Quality in Competitive Fresh Produce Supply Chains with Application to Farmers' Markets

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Background

Knowledgeable modern consumers are increasingly demanding **high quality** in their food products, yet, they may be unaware of the great distances the food has traveled through intricate supply chains and the length of time from the initial production or "picking" of the fruits and vegetables to the ultimate delivery and consumption.

Motivation

Even though the transformation of food supply chains from **local to global** is remarkable, there may be some drawbacks.

- Consumers are facing **information asymmetry**.
- The great distances traveled create issues associated with **environmental impact, sustainability, and quality** since fresh produce is perishable (Nahmias (2011) and Nagurney et al. (2013)).

We focus on **quality deterioration** through **kinetics** in food supply chains, direct to consumer chains, and, specifically **farmers' markets**.

- Consumers tend to connect the terms **'fresh,' 'good quality,' and 'tasty'** with **locally** produced foods.
- Farmers' markets in **Norway**, have the potential to reduce both physical and social distances between producers and consumers, and, hence, contribute to the sustainability of local food production (Acebo et al.,(2007)).
- There were **8,268 farmers' markets** in the United States in 2014, with the number having increased by **180%** since 2006 (USDA(2014)).

Relevant Literature

- Various authors have emphasized quality; see Sloof, Tijskens, and Wilkinson (1996), Van der Vorst (2000), Lowe and Preckel (2004), Ahumada and Villalobos (2009, 2011), Blackburn and Scudder (2009), Akkerman, Farahani, and Grunow (2010), and Aiello, La Scalia, and Micale (2012).
- Yu and Nagurney (2013) propose a game theory model for oligopolistic competition in brand differentiated fresh produce supply chains with perishability.
- Tong, Ren, and Mack (2012) propose an optimal site selection model for farmers' markets in Arizona.
- There is limited research on quality decay through kinetics in direct-to-consumer food supply chains.

What is Quality Decay?

It is difficult to make a globally accepted definition of quality of fresh produce.

Quality of fresh foods can be defined over the combination of their physical attributes such as: **color and appearance, flavor, texture, and nutritional value.**

An understanding of the biochemical/physicochemical reactions can explain the quality deterioration.

Taoukis and Labuza (1989) explain the rate of quality deterioration of the quality attributes as a function of **microenvironment, gas composition, relative humidity, and temperature.**

Quality as a Function of Time and Temperature

Taoukis and Labuza (1989) and Labuza (1984) show the quality decay of a food attribute Q, over time t, through the differential equation:

Differential Equation of Quality Decay

$$\frac{-d[Q]}{dt} = -k[Q]^n = -Ae^{(-E/RT)}[Q]^n, \quad (1)$$

where k is the reaction rate defined by the **Arrhenius formula**:

Arrhenius Formula

$$Ae^{(-E/RT)}[Q]^n.$$

- A is the pre-exponential constant, T is temperature, E is activation energy and R is universal gas constant.
- n is the reaction order that belongs to the set $\mathrm{Z}^* = \{0\} \cup \mathrm{Z}^+$.

Types of Quality Decay Functions

The deterioration function changes with respect to the reaction order of the attribute.

When the initial quality is Q_0, Tijskens and Polderdijk (1996) categorize the decay functions as:

Reaction Order	**Type**	**Quality at Time t**
0	Linear	$Q_0 - kt$
1	Exponential	$Q_0 e^{-kt}$

Table: Reaction Kinetics and Quality at Time t

Some Fruits, Vegetables and Quality Decay

Attribute	Fresh Produce	Reaction Order	Reference
Color Change	**Peaches**	**First**	**Toralles et al. (2005)**
Color Change	Raspberries	First	Ochoa et al. (2001)
Color Change	Blueberries	First	Zhang, Guo, and Ma (2012)
Nutritional (Vitamin C)	Strawberries	First	Castro et al. (2004)
Color Change	Watermelons	Zero	Dermesonlouoglou, Giannakourou, and Taoukis (2007)
Moisture Content	Tomatoes	First	Krokida et al. (2003)
Color Change	Cherries	First	Ochoa et al. (2001)
Texture Softening	**Apples**	**First**	**Tijskens (1979)**
Nutritional (Vitamin C)	Pears	First	Mrad et al. (2012)
Texture Softening	Avocados	First	Maftoonazad and Ramaswamy (2008)
Nutritional (Vitamin C)	Pineapples	First	Karim and Adebowale (2009)
Color Change	Spinach	Zero	Aamir et al. (2013)
Color Change	Asparagus	First	Aamir et al. (2013)
Color Change	Peas	First	Aamir et al. (2013)
Texture Softening	Beans	First	Aamir et al. (2013)
Texture Softening	Brussel Sprouts	First	Aamir et al. (2013)
Texture Softening	Carrots	First	Aamir et al. (2013)
Texture Softening	Peas	First	Aamir et al. (2013)
Color Change	Coriander Leaves	First	Aamir et al. (2013)

Table: Fresh Produce Attributes and Decay Kinetics

Integration of Quality Decay Into the Supply Chain Network

Let β_a denote the quality decay incurred on link a, which depends on the reaction order n, reaction rate k_a and time t_a on link a, as:

Quality Decay Over a Link

$$\beta_a \equiv \begin{cases} -k_a t_a,, & \text{if } n = 0, \forall a \in L \\ e^{-k_a t_a}, & \text{if } n \neq 0, \forall a \in L. \end{cases} \quad (2)$$

where

Reaction Rate

$$k_a = Ae^{(-E_A/RT_a)}. \quad (3)$$

Integration of Quality Decay Into the Supply Chain Network

The quality q_p, over a path p, joining the origin destination farm, i, with a destination node farmers' market, j, can also be shown as:

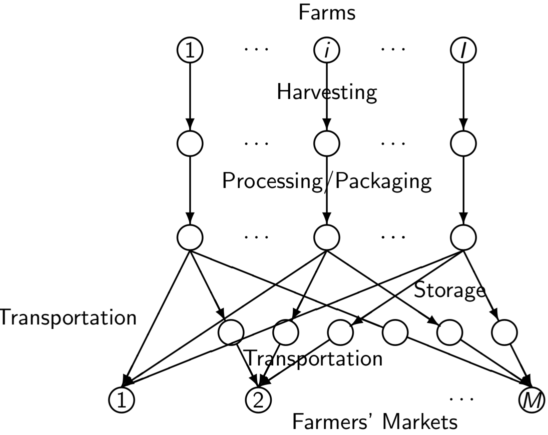
Quality Over a Path

$$q_p \equiv \begin{cases} q_{0i} + \sum_{a \in p} \beta_a, & \text{if } \; n = 0, \forall a \in L, \; p \in P_j^i, \forall i, j, \\ \\ q_{0i} \prod_{a \in p} \beta_a, & \text{if } \; n = 1, \forall a \in L, \; p \in P_j^i, \forall i, j, \end{cases} \tag{4}$$

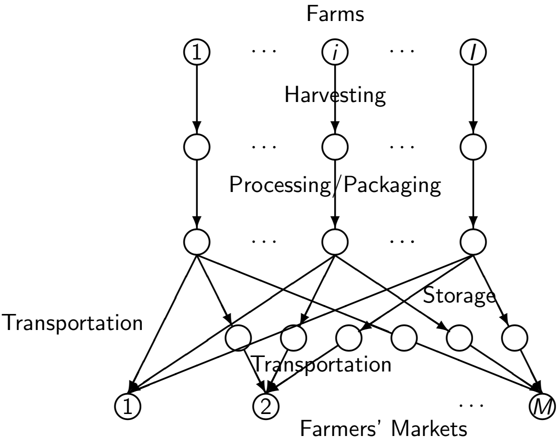
- where q_{0i} is the initial quality of food product at farm i,
- P_j^i represents the set of all paths that have origin i and destination j.

The Fresh Produce Supply Chain Network Topology

- The I farms compete **noncooperatively** in an **oligopolistic** manner.
- Products are differentiated based on **quality** at the farmers' markets.



The Fresh Produce Supply Chain Network Topology



1. **Fixed time horizon** in a given season of the fresh fruit or vegetable, **typically a week,** is assumed.
2. **The demand points** are selected **farmers' markets**.
3. **Picking is made right before the time horizon**, so that there is **no storage** for the first farmers' market of the week.
4. Consumers can buy products that are substitutes of one another within or across the demand points.

The Uncapacitated Fresh Produce Supply Chain Problem

Nonnegativity Constraints of the Path Flows

The flow on the path, joining the farm i to the farmers markets k, is denoted by x_p and it should be nonnegative:

$$x_p \geq 0, \quad \forall p \in P_k^i;\ i = 1, \ldots, I;\ k = 1, \ldots, n_R. \tag{5}$$

Link Flows

The flow on a link a is equal to the sum of the path flows x_p, on paths that include the link a, expressed as:

$$f_a = \sum_{p \in P_k^i} x_p \delta_{ap}, \quad \forall a \in L. \tag{6}$$

Demand

The demand at the farmers' market j for the fresh produce product of farmer i is given by:

$$\sum_{p \in P_j^i} x_p = d_{ij}, \quad p \in P_j^i; i = 1, \ldots, I;\ j = 1, \ldots, M. \tag{7}$$

The Uncapacitated Fresh Produce Supply Chain Problem

Demand Prices

The demand price function ρ_{ij} for farm i's product at the farmers' market j, is:

$$\rho_{ij} = \rho_{ij}(d, q), \quad i = 1, \ldots, I; \; j = 1, \ldots, M. \tag{8}$$

Link Costs

The total operational cost of each link a, denoted by $\hat{c}_a$, depends on the flows on all the links in the fresh produce supply chain network, that is,

$$\hat{c}_a = \hat{c}_a(f), \quad \forall a \in L, \tag{9}$$

Profit/Utility

The profit/utility function of farm i, denoted by U_i, is given by:

$$U_i = \sum_{j=1}^{M} \rho_{ij}(d, q) d_{ij} - \sum_{a \in L^i} \hat{c}_a(f). \tag{10}$$

The Uncapacitated Fresh Produce Supply Chain Problem

Definition 1: Fresh Produce Supply Chain Network Cournot-Nash Equilibrium for Farmers' Markets in the Uncapacitated Case

A path flow pattern $X^* \in K = \prod_{i=1}^{I} K_i$ constitutes a fresh produce supply chain network Cournot-Nash equilibrium if for each farm i; $i = 1, \ldots, I$:

$$\hat{U}_i(X_i^*, \hat{X}_i^*) \geq \hat{U}_i(X_i, \hat{X}_i^*), \quad \forall X_i \in K_i, \tag{11}$$

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

- A Cournot-Nash Equilibrium is established if no farm can unilaterally improve its profit by changing its product flows throughout its supply chain network, given the product flow decisions of the other farms.

The Uncapacitated Fresh Produce Supply Chain Problem

Theorem 1: Variational Inequality Formulations of the Uncapacitated Model

$X^* \in K$ is a fresh produce supply chain network Cournot-Nash equilibrium for famers' markets according to Definition 1 if and only if it satisfies the variational inequality:

$$-\sum_{i=1}^{I} \langle \nabla_{X_i} \hat{U}_i(X^*), X_i - X_i^* \rangle \geq 0, \quad \forall X \in K, \tag{12}$$

where $\langle \cdot, \cdot \rangle$ denotes the inner product in the corresponding Euclidean space and $\nabla_{X_i} \hat{U}_i(X)$ denotes the gradient of $\hat{U}_i(X)$ with respect to X_i.

The Uncapacitated Fresh Produce Supply Chain Problem

The variational inequality for our uncapacitated model is equivalent to the variational inequality that determines the vector of equilibrium path flows $x^* \in K^1$ such that:

$$\sum_{i=1}^{I}\sum_{j=1}^{M}\sum_{p\in P_j^i}\left[\frac{\partial \hat{C}_p(x^*)}{\partial x_p} - \hat{\rho}_{ij}(x^*,q) - \sum_{l=1}^{M}\frac{\partial \hat{\rho}_{il}(x^*,q)}{\partial x_p}\sum_{r\in P_l^i} x_r^*\right]\times[x_p - x_p^*] \geq 0, \quad \forall x \in K^1, \quad (13)$$

where $K^1 \equiv \{x | x \in R_+^{n_P}\}$, and for each path p; $p \in P_j^i$; $i = 1, \ldots, I$; $j = 1, \ldots, M$,

$$\frac{\partial \hat{C}_p(x)}{\partial x_p} \equiv \sum_{a\in L^i}\sum_{b\in L^i}\frac{\partial \hat{c}_b(f)}{\partial f_a}\delta_{ap} \text{ and } \frac{\partial \hat{\rho}_{il}(x,q)}{\partial x_p} \equiv \frac{\partial \rho_{il}(d,q)}{\partial d_{ij}}. \quad (14)$$

The Uncapacitated Fresh Produce Supply Chain Problem

The variational inequality can also be rewritten in terms of link flows as: determine the vector of equilibrium link flows and the vector of equilibrium demands $(f^*, d^*) \in K^2$, such that:

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

$$+ \sum_{i=1}^{I} \sum_{j=1}^{M} \left[-\rho_{ij}(d^*, q) - \sum_{l=1}^{M} \frac{\partial \rho_{il}(d^*, q)}{\partial d_{ik}} d_{il}^* \right] \times [d_{ij} - d_{ij}^*] \geq 0, \quad \forall (f, d) \in K^2, \tag{15}$$

where $K^2 \equiv \{(f, d) | x \geq 0, \mathit{and} \, (6) \, \mathit{and} \, (7) \, \mathit{hold}\}$.

- **Proof:** (12) follows from Gabay and Moulin (1980); see, also, Masoumi, Yu, and Nagurney (2012). (13) and (15) then follow using algebraic substitutions. □

The Uncapacitated Fresh Produce Supply Chain Problem

Variational inequalities (13) and (15) can be put into standard form (see Nagurney (1999)): determine $X^* \in \mathcal{K}$ such that:

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

where $\langle \cdot, \cdot \rangle$ denotes the inner product in N-dimensional Euclidean space with $N = n_P$ in our model. Let $X \equiv x$ and

$$F(X) \equiv \left[\frac{\partial \hat{C}_p(x)}{\partial x_p} - \hat{\rho}_{ij}(x, q) - \sum_{l=1}^{M} \frac{\partial \hat{\rho}_{il}(x, q)}{\partial x_p} \sum_{r \in P_l^i} x_r; \right.$$

$$\left. p \in P_j^i;\ i = 1, \ldots, I;\ j = 1, \ldots, M \right], \tag{17}$$

and $\mathcal{K} \equiv K^1$, then (10) can be re-expressed as (13).

Theorem 2: Existence

There exists at least one solution to variational inequality (13) (equivalently, to (15)), since there exists a $c > 0$*, such that variational inequality (17) admits a solution in* $\mathcal{K}_c$ *with*

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

Theorem 3: Uniqueness

With Theorem 2, the variational inequalities admit at least one solution. Moreover, if the function $F(X)$ *is strictly monotone on* $\mathcal{K} \equiv K^2$*, that is,*

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

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

The Capacitated Fresh Produce Supply Chain Problem

- Labor shortages, weather conditions, disruptions to storage or transportation can limit the supply chain activities.
- The objective function, the constraints, with conservation of flow equations stay the same.

Link Capacity Constraints

$$f_a \leq u_a, \quad \forall a \in L, \tag{20a}$$

$$\sum_{p \in P} x_p \delta_{ap} \leq u_a, \quad \forall a \in L, \tag{20b}$$

where $K_i^3 \equiv \{X_i | X_i \in R_+^{n_{P^i}}$ and $(20b)$ holds for $a \in L^i\}$ and $K^3 \equiv \prod_{i=1}^{I} K_i^3$.

The Capacitated Fresh Produce Supply Chain Problem

The variational inequality is equivalent to the variational inequality problem: determine $(x^*, \lambda^*) \in K^4$, where $K^4 \equiv \{x \in R_+^{n_P}, \lambda \in R_+^{n_L}\}$, such that:

$$\sum_{i=1}^{I}\sum_{j=1}^{M}\sum_{p\in P_j^i}\left[\frac{\partial \hat{C}_p(x^*)}{\partial x_p} - \hat{\rho}_{ij}(x^*, q) - \sum_{l=1}^{M}\frac{\partial \hat{\rho}_{il}(x^*, q)}{\partial x_p}\sum_{r\in P_l^i} x_r^* + \sum_{a\in L}\lambda_a^*\delta_{ap}\right] \times [x_p - x_p^*]$$

$$+\sum_{a\in L}\left[u_a - \sum_{p\in P} x_p^*\delta_{ap}\right] \times [\lambda_a - \lambda_a^*] \geq 0, \quad \forall (x, \lambda) \in K^4, \tag{21}$$

where $\frac{\partial \hat{C}_p(x)}{\partial x_p}$ and $\frac{\partial \hat{\rho}_{il}(x,q)}{\partial x_p}$ are as defined in (14).

The Euler Method

Euler method, which is induced by the general iterative scheme of Dupuis and Nagurney (1993) is shown as:

$$X^{\tau+1} = P_{\mathcal{K}}(X^{\tau} - a_{\tau}F(X^{\tau})), \tag{22}$$

The Euler method, the sequence $\{a_{\tau}\}$ must satisfy: $\sum_{\tau=0}^{\infty} a_{\tau} = \infty$, $a_{\tau} > 0$, $a_{\tau} \to 0$, as $\tau \to \infty$.

The Euler Method Explicit Formulae for the Uncapacitated Model

Closed form expressions for the fresh produce path flows, for each path $p \in P_j^i$, $\forall i, j$:

$$x_p^{\tau+1} = \max\{0, x_p^\tau + a_\tau(\hat{\rho}_{ij}(x^\tau, q) + \sum_{l=1}^{M} \frac{\partial \hat{\rho}_{il}(x^\tau, q)}{\partial x_p} \sum_{r \in P_l^i} x_r^\tau - \frac{\partial \hat{C}_p(x^\tau)}{\partial x_p})\}, \tag{23}$$

$$\forall p \in P_j^i;\ i = 1, \ldots, I;\ j = 1, \ldots, M.$$

The Euler Method Explicit Formulae for the Capacitated Model

For each path $p \in P_j^i$, $\forall i, j$, compute:

$$x_p^{\tau+1} = \max\{0, x_p^\tau + a_\tau(\hat{\rho}_{ij}(x^\tau, q) + \sum_{l=1}^{M} \frac{\partial \hat{\rho}_{il}(x^\tau, q)}{\partial x_p} \sum_{r \in P_l^i} x_r^\tau - \frac{\partial \hat{C}_p(x^\tau)}{\partial x_p} - \sum_{a \in L} \lambda_a^\tau \delta_{ap})\}, \quad (24)$$

$$\forall p \in P_j^i;\ i = 1, \ldots, I;\ j = 1, \ldots, M.$$

The Lagrange multipliers for each link $a \in L^i$; $i = 1, \ldots, I$, compute:

$$\lambda_a^{\tau+1} = \max\{0, \lambda_a^\tau + a_\tau(\sum_{p \in P} x_p^\tau \delta_{ap} - u_a)\}, \ \forall a \in L. \quad (25)$$

Case Study

We focus on apple orchard/farms and Farmers' Markets in **western Massachusetts**.

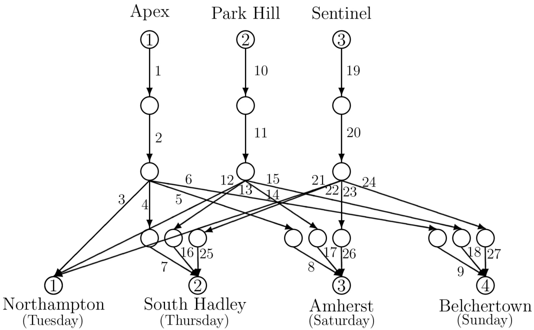
Orchard/farms:

- Apex Orchards are located in Shelburne Falls.
- Park Hill Orchard is located in Easthampton.
- Sentinel Farm is located in Belchertown.

Farmers' markets:

- Northampton Farmers' Market is open on Tuesdays.
- South Hadley Farmers' Market is open on Thursdays.
- Amherst Farmers' Market is open on Saturdays.
- Belchertown Farmers' Market is open on Sundays.

Scenario 1 - Some Information



- Picking is made **on Monday**; therefore, there are **no storage links for the Northampton Farmers' Market**.
- Golden Delicious apples follow **first order** quality decay.
- Harvesting is made between **September and October**, with average temperatures **19-22 C°**.

Scenario 1 - Some Information

- Apex Orchards have the largest land size (170 acres), followed by Park Hill Orchard (127 acres) and Sentinel Farm (8 acres).
- Apex is located in a higher altitude, so that the average harvesting temperature at the orchard is lower than others.
- Apex uses controlled atmosphere storage which maintains the optimal temperature, $0\ C^{\circ}$.
- We assume that orchard/farm i; $i = 1, 2, 3$, in the supply chain network has initial quality, respectively, of: $q_{01} = 1$, $q_{02} = 0.8$, and $q_{03} = 0.7$.
- Uncapacitated model is used.

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Sentinel Farm

Scenario 1- Quality Decay

Operations	Link a	Hours	Temp (C°)	β_a
harvesting	**1**	**4.00**	**19**	**0.992**
processing	2	3.00	19	0.994
transportation	3	2.50	19	0.999
storage (2 days)	4	**48.00**	0	**0.994**
storage (4 days)	5	96.00	0	0.988
storage (5 days)	6	120.00	0	0.985
transportation	7	4.00	19	0.993
transportation	8	3.25	19	0.994
transportation	9	4.00	19	0.993
harvesting	**10**	**3.00**	**22**	**0.992**
processing	11	3.00	22	0.992
transportation	12	2.5	19	0.999
storage (2 days)	**13**	**48.00**	**9**	**0.978**
storage (4 days)	14	96.00	9	0.957
storage (5 days)	15	120.00	9	0.947

Scenario 1 - Quality Decay

Operations	**Link** a	**Hours**	**Temp** (C°)	β_a
transportation	16	3.75	19	0.993
transportation	17	5.16	19	0.990
transportation	18	3.00	19	0.992
harvesting	**19**	**5.00**	**22**	**0.986**
processing	20	5.00	22	0.986
transportation	21	2.50	22	0.998
storage (2 days)	**22**	**48.00**	**12**	**0.967**
storage (4 days)	23	96.00	12	0.936
storage (5 days)	24	120.00	12	0.921
transportation	25	3.75	22	0.990
transportation	26	5.16	22	0.986
transportation	27	3.00	22	0.992

Scenario 1- Demand Price Functions

Demand Price Functions of Apex Orchards:

$$\rho_{11}(d,q) = -0.04d_{11} - 0.01d_{21} - 0.01d_{31} + 8q_{p_1} - 4q_{p_5} - 3q_{p_9} + 30,$$
$$\rho_{12}(d,q) = -0.02d_{12} - 0.01d_{22} - 0.01d_{32} + 3q_{p_2} - 2q_{p_6} - 2q_{p_{10}} + 25,$$
$$\rho_{13}(d,q) = -0.04d_{13} - 0.02d_{23} - 0.01d_{33} + 8q_{p_3} - 4q_{p_7} - 3q_{p_{11}} + 30,$$
$$\rho_{14}(d,q) = -0.04d_{14} - 0.02d_{24} - 0.02d_{34} + 3q_{p_4} - q_{p_8} - 2q_{p_{12}} + 25,$$

Demand Price Functions of Park Hill Orchard:

$$\rho_{21}(d,q) = -0.04d_{21} - 0.02d_{11} - 0.02d_{31} + 3q_{p_5} - 2q_{p_1} - q_{p_9} + 27,$$
$$\rho_{22}(d,q) = -0.04d_{22} - 0.01d_{12} - 0.02d_{32} + 3q_{p_6} - 2q_{p_2} - q_{p_{10}} + 28,$$
$$\rho_{23}(d,q) = -0.04d_{23} - 0.02d_{13} - 0.02d_{33} + 4q_{p_7} - 2q_{p_3} - q_{p_{11}} + 27,$$
$$\rho_{24}(d,q) = -0.02d_{24} - 0.01d_{14} - 0.01d_{34} + 2q_{p_8} - q_{p_4} - q_{p_{12}} + 28,$$

Demand Price Functions of Sentinel Farm:

$$\rho_{31}(d,q) = -0.04d_{31} - 0.02d_{11} - 0.02d_{21} + 4q_{p_9} - q_{p_1} - 2q_{p_5} + 25,$$
$$\rho_{32}(d,q) = -0.04d_{32} - 0.01d_{12} - 0.02d_{22} + 4q_{p_{10}} - 3q_{p_2} - q_{p_6} + 28,$$
$$\rho_{33}(d,q) = -0.02d_{23} - 0.01d_{13} - 0.01d_{33} + 4q_{p_{11}} - 2q_{p_3} - q_{p_7} + 25,$$
$$\rho_{34}(d,q) = -0.04d_{34} - 0.02d_{14} - 0.02d_{24} + 3q_{p_{12}} - 2q_{p_4} - 2q_{p_8} + 28.$$

Scenario 1 - Total Link Cost Functions and Equilibrium Link Flows

Operations	**Link** a	$\hat{c}_a(f)$	f_a^*
harvesting	1	$0.02f_1^2 + 3f_1$	165.8395
processing	2	$0.015f_2^2 + 3f_2$	165.8395
transportation	3	$0.01f_3^2 + 3f_3$	111.9827
storage (2 days)	4	$0.01f_4^2 + 3f_4$	0.0000
storage (4 days)	5	$0.015f_5^2 + 4f_5$	53.8568
storage (5 days)	6	$0.03f_6^2 + 5f_6$	0.0000
transportation	7	$0.02f_7^2 + 6f_7$	0.0000
transportation	8	$0.0125f_8^2 + 4f_8$	53.8568
transportation	9	$0.02f_9^2 + 6.6f_9$	0.0000
harvesting	10	$0.0125f_{10}^2 + 6f_{10}$	94.7414
processing	11	$0.0125f_{11}^2 + 6f_{11}$	94.7414
transportation	12	$0.0045f_{12}^2 + f_{12}$	71.7812
storage (2 days)	13	$0.01f_{13}^2 + 1.67f_{13}$	22.9601
storage (4 days)	14	$0.015f_{14}^2 + 6f_{14}$	0.0000
storage (5 days)	15	$0.015f_{15}^2 + 6.6f_{15}$	0.0000

Scenario 1 - Total Link Cost Functions and Equilibrium Link Flows

Operations	**Link** a	$\hat{c}_a(f)$	f_a^*
transportation	16	$0.0075 f_{16}^2 + 6 f_{16}$	22.9601
transportation	17	$0.01 f_{17}^2 + 6 f_{17}$	0.0000
transportation	18	$0.02 f_{18}^2 + 4 f_{18}$	0.0000
harvesting	19	$0.0125 f_{19}^2 + 6 f_{19}$	98.5294
processing	20	$0.015 f_{20}^2 + 4 f_{20}$	98.5294
transportation	21	$0.02 f_{21}^2 + 4 f_{21}$	17.2084
storage (2 days)	22	$0.007 f_{22}^2 + 1.67 f_{22}$	32.4314
storage (4 days)	23	$0.009 f_{23}^2 + 6 f_{23}$	0.0000
storage (5 days)	24	$0.01 f_{24}^2 + 6 f_{24}$	48.8896
transportation	25	$0.005 f_{25}^2 + 6 f_{25}$	32.4314
transportation	26	$0.005 f_{26}^2 + 6 f_{26}$	0.0000
transportation	27	$0.0005 f_{27}^2 + 0.1 f_{27}$	48.8896

Scenario 1 - Equilibrium Path Flows and Path Quality Decay

Farm	Path p	q_p	x_p^*	Farmers' Market
Apex	p_1	**0.9851**	**111.9827**	**Northampton**
Apex	p_2	0.9733	0.0000	South Hadley
Apex	p_3	0.9684	53.8568	Amherst
Apex	p_4	**0.9645**	**0.0000**	**Belchertown**
Park Hill	p_5	**0.7864**	**71.7812**	**Northampton**
Park Hill	p_6	0.7645	22.9602	South Hadley
Park Hill	p_7	0.7458	0.0000	Amherst
Park Hill	p_8	**0.7395**	**0.0000**	**Belchertown**
Sentinel	p_9	**0.6791**	**17.2084**	**Northampton**
Sentinel	p_{10}	0.6514	32.4314	South Hadley
Sentinel	p_{11}	0.6280	0.0000	Amherst
Sentinel	p_{12}	**0.6217**	**48.8896**	**Belchertown**

Apex Orchards' Prices for its Peck of Apples:

$$\rho_{11} = 27.33, \quad \rho_{12} = 24.53, \quad \rho_{13} = 30.72, \quad \rho_{14} = 25.42,$$

Park Hill Orchard's Prices for its Peck of Apples:

$$\rho_{21} = 21.25, \quad \rho_{22} = 26.13, \quad \rho_{23} = 26.34, \quad \rho_{24} = 27.40,$$

Sentinel Farm's Prices for its Peck of Apples:

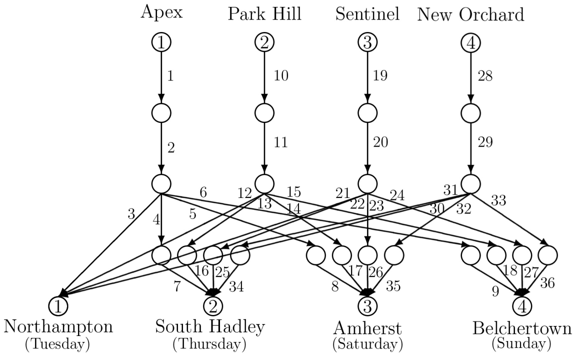
$$\rho_{31} = 20.79, \quad \rho_{32} = 25.16, \quad \rho_{33} = 24.29, \quad \rho_{34} = 24.50.$$

Profits of the Orchard/Farms, in Dollars:

$$\mathbf{U_1(X^*) = 1785.40}, \quad U_2(X^*) = 484.03, \quad U_3(X^*) = 460.15.$$

Scenario 2 - Some Information

- It is assumed that a new orchard, which was solely selling to retailers and wholesalers previously, is attracted by the demand for apples at the farmers' markets.



Scenario 2 - Quality Decay

- It has **similar** orchard characteristics to **Apex Orchards**.
- It is located in **Belchertown**, which has similar seasonal temperatures to the other farm/orchards.
- The **transportation time** from the New Orchard to the farmers' markets is similar to **Sentinel Farm**.

Operations	**Link** a	**Hours**	**Temp** (C°)	β_a
harvesting	28	4.00	19	0.988
processing	29	4.00	19	0.988
transportation	30	0.50	19	0.998
storage (2 days)	**31**	**48.00**	**0**	**0.968**
storage (4 days)	32	**96.00**	**0**	**0.989**
storage (5 days)	**33**	**120.00**	**0**	**0.986**
transportation	34	3.50	19	0.989
transportation	35	3.00	19	0.991
transportation	36	3.00	19	0.991

Scenario 2 - Demand Price Functions

Demand Price Functions of Apex Orchards:

$$\rho_{11}(d,q) = -0.053d_{11} - 0.01d_{21} - 0.01d_{31} - 0.03d_{41} + 8q_{p_1} - 2q_{p_5} - 2q_{p_9} - 4q_{p_{13}} + 30,$$

$$\rho_{12}(d,q) = -0.03d_{12} - 0.01d_{22} - 0.01d_{32} - 0.004d_{42} + 3q_{p_2} - 2q_{p_6} - 2q_{p_{10}} - q_{p_{14}} + 25,$$

$$\rho_{13}(d,q) = -0.053d_{13} - 0.01d_{23} - 0.01d_{33} - 0.03d_{43} + 8q_{p_3} - 2q_{p_7} - 2q_{p_{11}} - 4q_{p_{15}} + 30,$$

$$\rho_{14}(d,q) = -0.03d_{14} - 0.01d_{24} - 0.014d_{34} - 0.004d_{44} + 3q_{p_4} - q_{p_8} - 2q_{p_{12}} - q_{p_{15}} + 25,$$

Demand Price Functions of Park Hill Orchard:

$$\rho_{21}(d,q) = -0.05d_{21} - 0.01d_{11} - 0.01d_{31} - 0.01d_{41} + 3q_{p_5} - q_{p_1} - q_{p_9} - q_{p_{13}} + 27,$$

$$\rho_{22}(d,q) = -0.04d_{22} - 0.01d_{12} - 0.02d_{32} - 0.004d_{42} + 3q_{p_6} - 2q_{p_2} - q_{p_{10}} - q_{p_{14}} + 28,$$

$$\rho_{23}(d,q) = -0.05d_{23} - 0.02d_{13} - 0.01d_{33} - 0.02d_{43} + 4q_{p_7} - 2q_{p_3} - q_{p_{11}} - 2q_{p_{15}} + 27,$$

$$\rho_{24}(d,q) = -0.04d_{24} - 0.01d_{14} - 0.02d_{34} - 0.004d_{44} + 2q_{p_8} - q_{p_4} - q_{p_{12}} - q_{p_{16}} + 28,$$

Scenario 2 - Demand Price Functions

Demand Price Functions of Sentinel:

$$\rho_{21}(d,q) = -0.05d_{21} - 0.01d_{11} - 0.01d_{31} - 0.01d_{41} + 3q_{p_5} - q_{p_1} - q_{p_9} - q_{p_{13}} + 27,$$

$$\rho_{22}(d,q) = -0.04d_{22} - 0.01d_{12} - 0.02d_{32} - 0.004d_{42} + 3q_{p_6} - 2q_{p_2} - q_{p_{10}} - q_{p_{14}} + 28,$$

$$\rho_{23}(d,q) = -0.05d_{23} - 0.02d_{13} - 0.01d_{33} - 0.02d_{43} + 4q_{p_7} - 2q_{p_3} - q_{p_{11}} - 2q_{p_{15}} + 27,$$

$$\rho_{24}(d,q) = -0.04d_{24} - 0.01d_{14} - 0.02d_{34} - 0.004d_{44} + 2q_{p_8} - q_{p_4} - q_{p_{12}} - q_{p_{16}} + 28,$$

Demand Price Functions of New Orchard:

$$\rho_{41}(d,q) = -0.053d_{41} - 0.03d_{11} - 0.01d_{21} - 0.01d_{31} + 5q_{p_{13}} - 2q_{p_1} - q_{p_5} - q_{p_9} + 30,$$

$$\rho_{42}(d,q) = -0.03_{42} - 0.006d_{12} - 0.01d_{22} - 0.01d_{32} + 2q_{p_{14}} - q_{p_2} - q_{p_6} - q_{p_{10}} + 25,$$

$$\rho_{43}(d,q) = -0.053d_{43} - 0.03d_{13} - 0.01d_{23} - 0.01d_{33} + 5q_{p_{15}} - 2q_{p_3} - q_{p_7} - q_{p_{11}} + 30,$$

$$\rho_{44}(d,q) = -0.03d_{44} - 0.006d_{14} - 0.01d_{24} - 0.01d_{34} + 2q_{p_{16}} - q_{p_4} - q_{p_8} - q_{p_{12}} + 25.$$

Scenario 2 - Equilibrium Path Flows and Path Quality Decay

- Initial quality of the apples at the orchards is $q_{01} = 1$, $q_{02} = 0.8$, $q_{03} = 0.7$ and $q_{04} = 1$.

Farm	Path p	q_p	x_p^*	Farmers' Market
Apex	p_1	**0.9851**	**79.5849**	**Northampton**
Apex	p_2	0.9733	0.0000	South Hadley
Apex	p_3	0.9684	44.5036	Amherst
Apex	p_4	0.9645	0.0000	Belchertown
Park Hill	p_5	0.7864	69.2348	Northampton
Park Hill	p_6	**0.7645**	**18.2460**	**South Hadley**
Park Hill	p_7	0.7458	0.0000	Amherst
Park Hill	p_8	0.7395	0.0000	Belchertown
Sentinel	p_9	**0.6791**	**18.3520**	**Northampton**
Sentinel	p_{10}	0.6514	30.9408	South Hadley
Sentinel	p_{11}	0.6280	0.0000	Amherst
Sentinel	p_{12}	0.6217	36.7854	Belchertown
New Orchard	p_{13}	**0.9742**	**82.0895**	**Northampton**
New Orchard	p_{14}	0.9345	0.0000	South Hadley
New Orchard	p_{15}	**0.9567**	**44.0319**	**Amherst**
New Orchard	p_{16}	0.9538	0.0000	Belchertown

Apex Orchards' price of apples per peck:

$$\boldsymbol{\rho_{11} = 23.49}, \quad \rho_{12} = 23.66, \quad \rho_{13} = 27.49, \quad \rho_{14} = 24.44,$$

Park Hill Orchard's Prices for its Peck of Apples:

$$\rho_{21} = 21.46, \quad \rho_{22} = 25.41, \quad \rho_{23} = 25.49, \quad \rho_{24} = 26.20,$$

Sentinel Farm's Prices for its Peck of Apples:

$$\rho_{31} = 20.38, \quad \rho_{32} = 24.38, \quad \rho_{33} = 22.91, \quad \rho_{34} = 23.08,$$

New Orchard's Prices for its Peck of Apples:

$$\rho_{41} = 23.82, \quad \rho_{42} = 23.99, \quad \rho_{43} = 27.80, \quad \rho_{44} = 24.21.$$

Profits of the Orchard/Farms, in Dollars:

$$\mathbf{U_1(X^*) = 1097.39}, \quad U_2(X^*) = 471.71, \quad U_3(X^*) = 345.45, \quad \mathbf{U_4(X^*) = 1142.19}.$$

Scenario 3 - Some Information

- This scenario is constructed to illustrate the apple shortage experienced in **western Massachusetts in 2016.**
- According to various news articles, the **cold snap** happened in May damaged the **green apple buds** and **an apple shortage** at the local markets, which includes the farmers' markets, is expected.
- Expected shortage is assumed to **be more for Apex** due to being located in a **higher altitude.**
- The capacities are written according to the **expected damage level of harvest** at the orchard/farms.
- Initial quality of the apples at the orchards is $q_{01} = 0.4$, $q_{02} = 0.5$ and $q_{03} = 0.6$.

Scenario 3 - Link Capacities, Equilibrium Link Flows and Equilibrium Lagrange Multipliers

Operations	**Link** a	**Capacity**	f_a^*	λ_a^*
harvesting	**1**	**20**	**20.0000**	**16.4077**
processing	2	15000	20.0000	0.0000
transportation	3	15000	20.0000	0.0000
storage (2 days)	4	15000	0.0000	0.0000
storage (3 days)	5	15000	0.0000	0.0000
storage (4 days)	6	15000	0.0000	0.0000
transportation	7	15000	0.0000	0.0000
transportation	8	15000	0.0000	0.0000
transportation	9	15000	0.0000	0.0000
harvesting	**10**	**50**	**50.0000**	**6.4906**
processing	11	15000	50.0000	0.0000
transportation	12	15000	50.0000	0.0000
storage (2 days)	13	15000	0.0000	0.0000
storage (3 days)	14	15000	0.0000	0.0000
storage (4 days)	15	15000	0.0000	0.0000

Scenario 3 - Link Capacities, Equilibrium Link Flows and Equilibrium Lagrange Multipliers

Operations	**Link** a	**Capacity**	f_a^*	λ_a^*
transportation	16	15000	0.0000	0.0000
transportation	17	15000	0.0000	0.0000
transportation	18	15000	0.0000	0.0000
harvesting	**19**	**60**	**60.0000**	**5.6685**
processing	20	15000	60.0000	0.0000
transportation	21	15000	13.1918	0.0000
storage (2 days)	22	15000	18.7448	0.0000
storage (3 days)	23	15000	0.0000	0.0000
storage (4 days)	24	15000	28.0624	0.0000
transportation	25	15000	18.7448	0.0000
transportation	26	15000	0.0000	0.0000
transportation	27	15000	28.0624	0.0000

Scenario 3 - Equilibrium Path Flows and Path Quality Decay

Farm	Path p	q_p	x_p^*	Farmers' Market
Apex	p_1	**0.3940**	**20.0000**	**Northampton**
Apex	p_2	0.3893	0.0000	South Hadley
Apex	p_3	0.3873	0.0000	Amherst
Apex	p_4	0.3858	0.0000	Belchertown
Park Hill	p_5	**0.4915**	**50.0000**	**Northampton**
Park Hill	p_6	0.4778	0.0000	South Hadley
Park Hill	p_7	0.4662	0.0000	Amherst
Park Hill	p_8	0.4622	0.0000	Belchertown
Sentinel	p_9	**0.5821**	**13.1918**	**Northampton**
Sentinel	p_{10}	**0.5584**	**18.7448**	**South Hadley**
Sentinel	p_{11}	0.5383	0.0000	Amherst
Sentinel	p_{12}	**0.5329**	**28.0624**	**Belchertown**

Apex Orchards' Prices for its Peck of Apples:

$$\rho_{11} = 28.01, \quad \rho_{12} = 23.91, \quad \rho_{13} = 29.62, \quad \rho_{14} = 24.35.$$

Park Hill Orchard's Prices for its Peck of Apples:

$$\rho_{21} = 24.44, \quad \rho_{22} = 27.72, \quad \rho_{23} = 27.55, \quad \rho_{24} = 27.72,$$

Sentinel Farm's Prices for its Peck of Apples:

$$\rho_{31} = 24.02, \quad \rho_{32} = 27.84, \quad \rho_{33} = 25.91, \quad \rho_{34} = 26.78.$$

The profits of the Orchard/Farms, in Dollars:

$$\mathbf{U_1(X^*) = 362.15}, \quad U_2(X^*) = 498.28, \quad U_3(X^*) = 507.58.$$

Conclusion

- We provided **explicit formulae** for quality deterioration and found the quality associated with every path in the network.
- We focused on **farmers' markets** which are direct to consumer chains.
- We provided a **game theory model** for **supply chain** competition in a network framework for farmers' markets.
- This is the **first work** in the literature with a supply chain game theory model for farmers' markets with **quality deterioration.**

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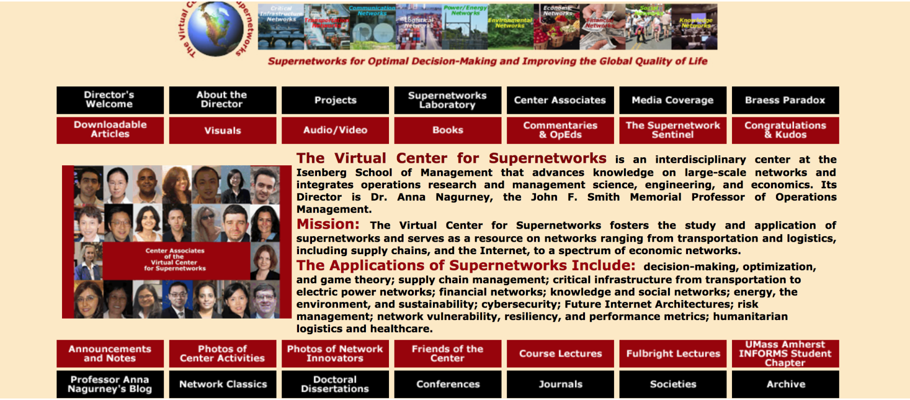
THANK YOU!



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