Competitive Food Supply Chain Networks with Application to Fresh Produce

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where a full list of references can be found, along with some additional results.

Outline

- Background and Motivation
- Literature Review
- The Fresh Produce Supply Chain Network Oligopoly Model
- Case Study
- Relationship of the Model to Others in the Literature
- 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)).
- 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)).

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

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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)).

- 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)).

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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)

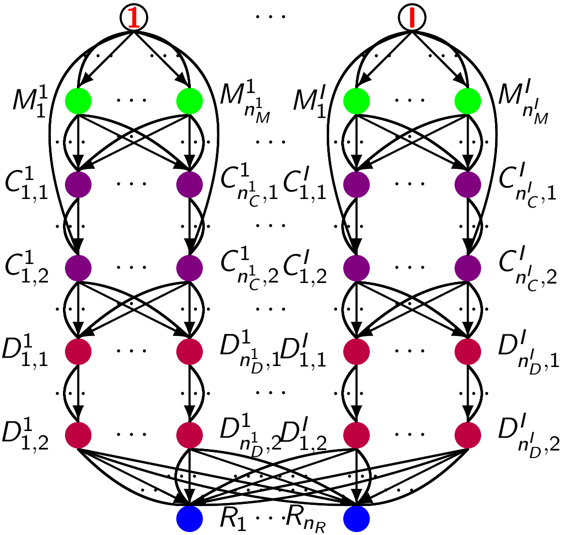
- Zhang, Habenicht, and Spieß (2003), Widodo et al. (2006), Monteiro (2007), Blackburn and Scudder (2009), Ahumada and Villalobos (2011), Rong, Akkerman, and Grunow (2011), Kopanos, Puigjaner, and Georgiadis (2012), and Liu and Nagurney (2012)

- Nagurney and Aronson (1989), Masoumi, Yu, and Nagurney (2012), Nagurney, Masoumi, and Yu (2012), Nagurney and Masoumi (2012), and Nagurney and Nagurney (2011)

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

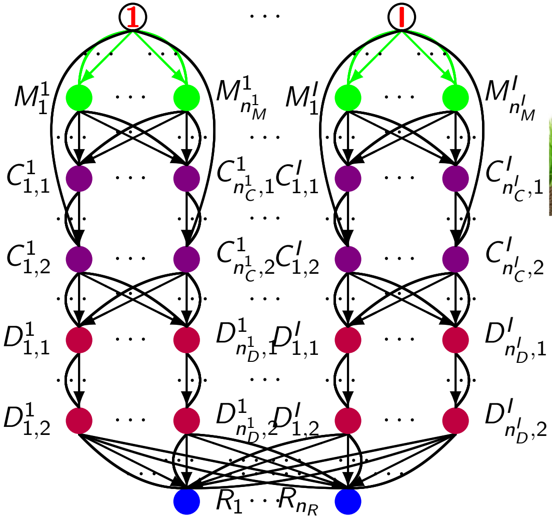
- They require simple or limited processing.
- The life cycle can be measured in days.

The Fresh Produce Supply Chain Network Topology



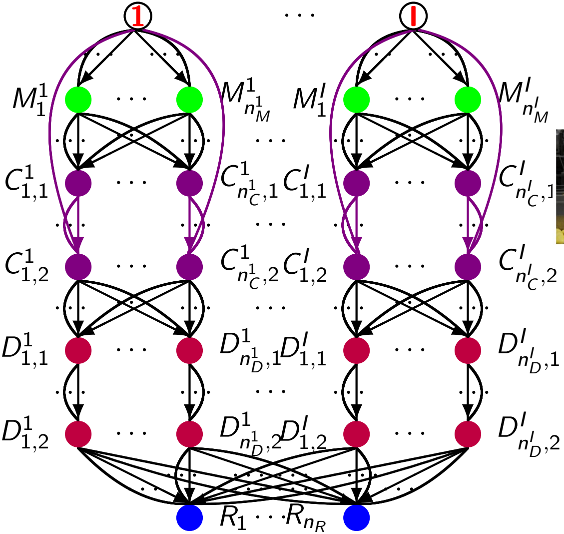
- The I food firms compete **noncooperatively** in an **oligopolistic** manner.
- The products may be <u>differentiated</u>, due to product **freshness** and **food safety** concerns.

Food Production



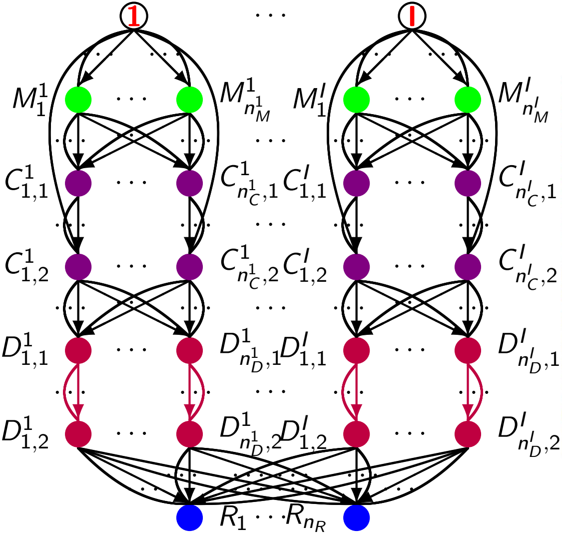
- Soil agitation
- Sowing
- Pest control
- Nutrient
- Water management
- Harvesting

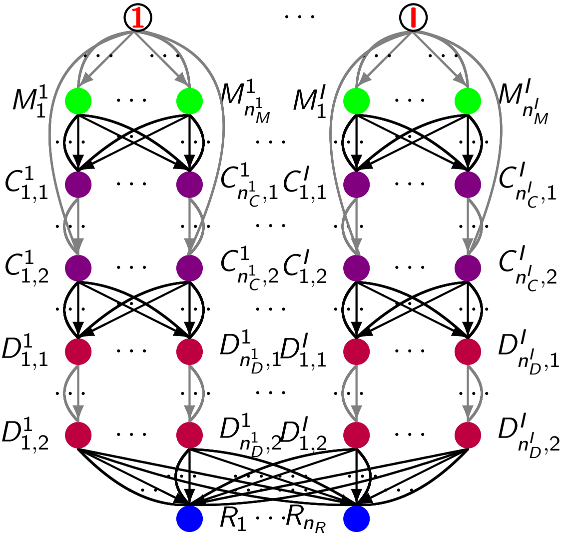
Food Processing



- Cleaning
- Sorting
- Labeling
- Packaging

Food Storage

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M_1^1
$M_{n_M^1}^1$
M_1^I
$M_{n_M^I}^I$
$C_{1,1}^1$
$C_{n_C^1,1}^1$
$C_{1,1}^I$
$C_{n_C^I,1}^I$
$C_{1,2}^1$
$C_{n_C^1,2}^1$
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$D_{1,1}^1$
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$D_{1,2}^1$
$D_{n_D^1,2}^1$
$D_{1,2}^I$
$D_{n_D^I,2}^I$
$R_1 \cdots R_{n_R}$


Say yes to the best

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.
- The **decay rate** varies significantly
  - With different temperatures, and
  - Under other environmental conditions.

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

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How to Handle Food Deterioration

Microbiological decay is one of the major causes of the food quality degradation, especially for the fresh produce.

Therefore, food deterioration usually follows the first-order reactions with **exponential time decay**.

- **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

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 $(0, 1]$.

- For a **production link**:

$$\alpha_a = 1, \quad (2a)$$

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

$$\alpha_a = e^{-\lambda_a t_a}, \quad (2b)$$

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.

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.

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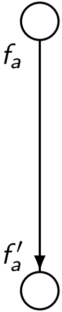
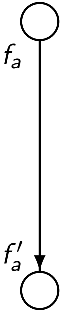


Let f_a denote the (initial) flow of product on link a; and f'_a denote the final flow on link a.

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

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

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



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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.

- 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.
- The model mainly focuses on the disposal of the decayed food products at **the processing, storage, and distribution stages**.

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How to Handle Food Deterioration

Multiplier α_{ap}

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

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

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

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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.

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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

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

In this oligopoly competition problem, the strategic variables are the path 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, $X \equiv \{\{X_i\}|i = 1, \ldots, I\}$.

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:*

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

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

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:*

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

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

$$\forall (f, d) \in K^2, \quad (15)$$

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*

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

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,

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

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

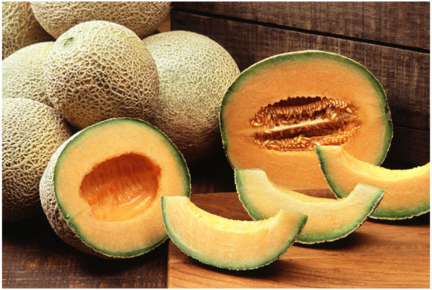
Closed Form Expression for Fresh Produce Path Flows

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

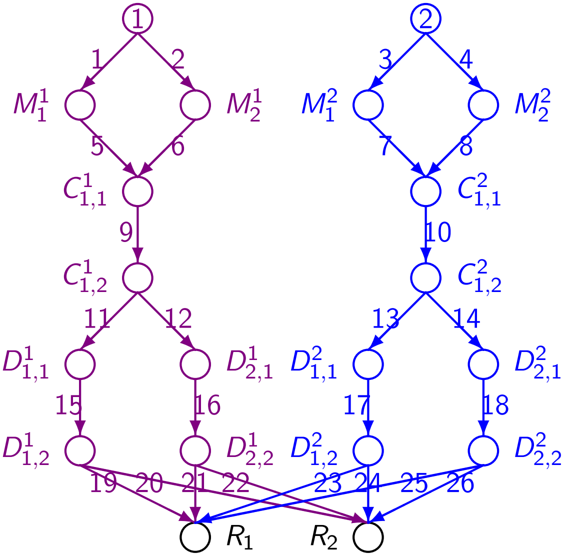
$$- \frac{\partial \hat{Z}_p(x^{\tau})}{\partial x_p})\}, \quad \forall p \in P_k^i; \; i = 1, \ldots, I; \; k = 1, \ldots, n_R. \tag{19}$$

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**.
- All the distribution centers and the demand markets are located in the United States.

- 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

- There is no shipment from distribution centers D_2^1 and D_2^2 to demand market R_1.
- The volume of product flows on distribution link 22 (or link 26) is higher than that of distribution link 20 (or link 24), which indicates that it is more cost-effective to provide fresh fruits from the nearby distribution centers.

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

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

- Since consumers do not differentiate the cantaloupes produced by these two firms, the prices of these two firms' cantaloupes at each demand market are identical.

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

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

- Due to the difference in consumers' willingness to pay, the price at demand market R_1 is relatively lower than the price at demand market R_2.

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

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

- As a result of its lower operational costs, Firm 2 dominates both of these two demand markets, leading to a substantially higher profit.

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

- The longer time durations associated with shipment links 13 and 14 are caused by more imported food inspections by the U.S. Food and Drug Administration.

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 distribution links: 20, 21, 24, and 25, have zero product flows, since the extremely low demand price cannot cover the costs associated with long-distance distribution.

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

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

- The demand for cantaloupes is battered by the cantaloupe-associated outbreak, with significant decreases in demand prices at demand markets R_1 and R_2.
- Both Firm 1 and Firm 2, in turn, experience dramatic declines in their profits.

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

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

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

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

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

- Consumers differentiate cantaloupes due to food safety and health concerns.
- With the newly designed label, Firm 1 has managed to encourage the consumption of its cantaloupes at both of these two demand markets.

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

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

- Practicing product differentiation may be an effective strategy for a food firm to maintain its profit at an acceptable level.
- Considering the cantaloupe-associated outbreak, it is certainly not easy to reclaim the same profit level as in Case 1.

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

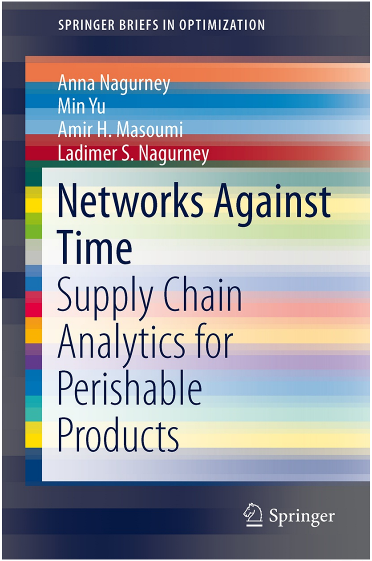
$$U_1 = 84.20 \quad \text{and} \quad U_2 = 1.38.$$

- The demand for Firm 1's product at demand market R_1 in Case 3 is even higher than that of Case 1, which is probably caused by the remarkable decrease in the price as well as the introduced guarantee of food safety.

A Multidisciplinary Perspective for Perishable Product Supply Chains

In our research on perishable and time-sensitive product supply chains, we utilize results from physics, chemistry, biology, and medicine in order to capture the perishability of various products over time from food to healthcare products such as blood, medical nucleotides, and pharmaceuticals.

A variety of perishable product supply chain models, computational procedures, and applications can be found in our book:



Supply Chain Networks – Optimization Models

Blood Supply Chains for the Red Cross

A. Nagurney, A. H. Masoumi, and M. Yu, “Supply Chain Network Operations Management of a Blood Banking System with Cost and Risk Minimization,” *Computational Management Science* **9(2)** (2012), pp 205-231.

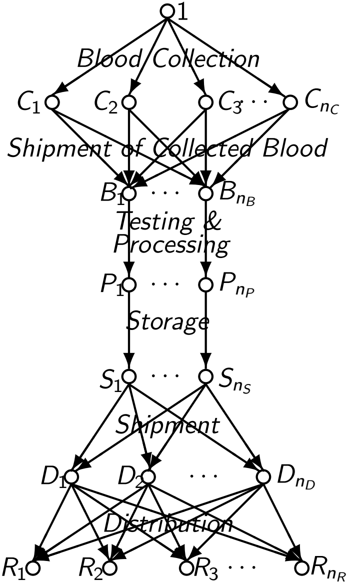
Blood Supply Chains for the Red Cross

The American Red Cross is the major supplier of blood products to hospitals and medical centers satisfying about **45%** of the demand for blood components nationally.

American Red Cross
Together, we can save a life

Blood Supply Chains for the Red Cross

- The shelf life of platelets is **5 days** and of red blood cells is **42**.
- Over **39,000** donations are needed everyday in the US, and the blood supply is frequently reported to be just **2 days** away from running out (American Red Cross (2010)).
- Some hospitals have delayed surgeries due to blood shortages on **120** days in a year (Whitaker et al. (2007)).
- The national estimate for the number of units blood products outdated by blood centers and hospitals was **1,276,000** out of 15,688,000 units (Whitaker et al. (2007)).
- As of February 1, 2016, the American Red Cross was facing **an emergency need for blood and platelet donors**. Severe winter weather in January forced the cancellation of more than 340 blood drives in 20 states, resulting in nearly 10,000 donations uncollected.



ARC Regional Division

Blood Collection Sites

Blood Centers

Component Labs

Storage Facilities

Distribution Centers

Demand Points

Blood Supply Chains for the Red Cross

We developed a supply chain network optimization model for the management of the procurement, testing and processing, and distribution of a perishable product – that of human blood.

Novel features of the model include:

- It captures **perishability of this life-saving product** through the use of arc multipliers;
- It contains **discarding costs** associated with waste/disposal;
- It handles **uncertainty** associated with demand points;
- It assesses **costs associated with shortages/surpluses at the demand points**, and
- It quantifies the **supply-side risk** associated with procurement.

Medical Nuclear Supply Chains

We developed a medical nuclear supply chain network design model which captures the decay of the radioisotope molybdenum.

"Medical Nuclear Supply Chain Design: A Tractable Network Model and Computational Approach," A. Nagurney and L. S. Nagurney, *International Journal of Production Economics* **140(2)** (2012), pp 865-874.

Medical Nuclear Supply Chains

Medical nuclear supply chains are essential supply chains in healthcare and provide the conduits for products used in nuclear medical imaging, which is routinely utilized by physicians for diagnostic analysis for both cancer and cardiac problems.

Such supply chains have unique features and characteristics due to the products' time-sensitivity, along with their hazardous nature.

Salient Features:

- complexity
- economic aspects
- underlying physics of radioactive decay
- importance of considering both waste management and risk management.

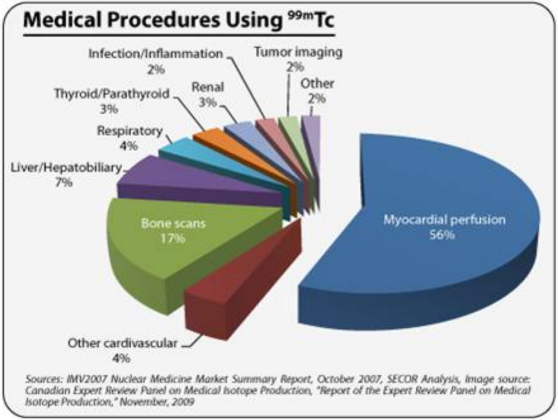
Over **100,000** hospitals in the world use radioisotopes (World Nuclear Association (2011)).

Technetium, ^{99m}Tc, which is a decay product of Molybdenum-99, ^{99}Mo, is the most commonly used medical radioisotope, used in more than **80%** of the radioisotope injections, with more than **30 million** procedures worldwide each year.

The half-life of Molybdenum-99 is 66 hours.

Each day, **41,000** nuclear medical procedures are performed in the United States using Technetium-99m.

A **radioactive isotope** is bound to a pharmaceutical that is injected into the patient and travels to the site or organ of interest in order to construct an image for **medical diagnostic** purposes.



For over two decades, all of the Molybdenum necessary for US-based nuclear medical diagnostic procedures has come from **foreign** sources.

^{99}Mo Supply Chain Challenges:

- The majority of the reactors are between **40 and 50 years old**. Several of the reactors currently used are due to be retired by the end of this decade (Seeverens (2010) and OECD Nuclear Energy Agency (2010a)).
- **Limitations in processing capabilities** make the world critically vulnerable to Molybdenum supply chain disruptions.
- The number of generator manufacturers is **under a dozen** (OECD Nuclear Energy Agency (2010b)).
- **Long-distance transportation** of the product raises safety and security risks, and also results in greater decay of the product.

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- The number of generator manufacturers is **under a dozen** (OECD Nuclear Energy Agency (2010b)).
- **Long-distance transportation** of the product raises safety and security risks, and also results in greater decay of the product.

In 2015, NorthStar Medical Radioisotopes LLC has received approval to begin routine production of molybdenum-99 (Mo-99) at the University of Missouri Research Reactor (MURR) facility in Columbia, Missouri. LEU rather than HEU will be used there.

This transitioning of NorthStar's Mo-99 line at MURR from a development process to a routine production process is another significant step toward establishing a domestic source of Mo-99.

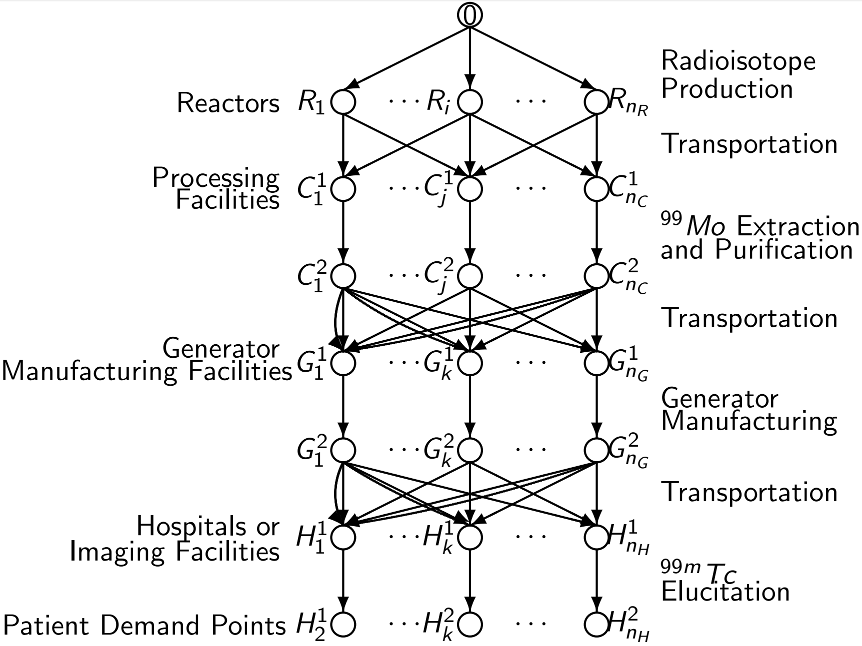

Figure: The Medical Nuclear Supply Chain Network Topology

Arc Multipliers

Because of the exponential decay of molybdenum, we have that the quantity of the radioisotope:

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

so that an arc multiplier on a link a that takes t_a hours of time corresponds to:

$$\alpha_a = e^{-\frac{ln2}{66.7} t_a}.$$

Supply Chain Networks – Additional Game Theory Models

Relationship of the Model to Others in the Literature

The above model is now related to several models in the literature.

If the arc multipliers are all equal to 1, in which case the product is not perishable, then the model is related to the sustainable fashion supply chain network model of Nagurney and Yu in the *International Journal of Production Economics* **135** (2012), pp 532-540. In that model, however, the other criterion, in addition to the profit maximization one, was emission minimization, rather than waste cost minimization, as in the model in this paper.

Relationship of the Model to Others in the Literature

If the product is homogeneous, and all the arc multipliers are, again, assumed to be equal to 1, and the total costs are assumed to be separable, then the above model collapses to the supply chain network oligopoly model of Nagurney (2010) in which synergies associated with mergers and acquisitions were assessed.

The Original Supply Chain Network Oligopoly Model

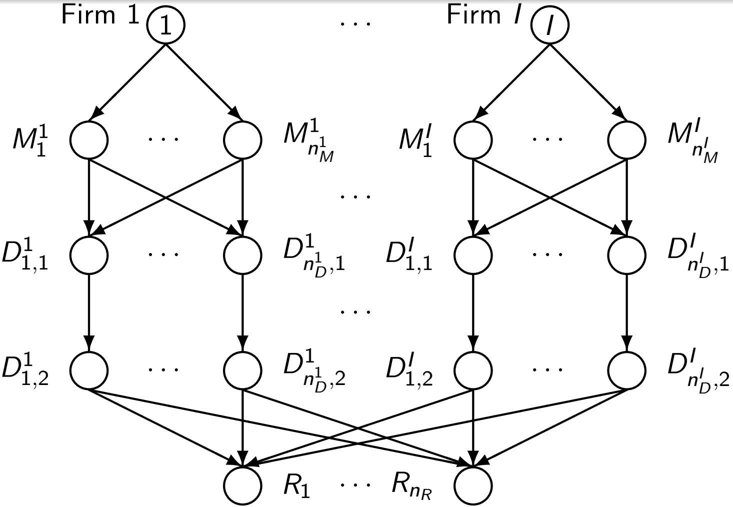

Figure: Supply Chain Network Structure of the Oligopoly Without Perishability; Nagurney, *Computational Management Science* **7**(2010), pp 377-401.

Mergers Through Coalition Formation

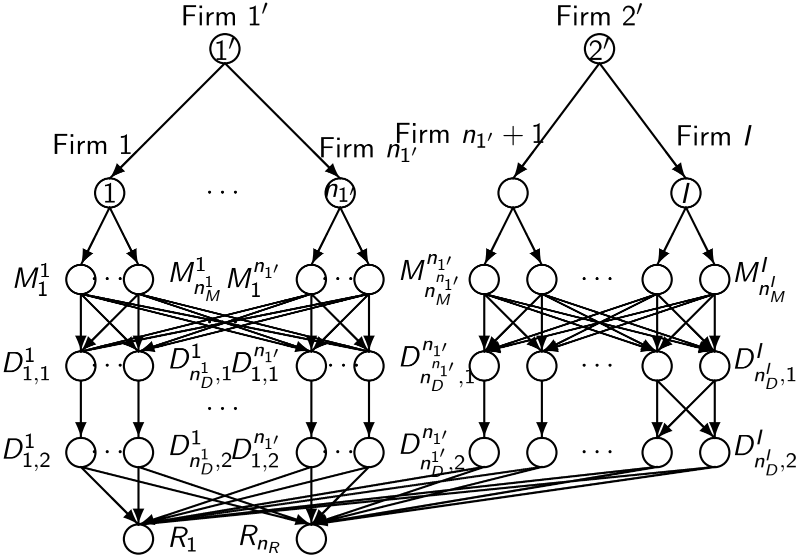

Figure: Mergers of the First $n_{1'}$ Firms and the Next $n_{2'}$ Firms

References can be found in our paper, "A Supply Chain Generalized Network Oligopoly Model for Pharmaceuticals Under Brand Differentiation and Perishability," A.H. Masoumi, M. Yu, and A. Nagurney, *Transportation Research E* **48** (2012), pp 762-780.

A Generalized Network Oligopoly Model for Pharmaceutical Supply Chains

We consider I pharmaceutical firms, with a typical firm denoted by i.

The firms compete noncooperatively, in an oligopolistic manner, and the consumers can differentiate among the products of the pharmaceutical firms through their individual product brands.

The supply chain network activities include manufacturing, shipment, storage, and, ultimately, the distribution of the brand name drugs to the demand markets.

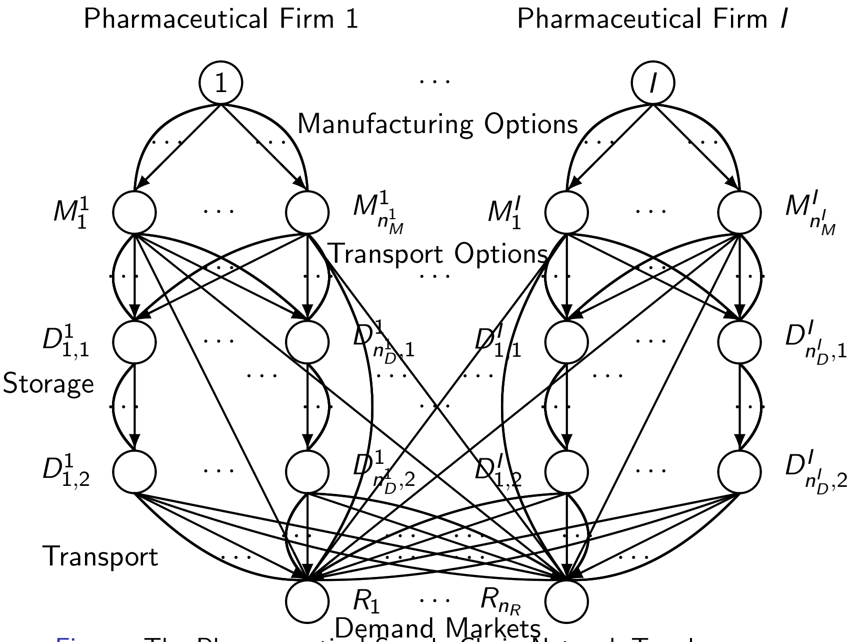

Figure: The Pharmaceutical Supply Chain Network Topology

Our recent research has returned to food supply chains in which we are also capturing explicit quality deterioation in fresh produce using chemical formulae that capture time and temperature of various supply chain network activities. Some of our applications are to farmers' markets.

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.

- We related the model to several others in the literature.

Thank You!

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