i\}\} \in R_+^{n_{P^i}}$.
X: the vector of all the firm' strategies, that is, $X \equiv \{\{X_i\} | i = 1, \ldots, I\}$.

$$\hat{U} = \hat{U}(X). \qquad (14)$$

Variational Inequality Formulation

Variational Inequality (Path Flows)

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

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

$$\left. - \sum_{l=1}^{n_R} \frac{\partial \hat{\rho}_{il}(x^*)}{\partial x_p} \sum_{p \in P_l^i} \mu_p x_p^* \right] \times [x_p - x_p^*] \geq 0, \quad \forall x \in K^1, \qquad (15)$$

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:*

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

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

$$\forall (f, d) \in K^2, \tag{16}$$

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 (15) (equivalently, to (16)), since there exists a $b > 0$*, such that variational inequality*

$$\langle F(X^b)^T, X - X^b \rangle \geq 0, \quad \forall X \in \mathcal{K}_b, \tag{17}$$

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

$$x^b \leq b. \tag{18}$$

Uniqueness

With existence, variational inequality (17) and, hence, variational inequality (16) admits at least one solution. Moreover, if the function $F(X)$ *of variational inequality (16) is strictly monotone on* $\mathcal{K} \equiv K^2$*, that is,*

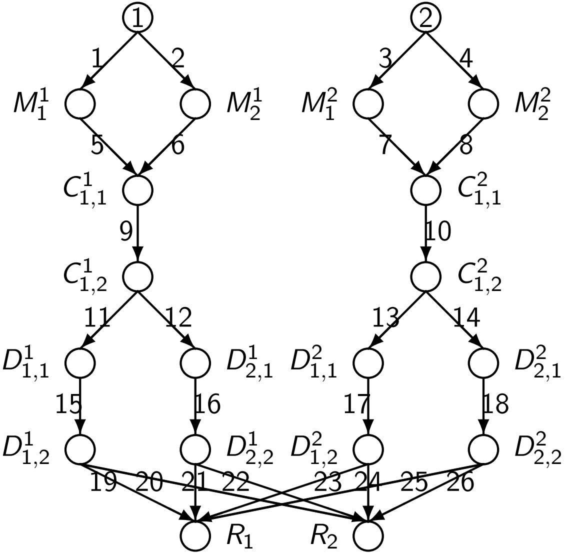
$$\langle (F(X^1) - F(X^2))^T, X^1 - X^2 \rangle > 0, \quad \forall X^1, X^2 \in \mathcal{K},\ X^1 \neq X^2, \qquad (19)$$

then the solution to variational inequality (16) is unique, that is, the equilibrium link flow pattern and the equilibrium demand pattern are unique.

Case Study

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 as Rhizopus, Fusarium, Geotrichum, etc., depending on the season, the region, and the handling technologies utilized between production and consumption.

Most of cantaloupes consumed in the United States are originally produced in California, Mexico, and in some countries in Central America. In this case study, there are two firms, Firm 1 and Firm 2, which may represent, for example, one food firm in California and one food firm in Central America, respectively.


1
2
1
2
3
4
M_1^1
M_2^1
M_1^2
M_2^2
5
6
7
8
$C_{1,1}^1$
$C_{1,1}^2$
9
10
$C_{1,2}^1$
$C_{1,2}^2$
11
12
13
14
$D_{1,1}^1$
$D_{2,1}^1$
$D_{1,1}^2$
$D_{2,1}^2$
15
16
17
18
$D_{1,2}^1$
$D_{2,2}^1$
$D_{1,2}^2$
$D_{2,2}^2$
19
20
21
22
23
24
25
26
R_1
R_2

Case 1

Consumers at the demand markets were indifferent between cantaloupes of Firm 1 and Firm 2. Furthermore, 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

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

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

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

Given the severe shrinkage in the demand for cantaloupes, Firm 1 has realized the importance of regaining consumers' confidence in its own product after the cantaloupe-associated outbreak. Thus, Firm 1 had its label of cantaloupes redesigned in order to incorporate the guarantee of food safety, with additional expenditures associated with its processing activities.

The Demand Price Functions

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

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

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	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.

With particular relevance to the food industries, we considered product differentiation due to product freshness and food safety concerns.

We 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!

The Virtual Center for Supernetworks

The Virtual Center for Supernetworks is an interdisciplinary center at the Isenberg School of Management that advances knowledge on large-scale networks and integrates operations research and management science, engineering, and economics. Its Director is Dr. Anna Nagurney, the John F. Smith Memorial Professor of Operations Management.

Mission: The Virtual Center for Supernetworks fosters the study and application of supernetworks and serves as a resource on networks ranging from transportation and logistics, including supply chains, and the Internet, to a spectrum of economic networks.

The Applications of Supernetworks Include: decision-making, optimization, and game theory; supply chain management; critical infrastructure from transportation to electric power networks; financial networks; knowledge and social networks; energy, the environment, and sustainability; risk management; network vulnerability, resiliency, and performance metrics; humanitarian logistics and healthcare.

Announcements and Notes from the Center Director Professor Anna Nagurney

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