Supply Chain Network Sustainability Under Competition and Frequencies of Activities from Production to Distribution

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where a full list of references can be found.

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Outline

- Background and Motivation
- An Overview of the Relevant Literature
- The Sustainable Supply Chain Network Model Under Competition and Frequencies
- The Algorithm
- Numerical Examples
- Summary and Conclusions

Background and Motivation

Supply chains have revolutionized the manner in which goods are produced, stored, and distributed around the globe and serve as critical infrastructure networks for economic activities.

Background and Motivation

Today, there are over 7 billion people on our planet with more than half of the world's population residing in cities.

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The quantification of environmental impacts associated with **supply chains** is essential to sustainability.

Background and Motivation

- In urban areas alone, the **freight transportation** may account for
  - 20-30% of the total vehicle distance traveled; and
  - 16-50% of the emissions from transportation.
- The transportation sector in **North America** is second only to electricity generation in terms of CO_2 emissions generated.
  - The United States: 7.8% of total emissions in 2008;
  - Canada: 8% of total CO_2 emissions in 2007
- In the **European Union** 27, transport emissions (freight and other) comprised 19.7% of the GHG emissions for 2010.

Background and Motivation

- Manufacturing and industrial processes release GHGs, which the Environmental Protection Agency (EPA) estimates are equivalent to approximately 350 million metric tons of carbon dioxide emissions – 5% of the total **US** greenhouse gas emissions.

- Industrial processes, including manufacturing, accounted for 7.3% of the GHG emissions in 2010 in the **European Union** 27.

Background and Motivation

- In 2011, **Hennes & Mauritz** (H&M) achieved its target of a 5% year-on-year reduction in its carbon emissions.
- The company's CO_2-equivalent emissions per million SEK ($\$148,500$) of sales were 3.16 metric tons, down from 3.33 in 2010.
- The reduction was achieved through
  - Reducing the transportation of goods via air by 32%;
  - Improving energy efficiency in its stores; and
  - offsetting using Gold Standard-verified carbon reduction projects.

Background and Motivation

- Since 2002. **Procter & Gamble** (P&G) has **more than halved the environmental impact** through
  - Energy usage
  - CO_2 emissions
  - Water usage
  - Waste disposal
- It has **redesigned its network** through the location of its distribution centers in Europe as well as its use (and loadage) of transport modes.

Background and Motivation

- **Ford** is targeting a 30% reduction in carbon dioxide emissions per vehicle from its factories by 2025 after a 37% cut from 2000 to 2010.
- **ICA**, a Swedish grocery chain, reduced emissions by **centralizing its distribution network**.
    - The suppliers are all routed to a single central warehouse from which ICA then sends one large consolidated truck to the store.
    - More tonne-kms but fewer vehicle-kms, which has resulted in lower emissions, an estimated reduction of 20%.

Relevant Literature

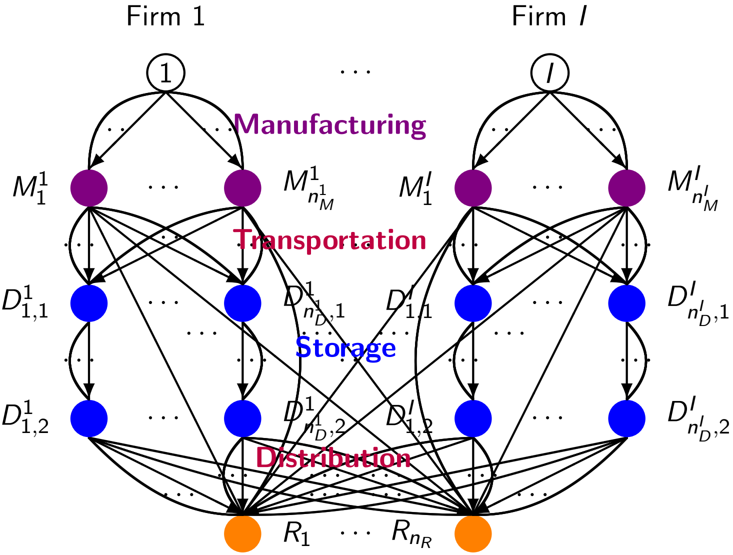
- Sustainable Supply Chains:
  Beamon (1999), Sarkis (2003), Corbett and Kleindorfer (2003), Nagurney and Toyasaki (2005), Sheu, Chou, and Hu (2005), Kleindorfer, Singhal, and van Wassenhove (2005), Nagurney, Liu, and Woolley (2007), Seuring and Muller (2008), Linton, Klassen, and Jayaraman (2007), Nagurney and Woolley (2010), Boone, Jayaraman, and Ganeshan (2012)

- Network Economics:
  Nagurney and Nagurney (2011), Nagurney, Masoumi, and Yu (2012), Nagurney and Nagurney (2012), Nagurney and Yu (2012), Nagurney (2013), Yu and Nagurney (2013)

The Sustainable Supply Chain Network Model Under Competition and Frequencies

- The **profit-maximizing** firms compete noncooperatively in an **oligopolistic** manner.
- Firms produce **substitutable**, but **differentiated**, products.
  - Pharmaceuticals
  - High technology
  - Fashion apparel
  - Food products
- All the firms are concerned with their **environmental impacts** along their supply chains, but, possibly, to *different degrees*.

The Sustainable Supply Chain Network Topology



Conservation of Flow Equations

- f_a: the flow on **link** a;
- x_p: the nonnegative flow on **path** p joining (origin) node i with a (destination) demand market node;
- d_{ik}: the **demand** for firm i's product at demand market R_k.

Relationship between link flows and path flows

$$f_a = \sum_{p \in P} x_p \delta_{ap}, \quad \forall a \in L. \tag{1}$$

Relationship between path flows and demands

$$\sum_{p \in P_k^i} x_p = d_{ik}, \quad \forall i, \forall k. \tag{2}$$

Nonnegativity

$$x_p \geq 0, \quad \forall p \in P. \tag{3}$$

Frequencies

- γ_a: the **activity frequency** of link a, e.g.
  - The number of manufacturing runs needed
  - The number of shipments
  - The number of warehouse content replacements
- $\bar{u}_a$: the existing **capacity** of link a.
  - The production amount in a single manufacturing run
  - The volumes (flows) of the product that the mode can transport

$$f_a \leq \bar{u}_a \gamma_a, \quad \forall a \in L, \tag{4}$$

Demand Prices

Demand Price Functions

$$\rho_{ik} = \rho_{ik}(d) = \hat{\rho}_{ik}(x), \quad \forall i, \forall k. \tag{5}$$

- The functions capture the **demand-side competition** of the competitive supply chain network..
- The functions are assumed to be continuous, continuously differentiable, and monotone decreasing.

Operational Costs

Total Operational Cost Functions

$$\hat{c}_a = \hat{c}_a(f), \quad \forall a \in L. \tag{6}$$

$$\hat{g}_a = \hat{g}_a(\gamma_a), \quad \forall a \in L. \tag{7}$$

- The total cost expressions capture **supply-side competition** among the firms for resources used in the manufacture, transportation, storage, and distribution of their products.
- The operational cost functions is assumed to be convex and continuously differentiable.

Emissions

Emission-Generation Functions

$$\hat{e}_a = \hat{e}_a(f_a, \gamma_a), \quad \forall a \in L. \tag{8}$$

- The emission functions are assumed to correspond to **GHG emissions** as in carbon emissions.
- The model are also relevant to <u>other emissions</u>, including **particulate matter** (PM).
- These functions are also assumed to be convex and continuously differentiable.

The Profit Function of Firm i

$$\text{Maximize} \quad \sum_{k=1}^{n_R} \hat{\rho}_{ik}(x) \sum_{p \in P_k^i} x_p - \sum_{a \in L^i} \hat{c}_a(f) - \sum_{a \in L^i} \hat{g}_a(\gamma_a). \tag{9}$$

The Environmental Impact of Firm i

$$\text{Minimize} \quad \sum_{a \in L^i} \hat{e}_a(f_a, \gamma_a). \tag{10}$$

The Utility Function of Firm i

$$U_i = \sum_{k=1}^{n_R} \hat{\rho}_{ik}(x) \sum_{p \in P_k^i} x_p - \sum_{a \in L^i} \hat{c}_a(f) - \sum_{a \in L^i} \hat{g}_a(\gamma_a) - \omega_i \sum_{a \in L^i} \hat{e}_a(f_a, \gamma_a). \tag{11}$$

- Each firm weights its generated emissions in an **individual** way.
- In the case of governmental regulations, the ω_is would correspond to a **tax** on emissions (carbon or related).
- In this oligopoly competition problem, the strategic variables are the **product flows** and the **activity frequencies**,

$$Y_i \equiv (X_i, \Gamma_i) \quad \text{and} \quad Y \equiv \{\{Y_i\} | i = 1, \ldots, I\}$$

Supply Chain Network Cournot-Nash Equilibrium

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

$$\hat{U}_i(Y_i^*, \hat{Y}_i^*) \geq \hat{U}_i(Y_i, \hat{Y}_i^*), \quad \forall Y_i \in K_i, \tag{12}$$

where $\hat{Y}_i^* \equiv (Y_1^*, \ldots, Y_{i-1}^*, Y_{i+1}^*, \ldots, Y_I^*)$ and $K_i \equiv \{Y_i | Y_i \in R_+^{n_{P^i}+n_{L^i}}\}$.

An equilibrium is established if *NO* firm can unilaterally improve its profit by changing its product flows throughout its supply chain network, given the product flow decisions of the other firms.

Variational Inequality Formulation

Variational Inequality (Path Flows)

Determine $(x^*, \gamma^*, \lambda^*) \in K^1$ satisfying:

$$\sum_{i=1}^{I} \sum_{k=1}^{n_R} \sum_{p \in P_k^i} \left[\frac{\partial \hat{C}_p(x^*)}{\partial x_p} + \omega_i \frac{\partial \hat{E}_p(x^*, \gamma^*)}{\partial x_p} + \sum_{a \in L^i} \lambda_a^* \delta_{ap} - \hat{\rho}_{ik}(x^*) \right.$$
$$\left. - \sum_{l=1}^{n_R} \frac{\partial \hat{\rho}_{il}(x^*)}{\partial x_p} \sum_{q \in P_l^i} x_q^* \right] \times [x_p - x_p^*]$$
$$+ \sum_{i=1}^{I} \sum_{a \in L^i} \left[\frac{\partial \hat{g}_a(\gamma_a^*)}{\partial \gamma_a} + \omega_i \frac{\partial \hat{E}_p(x^*, \gamma^*)}{\partial \gamma_a} - \bar{u}_a \lambda_a^* \right] \times [\gamma_a - \gamma_a^*]$$
$$+ \sum_{i=1}^{I} \sum_{a \in L^i} \left[\bar{u}_a \gamma_a^* - \sum_{q \in P} x_q^* \delta_{aq} \right] \times [\lambda_a - \lambda_a^*] \geq 0, \quad \forall (x, \gamma, \lambda) \in K^1, \tag{13}$$

where $K^1 \equiv \{(x, \gamma, \lambda) | x \in R_+^{n_P}, \gamma \in R_+^{n_L}, \lambda \in R_+^{n_L}\}$.

Variational Inequality Formulation

Variational Inequality (Link Flows)

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

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

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

$$+ \sum_{i=1}^{I} \sum_{a \in L^i} \left[\frac{\partial \hat{g}_a(\gamma_a^*)}{\partial \gamma_a} + \omega_i \frac{\partial \hat{e}_a(f_a^*, \gamma_a^*)}{\partial \gamma_a} - \bar{u}_a \lambda_a^* \right] \times [\gamma_a - \gamma_a^*]$$

$$+ \sum_{i=1}^{I} \sum_{a \in L^i} [\bar{u}_a \gamma_a^* - f_a^*] \times [\lambda_a - \lambda_a^*] \geq 0, \quad \forall (f, d, \gamma, \lambda) \in K^2, \qquad (14)$$

where $K^2 \equiv \{(f, d, \gamma, \lambda) | \exists x \geq 0$, and (1) and (2) hold, and $\gamma \geq 0$, $\lambda \geq 0\}$.

Algorithm – Euler Method

Closed Form Expressions for Product Path Flows, Activity Frequencies, and Lagrange Multipliers

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

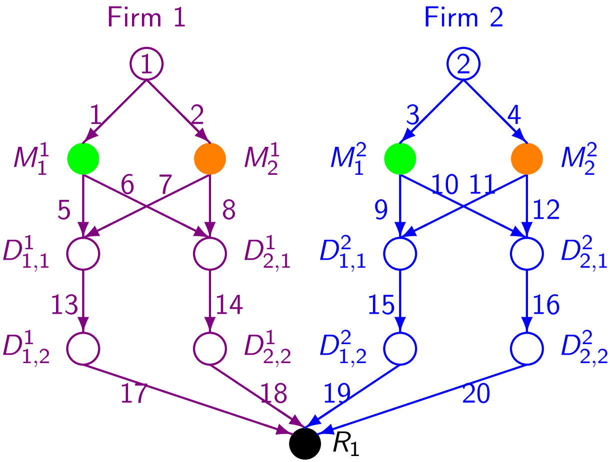
$$-\omega_i \frac{\partial\hat{E}_p(x^\tau,\gamma^\tau)}{\partial x_p} - \sum_{a\in L^i} \lambda_a^\tau \delta_{ap}\ , \tag{15a}$$

$$\gamma_a^{\tau+1} = \max\Big\{0, \gamma_a^\tau + a_\tau\big(\bar{u}_a\lambda_a^\tau - \frac{\partial\hat{g}_a(\gamma_a^\tau)}{\partial\gamma_a} - \omega_i \frac{\partial\hat{E}_p(x^\tau,\gamma^\tau)}{\partial\gamma_a}\big)\Big\}, \tag{15b}$$

$$\lambda_a^{\tau+1} = \max\Big\{0, \lambda_a^\tau + a_\tau\big(\sum_{q\in P} x_q^\tau \delta_{aq} - \bar{u}_a\gamma_a^\tau\big)\Big\}. \tag{15c}$$

This computational procedure can be interpreted as a **discrete-time adjustment process** where the iteration corresponds to a time period.

Exampl 1



- M_1^1 and M_1^2 are **domestic** plants in the U.S.;
- M_2^1 and M_2^2 are **off-shore** plants;
- The distribution centers and the demand market are in the U.S.

Exampl 1

- Firm 1 cares about the emissions that it generates much more than Firm 2 does.

$$\omega_1 = 5, \quad \text{and} \quad \omega_2 = 1.$$

- Firm 1 utilizes more advanced technologies in its supply chain activities in order to lower the emissions that it generates, but at relatively higher costs.

- The demand price functions for the two products at demand market R_1 are:

$$\rho_{11}(d) = -d_{11} - .2d_{21} + 400, \quad \rho_{21}(d) = -2d_{21} - .5d_{11} + 400.$$

Exampl 1

Link a	$\bar{u}_a$	$\hat{c}_a(f)$	$\hat{g}_a(\gamma_a)$	$\hat{e}_a(f_a, \gamma_a)$
1	100	$5f_1^2 + 5f_1$	$\gamma_1^2 + 2\gamma_1$	$.05f_1^2 + .5f_1 + .5\gamma_1^2 + \gamma_1$
2	100	$.5f_2^2 + 4f_2$	$.5\gamma_2^2 + \gamma_2$	$.08f_2^2 + .8f_2 + .8\gamma_2^2 + 1.5\gamma_2$
3	100	$5f_3^2 + 4f_3$	$\gamma_3^2 + 1.5\gamma_3$	$.1f_3^2 + .5f_3 + \gamma_3^2 + 1.5\gamma_3$
4	100	$.5f_4^2 + 2f_4$	$.5\gamma_4^2 + .8\gamma_4$	$.15f_4^2 + .8f_4 + 2\gamma_4^2 + 2\gamma_4$
5	20	$.5f_5^2 + 2f_5$	$\gamma_5^2 + \gamma_5$	$.08f_5^2 + .5f_5 + \gamma_5^2 + \gamma_5$
6	20	$.5f_6^2 + 3f_6$	$\gamma_6^2 + \gamma_6$	$.08f_6^2 + .8f_6 + \gamma_6^2 + \gamma_6$
7	50	$f_7^2 + 10f_7$	$1.5\gamma_7^2 + .5\gamma_7$	$.05f_7^2 + .8f_7 + 1.5\gamma_7^2 + \gamma_7$
8	50	$f_8^2 + 8f_8$	$1.5\gamma_8^2 + .5\gamma_8$	$.05f_8^2 + .5f_8 + 1.5\gamma_8^2 + \gamma_8$
9	20	$.5f_9^2 + 1.5f_9$	$\gamma_9^2 + .8\gamma_9$	$.1f_9^2 + .5f_9 + \gamma_9^2 + 1.5\gamma_9$
10	20	$.5f_{10}^2 + 2f_{10}$	$\gamma_{10}^2 + .8\gamma_{10}$	$.1f_{10}^2 + .8f_{10} + \gamma_{10}^2 + 1.5\gamma_{10}$
11	50	$.8f_{11}^2 + 10f_{11}$	$1.5\gamma_{11}^2 + .3\gamma_{11}$	$.08f_{11}^2 + .8f_{11} + 1.75\gamma_{11}^2 + \gamma_{11}$
12	50	$.8f_{12}^2 + 8f_{12}$	$1.5\gamma_{12}^2 + .3\gamma_{12}$	$.08f_{12}^2 + .5f_{12} + 1.75\gamma_{12}^2 + \gamma_{12}$
13	100	$.5f_{13}^2 + 1.5f_{13}$	$\gamma_{13}^2 + .5\gamma_{13}$	$.01f_{13}^2 + .1f_{13} + .1\gamma_{13}^2 + .1\gamma_{13}$
14	100	$.5f_{14}^2 + 1.5f_{14}$	$\gamma_{14}^2 + .5\gamma_{14}$	$.01f_{14}^2 + .1f_{14} + .1\gamma_{14}^2 + .1\gamma_{14}$
15	100	$.5f_{15}^2 + f_{15}$	$.8\gamma_{15}^2 + \gamma_{15}$	$.05f_{15}^2 + .1f_{15} + .1\gamma_{15}^2 + .2\gamma_{15}$
16	100	$.5f_{16}^2 + f_{16}$	$.8\gamma_{16}^2 + \gamma_{16}$	$.05f_{16}^2 + .1f_{16} + .1\gamma_{16}^2 + .2\gamma_{16}$
17	20	$f_{17}^2 + f_{17}$	$\gamma_{17}^2 + \gamma_{17}$	$.1f_{17}^2 + f_{17} + 2\gamma_{17}^2 + 1.5\gamma_{17}$
18	20	$f_{18}^2 + 1.5f_{18}$	$\gamma_{18}^2 + \gamma_{18}$	$.1f_{18}^2 + 1.5f_{18} + 2\gamma_{18}^2 + 1.5\gamma_{18}$
19	20	$.8f_{19}^2 + f_{19}$	$\gamma_{19}^2 + .8\gamma_{19}$	$.2f_{19}^2 + f_{19} + 3\gamma_{19}^2 + 2\gamma_{19}$
20	20	$.8f_{20}^2 + 1.5f_{20}$	$\gamma_{20}^2 + .8\gamma_{20}$	$.2f_{20}^2 + 1.5f_{20} + 3\gamma_{20}^2 + 2\gamma_{20}$

Exampl 1

Link a	f_a^*	γ_a^*	λ_a^*
1	12.23	.1223	.0786
2	43.48	.4348	.1241
3	8.55	.0855	.0334
4	39.83	.3983	.0479
5	6.97	.3486	.5091
6	5.26	.2630	.4578
7	21.17	.4233	.2624
8	22.31	.4462	.2706
9	4.84	.2418	.1634
10	3.71	.1855	.1521
11	19.42	.3884	.0765
12	20.41	.4082	.0791
13	28.14	.2814	.0184
14	27.57	.2757	.0183
15	24.26	.2427	.0165
16	24.12	.2413	.0164
17	28.14	1.4069	1.9726
18	27.57	1.3784	1.9413
19	24.26	1.2130	.6252
20	24.12	1.2060	.6224

Exampl 1

	Firm 1	**Firm 2**
Demand	55.71	48.38
Price	334.62	275.39
Profit	12, 818.14	9, 387.54
Emission	549.68	754.66
Utility	10, 069.74	8, 632.88

- Given Firm 1's effort to reduce its generated emissions, the consumers reveal their preferences for the product of Firm 1.
- Therefore, consumers are willing to pay more for Firm 1's product.
- Firm 1 emits less pollution and has both a higher profit and a higher utility than Firm 2.

- Firm 1 and Firm 2 decide their product flows and activity frequencies without the consideration of their generated emissions.

$$\omega_1 = \omega_2 = 0.$$

	Firm 1	**Firm 2**
Demand	72.31	51.36
Price	317.42	261.12
Profit	13,551.23	9,023.13
Emission	903.90	857.36

Exampl 1: Sensitivity Analysis

- Firm 1 and Firm 2 decide their product flows and activity frequencies without the consideration of their generated emissions.

$$\omega_1 = \omega_2 = 0.$$

	Firm 1	**Firm 2**
Demand	72.31	51.36
Price	317.42	261.12
Profit	13,551.23	9,023.13
Emission	903.90	857.36

- Due to consumers' preference, the profit of Firm 1 is still significantly higher than that of Firm 2.

Exampl 1: Sensitivity Analysis

- Firm 1 and Firm 2 decide their product flows and activity frequencies without the consideration of their generated emissions.

$$\omega_1 = \omega_2 = 0.$$

	Firm 1	**Firm 2**
Demand	72.31	51.36
Price	317.42	261.12
Profit	13,551.23	9,023.13
Emission	903.90	857.36

- The total emissions increase substantially.

Exampl 1: Sensitivity Analysis

- Firm 1 and Firm 2 decide their product flows and activity frequencies without the consideration of their generated emissions.

$$\omega_1 = \omega_2 = 0.$$

	Firm 1	**Firm 2**
Demand	72.31	51.36
Price	317.42	261.12
Profit	13,551.23	9,023.13
Emission	903.90	857.36

- The profit of Firm 2 is lower without the consideration of the emissions!

Exampl 1: Sensitivity Analysis

- Firm 1 and Firm 2 decide their product flows and activity frequencies without the consideration of their generated emissions.

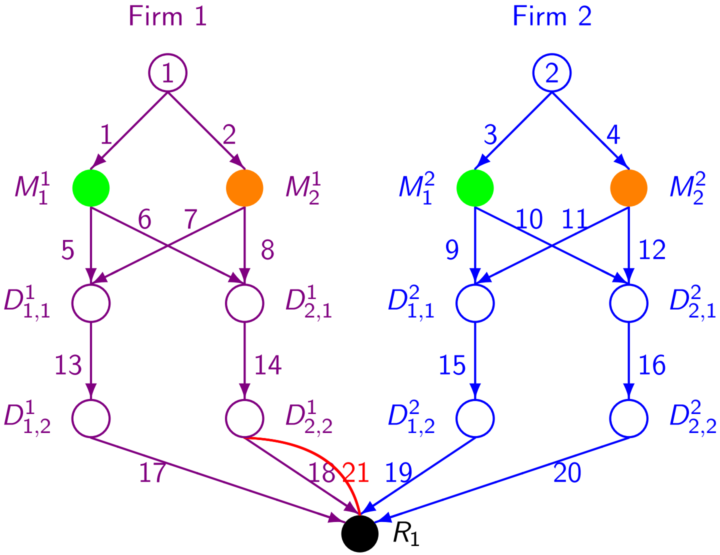
$$\omega_1 = \omega_2 = 0.$$

	Firm 1	**Firm 2**
Demand	72.31	51.36
Price	317.42	261.12
Profit	13, 551.23	9, 023.13
Emission	903.90	857.36

- The profit of Firm 2 is lower without the consideration of the emissions!

Sacrificing of profit may not be necessary for accomplishment in sustainability.

Example 2 & Example 3



Example 2 & Example 3

Example 2

Firm 1 is considering the utilization of **large trucks** for distribution.

$$\bar{u}_{21} = 30,$$
$$\hat{c}_{21}(f) = f_{21}^2 + 1.5f_{21},$$
$$\hat{g}_{21}(\gamma_{21}) = \gamma_{21}^2 + 1.5\gamma_{21},$$
$$\hat{e}_{21}(f_{21}, \gamma_{21}) = .1f_{21}^2 + 1.5f_{21} + 2\gamma_{21}^2 + 2\gamma_{21}.$$

Example 3

Link 21 represents the option of **rail-truck intermodal transport** with an even larger capacity.

$$\bar{u}_{21} = 50,$$
$$\hat{c}_{21}(f) = f_{21}^2 + f_{21},$$
$$\hat{g}_{21}(\gamma_{21}) = 1.5\gamma_{21}^2 + 1.5\gamma_{21},$$
$$\hat{e}_{21}(f_{21}, \gamma_{21}) = .01f_{21}^2 + .5f_{21} + .5\gamma_{21}^2 + .5\gamma_{21}.$$

Example 2 & Example 3

	Example 2			Example 3		
Link a	f_a^*	γ_a^*	λ_a^*	f_a^*	γ_a^*	λ_a^*
1	13.10	.1310	.0792	13.38	.1338	.0794
2	46.73	.4673	.1271	47.77	.4777	.1280
3	8.50	.0850	.0334	8.49	.0849	.0334
4	39.60	.3960	.0478	39.52	.3952	.0478
5	4.45	.2224	.4334	3.64	.1819	.4091
6	8.65	.4326	.5596	9.74	.4871	.5923
7	20.63	.4126	.2586	20.46	.4092	.2573
8	26.09	.5219	.2979	27.31	.5462	.3066
9	4.81	.2407	.1631	4.81	.2403	.1631
10	3.69	.1844	.1519	3.68	.1840	.1518
11	19.31	.3861	.0762	19.27	.3854	.0761
12	20.29	.4058	.0788	20.25	.4051	.0787
13	25.08	.2508	.0175	24.10	.2410	.0172
14	34.75	.3475	.0204	37.05	.3705	.0211
15	24.12	.2411	.0163	24.07	.2408	.0164
16	23.98	.2397	.0162	23.93	.2394	.0164
17	25.08	1.2540	1.8044	24.10	1.2049	1.7504
18	17.28	.8640	1.3754	13.97	.6987	1.1936
19	24.12	1.2060	.6224	24.07	1.2037	.6215
20	23.98	1.1990	.6196	23.93	1.1967	.6187
21	17.47	.5823	.8103	23.08	.4616	.1539

		Example 1	Example 2	Example 3
Demands	Firm 1	72.31	59.83	61.15
	Firm 2	51.36	48.10	48.01
Prices	Firm 1	317.42	330.55	329.25
	Firm 2	261.12	273.89	273.41
Profits	Firm 1	13,551.23	13,643.14	13,707.86
	Firm 2	9,023.13	9,280.21	9,245.87
Emissions	Firm 1	903.90	566.85	518.91
	Firm 2	857.36	746.74	744.20

		Example 1	Example 2	Example 3
Demands	Firm 1	72.31	59.83	61.15
	Firm 2	51.36	48.10	48.01
Prices	Firm 1	317.42	330.55	329.25
	Firm 2	261.12	273.89	273.41
Profits	Firm 1	$13,551.23$	$13,643.14$	$13,707.86$
	Firm 2	$9,023.13$	$9,280.21$	$9,245.87$
Emissions	Firm 1	903.90	566.85	518.91
	Firm 2	857.36	746.74	744.20

- Firm 1 is able to provide more products at even lower prices with the **multiple modes for distribution**.
  - The profit of Firm 1 increases in both Examples 2 and 3;
  - The profit of Firm 2 decline slightly in those two examples.

		Example 1	Example 2	Example 3
Demands	Firm 1	72.31	59.83	61.15
	Firm 2	51.36	48.10	48.01
Prices	Firm 1	317.42	330.55	329.25
	Firm 2	261.12	273.89	273.41
Profits	Firm 1	13,551.23	13,643.14	13,707.86
	Firm 2	9,023.13	9,280.21	9,245.87
Emissions	Firm 1	903.90	566.85	518.91
	Firm 2	857.36	746.74	744.20

- Due to the lower emission nature of **intermodal transport**, the rail-truck intermodal option is more appealing than the utilization of large trucks for distribution.
  - In Example 2, the **large truck transportation** accounts for about 50% of the distribution;
  - In Example 3, the **intermodal transport** accounts for more than 60% of the distribution.
  - The emissions generated by Firm 1 in Example 3 are lower than in Example 2.

Example 3: Sensitivity Analysis

At which value of ω_1, which represents Firm 1's environmental concern, would the distribution from the distribution center $D^1_{2,2}$ to the demand market R_1 solely rely on the **rail-truck intermodal transport**?

- When ω_1 is equal to 43 (or greater) then $f^*_{18} = 0.00$, and also then γ^*_{18} is equal to 0.00.
- $\omega_1 = 43$ could also be an **environmental tax**. This example demonstrates how a policy-maker can effect positive environmental change through such a policy instrument.

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Summary and Conclusions

- It is a **competitive supply chain network model** with multiple firms.
  - Each firm produces a **differentiated product** by brand;
  - Each weights the emissions that it generates through its supply chain network activities in an **individual** way;
  - The firms seek to determine their optimal **product flows** and **frequencies of operation** so that their utilities are maximized.
- **Multiple options** for production, transport, storage, and distribution are allowed.
- The emission functions associated with a link depend both on the <u>flow</u> on the link as well as on the <u>frequency</u> of the link.
- Although the focus here is on carbon emissions, the framework is sufficiently general to handle other types of emissions.

Summary and Conclusions

- We utilize **variational inequality theory** for the formulation of the governing **Cournot-Nash equilibrium conditions**.
- The proposed computational procedure has nice features for implementation; and can be interpreted as a **discrete-time adjustment process**.
- The model could provide valuable information to both **managerial decision-makers** as well as to **policy-makers**.

Thank You!

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