# Sustainable Supply Chain Networks for Sustainable Cities

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# Outline

# Background and Motivation

# What is Sustainability?

**The general definition of sustainability is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission Environment and Development (WCED) (1987)).**

# The Debates Continue

There are, nevertheless, debates as to the correct methods to operationalize sustainability, as questions arise such as:

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- What **policies** are required to achieve sustainability?

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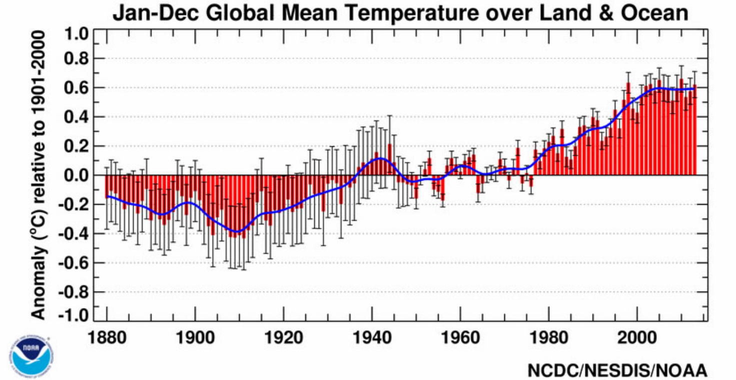
There are, nevertheless, debates as to the correct methods to operationalize sustainability, as questions arise such as:

- What **resources** will future generations require?
- What **level of emissions** can be released without negatively affecting future generations?
- What **policies** are required to achieve sustainability?
- What are the effects of **market forces**, etc.?

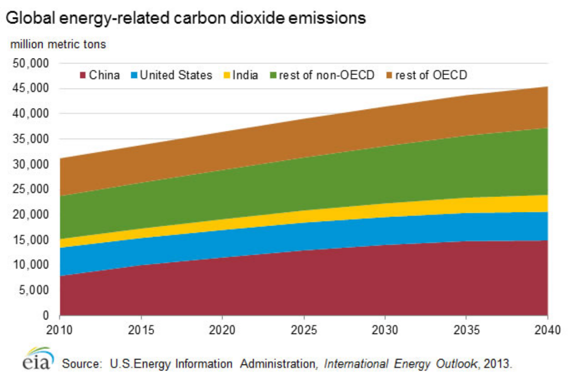
# Climate Change




**In the Northern Hemisphere, where most of Earth's land mass is located, the three decades from 1983 to 2012 were likely the warmest 30-year period of the last 1400 years, according to the IPCC.**

# Pollution and Environmental Impacts

In the US alone, greenhouse gas emissions are projected to rise 35% between 2005 and 2030 due to fewer forests and agricultural land to absorb the carbon, an increasing population, expansion of the economy, and an increased use of fossil fuel powered power plants to generate energy (Creyts et al. (2007)).



# Some Examples of Cities

# Cities and Sustainability

Cities are also **the repositories and generators of waste output and other environmental pollutants, such as carbon and other emissions, sewage, noise, etc.**

# Some Negative Externalities Associated with Cities

# Cities and Supply Chains

**Cities are supplied by a complex array of supply chains** servicing an immense spectrum of economic activities from food stores and restaurants, office supplies and high tech equipment, apparel, construction materials, as well as raw materials, to name just a few.

# Supply Chains

# Supply Chains

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.

# The World's Population and Cities

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.

# Emissions and Transportation

- 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.

# Emissions and Manufacturing

- 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.

# Characteristics of Supply Chains and Networks Today

- **large-scale nature** and complexity of network topology;
- **congestion**, which leads to nonlinearities;
- **alternative behavior of users of the networks**, which may lead to paradoxical phenomena (Braess paradox);
- **possibly conflicting criteria associated with optimization**;
- **interactions among the underlying networks themselves**, such as the Internet with electric power networks, financial networks, and transportation and logistical networks;
- recognition of **their fragility and vulnerability**;
- policies surrounding networks today may have major impacts not only economically, but also **environmentally, socially, politically, and security-wise**.

# Supply Chains Are Network Systems

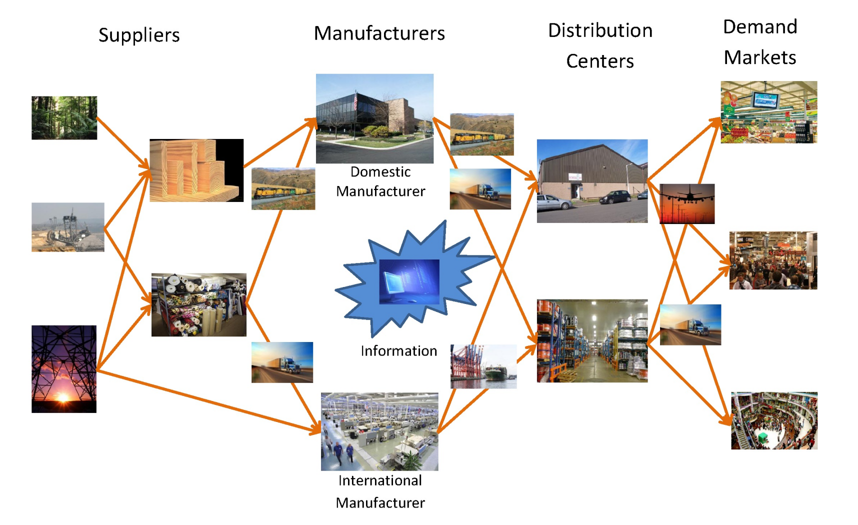
Supply chains are, in fact, **Complex Network Systems**.

Hence, **any formalism that seeks to model supply chains and to provide quantifiable insights and measures must be a system-wide one and network-based.**

Such crucial issues as the stability and resiliency of supply chains, as well as their adaptability and responsiveness to events in *a global environment of increasing risk and uncertainty* can only be rigorously examined from the view of supply chains as network systems.

Supply chains may be characterized by **decentralized decision-making** associated with the different economic agents or by *centralized* decision-making.

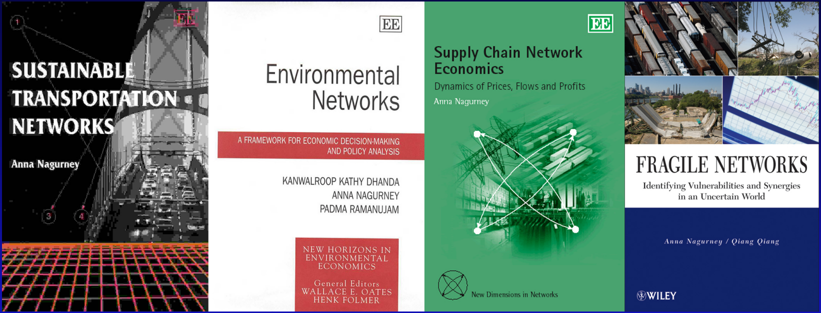
# A General Supply Chain



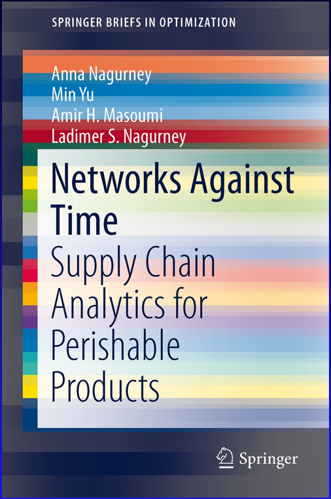
# Examples of Supply Chains

**Sustainability of supply chains is, hence, a precursor to the sustainability of our cities**. According to a Business for Social Responsibility (2009) paper, it is now widely acknowledged that making significant progress on mitigating the impact of climate change depends on reducing the negative environmental impacts of supply chains through their redesign and enhanced management (see also McKinsey Quarterly (2008)).

# Our Approach to Sustainability



# Our Most Recent Book



# Why More Research is Needed

Although the importance of sustainable supply chains to the sustainability of cities is being increasingly recognized (cf. Grant Thornton (2011)), in terms of not only the enhancement of business processes in terms of efficiency and cost reduction but also the reduction of negative environmental externalities as well as waste **there have been only limited modeling efforts that capture supply chains within a cities framework**.

# Methodology

# Methodology - The Variational Inequality Problem

We utilize the theory of variational inequalities for the formulation, analysis, and solution of both centralized and decentralized supply chain network problems.

**Definition: The Variational Inequality Problem**

*The finite-dimensional variational inequality problem,* $\mathrm{VI}(F, \mathcal{K})$, *is to determine a vector* $X^* \in \mathcal{K}$, *such that:*

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

*where* $F$ *is a given continuous function from* $\mathcal{K}$ *to* $R^N$, $\mathcal{K}$ *is a given closed convex set, and* $\langle \cdot, \cdot \rangle$ *denotes the inner product in* $R^N$.

# Methodology - The Variational Inequality Problem

The vector $X$ consists of the decision variables – typically, the flows (products, prices, etc.).

$\mathcal{K}$ is the feasible set representing how the decision variables are constrained – for example, the flows may have to be nonnegative; budget constraints may have to be satisfied; similarly, quality and/or time constraints may have to be satisfied.

The function $F$ that enters the variational inequality represents functions that capture the behavior in the form of the functions such as costs, profits, risk, etc.

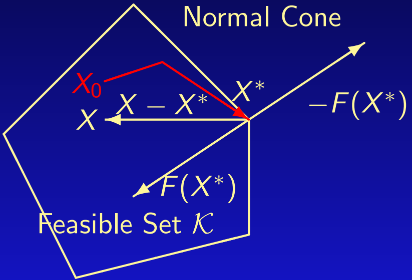
The variational inequality problem contains, as special cases, such mathematical programming problems as:

- systems of equations,
- optimization problems,
- complementarity problems,
- game theory problems, operating under Nash equilibrium,
- and is related to the fixed point problem.

**Hence, it is a natural methodology for a spectrum of supply chain network problems from centralized to decentralized ones as well as to design problems.**

# Geometric Interpretation of VI($F, \mathcal{K}$) and a Projected Dynamical System (Dupuis and Nagurney (1993), Nagurney and Zhang (1996))

In particular, $F(X^*)$ is "orthogonal" to the feasible set $\mathcal{K}$ at the point $X^*$.




Associated with a VI is a Projected Dynamical System, which provides natural underlying dynamics associated with travel (and other) behavior to the equilibrium.

To model the *dynamic behavior of complex networks*, including supply chains, we utilize *projected dynamical systems* (PDSs) advanced by Dupuis and Nagurney (1993) in *Annals of Operations Research* and by Nagurney and Zhang (1996) in our book *Projected Dynamical Systems and Variational Inequalities with Applications*.

Such nonclassical dynamical systems are now being used in

**evolutionary games** (Sandholm (2005, 2011)),

**ecological predator-prey networks** (Nagurney and Nagurney (2011a, b)), and

even **neuroscience** (Girard et al. (2008)).

# Applied Supply Chain Network Game Theory Models of Relevance to Sustainable Cities

# Electric Power Supply Chains

We developed **an empirical, large-scale electric supply chain network equilibrium model**, formulated it as a VI problem, and were able to solve it by **exploiting the connection between electric power supply chain networks and transportation networks** using our proof of a hypothesis posed in the classic book, *Studies in the Economics of Transportation*, by Beckmann, McGuire, and Winsten (1956).

The paper, "An Integrated Electric Power Supply Chain and Fuel Market Network Framework: Theoretical Modeling with Empirical Analysis for New England," by Z. Liu and A. Nagurney was published in *Naval Research Logistics* **56** (2009) pp 600-624;

http://supernet.isenberg.umass.edu/articles/LiuNagurneyNRL.pdf

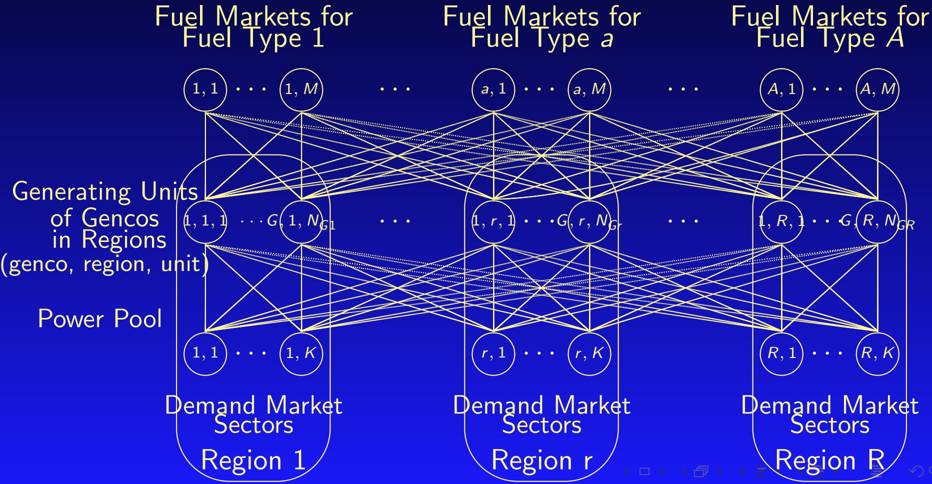
# An Empirical Example of an Electric Power Supply Chain for New England

There are 82 generating companies who own and operate 573 generating units. We considered 5 types of fuels: natural gas, residual fuel oil, distillate fuel oil, jet fuel, and coal. The whole area was divided into 10 regions:

1. Maine,
2. New Hampshire,
3. Vermont,
4. Connecticut (excluding Southwest Connecticut),
5. Southwestern Connecticut (excluding the Norwalk-Stamford area),
6. Norwalk-Stamford area,
7. Rhode Island,
8. Southeastern Massachusetts,
9. Western and Central Massachusetts,
10. Boston/Northeast Massachusetts.

# Graphic of New England

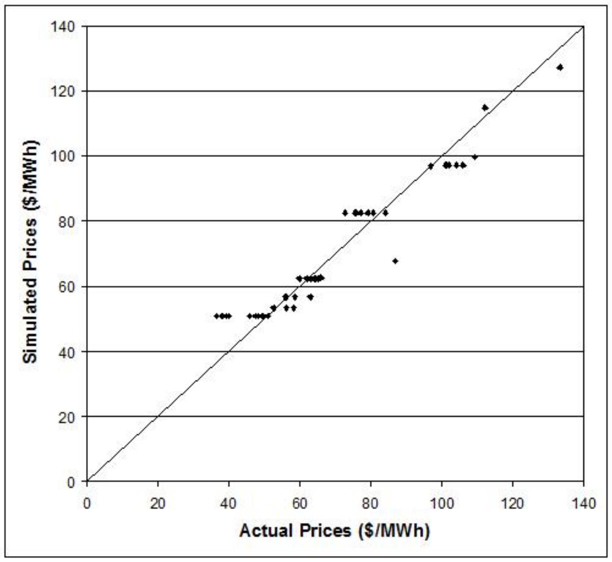
# The Electric Power Supply Chain Network with Fuel Supply Markets



We tested the model on the data of July 2006 which included $24 \times 31 = 744$ hourly demand/price scenarios. We sorted the scenarios based on the total hourly demand, and constructed the load duration curve. We divided the duration curve into 6 blocks ($L_1 = 94$ hours, and $L_w = 130$ hours; $w = 2, ..., 6$) and calculated the average regional demands and the average weighted regional prices for each block.

*The empirical model had on the order of* $20,000$ *variables.*

# Actual Prices Vs. Simulated Prices ($/Mwh)



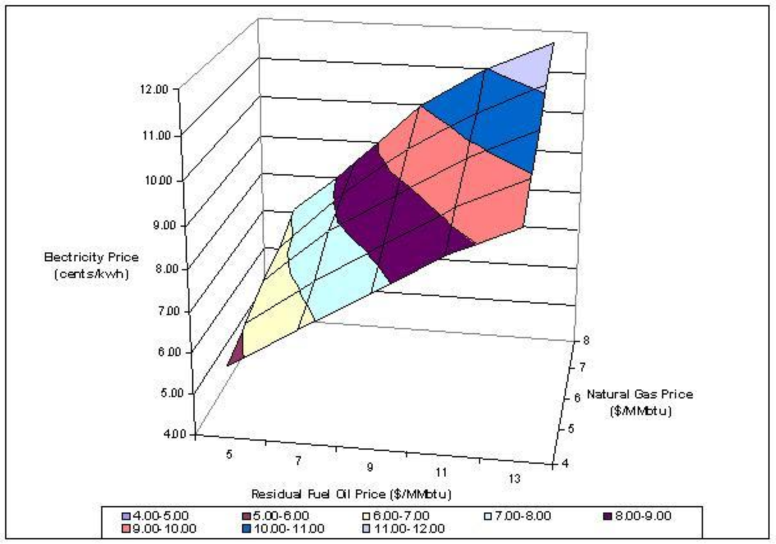
# Sensitivity Analysis

We used the same demand data, and then varied the prices of natural gas and residual fuel oil. We assumed that the percentage change of distillate fuel oil and jet fuel prices were the same as that of the residual fuel oil price.

The next figure presents the average electricity price for the two peak blocks under oil/gas price variations.

The surface in the figure represents the average peak electricity prices under different natural gas and oil price combinations.

# Sensitivity Analysis



# Food Supply Chains

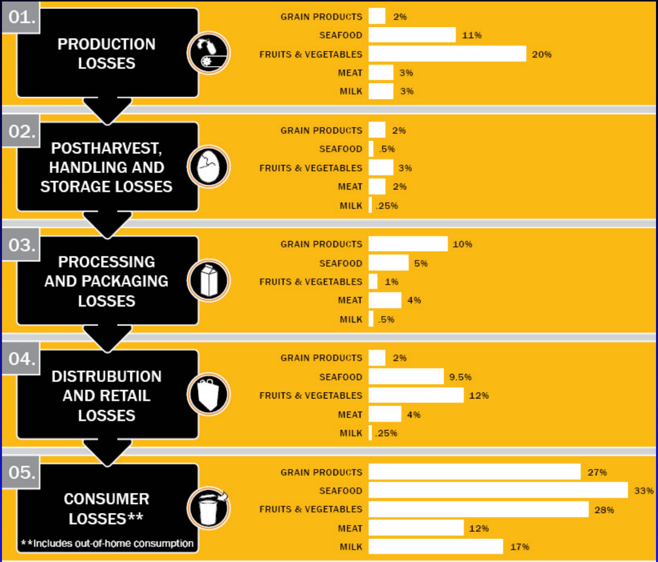
Food is something anyone can relate to.

# Fascinating Facts About Food Perishability

## THE SHELF LIFE OF FOOD

| Foods unopened, uncut or uncooked unless stated otherwise | COUNTER/PANTRY (1 DAY ◂—▸ 1 MONTH) | REFRIGERATOR (1 DAY ◂—▸ 3 MONTHS) | FREEZER (1 MONTH ◂—▸ 1 YEAR) |
|---|---|---|---|
| APPLES | 2-4 weeks | 1-2 months | 8-12 months |
| BANANAS | 2-7 days | 5-9 days | 2-3 months |
| CANTALOUPE | Until ripe | 1 week | 8-12 months |
| CARROTS | Up to 4 days | 4-5 weeks | 8-12 months |
| CUCUMBERS | 1-3 days | 1 week | 8-12 months |
| EGGS | Few hours | 3-4 weeks | Do not freeze |
| MILK | Few hours | 5-7 days | 1 month |
| YOGURT | Few hours | 2-3 weeks | 1-2 months |

# Fascinating Facts About Food Perishability




Source: Food and Agriculture Organization 2011

# Fascinating Facts About Food Perishability


Source: Food and Agriculture Organization 2011

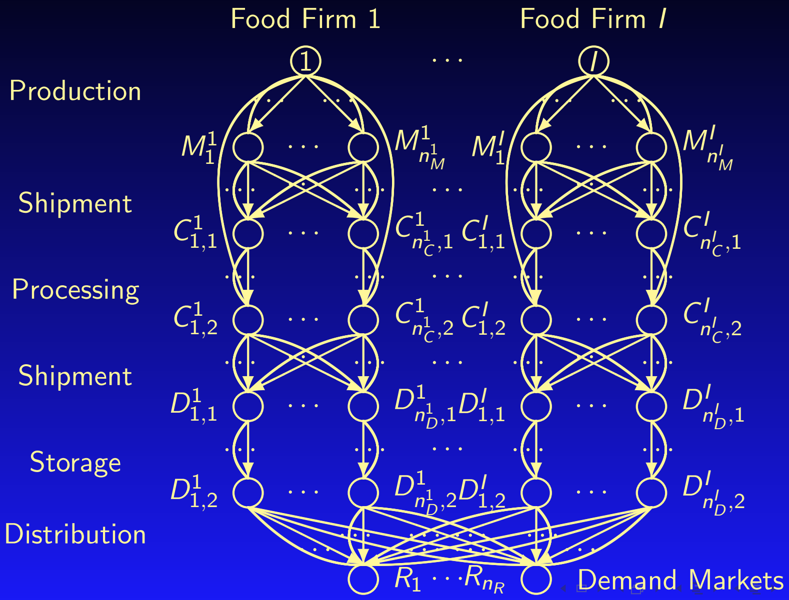
# Fresh Produce Food Supply Chains

We developed a fresh produce supply chain network oligopoly model that

1. captures the deterioration of fresh food along the entire supply chain from a network perspective;
2. handles the exponential time decay through the introduction of arc multipliers;
3. formulates oligopolistic competition with product differentiation;
4. includes the disposal of the spoiled food products, along with the associated costs;
5. allows for the assessment of alternative technologies involved in each supply chain activity.

Reference: "Competitive Food Supply Chain Networks with Application to Fresh Produce," M. Yu and A. Nagurney, *European Journal of Operational Research* **224(2)** (2013) pp 273-282.

# Fresh Produce Food Supply Chains



# The Sustainable Supply Chain Network Model with Frequency of Activities

# The Sustainable Supply Chain Network Game Theory Model with Frequency of Activities

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- Logistics in cities are often characterized by more frequent shipments, especially using primarily freight vehicles such as trucks.

# The Sustainable Supply Chain Network Game Theory Model with Frequency of Activities

• We present the game theory model for sustainable supply chain networks with a focus of the frequency of the various supply chain activities.

• Logistics in cities are often characterized by more frequent shipments, especially using primarily freight vehicles such as trucks.

• However, the scope of our model is broader and we also capture the optimal frequencies of the other activities, that is, those of manufacturing, storage, etc.

# The Sustainable Supply Chain Network Game Theory Model with Frequency of Activities

This paper is inspired, in part, by paper presented by Martin J. Beckmann: "Vehicle and Passenger Flows in Mass Transportation: Optimal Routing of Buses and Planes," at the Symposium on Transportation Network Design and Economics, Northwestern University, Evanston, Illinois, January 29, 2010.

This part of the presentation is based on the paper:

Nagurney, A., Yu, M., Floden, J., 2013. Supply chain network sustainability under competition and frequencies of activities from production to distribution. *Computational Management Science* 10(4), 397-422.

where a full list of references can be found.

# Proactive Firms

- 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.

# Proactive Firms

- 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 of transport modes.

# Proactive Firms

- **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

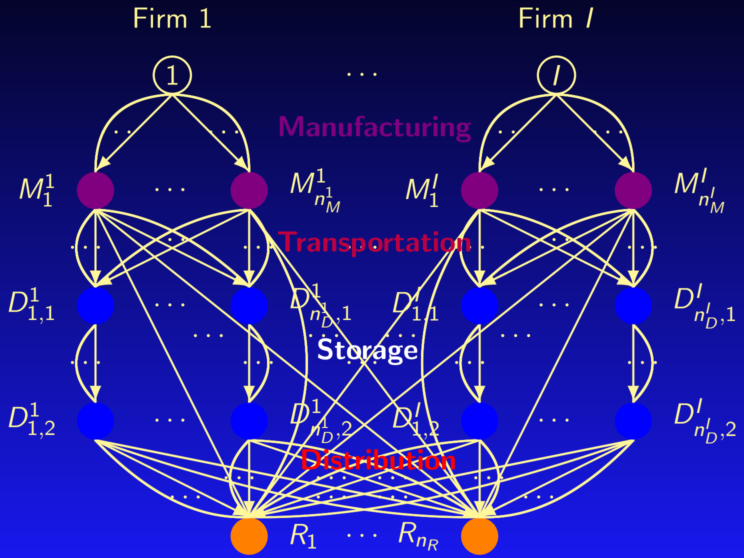
- Sustainable Supply Chains:
  Beamon (1999), Sarkis (2003), Corbett and Kleindorfer (2003), Nagurney and Toyasaki (2005), Sheu, Chou, and Hu (2005), Kleindorfer, Singhal, and van Wassenhove (2005), Nagurney, Liu, and Woolley (2007), Seuring and Muller (2008), Linton, Klassen, and Jayaraman (2007), Nagurney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

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

Nonnegativity

# Frequencies

- $\gamma_a$: 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 $a$, e.g.
  - 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 are 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 is also relevant to other emissions, 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 $\omega_i$s 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 $i$; $i = 1, \dots, I$:

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

where $\hat{Y}_i^* \equiv (Y_1^*, \dots, Y_{i-1}^*, Y_{i+1}^*, \dots, Y_I^*)$ 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 and its activity frequencies, given the 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 $K^1 = \{(x,\gamma,\lambda) | x \in R_+^{n_P}, \gamma \in R_+^{n_L}, \lambda \in R_+^{n_L}\}$.

# 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

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

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

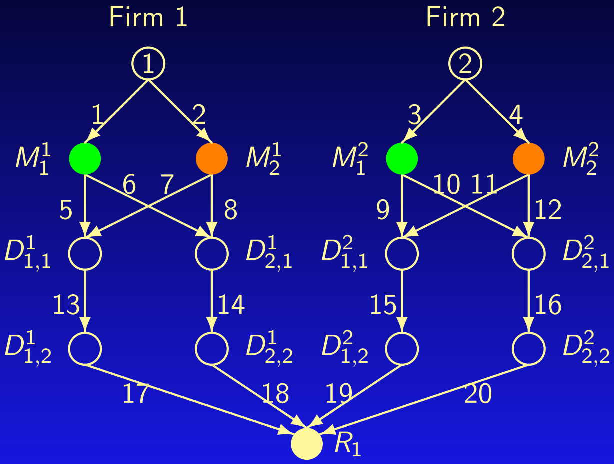
$$\gamma_a^{\tau+1} = \max\left\{0, \gamma_a^\tau + a_\tau\left(\bar{u}_a \lambda_a^\tau - \frac{\partial \hat{g}_a(\gamma_a^\tau)}{\partial \gamma_a} - \omega_i \frac{\partial \hat{E}_p(x^\tau, \gamma^\tau)}{\partial \gamma_a}\right)\right\}, \quad (15b)$$

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

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

# Numerical Examples

# Example 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.

# Example 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:

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

# Example 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 | $.8f_{20}^2 + 1.5f_{20}$ | $\gamma_{20}^2 + .8\gamma_{20}$ | $.2f_{20}^2 + 1.5f_{20} + 3\gamma_{20}^2 + 2\gamma_{20}$ |

# Example 1

| Link $a$ | $f_a^*$ | $\gamma_a^*$ | $\lambda_a^*$ |
|---|---|---|---|
| 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 |

# Example 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.

# Example 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 |

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

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- The total emissions increase substantially.

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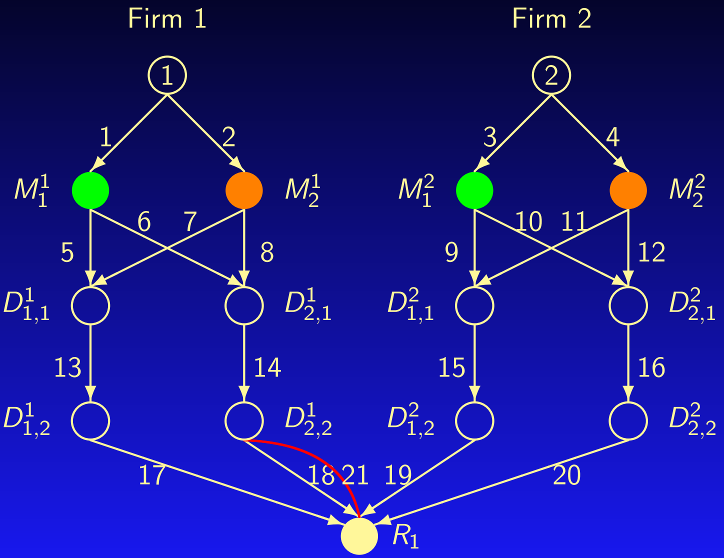
- The profit of Firm 2 is lower without the consideration of the emissions!

**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.

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

# Example 2 & Example 3

| | Example 2 | | | Example 3 | | |
|---|---|---|---|---|---|---|
| Link $a$ | $f_a^*$ | $\gamma_a^*$ | $\lambda_a^*$ | $f_a^*$ | $\gamma_a^*$ | $\lambda_a^*$ |
| 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** | 55.71 | 59.83 | 61.15 |
| | **Firm 2** | 48.38 | 48.10 | 48.01 |
| **Prices** | **Firm 1** | 334.62 | 330.55 | 329.25 |
| | **Firm 2** | 275.39 | 273.89 | 273.41 |
| **Profits** | **Firm 1** | 12,818.14 | 13,643.14 | 13,707.86 |
| | **Firm 2** | 9,387.54 | 9,280.21 | 9,245.87 |
| **Emissions** | **Firm 1** | 549.68 | 566.85 | 518.91 |
| | **Firm 2** | 754.66 | 746.74 | 744.20 |

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- 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 declines slightly in those two examples.

| | | Example 1 | Example 2 | Example 3 |
|---|---|---|---|---|
| Demands | Firm 1 | 55.71 | 59.83 | 61.15 |
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- 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 $\omega_1$, 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**?

# Example 3: Sensitivity Analysis

At which value of $\omega_1$, 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 $\omega_1$ is equal to 43 (or greater) then $f^*_{18} = 0.00$, and also then $\gamma^*_{18}$ is equal to 0.00.

# Example 3: Sensitivity Analysis

At which value of $\omega_1$, 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 $\omega_1$ is equal to 43 (or greater) then $f^*_{18} = 0.00$, and also then $\gamma^*_{18}$ 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.

# 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 flow on the link as well as on the frequency 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

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- We emphasized the importance of the sustainability of supply chains for sustainable cities.
- We described some applied supply chain network models of relevance to cities from electric power ones to food ones.
- We utilized **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/