

Sustainable Supply Chain Networks for Sustainable Cities

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- ▶ Methodology
- ▶ Applied Supply Chain Network Game Theory Models of Relevance to Sustainable Cities
- ▶ The Sustainable Supply Chain Network Game Theory Model with Frequency of Activities
- ▶ Numerical Examples
- ▶ Summary and Conclusions

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 on Environment and Development (1987)).

We believe that smart cities necessarily have to take on an environmental focus.

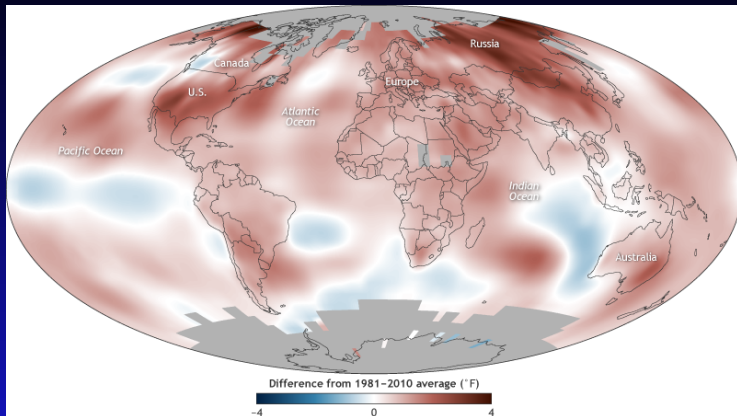
The Debates Continue

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.?



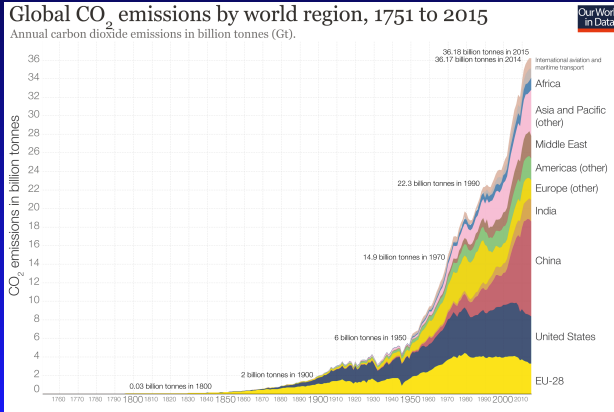
Climate Change



Global surface temperature in 2017 compared to the 1981-2010 average. High latitudes of the Northern Hemisphere were especially warm, though temperatures across most of the planet were warmer than average (red colors). NOAA Climate.gov map

Pollution and Environmental Impacts

Greenhouse gas emissions are projected to rise, for many reasons, including fewer forests and agricultural land to absorb the carbon, an increasing population, economic expansion in the developing world, and continuing use of fossil fuel powered power plants to generate energy in certain parts of the globe.



Cities



Today, over half of the world's population lives in cities, with the percentage projected to be 66% by 2050, according to the Population Division of the UN Department of Economic and Social Affairs in its 2014 report. **80% of the US population lives in cities.**

Cities, Climate Change, and Sustainability

Cities, in addition to being **knowledge innovation hubs and artistic and entertainment centers** are also **generators and repositories of environmental pollutants, such as carbon and other emissions, and major generators of waste output and sewage, noise, etc.**

Cities affect climate change and are affected by it.



Manhattan without power on October 30, 2012 as a result of the devastation wrought by Superstorm Sandy.

Some Negative Externalities Associated with Cities



Supply Chains

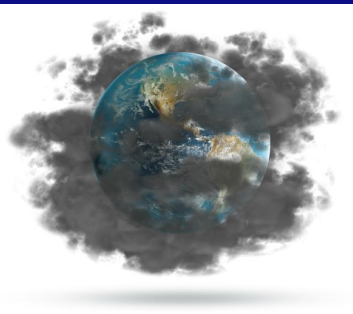
Supply Chains

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.



Cities and Supply Chains

Cities and businesses and residences therein 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. **The quantification of environmental impacts** associated with **supply chains** is essential to sustainability.



Emissions and Transportation

- ▶ In urban areas alone, **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 CO₂ emissions generated, according to the EPA.
 - ▶ The United States: **28%** of total emissions in 2016.
- ▶ In the **European Union 28**, transport emissions were **20.8%** of the overall greenhouse gas emissions in 2014. The transport sector is currently the second most important source of emissions there.



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 **50%** of the latest accounted for GHG emissions in the **European Union** 28.

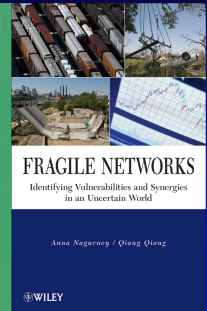
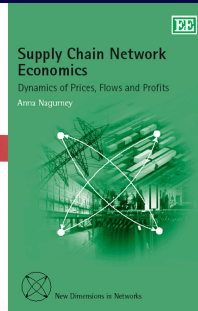
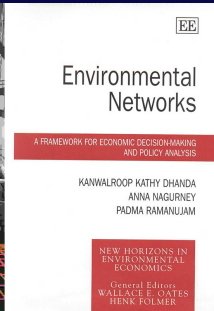
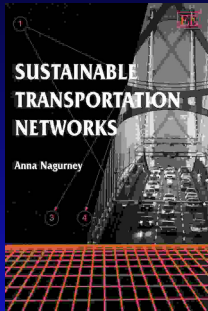


Examples of Supply Chains

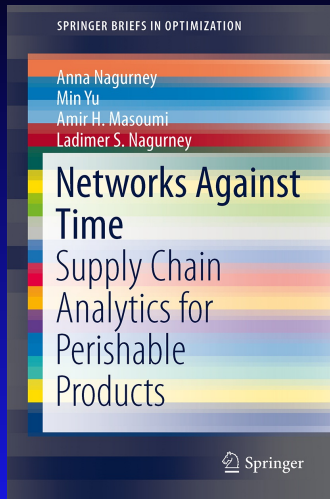


Sustainability of supply chains is, hence, a precursor to the sustainability of our cities. According to a Business for Social Responsibility (2009) paper, it is now widely acknowledged that making significant progress on mitigating the impact of climate change depends on reducing the negative environmental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

Our Approach to Sustainability



A Recent Book of Ours



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.**



There is very little research, above and beyond conceptual research, and that is also very recent, on smart cities and supply chains.

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, $VI(F, \mathcal{K})$, 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.

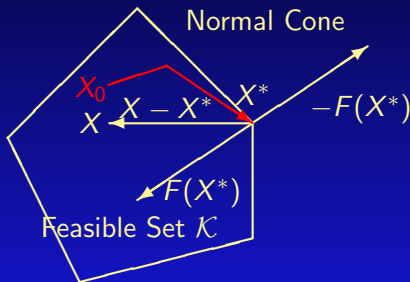
The variational inequality problem contains, as special cases, such mathematical programming problems as:

- 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 $\text{VI}(F, \mathcal{K})$ 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 Liu and Nagurney was published in *Naval Research Logistics* **56** (2009) pp 600-624.

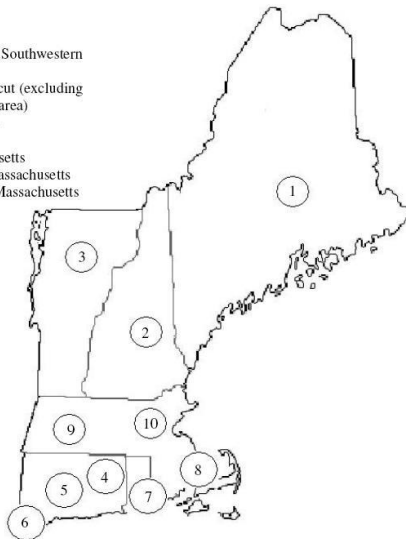
An Empirical Example of an Electric Power Supply Chain for New England

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:

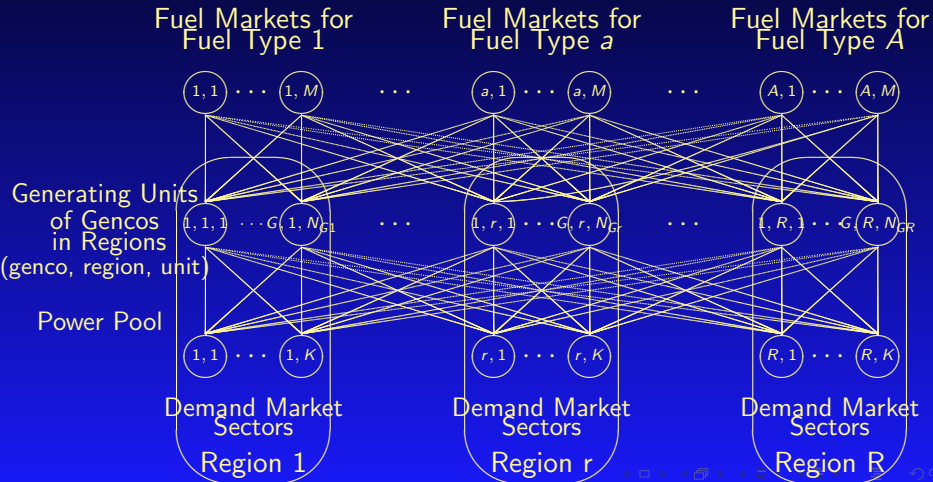
1. Maine,
2. New Hampshire,
3. Vermont,
4. Connecticut (excluding Southwest Connecticut),
5. Southwestern Connecticut (excluding the Norwalk-Stamford area),
6. Norwalk-Stamford area,
7. Rhode Island,
8. Southeastern Massachusetts,
9. Western and Central Massachusetts,
10. Boston/Northeast Massachusetts.

Graphic of New England

1. Maine
2. New Hampshire
3. Vermont
4. Connecticut (excluding Southwestern 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/Northeastern Massachusetts



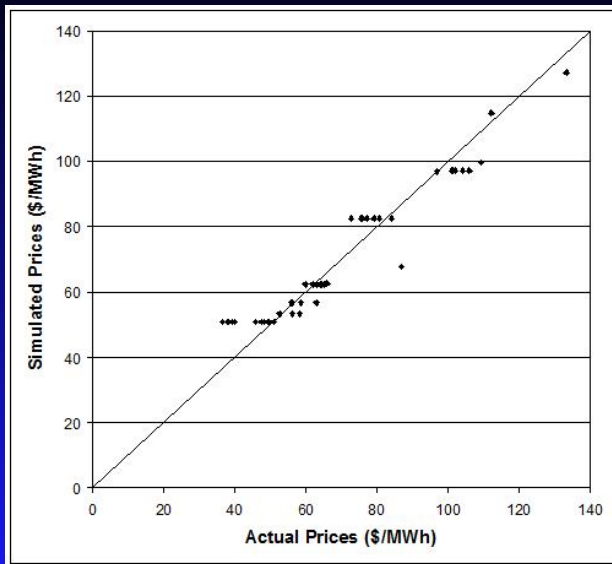
The Electric Power Supply Chain Network with Fuel Supply Markets



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; $w = 2, \dots, 6$) 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)



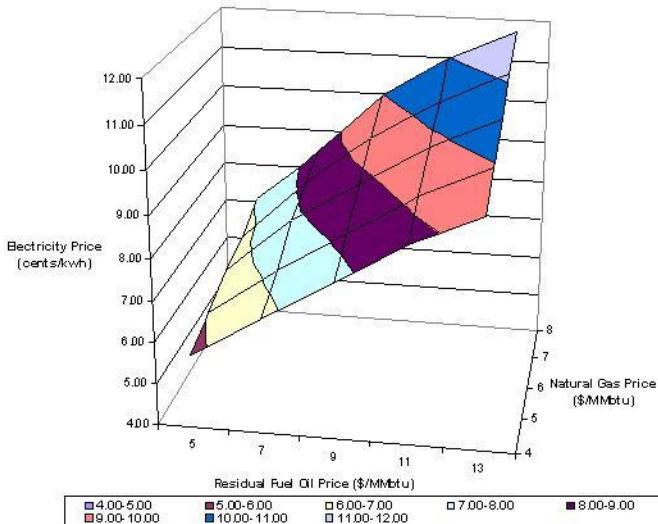
Sensitivity Analysis

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

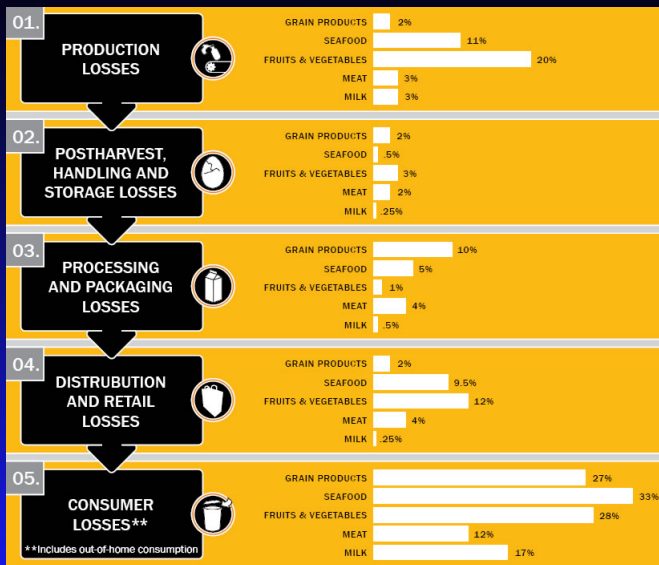
Food is something anyone can relate to.



Fascinating Facts About Food Perishability

THE SHELF LIFE OF FOOD			
Foods unopened, uncut or uncooked unless stated otherwise	COUNTER/PANTRY	REFRIGERATOR	FREEZER
	1 DAY ← → 1 MONTH	1 DAY ← → 3 MONTHS	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

**ABOUT 10 PERCENT OF THE
U.S. ENERGY BUDGET GOES TO
BRINGING FOOD TO OUR TABLES.**

Source: Webber, Michael, "How to Make the Food System More Energy Efficient," *Scientific American*, December 29, 2011.



**ONE INDUSTRY CONSULTANT
ESTIMATES THAT UP TO ONE
IN SEVEN TRUCKLOADS OF
PERISHABLES DELIVERED TO
SUPERMARKETS IS THROWN AWAY.**

Source: Beswick, P. et al, "A Retailer's Recipe for Fresher Food and Far Less Shrink," Oliver Wyman, Boston. [ergoeditorial.biz/worksamples/OW%20grocery%20shrinkage.pdf](http://www.ow.com/worksamples/OW%20grocery%20shrinkage.pdf).

**FOR THE AVERAGE U.S. HOUSEHOLD OF
FOUR, FOOD WASTE TRANSLATES INTO
AN ESTIMATED \$1,350 TO \$2,275 IN
ANNUAL LOSSES.**



Source: Bloom, American Household, 187. Another report using updated USDA consumer loss numbers and 2011 prices estimates \$1,600 in annual losses per household of four. Clean Metrics, "The Climate Change and Economic Impacts of Food Waste in the United States," <http://www.cleanmetrics.com/wp-content/uploads/2012/01/foodwaste.pdf>

Source: Food and Agriculture Organization 2011



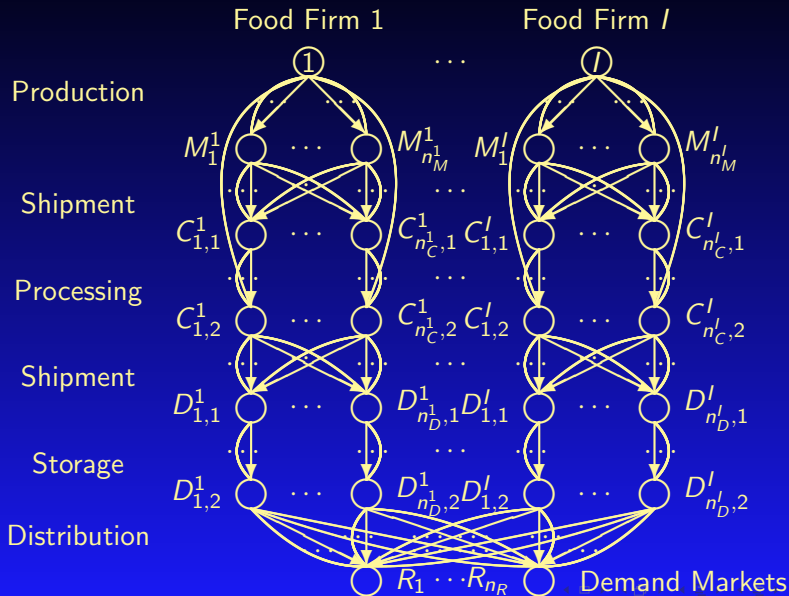
Fresh Produce Food Supply Chains

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,” Yu and Nagurney, *European Journal of Operational Research* **224(2)** (2013) pp 273-282.

Fresh Produce Food Supply Chains



Smart Cities and Energy and Food Supply Chains

Clearly, smart cities with enhanced ICT, Big Data, sensors, and other technologies can play a big role in energy supply chains and demand management and also in food supply chains in terms of greater transparency, waste reduction, and food traceability, as well as the possible lowering of emissions.

However, in implementing ICT we should be careful that energy demands for computing infrastructure do not negatively impact any programs for pollution abatement and the reduction of emissions. As noted by Mark Sawyer in a recent article in *The Conversation*: At best, smart cities may end up a zero-sum game in terms of sustainability because their “positive and negative impacts tend to cancel each other out”.

The Sustainable Supply Chain Network Model with Frequency of Activities

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.

This part of the presentation is based on the paper, “Supply Chain Network Sustainability Under Competition and Frequencies of Activities from Production to Distribution,” Nagurney, Yu, and Floden, *Computational Management Science* **10(4)** (2013) pp 397-422, where a full list of references can be found.

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

This work is inspired, in part, by the 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. The Symposium was organized by David E. Boyce and Hani S. Mahmassani.



Anna Nagurney



Sustainable Supply Chain Networks for Sustainable Cities

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 CO₂-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
 - ▶ CO₂ 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%**.



Some of the 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), Bouchery, Corbett, Fransoo, and Tan (2007), Saberi, Cruz, Sarkis, and Nagurney (2018)

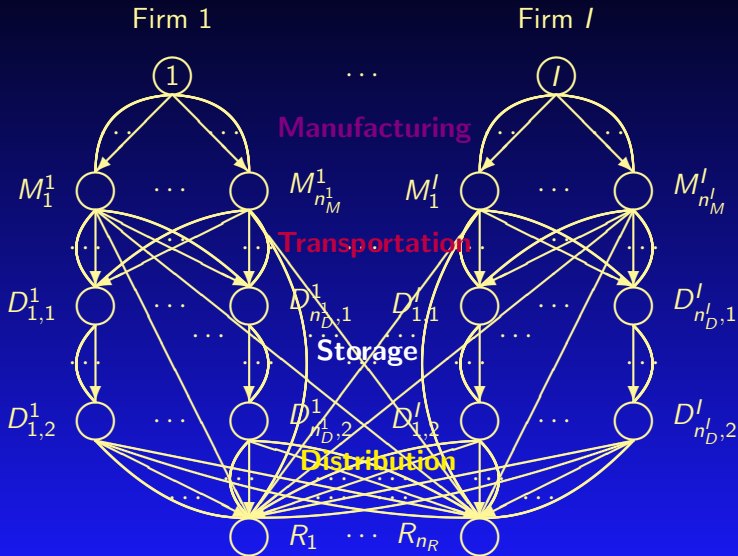
► Network Economics:

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, such as:
 - ▶ 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

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

Relationship between Link Flows and Path Flows

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

Relationship between Path Flows and Demands

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

Nonnegativity of the Path Flows

$$x_p \geq 0, \quad \forall p \in P. \quad (3)$$

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 , e.g.
 - ▶ The production amount in a single manufacturing run;
 - ▶ The volumes (flows) of the product that the mode can transport.

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

Demand Price Functions

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

- ▶ 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.

Total Operational Cost Functions

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

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

- ▶ 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.

Emission-Generation Functions

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

- ▶ 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

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

The Environmental Impact of Firm i

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

The Utility Function of Firm i

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

- ▶ Each firm weights its generated emissions in an **individual** way.
- ▶ In the case of **governmental regulations**, the ω_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**,

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

Supply Chain Network Cournot-Nash Equilibrium

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

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

where $\hat{Y}_i^* \equiv (Y_1^*, \dots, Y_{i-1}^*, Y_{i+1}^*, \dots, Y_l^*)$ and $K_i \equiv \{Y_i | Y_i \in R_+^{n_{Pi} + n_{Li}}\}$.

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 in Path Flows

Variational Inequality (Path Flows)

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

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

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 in Path Flows

$$\frac{\partial \hat{C}_p(x)}{\partial x_p} \equiv \sum_{b \in L^i} \sum_{a \in L^i} \frac{\partial \hat{c}_b(f)}{\partial f_a} \delta_{ap}, \quad (14a)$$

$$\frac{\partial \hat{E}_p(x, \gamma)}{\partial x_p} \equiv \sum_{a \in L^i} \frac{\partial \hat{e}_a(f_a, \gamma_a)}{\partial f_a} \delta_{ap}, \quad (14b)$$

$$\frac{\partial \hat{E}_p(x, \gamma)}{\partial \gamma_a} \equiv \frac{\partial \hat{e}_a(f_a, \gamma_a)}{\partial \gamma_a}, \quad (14c)$$

$$\frac{\partial \hat{\rho}_{il}(x)}{\partial x_p} \equiv \frac{\partial \rho_{il}(d)}{\partial d_{ik}}. \quad (14d)$$

Variational Inequality Formulation in Link Flows

Variational Inequality (Link Flows)

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

$$\begin{aligned} & \sum_{i=1}^I \sum_{a \in L^i} \left[\sum_{b \in L^i} \frac{\partial \hat{c}_b(f^*)}{\partial f_a} + \omega_i \frac{\partial \hat{e}_a(f_a^*, \gamma_a^*)}{\partial f_a} + \lambda_a^* \right] \times [f_a - f_a^*] \\ & + \sum_{i=1}^I \sum_{k=1}^{n_R} \left[-\rho_{ik}(d^*) - \sum_{l=1}^{n_R} \frac{\partial \rho_{il}(d^*)}{\partial d_{ik}} d_{il}^* \right] \times [d_{ik} - d_{ik}^*] \\ & + \sum_{i=1}^I \sum_{a \in L^i} \left[\frac{\partial \hat{g}_a(\gamma_a^*)}{\partial \gamma_a} + \omega_i \frac{\partial \hat{e}_a(f_a^*, \gamma_a^*)}{\partial \gamma_a} - \bar{u}_a \lambda_a^* \right] \times [\gamma_a - \gamma_a^*] \\ & + \sum_{i=1}^I \sum_{a \in L^i} [\bar{u}_a \gamma_a^* - f_a^*] \times [\lambda_a - \lambda_a^*] \geq 0, \quad \forall (f, d, \gamma, \lambda) \in K^2, \quad (15) \end{aligned}$$

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

Algorithm – Euler Method

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

$$x_p^{\tau+1} = \max \left\{ 0, x_p^{\tau} + a_{\tau} \left(\hat{\rho}_{ik}(x^{\tau}) + \sum_{l=1}^{n_R} \frac{\partial \hat{\rho}_{il}(x^{\tau})}{\partial x_p} \sum_{q \in P_l^i} x_q^{\tau} - \frac{\partial \hat{C}_p(x^{\tau})}{\partial x_p} - \omega_i \frac{\partial \hat{E}_p(x^{\tau}, \gamma^{\tau})}{\partial x_p} - \sum_{a \in L^i} \lambda_a^{\tau} \delta_{ap} \right) \right\}, \quad (16a)$$

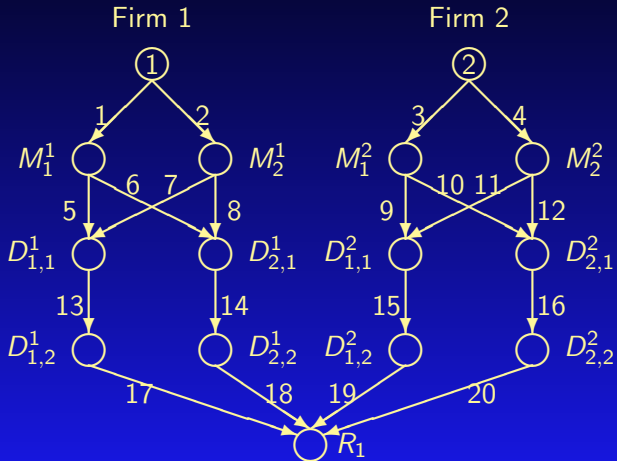
$$\gamma_a^{\tau+1} = \max \left\{ 0, \gamma_a^{\tau} + a_{\tau} \left(\bar{u}_a \lambda_a^{\tau} - \frac{\partial \hat{g}_a(\gamma_a^{\tau})}{\partial \gamma_a} - \omega_i \frac{\partial \hat{E}_p(x^{\tau}, \gamma^{\tau})}{\partial \gamma_a} \right) \right\}, \quad (16b)$$

$$\lambda_a^{\tau+1} = \max \left\{ 0, \lambda_a^{\tau} + a_{\tau} \left(\sum_{q \in P} x_q^{\tau} \delta_{aq} - \bar{u}_a \gamma_a^{\tau} \right) \right\}. \quad (16c)$$

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^*	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

Example 1

	Firm 1	Firm 2
Demand	55.71	48.38
Price	334.62	275.39
Profit	12,818.14	9,387.54
Emissions	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

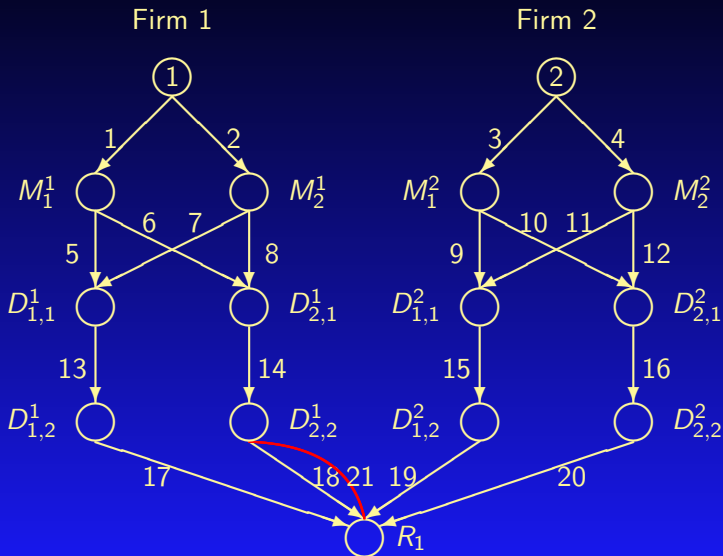
- ▶ Firm 1 and Firm 2 decide their product flows and activity frequencies without the consideration of their generated emissions.

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

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

- ▶ Due to consumers' preference, the profit of Firm 1 is still significantly higher than that of Firm 2.
- ▶ The total emissions increase substantially.
- ▶ 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 and Example 3



Example 2 and 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 and 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	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

- ▶ 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.

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.

Example 3: Sensitivity Analysis

At which value of ω_1 , which represents Firm 1's environmental concern, would the distribution from the distribution center $D_{2,2}^1$ 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.

Summary and Conclusions

- ▶ We presented a **competitive supply chain network model** with multiple firms.
 - ▶ Each firm produces a **differentiated product** by brand.
 - ▶ Each assigns a weight on 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

Summary and Conclusions

- ▶ We emphasized the **importance of the sustainability of supply chains for sustainable cities in the context of smart cities.**
- ▶ We described some applied supply chain network models of relevance to cities from electric power ones to food ones and noted what smart cities analytics could provide us with.
- ▶ 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!



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