A Competitive Multiperiod Supply Chain Network Model with Freight Carriers and Green Technology Investment Option

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EURO 2028
July 8-11, 2018, Valencia, Spain

This presentation is based on the paper:

Saberi, S., Cruz, J.M., Sarkis, J., Nagurney, A. (2017). A Competitive Multiperiod Supply Chain Network Model with Freight Carriers and Green Technology Investment Option. Accepted for publication in *European Journal of Operational Research*.

Motivation

- Increase environmental awareness and improve ecological footprint
- Walmart plan for CO_2 reduction with its extended supply chain
- Siemens (2015) will spend nearly $110 million to lower the company's emissions. To reduce carbon emissions in half by 2020 and save between $ 20 to $30 million annually.
- Dell plan to use packaging material made of wheat straw; This new material uses 40% less energy to produce, 90% less water, and costs less to make than traditional packaging
- Literature on sustainable supply chain management focused on environmental decision making and closed-loop supply chains

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Contributions

- Explicitly model competition among manufacturing firms, retail stores, and freight carriers in terms of:
  - products and inventory quantities
  - product shipping costs
  - energy rating
  - and initial technology investments
- Explicit integration of environmental preferences of retailers and manufacturers in selecting their manufacturers and carriers
- Consumer awareness of green technology and foot print outcomes in spatial price equilibrium conditions

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- Modeling supply chain decision making and management from operational, tactical, and strategic business perspectives (Brandenburg et al. (2014); Ding et al. (2016); Fahimnia et al. (2015); Ouardighi et al. (2016); Zhu and He (2017))
- Environmental decision making in supply chain management processes and associated optimization from a number of dimensions (Nagurney et al. (2007); Cruz (2008); Frota Neto et al. (2008))
- Utilizing regulatory policies related to internalizing externalities such as including emission taxes (Cruz and Liu (2011); Dhavale and Sarkis (2015); Diabat and Simchi-Levi (2009); Zakeri et al. (2015))
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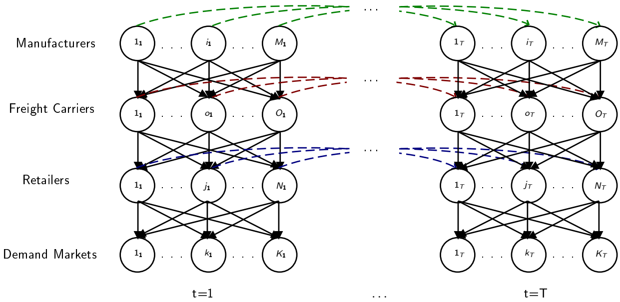
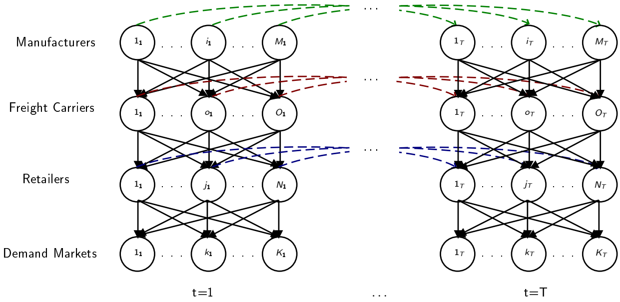


Figure: The supply chain network with freight carriers



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Notation	Definition
δ_{mi}	Energy rating of manufacturer i.
δ_{co}	Energy rating of carrier o.
δ_{rj}	Energy rating of retailer j.
δ_{max}	Maximum possible level of energy rating.

$$\text{Maximize} \quad \sum_{t=1}^{T} \frac{1}{(1+r)^t} \Big\{ \sum_{j=1}^{N} p_{ijt}^{1*} q_{ijt}^{1} - PC_{it}(S_t, \delta_{mi}) - \sum_{j=1}^{N} TC_{ijt}(q_{ijt}^{1}, \delta_{mi}) - WC_{it}(I_{it}, \delta_{mi}) - \sum_{j=1}^{N} \sum_{o=1}^{O} R_{ijot}(p_t^{2*}, \delta_{co}) p_{ijot}^{2*} \Big\} - TSI_i(\delta_{mi}) \tag{1}$$

subject to:

$$S_{i1} - I_{i1} \geq \sum_{j=1}^{N} q_{ij1}^{1} \tag{2}$$

$$I_{i(t-1)} + S_{it} - I_{it} \geq \sum_{j=1}^{N} q_{ijt}^{1}, \qquad \forall t = 2, \ldots, T \tag{3}$$

$$q_{ijt}^{1} = \sum_{o=1}^{O} R_{ijot}(p_t^{2}, \delta_{co}), \qquad \forall j, t \tag{4}$$

$$\delta_{mi} \leq \delta_{co}, \qquad \forall o \tag{5}$$

and the nonnegativity constraints: $q_{ijt}^{1} \geq 0$, $S_{it} \geq 0$, $I_{it} \geq 0$, $0 \leq \delta_{mi} \leq \delta_{max}$, $\forall j, t$.

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subject to:

$$\sum_{j=1}^{N} R_{ijo1}(p_1^2, \delta_{co}) - B_{io1} \geq \sum_{j=1}^{N} q_{ijo1}^2 \quad (7)$$

$$B_{io(t-1)} + \sum_{j=1}^{N} R_{ijot}(p_t^2, \delta_{co}) - B_{iot} \geq \sum_{j=1}^{N} q_{ijot}^2, \qquad \forall t = 2, \ldots, T \quad (8)$$

$$\sum_{t=1}^{T} \sum_{o=1}^{O} q_{ijot}^2 = \sum_{t=1}^{T} q_{ijt}^1, \qquad \forall i, j \quad (9)$$

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and

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Conditions (18) and (19) must hold simultaneously for all demand markets. These conditions correspond to the well-known spatial price equilibrium conditions (cf. Nagurney (1999); Takayama and Judge (1964)).

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Conditions (18) and (19) must hold simultaneously for all demand markets. These conditions correspond to the well-known spatial price equilibrium conditions (cf. Nagurney (1999); Takayama and Judge (1964)).

Theorem 1: Variational Inequality Formulation

The equilibrium conditions governing the multiperiod supply chain - freight carrier model are equivalent to the solution of the variational inequality problem given by: determine $(q^{1*}, q^{2*}, q^{3*}, S^*, I^*, \delta_m^*, p^{2*}, B^*, \delta_c^*, Y^*, Z^*, \delta_r^*, p^{4*}, \mu^{1*}, \mu^{2*}, \mu^{3*}, \theta^*, \eta^{1*}, \eta^{2*}, \nu^{1*}, \nu^{2*}, \gamma^*) \in \mathcal{K}$*, satisfying*

$$\langle F(X^*), X - X^* \rangle \geq 0, \qquad \forall X \in \mathcal{K} \tag{20}$$

where

$X \equiv (q^1, q^2, q^3, S, I, \delta_m, p^2, B, \delta_c, Y, Z, \delta_r, p^4, \mu^1, \mu^2, \mu^3, \theta, \eta^1, \eta^2, \nu^1, \nu^2, \gamma)$

$$F(X) \equiv (F_{q^1_{ijt}}, F_{q^2_{ijot}}, F_{q^3_{jkt}}, F_{S_{it}}, F_{I_{it}}, F_{\delta_{mi}}, F_{p^2_{ijot}}, F_{B_{iot}}, F_{\delta_{co}}, F_{Y_{jt}}, F_{Z_{jt}}, F_{\delta_{rj}}, F_{p^4_{jkt}},$$

$$F_{\mu^1_{it}}, F_{\mu^2_{iot}}, F_{\mu^3_{jt}}, F_{\theta_{ijt}}, F_{\eta^1}, F_{\eta^2}, F_{\nu^1}, F_{\nu^2}, F_{\gamma})$$

. The term $\langle \cdot, \cdot \rangle$ denotes the inner product in N-dimensional Euclidean space.

The Modified Projection Method

Step 0: Initialization
Start with $X^0 \in \mathcal{K}$, as a feasible initial point, and let $\tau = 1$. Set ω such that $0 < \omega < \frac{1}{L}$, where L is the Lipschitz constant for function $F(X)$.

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

$$\langle \bar{X}^\tau + \omega F(X^{\tau-1}) - X^{\tau-1}, X - \bar{X}^\tau \rangle \geq 0, \qquad \forall X \in \mathcal{K}. \tag{21}$$

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

$$\langle X^\tau + \omega F(\bar{X}^\tau) - X^{\tau-1}, X - X^\tau \rangle \geq 0, \qquad \forall X \in \mathcal{K}. \tag{22}$$

Example 1

Two manufacturers, $M = 2$; two retailers, $N = 2$; two carriers, $O = 2$; and two demand markets, $K = 2$; competing over five planning periods, $T = 5$.

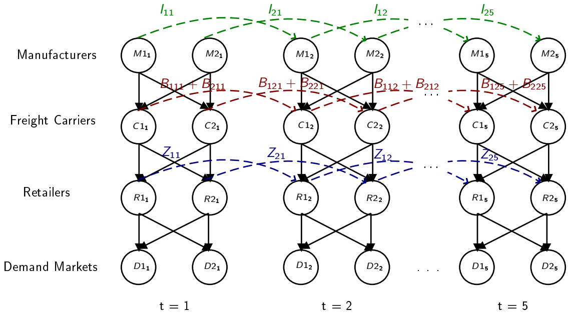

Figure: Example 1 Supply Chain Network

The energy rating, δ, can be zero and should not be more than 1, ($\delta_{max} = 1$)

The cost functions are:

$$PC_{it}(S_{it}, \delta_{mi}) = \alpha^{it} S_{1t} + 0.05(S_{it})^2 - \delta_{mi} S_{it}, \qquad i = 1, 2, t = 1, \ldots, 5.$$

$$\alpha^{1t} = [2, 2.5, 3, 3.5, 4], \qquad \alpha^{2t} = [3, 4, 4.5, 5, 5.5].$$

$$WC_{it}(I_{it}, \delta_{mi}) = 1.05 I_{it} + 0.002(I_{it})^2 - \delta_{mi} I_{it} + 10, \qquad i = 1, 2;\ t = 1, \ldots, 5.$$

$$TC_{ijt}(q_{ijt}, \delta_{mi}) = 1.5 q_{ijt} + 0.8(q_{ijt})^2 - \delta_{mi} q_{ijt}, \qquad i = 1, 2; j = 1, 2;\ t = 1, \ldots, 5.$$

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$$R_{ijot}(p_t^2, \delta_{co}) = 20 - 1.5 p_{ijot}^2 + 0.5 \sum_{c \neq o} p_{ijct}^2 + 3\delta_{co}, \qquad i = 1, 2; j = 1, 2; o = 1, 2;\ t = 1, \ldots, 5.$$

$$CC_{ijot}(q_{ijot}^2, \delta_{co}) = 1.1 q_{ijot}^2 + 0.003 q_{ijot}^2 - \delta_{co} q_{ijot}^2, \qquad i = 1, 2; j = 1, 2; o = 1, 2; t = 1, \ldots, 5.$$

$$AC_{iot}(B_{iot}, \delta_{co}) = B_{iot} + 0.001(B_{iot})^2 - \delta_{co} B_{iot}, \qquad i = 1, 2;\ o = 1, 2;\ t = 1, \ldots, 5.$$

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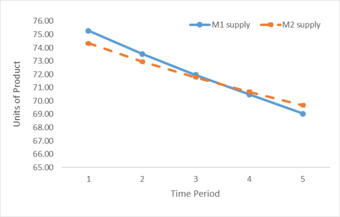
The demand functions for customers within demand market 1 are defined to be less sensitive to future product prices, while customers within demand market 2 are defined to be more sensitive to future product prices.

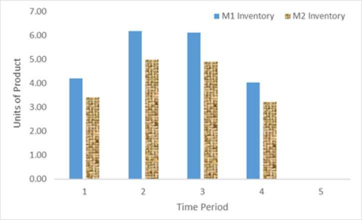
$$D_{1j1}(p^4,\delta_{rj}) = 130 - 1.3p^4_{1j1} + 2\delta_{rj}, \quad D_{1j2}(p^4,\delta_{rj}) = 110 - 1.1p^4_{1j2} + 2\delta_{rj},$$
$$D_{1j3}(p^4,\delta_{rj}) = 80 - 0.9p^4_{1j3} + 2\delta_{rj}, \quad D_{1j4}(p^4,\delta_{rj}) = 50 - 0.7p^4_{1j4} + 2\delta_{rj},$$
$$D_{1j5}(p^4,\delta_{rj}) = 40 - 0.4p^4_{1j5} + 2\delta_{rj}, \quad j = 1,2.$$

$$D_{2j1}(p^4,\delta_{rj}) = 80 - 0.7p^4_{2j1} + 2\delta_{rj}, \quad D_{2j2}(p^4,\delta_{rj}) = 120 - 1p^4_{2j2} + 2\delta_{rj},$$
$$D_{2j3}(p^4,\delta_{rj}) = 150 - 1.2p^4_{2j3} + 2\delta_{rj}, \quad D_{2j4}(p^4,\delta_{rj}) = 180 - 1.7p^4_{2j4} + 2\delta_{rj},$$
$$D_{2j5}(p^4,\delta_{rj}) = 200 - 2p^4_{2j5} + 2\delta_{rj}, \quad j = 1,2.$$

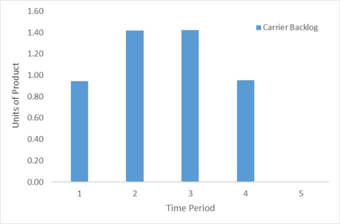
Example 1: Equilibrium Solution



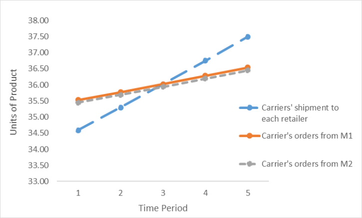
(a) Supplies at manufacturers



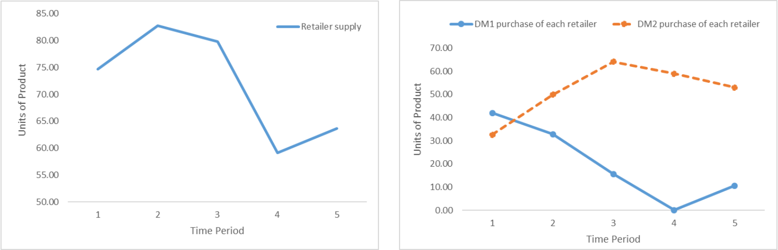
(b) Manufacturers' inventories



(c) Carriers' service backlogs



(d) Carriers' orders and shipment services from manufacturers



(a) Retailers' supply (b) Customers' purchase

Figure: Retailers' and customers' product flow

Energy rating level

$\delta_m = 1, \qquad \delta_c = 1, \qquad \delta_r = 0$

Baseline is Example 1, but the time periods have been extended $(T = 10)$.

The demand functions for periods 6 to 10 are:

$$D_{1j6}(p^4, \delta_{rj}) = 40 - 0.4p^4_{1j6} + 2\delta_{rj}, \quad D_{1j7}(p^4, \delta_{rj}) = 40 - 0.4p^4_{1j7} + 2\delta_{rj},$$
$$D_{1j8}(p^4, \delta_{rj}) = 40 - 0.4p^4_{1j8} + 2\delta_{rj}, \quad D_{1j9}(p^4, \delta_{rj}) = 40 - 0.4p^4_{1j9} + 2\delta_{rj},$$
$$D_{1j10}(p^4, \delta_{rj}) = 40 - 0.4p^4_{1j10} + 2\delta_{rj}, \quad j = 1, 2.$$

$$D_{2j6}(p^4, \delta_{rj}) = 200 - 2p^4_{2j6} + 2\delta_{rj}, \quad D_{2j7}(p^4, \delta_{rj}) = 160 - 1.7p^4_{2j7} + 2\delta_{rj},$$
$$D_{2j8}(p^4, \delta_{rj}) = 130 - 1.5p^4_{2j8} + 2\delta_{rj}, \quad D_{2j9}(p^4, \delta_{rj}) = 130 - p^4_{2j9} + 2\delta_{rj},$$
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Energy rating level

$\delta_m = 1$, $\delta_c = 1$, $\delta_r = 1$

Example 3

Follows the same network structure as Example 1 but with varying cost functions for all network parties in order to focus on constraints

$$\delta_{mi} \leq \delta_{co}, \qquad \forall o \qquad (5)$$

$$\delta_{rj} \leq \delta_{mi}, \qquad \forall i \qquad (17)$$

Here, we vary the coefficient of δ in cost functions

$$TSI_i^1 = 500 + 360(\delta_{mi})^2, \qquad i = 1, 2.$$

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from 360 to 560 by increment of 20 and analyze the companies' capability in acquiring green technology.

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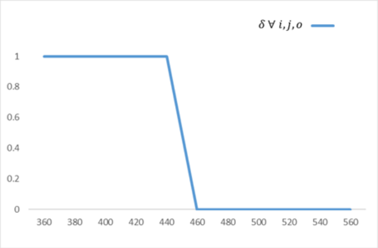
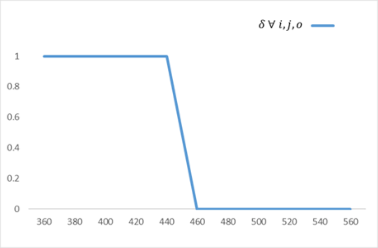


(a) In an obliged network

Figure: Energy rating of all entities for different investment levels



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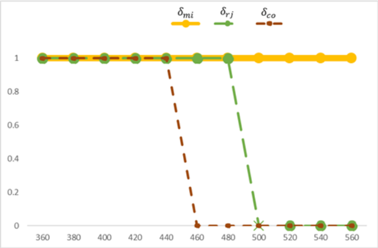

(b) In an uncommitted network

Figure: Energy rating of all entities for different investment levels

- Sustainability and greenness in supply chain should be viewed holistically
- The decisions to manage supply chain must be conditioned by the structure of any game that underlies the determination of decisions by supply chain partners
- Time and the cost of investment affect firms' decisions, profitability, competitive advantage, and their environmental impact
- Governments can bring down the barrier of entry for green energy by taking steps to subsidize the green technology adoption and protect the posterity of our planet

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Thank you!

The price that manufacturer $i; i = 1, \ldots, M$ charges retailer $j; j = 1, \ldots, N$ at time period $t; t = 1, \ldots, T$:

$$p_{ijt}^{1*} = (1+r)^t(\mu_{it}^* + \theta_{ijt}^*) + \frac{\partial TC_{ijt}(q_{ijt}^{1*}, \delta_{mi}^*)}{\partial q_{ijt}^1}, \tag{23}$$

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The feasible set underlying the variational inequality problem is not compact. However, by imposing a rather weak condition, we can guarantee the existence of a solution pattern. Let

$$\mathcal{K}_b = \{(q^1, q^2, q^3, S, I, \delta_m, p^2, B, \delta_c, Y, Z, \delta_r, p^4, \mu^1, \mu^2, \mu^3, \theta, \eta^1, \eta^2, \nu^1, \nu^2, \gamma) | 0 \leqslant q^1 \leqslant b_1; \\ 0 \leqslant q^2 \leqslant b_2; 0 \leqslant q^3 \leqslant b_3; 0 \leqslant S \leqslant b_4; 0 \leqslant I \leqslant b_5; 0 \leqslant \delta_m \leqslant \delta^b_{max}; 0 \leqslant p^2 \leqslant b_6; 0 \leqslant B \leqslant b_7; \\ 0 \leqslant \delta_c \leqslant \delta^b_{max}; 0 \leqslant Y \leqslant b_8; 0 \leqslant Z \leqslant b_9; 0 \leqslant \delta_r \leqslant \delta^b_{max}; 0 \leqslant p^4 \leqslant b_{10}; 0 \leqslant \mu^1 \leqslant b_{11}; 0 \leqslant \mu^2 \leqslant b_{12}; \\ 0 \leqslant \mu^3 \leqslant b_{13}; -b_{14} \leqslant \theta \leqslant b_{15}; 0 \leqslant \eta^1 \leqslant b_{16}; 0 \leqslant \eta^2 \leqslant b_{17}; 0 \leqslant \nu^1 \leqslant b_{18}; -b_{19} \leqslant \nu^2 \leqslant b_{20}, \\ -b_{21} \leqslant \gamma \leqslant b_{22}\} \quad (25)$$

Hence, the following variational inequality admits at least one solution $X^b \in \mathcal{K}_b$ since $\mathcal{K}_b$ is compact and F is continuous.

$$\langle F(X^b), X - X^b \rangle \geq 0, \qquad \forall X^b \in \mathcal{K}_b. \quad (26)$$

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$$\mathcal{K}_b = \{(q^1, q^2, q^3, S, I, \delta_m, p^2, B, \delta_c, Y, Z, \delta_r, p^4, \mu^1, \mu^2, \mu^3, \theta, \eta^1, \eta^2, \nu^1, \nu^2, \gamma) | 0 \leqslant q^1 \leqslant b_1; \\ 0 \leqslant q^2 \leqslant b_2; 0 \leqslant q^3 \leqslant b_3; 0 \leqslant S \leqslant b_4; 0 \leqslant I \leqslant b_5; 0 \leqslant \delta_m \leqslant \delta^b_{max}; 0 \leqslant p^2 \leqslant b_6; 0 \leqslant B \leqslant b_7; \\ 0 \leqslant \delta_c \leqslant \delta^b_{max}; 0 \leqslant Y \leqslant b_8; 0 \leqslant Z \leqslant b_9; 0 \leqslant \delta_r \leqslant \delta^b_{max}; 0 \leqslant p^4 \leqslant b_{10}; 0 \leqslant \mu^1 \leqslant b_{11}; 0 \leqslant \mu^2 \leqslant b_{12}; \\ 0 \leqslant \mu^3 \leqslant b_{13}; -b_{14} \leqslant \theta \leqslant b_{15}; 0 \leqslant \eta^1 \leqslant b_{16}; 0 \leqslant \eta^2 \leqslant b_{17}; 0 \leqslant \nu^1 \leqslant b_{18}; -b_{19} \leqslant \nu^2 \leqslant b_{20}, \\ - b_{21} \leqslant \gamma \leqslant b_{22}\} \quad (25)$$

Hence, the following variational inequality admits at least one solution $X^b \in \mathcal{K}_b$ since $\mathcal{K}_b$ is compact and F is continuous.

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$$0 \leqslant \delta_c \leqslant \delta^b_{max}; 0 \leqslant Y \leqslant b_8; 0 \leqslant Z \leqslant b_9; 0 \leqslant \delta_r \leqslant \delta^b_{max}; 0 \leqslant p^4 \leqslant b_{10}; 0 \leqslant \mu^1 \leqslant b_{11}; 0 \leqslant \mu^2 \leqslant b_{12};$$
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