Sustainable Supply Chains: Multicriteria Decision-Making and Policy Analysis for the Environment

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Dissertation Defense

Sustainability and Supply Chains

- It is believed that the critical next step from examinations of operations and the environment is the study of sustainability and supply chains (Linton, Klassen, and Jayaraman (2007)).
- 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" (WCED (1987)).
- The integration of an environmental perspective into a business context can be traced back to the 1990's, and is linked to the book *Our Common Future* (WCED (1987)), also referred to as the Brundtland Report (Linton, Klassen, and Jayaraman (2007)).

Sustainability and Supply Chains

- There is still a debate as to the method to operationalize sustainability, as questions arise such as what resources future generations will require, the level of emissions that can be released without negatively affecting future generations, what policies would be required to achieve sustainability, the effect of market forces, etc. (Wilkinson, Hill, and Gollan (2001), Linton, Klassen, and Jayaraman (2007)).
- This research is a contribution to the growing research in the development of rigorous mathematical frameworks for environmental-friendly modeling.
- The proposed dissertation will focus on source reduction and pollution prevention.

Pollution and Environmental impact

- The release of CO_2 into the atmosphere, through the combustion of fossil fuels (coal, oil, and natural gas), has risen 30% in the 200 years since the industrial revolution (Burruss (2004)).
- The average surface temperature of the earth, expressed as a global average, has increased by about 0.74C over the past hundred years (between 1906 – 2005) with 11 of the 12 warmest years occurring between 1995–2006 (IPCC (2007)).
- In the US alone, greenhouse gas emissions are projected to rise 35% between 2005 – 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 fired power plants to generate energy (Creyts et al. (2007)).
- Several environmental regulations have been geared towards, specifically, the electric power industry, which underpins modern society.

The Electric Power Industry

- The power industry is expected to grow by 39% between 2005–2030 due to population growth and other factors.
- Coal-fired power plants are expected to meet this growth in demand, accounting for 81% of the incremental load of electric power through 2030, and of which is also responsible for a majority of the electricity generated carbon emissions (Creyts et al. (2007)).
- Regulatory mandates that lead to efficiency improvements, include, for example, taxes and/or tradable pollution permit programs.

Integration of Supply Chains

- Environmental performance can be seen as a source of reputational, competitive, and financial advantage (Miles and Covin (2000), Fabian (2000)).
- It has been argued that customers and suppliers will punish polluters in the marketplace that violate environmental rules, also called a "reputational penalty" (Klein and Leffler (1981), Klassen and McLaughlin (1996)).
- According to a survey sponsored by DuPont and Mohawk Industries in October of 2007, despite the weak economy 65% of consumers are willing to pay an additional 8.3% for products made with renewable resources (Environmental Leader (2008)).
- A firm's success has been tied, in part, to the strength of its ability to coordinate and integrate activities along the entire supply chain (Spekman, Kamauff Jr., and Myhr (1998)), and to effectively implement multicriteria decision-making tools to aid in their strategic decisions.
- A method for companies to achieve voluntary efficiency, through supply chain merger/integration, can, possibly, result in synergistic gains.

This Section corresponds to Chapter 3 of the Dissertation and is based on the following paper:

Nagurney, A., Liu, Z., and Woolley, T. (2007) **Sustainable Supply Chain and Transportation Networks**. *The International Journal of Sustainable Transportation*, 1, 29-51.

Contribution

- Develop a new sustainable supply chain model
  - Incorporated differing manufacturing plants
  - Incorporated distinct environmental emissions of each plant with general emission functions
  - Multicriteria decision-making
- Compute the product flows and associated prices of the sustainable supply chain network and resulting emissions
- Show how a sustainable supply chain can be transformed into and studied as an elastic demand transportation network equilibrium problem.
- Numerical examples

Motivation

There is a wealth of literature addressing both production planning and distribution planning; however, few models attempt to address these problems simultaneously (Cattanach (1995), Thomas and Griffin (1996) and references therein)

Reputation: Accountable for not only own performance, but also that of their suppliers, subcontractors, and distribution outlets.

Motivation

Green Supply Chain Management: Integrating environment thinking into supply chain management

- In 2005, Wal-Mart at least vowed to buy 100% of its electricity from renewable resources, produce no waste, double the fuel efficiency of its trucks and reduce GHG emissions by 20%. It also said it expected its 60,000 suppliers worldwide to follow its lead if they wanted to continue doing business with Wal-Mart. -usinfo.state.gov

- Ford Motor company demanded that all of its 5000 worldwide suppliers with manufacturing plants obtain a third party certification of environmental management system (EMS) by 2003 (Rao (2002)).

Motivation

Multicriteria Decision-Making

- Regarding supply chain applications, traditionally, the research has focused on a single objective to either minimize costs or to maximize profits.
  - Maximize Profit
  - Minimize Pollution

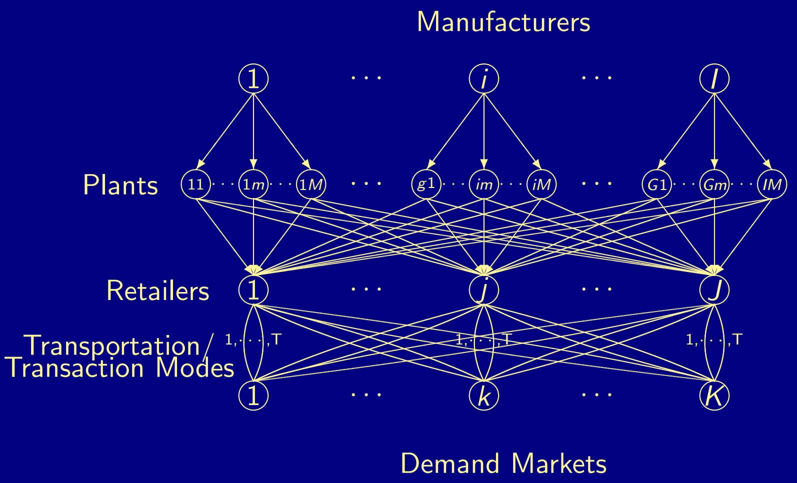
Transformation into a Transportation Network

- Theoretical Insights
- Computation Efficiency

Relevant Literature

- Schneider (1968), Quandt (1967)
- Dong, Zhang, and Nagurney (2002), Chen and Lee (2004), Dong, Zhang, Yan, and Nagurney (2005)
- Nagurney (2000), Nagurney, Dong, and Mokhtarian (2002), Nagurney and Toyasaki (2003)
- Nagurney and Liu (2005), Wu et al. (2006), Nagurney (2006)

The Supply Chain Network with Manufacturing Plants



The Multicriteria Decision-Making Behavior of the Manufacturers and Their Optimality Conditions

Since it is assumed that each individual manufacturer i; $i = 1, \ldots, I$, is a profit maximizer, the profit-maximization objective function of manufacturer i can be expressed as follows:

$$\text{Maximize} \quad \sum_{m=1}^{M} \sum_{j=1}^{J} \rho^*_{1imj} q_{imj} - \sum_{m=1}^{M} f_{im}(q_m) - \sum_{m=1}^{M} \sum_{j=1}^{J} c_{imj}(q_{imj}).$$

Since it is assumed that each individual manufacturer i; $i = 1, \ldots, I$, strives to reduce pollution, the emission-minimization objective function of manufacturer i can be expressed as follows:

$$\text{Minimize} \sum_{m=1}^{M} e_{im}(q_{im}) + \sum_{m=1}^{M} \sum_{j=1}^{J} e_{imj}(q_{imj}).$$

The Multicriteria Decision-Making Behavior of the Manufacturers and Their Optimality Conditions

The multicriteria decision-making problem for manufacturer i is transformed into:

$$\text{Maximize} \quad \sum_{m=1}^{M}\sum_{j=1}^{J}\rho^*_{1imj}q_{imj} - \sum_{m=1}^{M} f_{im}(q_m) - \sum_{m=1}^{M}\sum_{j=1}^{J} c_{imj}(q_{imj})$$

$$-\alpha_i(\sum_{m=1}^{M} e_{im}(q_{im}) + \sum_{m=1}^{M}\sum_{j=1}^{J} e_{imj}(q_{imj}))$$

subject to:

$$\sum_{j=1}^{J} q_{imj} = q_{im}, \quad m = 1, \ldots, M,$$

$$q_{imj} \geq 0, \quad m = 1, \ldots, M; j = 1, \ldots, J.$$

A nonnegative constant, α_i can be assumed the price that each manufacturer, i, would be willing to pay for each unit of emission. Thus, α_i, represents the environmental concern for each manufacturer, i, and a higher α_i represents a greater concern for the environment.

The Multicriteria Decision-Making Behavior of the Retailers and Their Optimality Conditions

The profit-maximization objective function faced by retailer j may be expressed as follows:

$$\text{Maximize} \quad \sum_{k=1}^{K}\sum_{t=1}^{T}\rho_{2jk}^{t*}q_{jk}^{t} - c_j(Q^1) - \sum_{i=1}^{I}\sum_{m=1}^{M}\rho_{1imj}^{*}q_{imj} - \sum_{k=1}^{K}\sum_{t=1}^{T}c_{jk}^{t}(q_{jk}^{t}).$$

The emission-minimization objective function faced by retailer j may be expressed as follows:

$$\text{Minimize} \quad e_j(h_j) + \sum_{k=1}^{K}\sum_{t=1}^{T}e_{jk}^{t}(q_{jk}^{t}),$$

$$\text{where } \; h_j \equiv \sum_{i=1}^{I}\sum_{m=1}^{M}q_{imj}, \quad j = 1, \ldots, J.$$

The Multicriteria Decision-Making Behavior of the Retailers and Their Optimality Conditions

Retailer j's multicriteria decision-making problem is now given by:

$$\text{Maximize} \quad \sum_{k=1}^{K}\sum_{t=1}^{T}\rho_{2jk}^{t*}q_{jk}^{t} - c_j(Q^1) - \sum_{i=1}^{I}\sum_{m=1}^{M}\rho_{1imj}^{*}q_{imj} - \sum_{k=1}^{K}\sum_{t=1}^{T}c_{jk}^{t}(q_{jk}^{t})$$

$$-\beta_j(e_j(h_j) + \sum_{k=1}^{K}\sum_{t=1}^{T}e_{jk}^{t}(q_{jk}^{t}))$$

subject to:

$$\sum_{k=1}^{K}\sum_{t=1}^{T}q_{jk}^{t} = \sum_{i=1}^{I}\sum_{m=1}^{M}q_{imj},$$

$$q_{imj} \geq 0, \quad i = 1, \ldots, I, \quad m = 1, \ldots, M,$$

$$q_{jk}^{t} \geq 0, \quad k = 1, \ldots, K; t = 1, \ldots, T.$$

A nonnegative constant, β_j can be assumed the price that each retailer, j, would be willing to pay for each unit of emission; which represents the environmental concern for each retailer, j, and a higher β_j represent a greater concern for the environment.

The Equilibrium Conditions for the Demand Markets

At each demand market k; $k = 1, \ldots, K$, the following conservation of flow equation must be satisfied:

$$d_k = \sum_{j=1}^{J} \sum_{t=1}^{T} q_{jk}^t.$$

Since the demand market price functions are given, the market equilibrium conditions at demand market k then take the form: for each retailer j; $j = 1, ..., J$ and transportation/transaction mode t; $t = 1, ..., T$:

$$\rho_{2jk}^{t*} + \hat{c}_{jk}^t(Q^{2*}) + \eta_k \frac{\partial e_{jk}^t(q_{jk}^{t*})}{\partial q_{jk}^t} \begin{cases} = \rho_{3k}(d^*), & \text{if} \quad q_{jk}^{t*} > 0, \\ \geq \rho_{3k}(d^*), & \text{if} \quad q_{jk}^{t*} = 0. \end{cases}$$

The Equilibrium Conditions for the Supply Chain Network with Manufacturing Plants and Environmental Concerns

In equilibrium, the optimality conditions for all the manufacturers, the optimality conditions for all the retailers, and the equilibrium conditions for all the demand markets must be simultaneously satisfied so that no decision-maker has any incentive to alter his transactions.

It is assumed that the cost functions are continuously differentiable and convex, and the manufacturers, as well as the retailers, compete in a noncooperative manner in the sense of Nash (1950, 1951).

Variational Inequality Formulation of the Supply Chain Network Equilibrium with Manufacturing Plants and Environmental Concerns

Theorem

The equilibrium conditions governing the supply chain network coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*) \in \mathcal{K}_3^5$ satisfying:

$$\sum_{i=1}^{I}\sum_{m=1}^{M}\left[\frac{\partial f_{im}(q_m^*)}{\partial q_{im}}+\alpha_i\frac{\partial e_{im}(q_{im}^*)}{\partial q_{im}}\right]\times[q_{im}-q_{im}^*]+\sum_{j=1}^{J}\left[\frac{\partial c_j(h^*)}{\partial h_j}+\beta_j\frac{\partial e_j(h_j^*)}{\partial h_j}\right]\times[h_j-h_j^*]$$

$$+\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J}\left[\frac{\partial c_{imj}(q_{imj}^*)}{\partial q_{imj}}+\alpha_i\frac{\partial e_{imj}(q_{imj}^*)}{\partial q_{imj}}\right]\times[q_{imj}-q_{imj}^*]$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{jk}^t(q_{jk}^{t*})}{\partial q_{jk}^t}+\hat{c}_{jk}^t(Q^{2*})+(\beta_j+\eta_k)\frac{\partial e_{jk}^t(q_{jk}^{t*})}{\partial q_{jk}^t}\right]\times[q_{jk}^t-q_{jk}^{t*}]$$

$$-\sum_{k=1}^{K}\rho_{3k}(d^*)\times[d_k-d_k^*]\geq 0, \quad \forall (q,h,Q^1,Q^2,d)\in\mathcal{K}_3^5,$$

where $\mathcal{K}_3^5 \equiv \{(q,h,Q^1,Q^2,d)|(q,h,Q^1,Q^2,d)\in R_+^{IM+J+IMJ+TJK+K}$ and

$$\sum_{j=1}^{J} q_{imj}=q_{im},\ m=1,\ldots,M,\ \sum_{k=1}^{K}\sum_{t=1}^{T} q_{jk}^t=\sum_{i=1}^{I}\sum_{m=1}^{M} q_{imj},\ \text{and}\ h_j\equiv\sum_{i=1}^{I}\sum_{m=1}^{M} q_{imj},\ j=1,\ldots,J,\ \text{hold}\}.$$

Corollary: Variational Inequality Formulation for the Case of Fixed Emissions

The equilibrium conditions governing the supply chain network coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*) \in \mathcal{K}_3^6$ satisfying:

$$\sum_{i=1}^{I}\sum_{m=1}^{M}\left[\frac{\partial f_{im}(q_m^*)}{\partial q_{im}} + \alpha_i e_{im}\right] \times [q_{im} - q_{im}^*] + \sum_{j=1}^{J}\left[\frac{\partial c_j(h^*)}{\partial h_j} + \beta_j e_j\right] \times [h_j - h_j^*]$$

$$+ \sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J}\left[\frac{\partial c_{imj}(q_{imj}^*)}{\partial q_{imj}} + \alpha_i e_{imj}\right] \times [q_{imj} - q_{imj}^*]$$

$$+ \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{jk}^t(q_{jk}^{t*})}{\partial q_{jk}^t} + \hat{c}_{jk}^t(Q^{2*}) + (\beta_j + \eta_k)e_{jk}^t\right] \times [q_{jk}^t - q_{jk}^{t*}]$$

$$- \sum_{k=1}^{K} \rho_{3k}(d^*) \times [d_k - d_k^*] \geq 0, \quad \forall (q, h, Q^1, Q^2, d) \in \mathcal{K}_3^6,$$

where $\mathcal{K}_3^6 \equiv \{(q, h, Q^1, Q^2, d) | (q, h, Q^1, Q^2, d) \in R_+^{IM+J+IMJ+TJK+K}$.

Corresponding Paper and Section of the Dissertation

This Section corresponds to Chapter 4 of the Dissertation and is based on the following paper:

Nagurney, A., Liu, Z., and Woolley, T. (2006) **Optimal Endogenous Carbon Taxes for Electric Power Supply Chains with Power Plants**. *Mathematical and Computer Modelling*, 44, 899-916.

Contribution

- Develop a modeling and computational framework that allows for the determination of:
  - The optimal carbon taxes applied to electric power plants in the context of electric power supply chain (generation/distribution/consumption) networks.
  - The equilibrium electric power transactions, demands, and prices.

- The general framework that I develop allows for three distinct types of carbon taxation environmental policies.
  - A completely decentralized scheme in which taxes can be applied to each individual power generator/ power plant in order to guarantee that each assigned emission bound is not exceeded.
  - A centralized scheme which assumes a fixed bound over the entire electric power supply chain in terms of total carbon emissions.
  - A centralized scheme which assumes the bound to be a function of the tax.

- Numerical examples

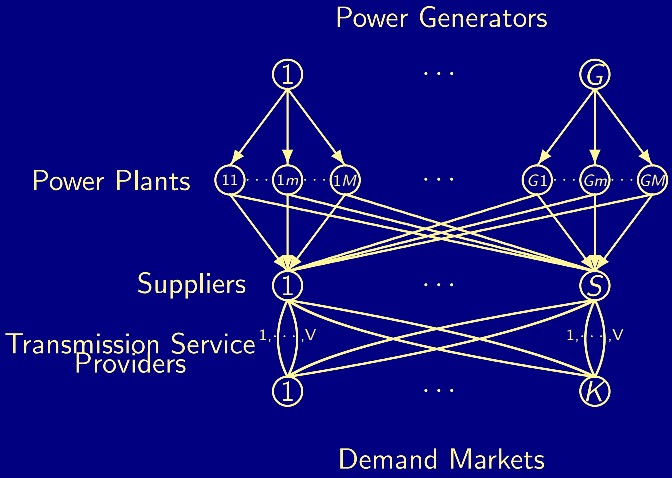
Motivation

- Electric Power Industry
  - Of the total US emissions of carbon dioxide and nitrous oxide, more than a third arises from generating electricity. The electric power sector currently accounts for more than one-third of its annual coal consumption with such power plants generating over 75% of the air pollution in China (see Pew Center (2006)).
  - With oil trading at more than $100 per barrel in 2008, energy is the major supply chain focus for companies, with an emphasis on reduction in costs and energy consumption, and the use of alternative energy options (ethanol, biomass, fuel cells, wind, solar, nuclear, and other various energy options) (Penfield (2008)).
  - Contribution to recessionary periods through the rise in energy prices. For example, the last three recession periods in the US (1974–75, 1980-82, and 1990-91) were preceded by spikes in oil prices (Greenspan (2001)).

Literature

- Pigou (1920) *"Pigouvian Taxes"*
- Pearce (1991) (Literature Review)
- Hogan (1992)
- Hobbs and Pang (2007)
- Jing-Yuan and Smeers (1999)
- Zaccour (1998)
- Nagurney and Matsypura (2005)
- Wu, Nagurney, Liu, and Stranlund (2006)

The Electric Power Supply Chain Network with Power Plants



A Decentralized Carbon Taxation Scheme - The Behavior of the Power Generators and Their Optimality Conditions

Since it is assumed that each individual power generator is a profit-maximizer, the optimization problem of power generator g can be expressed as follows:

$$\text{Maximize} \quad \sum_{m=1}^{M}\sum_{s=1}^{S}\rho^*_{1gms}q_{gms} - \sum_{m=1}^{M} f_{gm}(q_m) -$$

$$\sum_{m=1}^{M}\sum_{s=1}^{S} c_{gms}(q_{gms}) - \sum_{m=1}^{M}\tau^*_{gm}e_{gm}(q_{gm})$$

subject to:

$$\sum_{s=1}^{S} q_{gms} = q_{gm}, \quad m = 1, \ldots, M,$$

$$q_{gms} \geq 0, \quad m = 1, \ldots, M; s = 1, \ldots, S.$$

A Centralized Carbon Taxation Scheme - The Behavior of the Power Generators and Their Optimality Conditions

Since it is assumed that each individual power generator is a profit-maximizer, the optimization problem of power generator g can be expressed as follows:

$$\text{Maximize} \quad \sum_{m=1}^{M}\sum_{s=1}^{S}\rho^*_{1gms}q_{gms} - \sum_{m=1}^{M} f_{gm}(q_m) -$$

$$\sum_{m=1}^{M}\sum_{s=1}^{S} c_{gms}(q_{gms}) - \sum_{m=1}^{M}\mathcal{T}^* e_{gm}(q_{gm})$$

subject to:

$$\sum_{s=1}^{S} q_{gms} = q_{gm}, \quad m = 1, \ldots, M,$$

$$q_{gms} \geq 0, \quad m = 1, \ldots, M; s = 1, \ldots, S.$$

The Equilibrium Conditions for the Electric Power Supply Chain Network

The Decentralized Carbon Tax Equilibrium Conditions

For all power generators g; $g = 1, \ldots, G$, and for all power plants m; $m = 1, \ldots, M$, a carbon tax policy is said to be in equilibrium if:

$$\bar{B}_{gm} - e_{gm}(q^*_{gm}) \begin{cases} = 0, & \text{if} \quad \tau^*_{gm} > 0, \\ \geq 0, & \text{if} \quad \tau^*_{gm} = 0. \end{cases}$$

The Centralized Carbon Tax Equilibrium Conditions

$$\bar{B} - \sum_{g=1}^{G} \sum_{m=1}^{M} e_{gm}(q^*_{gm}) \begin{cases} = 0, & \text{if} \quad \mathcal{T}^* > 0, \\ \geq 0, & \text{if} \quad \mathcal{T}^* = 0. \end{cases}$$

$$\bar{B}(\mathcal{T}^*) - \sum_{g=1}^{G} \sum_{m=1}^{M} e_{gm}(q^*_{gm}) \begin{cases} = 0, & \text{if} \quad \mathcal{T}^* > 0, \\ \geq 0, & \text{if} \quad \mathcal{T}^* = 0. \end{cases}$$

The Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Decentralized Carbon Taxes

Theorem

The equilibrium conditions governing the electric power supply chain network coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, \tau^*) \in \mathcal{K}_4^5$ satisfying:

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \tau_{gm}^*\frac{\partial e_{gm}(q_{gm}^*)}{\partial q_{gm}}\right]\times[q_{gm}-q_{gm}^*] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s}\times[h_s-h_s^*]$$
$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}}\right]\times[q_{gms}-q_{gms}^*]$$
$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{sk}^t(q_{sk}^{t*})}{\partial q_{sk}^t} + \hat{c}_{sk}^t(Q^{2*})\right]\times[q_{sk}^t-q_{sk}^{t*}] - \sum_{k=1}^{K}\rho_{3k}(d^*)\times[d_k-d_k^*]$$
$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\bar{B}_{gm}-e_{gm}(q_{gm}^*)\right]\times\left[\tau_{gm}-\tau_{gm}^*\right]\geq 0, \quad \forall (q,h,Q^1,Q^2,d,\tau)\in\mathcal{K}_4^5, \tag{4.19}$$

where $\mathcal{K}_4^5 \equiv \{(q,h,Q^1,Q^2,d,\tau)|(q,h,Q^1,Q^2,d,\tau)\in R_+^{2GM+S+GMS+TSK+K}$ and and the constraints hold$\}$.

Remark

Note that in the taxes could also be interpreted as "weights" associated with the minimization of the carbon emissions for each genco and power plant.

It is interesting to see, however, that positive, self-induced decision-making in terms of environmental decision-making could have the same result as the imposition of taxes by a governmental authority.

However, the weights would have to be determined endogenously to have the precise correspondence between the sustainable supply chain network with multicriteria decision-makers and the model with carbon taxes that is proposed here.

The Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Centralized Carbon Taxes and a Fixed Upper Bound

Theorem

The equilibrium conditions governing the electric power supply chain network coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, \mathcal{T}^*) \in \mathcal{K}_4^7$ *satisfying:*

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \mathcal{T}^*\frac{\partial e_{gm}(q_{gm}^*)}{\partial q_{gm}}\right]\times[q_{gm}-q_{gm}^*] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s}\times[h_s-h_s^*]$$
$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}}\right]\times[q_{gms}-q_{gms}^*]$$
$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{sk}^t(q_{sk}^{t*})}{\partial q_{sk}^t} + \hat{c}_{sk}^t(Q^{2*})\right]\times[q_{sk}^t-q_{sk}^{t*}] - \sum_{k=1}^{K}\rho_{3k}(d^*)\times[d_k-d_k^*]$$
$$+\left[\bar{B}-\sum_{g=1}^{G}\sum_{m=1}^{M}e_{gm}(q_{gm}^*)\right]\times[\mathcal{T}-\mathcal{T}^*]\geq 0, \quad \forall (q,h,Q^1,Q^2,d,\mathcal{T})\in\mathcal{K}_4^7, \tag{4.26}$$

where $\mathcal{K}_4^7 \equiv \{(q,h,Q^1,Q^2,d,\mathcal{T})|(q,h,Q^1,Q^2,d,\mathcal{T}) \in R_+^{GM+S+GMS+TSK+K+1}$ *and the constraints hold*$\}$.

Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Centralized Carbon Taxes and an Elastic Carbon Emission Bound

Theorem

The equilibrium conditions governing the electric power supply chain network coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, \mathcal{T}^*) \in \mathcal{K}_4^9$ *satisfying:*

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \mathcal{T}^*\frac{\partial e_{gm}(q_{gm}^*)}{\partial q_{gm}}\right]\times[q_{gm}-q_{gm}^*] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s}\times[h_s-h_s^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}}\right]\times[q_{gms}-q_{gms}^*]$$

$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{sk}^t(q_{sk}^{t*})}{\partial q_{sk}^t} + \hat{c}_{sk}^t(Q^{2*})\right]\times[q_{sk}^t-q_{sk}^{t*}] - \sum_{k=1}^{K}\rho_{3k}(d^*)\times[d_k-d_k^*]$$

$$+\left[B(\mathcal{T}^*) - \sum_{g=1}^{G}\sum_{m=1}^{M} e_{gm}(q_{gm}^*)\right]\times[\mathcal{T}-\mathcal{T}^*] \geq 0, \quad \forall (q, h, Q^1, Q^2, d, \mathcal{T}) \in \mathcal{K}_4^9.$$

Corollary 1 (Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Decentralized Carbon Taxes for the Case of Fixed Emissions)

The equilibrium conditions governing the electric power supply chain network coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, \tau^*) \in \mathcal{K}_4^6$ *satisfying:*

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \tau_{gm}^* e_{gm}\right] \times [q_{gm} - q_{gm}^*] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s} \times [h_s - h_s^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}}\right] \times [q_{gms} - q_{gms}^*]$$

$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{sk}^t(q_{sk}^{t*})}{\partial q_{sk}^t} + \hat{c}_{sk}^t(Q^{2*})\right] \times [q_{sk}^t - q_{sk}^{t*}] - \sum_{k=1}^{K}\rho_{3k}(d^*) \times [d_k - d_k^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\bar{B}_{gm} - e_{gm}q_{gm}^*\right] \times \left[\tau_{gm} - \tau_{gm}^*\right] \geq 0, \quad \forall (q, h, Q^1, Q^2, d, \tau) \in \mathcal{K}_4^6,$$

where $\mathcal{K}_4^6 \equiv \{(q, h, Q^1, Q^2, d, \tau) | (q, h, Q^1, Q^2, d, \tau) \in R_+^{2GM+S+GMS+TSK+K}.$

Corollary 2 (Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Centralized Carbon Taxes and a Fixed Upper Bound for the Case of Fixed Emissions)

The equilibrium conditions governing the electric power supply chain network coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, \mathcal{T}^*) \in \mathcal{K}_4^8$ *satisfying:*

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \mathcal{T}^* e_{gm}\right] \times [q_{gm} - q_{gm}^*] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s} \times [h_s - h_s^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}}\right] \times [q_{gms} - q_{gms}^*]$$

$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{sk}^t(q_{sk}^{t*})}{\partial q_{sk}^t} + \hat{c}_{sk}^t(Q^{2*})\right] \times [q_{sk}^t - q_{sk}^{t*}] - \sum_{k=1}^{K}\rho_{3k}(d^*) \times [d_k - d_k^*]$$

$$+\left[\bar{B} - \sum_{g=1}^{G}\sum_{m=1}^{M} e_{gm} q_{gm}^*\right] \times [\mathcal{T} - \mathcal{T}^*] \geq 0, \quad \forall (q, h, Q^1, Q^2, d, \mathcal{T}) \in \mathcal{K}_4^8,$$

where $\mathcal{K}_4^8 \equiv \{(q, h, Q^1, Q^2, d, \mathcal{T}) | (q, h, Q^1, Q^2, d, \mathcal{T}) \in R_+^{GM+S+GMS+TSK+K+1}$

Corollary 3 (Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Centralized Carbon Taxes and an Elastic Carbon Emission Bound for the Case of Fixed Emissions)

The equilibrium conditions governing the electric power supply chain network coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, \mathcal{T}^*) \in \mathcal{K}_4^{10}$ *satisfying:*

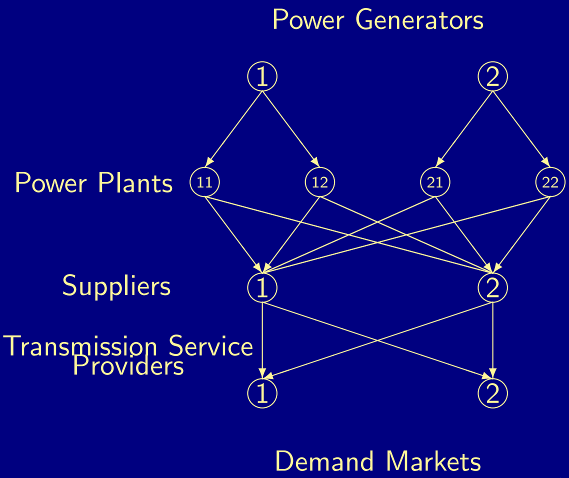
$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \mathcal{T}^* e_{gm}\right] \times [q_{gm} - q_{gm}^*] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s} \times [h_s - h_s^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}}\right] \times [q_{gms} - q_{gms}^*]$$

$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{sk}^t(q_{sk}^{t*})}{\partial q_{sk}^t} + \hat{c}_{sk}^t(Q^{2*})\right] \times [q_{sk}^t - q_{sk}^{t*}] - \sum_{k=1}^{K}\rho_{3k}(d^*) \times [d_k - d_k^*]$$

$$+\left[B(\mathcal{T}^*) - \sum_{g=1}^{G}\sum_{m=1}^{M} e_{gm} q_{gm}^*\right] \times [\mathcal{T} - \mathcal{T}^*] \geq 0, \quad \forall (q, h, Q^1, Q^2, d, \mathcal{T}) \in \mathcal{K}_4^{10}.$$

The Electric Power Supply Chain Network for the Numerical Examples



The Solutions to Examples 4.1, 4.2, 4.3, and 4.4

Equilibrium Solution	Example 4.1	Example 4.2	Example 4.3	Example 4.4
Computed Equilibrium Power Flows				
q_{11}^*	22.56	11.51	15.20	20.41
q_{12}^*	9.93	23.02	6.63	8.96
q_{21}^*	22.90	23.02	15.53	20.74
q_{22}^*	92.38	23.05	62.65	83.68
q_{111}^*	11.28	5.76	7.60	10.20
q_{112}^*	11.28	5.76	7.60	10.20
q_{121}^*	4.97	11.51	3.31	4.48
q_{122}^*	4.97	11.51	3.31	4.48
q_{211}^*	11.45	11.51	7.76	10.37
q_{212}^*	11.45	11.51	7.76	10.37
q_{221}^*	46.19	11.52	31.32	41.84
q_{222}^*	11.28	5.76	31.32	1.84
h_1^*	73.89	40.30	50.00	66.90
h_2^*	73.89	40.30	50.00	66.90
q_{11}^{1*}	36.94	20.15	25.00	33.45
q_{12}^{1*}	36.94	20.15	25.00	33.34
q_{21}^{1*}	36.94	20.15	25.00	33.45
q_{22}^{1*}	36.94	20.15	25.00	33.45
Computed Equilibrium Demands				
d_1^*	73.89	40.30	50.00	66.90
d_2^*	73.89	40.30	50.00	66.90
Computed Optimal Taxes				
τ_{11}^*	0.00	77.86	n/a	n/a
τ_{12}^*	0.00	92.38	n/a	n/a
τ_{21}^*	0.00	105.41	n/a	n/a
τ_{22}^*	0.00	185.96	n/a	n/a
Computed Optimal Tax				
$\mathcal{T}^*$	n/a	n/a	115.50	33.79

Corresponding Paper and Section of the Dissertation

This Section corresponds to Chapter 5 of the Dissertation and is based on the following paper:

Woolley, T., Nagurney, A., and Stranlund, J. (2009) **Spatially Differentiated Trade of Permits for Multipollutant Electric Power Supply Chains**. Kallrath, J., Pardalos, P., Rebennack, S., and Schei, M. (eds.) *Optimization in the Energy Industry*, Springer, Berlin, Germany, 277 - 296.

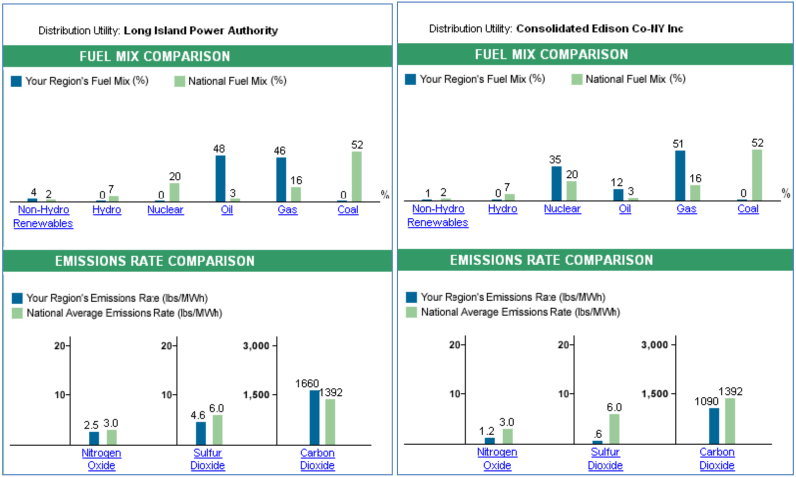
Contribution

- Develop a modeling and computational framework that allows for the determination of:
  - Optimal prices for the various permits and quantity transacted
  - Electricity prices, transactions, and demands
- This research captures
  - Substitutability and complementarity effects of multiple pollutants
  - Spatial nature of the pollutants
- Numerical examples

Electricity Generation and Emissions

	Nitrogen Oxides	Carbon Dioxide	Sulfur Dioxide	Methane	Mercury
Natural Gas	X	X			
Coal	X	X	X		X
Oil	X	X	X	X	X
Municipal Solid Waste	X		X		X
Other	Biomass, Landfill Gas		Biomass		

Electricity Generation and Emissions



Substitutability and Complementarity Effects of Pollutants

Table 2. Multi-Pollutant Impacts of Emission Control Options

Primary Emission Controlled			Multi-Pollutant Interactions	
Pollutant	**Method**	**Reduction[a]**	**Pollutant**	**Effect[a]**
SO_2	Low-S coal	83%	PM	34% increase
			Hg	36% increase
			NO_x	30% increase
SO_2	Wet FGD	89%	PM	50% decrease
			Hg	70% decrease
			CO_2	2% increase
NO_x	SCR	79%	PM	27% decrease
			SO_3	170% increase
			NH_3	trace increase
NO_x $+SO_2$	SCR + FGD	79% NO_x + 89% SO_2	Hg	94% decrease
			PM	54% decrease
			SO_3	40% increase
			CO_2	2% increase
Hg	ACI+H_2O	90%	PM	9% increase
CO_2	MEA	87%	SO_2	99% decrease
			NO_x	20% increase
			NH_3	trace increase
			MEA	trace increase

Spatial Nature of Pollutants

- The impacts of pollutants (such as SO_2, NO_x and Hg) depend critically on the location of their sources and where their impacts are realized.
- There has been noted traffic volumes of trans-Pacific transport of pollutants from Asia to North America (most frequently) as well as trans-Atlantic transport from North America to Europe (Akimoto (2003)).
- Pollutants released from power plants located in the Midwestern U.S. travel by winds toward the East Coast of the U.S. and Canada (EPA).

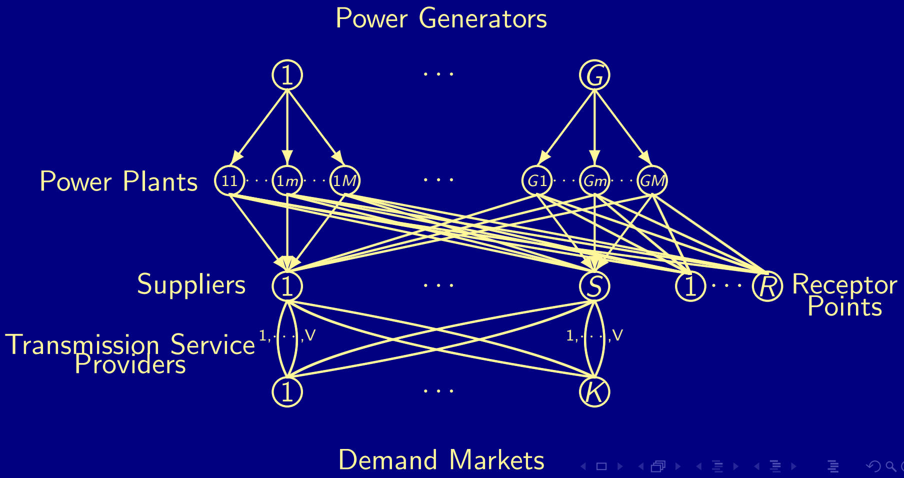
Existing and Proposed Market-Based Programs to Control Multiple Pollutants

- The Regional Clean Air Incentives Market (RECLAIM) program was implemented in California to control NO_x and SO_x pollutants.
- The proposed but not enacted Clear Skies was a national cap to reduce SO_2, NO_x and Hg by 73%, 67%, and 69% by 2018, respectively.
- EPA's Clean Air Interstate Rule (CAIR) capped emissions of SO_2 and NO_x in a large region covering more than 20 states, mostly east of the Mississippi, and the District of Columbia
- Together, the Clean Air Mercury Rule proposal and CAIR create a multi-pollutant strategy to improve air quality throughout the U.S.

Relevant Literature

- Crocker (1966), Dales (1968)
- Montgomery (1972)
- Tietenberg (1985), Hahn (1984), Stavins (1995)
- Dhanda, Nagurney, and Ramanujam (1999), Nagurney and Dhanda (1996,2000), Nagurney, Dhanda, and Stranlund (1997)
- Chen and Hobbs (2005)
- Rubin, Berkenpas, Farrel, Gibbon, and Smith (2001), Schwarz (2005)

The Electric Power Supply Chain Network with Power Plants and Associated Technologies and with Pollutant Receptor Points



The Behavior of the Power Generators and Their Optimality Conditions

Since one can assume that each individual power generator is a profit-maximizer, the objective function of power generator g can be expressed as follows:

$$\text{Maximize} \quad \sum_{m=1}^{M}\sum_{s=1}^{S}\rho_{1gms}^{*}q_{gms} - \sum_{m=1}^{M} f_{gm}(q_m) - \sum_{m=1}^{M}\sum_{s=1}^{S} c_{gms}(q_{gms})$$

$$-\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{r=1}^{R}\tau_r^{j*}(l_{gmr}^{j} - l_{gmr}^{j0})$$

subject to:

$$\sum_{s=1}^{S} q_{gms} = q_{gm}, \quad m = 1, \ldots, M,$$

$$l_{gmr}^{j} \geq e_{gmr}^{j} q_{gm}, \quad j = 1 \ldots J; m = 1 \ldots, M; r = 1, \ldots, R,$$

The following non-negativity conditions must also hold:

$$q_{gms} \geq 0, \quad m = 1, \ldots, M; s = 1, \ldots, S,$$

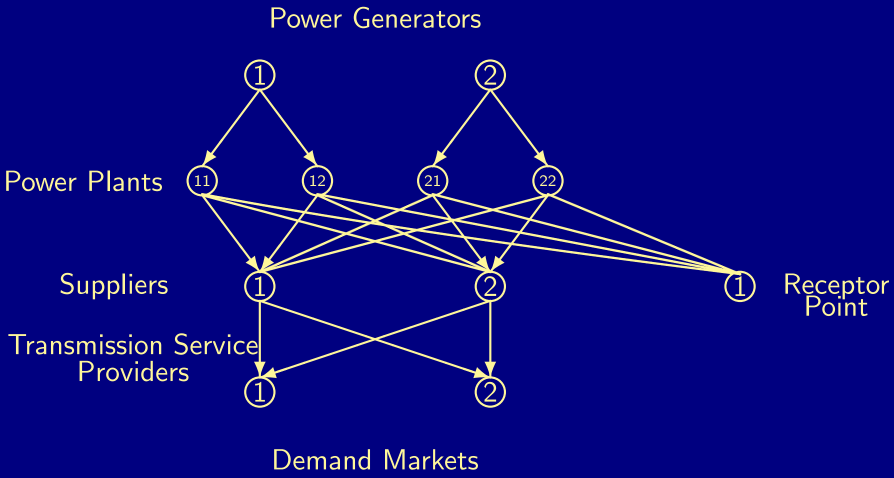
$$l_{gmr}^{j} \geq 0, \quad j = 1, \ldots, J; m = 1, \ldots, M; r = 1, \ldots, R.$$

The Equilibrium Conditions for the Permits

For each pollution permit of type j; $j = 1, \ldots, J$ and receptor point r; $r = 1, \ldots, R$, a multipollutant tradable permit scheme is said to be in equilibrium if:

$$\sum_{g=1}^{G} \sum_{m=1}^{M} [l_{gmr}^{j0} - l_{gmr}^{j*}] \begin{cases} = 0, & \text{if} \quad \tau_r^{j*} > 0, \\ \geq 0, & \text{if} \quad \tau_r^{j*} = 0. \end{cases}$$

The Electric Power Supply Chain Network with a Single Receptor Point for the Examples



The Solutions to Examples 5.1, 5.2, 5.3, and 5.4

Equilibrium Solution	Example 5.1	Example 5.2	Example 5.3	Example 5.4
Equilibrium Electric Power Flows				
q_{11}^*	15.20	7.48	2.85	2.87
q_{12}^*	6.63	3.17	1.10	1.10
q_{21}^*	15.53	7.82	3.19	3.20
q_{22}^*	62.65	31.53	12.86	12.91
q_{111}^*	7.60	3.74	1.43	1.43
q_{112}^*	7.60	3.74	1.43	1.43
q_{121}^*	3.31	1.59	0.55	0.55
q_{122}^*	3.31	1.59	0.55	0.55
q_{211}^*	7.76	3.91	1.59	1.60
q_{212}^*	7.76	3.91	1.59	1.60
q_{221}^*	31.32	15.77	6.43	6.46
q_{222}^*	31.32	15.77	6.43	6.46
h_1^*	50.00	25.00	10.00	10.00
h_2^*	50.00	25.00	10.00	10.00
q_{11}^{1*}	25.00	12.50	5.00	0.00
q_{12}^{1*}	25.00	12.50	5.00	10.00
q_{21}^{1*}	25.00	12.50	5.00	0.00
q_{22}^{1*}	25.00	12.50	5.00	10.00
Equilibrium Demands				
d_1^*	50.00	25.00	10.00	0.00
d_2^*	50.00	25.00	10.00	20.00
Equilibrium Pollution Permit Price and Shadow Prices				
$\tau^* = \lambda_{11}^* = \lambda_{12}^* = \lambda_{21}^* = \lambda_{22}^*$	115.50	236.38	308.91	656.96
Equilibrium Permits/Licenses				
l_{11}^*	15.20	7.48	2.85	2.87
l_{12}^*	6.63	3.17	1.10	1.10
l_{21}^*	15.53	7.82	3.19	3.20
l_{22}^*	62.65	31.53	12.86	12.91

Corresponding Paper and Section of the Dissertation

This Section corresponds to Chapter 6 of the Dissertation and is based on the following paper:

Nagurney, A., and Woolley, T. (2009) **Environmental and Cost Synergy in Supply Chain Network Integration in Mergers and Acquisitions**. Sustainable Energy and Transportation Systems, Proceedings of the 19th International Conference on Multiple Criteria Decision Making, Lecture Notes in Economics and Mathematical Systems, M. Ehrgott, B. Naujoks, T. Stewart, and J. Wallenius, Editors, Springer, Berlin, Germany, in press.

Contribution

- I focus on the case of horizontal mergers (or acquisitions) and extend the contributions in Nagurney (2009) to include multicriteria decision-making and environmental concerns.
- Construct a measure to evaluate the anticipated synergy
  - Operational (cost)
  - Environmental
- Analyze the relationship between cost and environmental synergy in numerical examples
- The framework is based on a supply chain network perspective, in a system-optimized context.

Motivation

- Consumer Pressures
  - Roper Starch Worldwide (1997) noted that more than 75% of the public will switch to a brand associated with the environment when price and quality are equal.
  - Nearly 60% percent of the public favors organizations that support the environment (Roper Starch Worldwide (1997)).
  - Environmentally Preferable Purchasing (EPP) Program
  - Corporate Social Responsibility: "Being in business for the long term means considering social and environmental impact in the short term." -Steve Hochman Forbes.com

Motivation

- DuPont, has the equivalent of 35% of its share price invested in capital and operating expenditures related to protecting the environment. A 15% improvement in efficiency, for instance, could yield nearly $3 per share (Walley and Whitehead (1994)).
- Coordination of the supply chain can improve competitiveness and efficiency at the channel level rather than at the firm level.
- "The real competition is not company against company but supply chain against supply chain" (Albino, Izzo, and Uhtz (2002))

Motivation

- Merger Activity
  - In the first 9 months of 2007, according to Thomson Financial, worldwide merger activity hit $3.6 trillion, surpassing the total from all of 2006 combined (Wong (2007)).
  - Successful mergers can add tremendous value; however, the failure rate is estimated to be between 74% and 83% (Devero (2004)).
  - It is worthwhile to develop tools to better predict the associated strategic gains, which include, among others, cost savings (Eccles, Lanes, and Wilson (1999)).
  - A successful merger depends on the ability to measure the anticipated synergy of the proposed merger (cf. Chang (1988)).

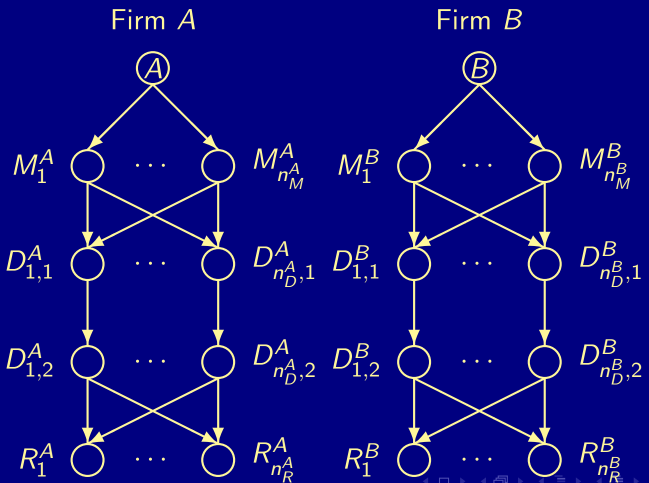
Motivation

- Developing Countries and the Environment
  - There is enormous potential for developing countries to adopt cleaner production, given current technologies as well as the levels of private capital investments.
  - For example, between 1988-1995, multinational corporations invested nearly $422 billion worth of new factories, supplies, and equipment in these countries (World Resources Institute (1998)).
  - Through globalization, firms of industrialized nations can acquire those firms in developing nations that offer lower production costs; however, more than not, combined with inferior environmental concerns.
  - The actions taken today will greatly influence the future scale of environmental and health problems.

Relevant Literature

- Farrell and Shapiro (1990), Spector (2003), Farrel and Shapiro (2001), Soylu et al. (2006), Xu (2007))
- Nagurney (2009) developed a system optimization perspective for supply chain network integration in the case of horizontal mergers.
- According to Stanwick and Stanwick (2002), if environmental issues are ignored the value of the proposed merger can be greatly compromised.
- Lambertini and Mantovani (2007) conclude that horizontal mergers can contribute to reduce negative externalities related to the environment.

Supply Chains of Firms A and B Prior to the Integration: Case 0



The Pre-Integration Multicriteria Decision-making Optimization Problem (Case 0)

It is assumed that each firm provides a homogeneous product to meet the demand at each retail market, R_k^i.

The demand, $d_{R_k^i}$ is assumed fixed and given for each retail market associated with firm $i = A, B$.

Let L_0 denote the links: $L_A \cup L_B$

A path, p, consists of a sequence of supply chain activities comprising supply/manufacturing, storage, and distribution of the product.

Let x_p denote the nonnegative flow of the product on path p.

Since it is first considered the two firms prior to any merger/integration, the paths associated with a given organization have no links in common with the paths of the other firm. This changes when the merger occurs, as the number of paths, and set and number of links changes.

The Pre-Integration Multicriteria Decision-making Optimization Problem (Case 0)

The following conservation of flow equations must hold for each firm i:

$$\sum_{p \in P^0_{R^i_k}} x_p = d_{R^i_k}, \quad i = A, B; k = 1, \ldots, n^i_R,$$

where $P^0_{R^i_k}$ denotes the set of paths connecting (origin) node i with (destination) retail node R^i_k.

One must also have the following conservation of flow equations satisfied:

$$f_a = \sum_{p \in P^0} x_p \delta_{ap}, \quad \forall a \in L^0,$$

where P^0 denotes the set of *all* paths, that is, $P^0 = \cup_{i=A,B;k=1,\ldots,n^i_R} P^0_{R^i_k}$.

The Pre-Integration Multicriteria Decision-making Optimization Problem (Case 0)

The path flows must be nonnegative, that is,

$$x_p \geq 0, \quad \forall p \in P^0.$$

The total cost on a link is assumed to be a function of the flow of the product on the link:

$$\hat{c}_a = \hat{c}_a(f_a), \quad \forall a \in L^0.$$

The total emissions on a link is assumed to be a function of the flow of the product on the link:

$$e_a = e_a(f_a), \quad \forall a \in L^0.$$

These costs are assumed convex, continuously differentiable, and have a bounded second order partial derivative.

The Pre-Integration Multicriteria Decision-making Optimization Problem (Case 0)

The individual cost minimization problems can be formulated jointly as follows:

$$\text{Minimize} \quad \sum_{a \in L^0} \hat{c}_a(f_a)$$

The individual emission minimization problems can be formulated jointly as follows:

$$\text{Minimize} \quad \sum_{a \in L^0} e_a(f_a)$$

The Pre-Integration Multicriteria Decision-making Optimization Problem (Case 0)

The multicriteria decision-making problem for the pre-integration case can be expressed as:

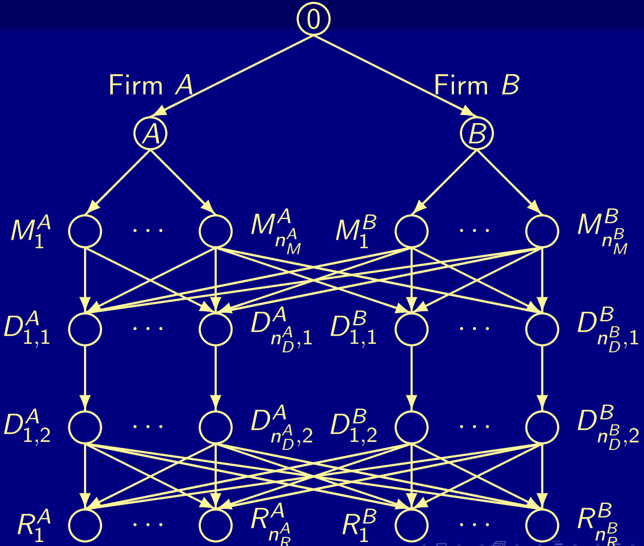
$$\text{Minimize} \quad \sum_{a \in L^0} \sum_{i=A,B} \hat{c}_a(f_a) + \alpha_{ia} e_a(f_a)$$

subject to the constraints presented earlier and

$$f_a \leq u_a, \quad \forall a \in L^0.$$

α_{ia} stands for a nonnegative constant assigned to the emissions-generation criterion for firms $i = A, B$ and links $a \in L_i$. α_{ia} can be assumed the price that each firm, i, would be willing to pay for each unit of emission. Thus, i, represents the weight of the environmental concern for each firm, i, and a higher α_{ia} represents a greater concern for the environment. For simplicity, $\alpha_{ia} \equiv 0$ if link $a \notin L_i$ and $\alpha_{ia} = \alpha_i$.

Supply Chain Network after Firms A and B Integrate: Case 1



The Post-Integration Multicriteria Decision-making Optimization Problem (Case 1)

Let L_1 denote the links: $L_A \cup L_B$

Associate total cost functions and emission functions with the new links and assume, for simplicity, that the corresponding functions on the links emanating from the supersource node are equal to zero.

A path, p, now originates at node 0 and is destined for one of the bottom demand nodes.

The multicriteria decision-making optimization problem for the post-integration case can be expressed as follows:

$$\text{Minimize} \quad \sum_{a \in L^1} [\hat{c}_a(f_a) + \alpha e_a(f_a)]$$

subject to the constraints described earlier.

The Post-Integration Multicriteria Decision-making Optimization Problem (Case 1)

The firms, pre-merger, assigned a weight representing their individual environmental concerns; post-merger, the weight was uniform, non-negative, denoted by α, representing a single decision-making economic entity.

α can be assumed the price that the firm would be willing to pay for each unit of emission, representing the weight of environmental concern; a higher α represents a greater concern for the environment.

There are distinct options for the weight which are explored in several concrete numerical examples:

- Amicable merger: α is a function of the firms' pre-merger weights
- Hostile merger: α takes on the value of the dominant firms' pre-merger weight

Quantifying Synergy Associated with Multicriteria Decision-Making Firms with Environmental Concerns in Mergers/Acquisitions

- I define the total generalized cost TGC^0 associated with the pre-integration problem, or Case 0 as the value of the pre-integration objective function evaluated at its optimal solution f^{*0}.
- I define the total generalized cost TGC^1 associated with the post-integration problem, or Case 1, as the value of the post-integration objective function evaluated at its optimal solution f^{*1}.
- These flow vectors are obtained from the solutions of the variational inequalities for the pre and post-integration cases, respectively.

The synergy associated with the total generalized costs which captures both the total costs and the weighted total emissions is denoted by $\mathcal{S}^{TGC}$ and is defined as follows:

$$\mathcal{S}^{TGC} \equiv [\frac{TGC^0 - TGC^1}{TGC^0}] \times 100\%$$

Quantifying Synergy Associated with Total Cost in Mergers/Acquisitions

- Define TC^0 as the total costs generated under solution f^{*0}.
- Define TC^1 as the total costs generated under solution f^{*1}.

One can also measure the synergy by analyzing the total costs pre and post the merger (cf. Eccles, Lanes, and Wilson (1999) and Nagurney (2009)) but not associated with the multicriteria decision-making context, which is denoted by S^{TC} is defined as follows:

$$\mathcal{S}^{TC} \equiv [\frac{TC^0 - TC^1}{TC^0}] \times 100\%$$

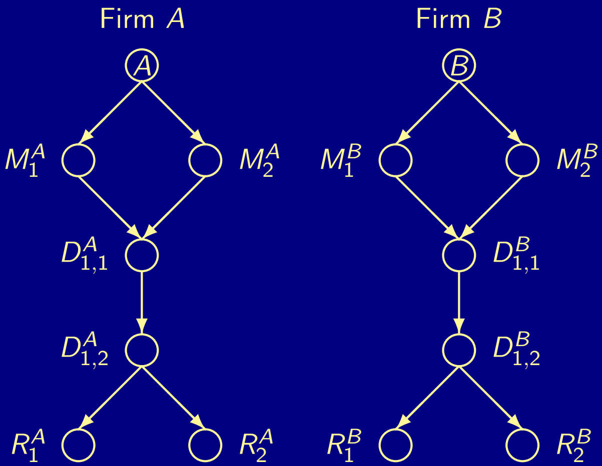
Quantifying Synergy Associated with with Environmental Concerns in Mergers/Acquisitions

- Define TE^0 as the total emissions generated under solution f^{*0}.
- Define TE^1 as the total emissions generated under solution f^{*1}.

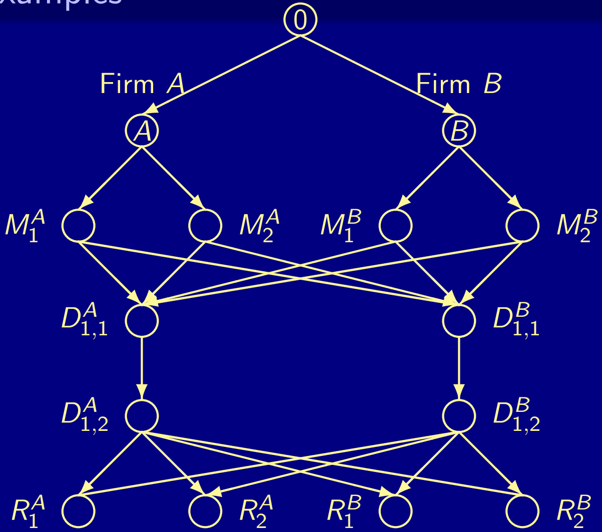
The synergy associated with the total emissions pre and post the integration, but not associated with the multicriteria decision-making context, which is denoted by S^{TE} is defined as follows:

$$\mathcal{S}^{TE} \equiv [\frac{TE^0 - TE^1}{TE^0}] \times 100\%$$

Pre-Integration Supply Chain Network Topology for the Numerical Examples



Post-Integration Supply Chain Network Topology for the Numerical Examples



Numerical Examples

- Capacity on each link initially set to 15 both pre and post-integration.
- The individual pre-integration weights as well as the uniform post-integration weight were set to 1.
- The total cost functions on all links (except those emanating from the supersource node) were represented by: $\hat{c}_a(f_a) = f_a^2 + 2f_a$
- The total emission functions on all links (except those emanating from the supersource node) were represented by: $e_a(f_a) = 10f_a$

Solutions for the Numerical Examples

Example	6.1	6.2	6.3	6.4
TC^0	660.00	660.00	660.00	660.00
TC^1	560.00	565.65	560.00	560.00
S^{TC}	15.15%	14.30%	15.15%	15.15%
TE^0	800.00	600.00	600.00	800.00
TE^1	800.00	574.63	600.00	800.00
S^{TE}	0.00%	4.23%	0.00%	0.00%
TGC^0	1460.00	860.00	860.00	1060.00
TGC^1	1360.00	852.97	560.00	1360.00
S^{TGC}	6.85%	0.82%	34.88%	−28.30%

Solutions to the Variant Numerical Examples

Example	6.1	6.2	6.3	6.4
TC^0	660.00	660.00	660.00	660.00
TC^1	660.00	577.89	560.00	660.00
S^{TC}	0.00%	12.44%	15.15%	0.00%
TE^0	800.00	600.00	600.00	800.00
TE^1	400.00	375.75	450.00	400.00
S^{TE}	50.00%	37.38%	25.00%	50.00%
TGC^0	1460.00	860.00	860.00	1060.00
TGC^1	1060.00	765.77	560.00	1060.00
S^{TGC}	27.40%	10.96%	34.88%	0.00%

Future Research Proposal

- I will extend upon the multiproduct dimension of supply chains with distinct firms and their horizontal integration to add multicriteria decision-making concerning the minimization of cost and the minimization of emissions.
- Supply chain integration though vertical integration versus separation and the resulting effects on anticipated operational synergy.
- Extend to incorporate associated environmental emissions and aid in the study of the relationship of cost synergistic effects to the environmental impact of the proposed merger/integration.

Future Research Proposal

- Include policy implications on resulting emissions in the study of supply chain integration.
- Apply a taxation and tradable permit scheme to include the empirical implementation for the electric power supply chain of New England (see Liu and Nagurney (2009)).

Thank you!