Sustainability: Methodology with Applications

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- Background and Motivation
- Supply Chains
- Characteristics of Networks and Supply Chains Today
- Why User Behavior Must be Captured in Network Design
- Methodologies for Formulation, Analysis, and Computations
- An Empirical Application to Electric Power Supply Chains
- The Sustainable Supply Chain Network Design Model
- Summary, Conclusions, and Suggestions for Future Research

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:

- 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.?

Pollution and Environmental Impacts

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)).

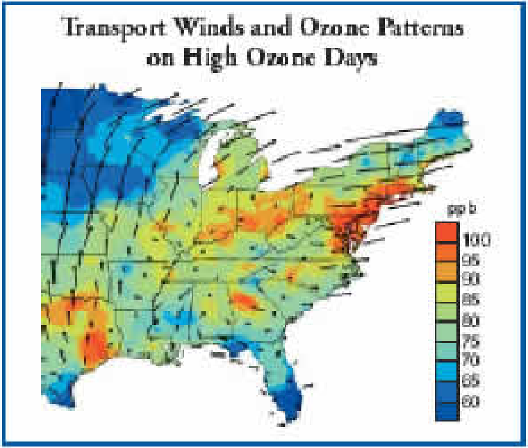
The average surface temperature of the earth, expressed as a global average, has increased by about 0.74C over the past hundred years (between 1906 and 2005) with 11 of the 12 warmest years occurring between 1995 and 2006 (IPCC (2007)).

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)).

Several environmental regulations have been geared towards, specifically, the electric power industry, which underpins modern society.

Spatial Nature of Pollutants



High ozone levels in the Northeast are typically associated with persistent transport from west to east. (Data represent high 90th percentile ozone conditions.)
Source: Ozone Transport Assessment Group

Some Data on Emissions Generated

Electricity generation is the dominant industrial source of air emissions in the US today. Fossil fuel-based power plants are responsible for 67% of the nations sulfur dioxide emissions, 23% of the nitrogen oxide emissions, and 40% of man-made carbon dioxide emissions (EPA).

Electricity worldwide is produced mainly by using coal, which is responsible for 40% of the carbon dioxide pollution (and, hence, global warming). Coal is expected to maintain about 36% share of the electricity generation market through 2020 (IPCC).

Motor vehicles contribute the majority of the carbon dioxide emitted and about 75% of the nitrogen oxides in major population centers such as London. Road traffic is the fastest growing source of pollution in Europe. Increasing vehicular usage in China and India is also contributing significantly to worldwide emissions.

Ironically, two of our critical infrastructure systems; in particular, transportation networks and electric power supply chains are also the dominant sources of emissions!

Sustainability and Supply Chains

The integration of an environmental perspective into a business context can be traced back to the 1990s, and is linked to the book Our Common Future (WCED (1987)), also referred to as the Brundtland Report (Linton, Klassen, and Jayaraman (2007)).

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)).

Environmental Performance

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.

Supply Chains

Supply Chains

Supply chains are the *critical infrastructure and backbones* for the production, distribution, and consumption of goods as well as services in our globalized *Network Economy*.

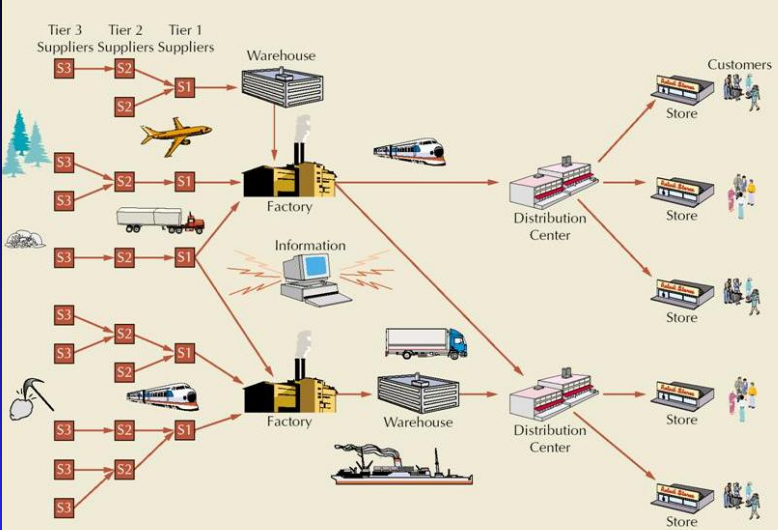
Supply chains, in their most fundamental realization, *consist of manufacturers and suppliers, distributors, retailers, and consumers at the demand markets*.

Today, supply chains may span thousands of miles across the globe, involve numerous suppliers, retailers, and consumers, and be underpinned by multimodal transportation and telecommunication networks.

Supply Chains

Supply chain networks provide the infrastructure for the production, storage, and distribution of products as varied as pharmaceuticals, vehicles, computers, food products, furniture, and clothing, throughout the globe.

A General Supply Chain



Some Compnents of Energy Supply Chains

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

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.*

Indeed, 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.

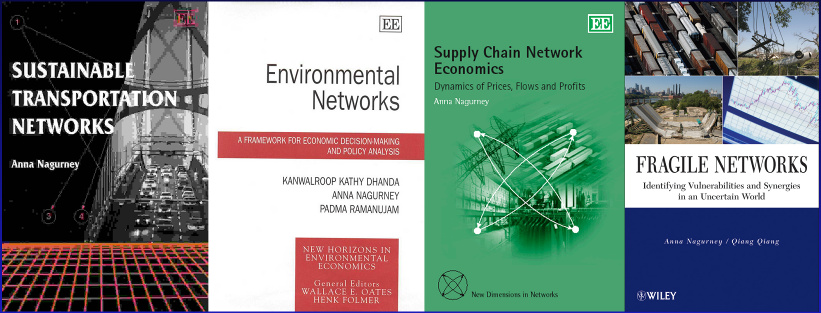
Characteristics of Networks and Supply Chains Today

- *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;
- *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 *socially, politically, and security-wise*.

Changes in the availability of supplies, price shocks, as well as disruptions to transportation modes or telecommunications may have negative effects and consequences that propagate throughout the supply chain.

On the other hand, *increases in demand for a product, entirely new demand markets, decreases in transaction costs, new suppliers, and even new modes of transaction, and new engineering technologies may provide new opportunities* for profit maximization for manufacturers, distributors, as well as retailers, and new linkages that were not previously possible.

Our Approach to Sustainability



Why User Behavior Must be Captured in Network Design

Supply Chain Network Design Must Capture the Behavior of Users

Behavior on Congested Networks

Decision-makers select their cost-minimizing routes.

				User-Optimized
Decentralized		Selfish		U–O
vs.	$\Leftrightarrow$	vs.	$\Leftrightarrow$	vs.
Centralized		Unselfish		S–O
				System-Optimized

Flows are routed so as to minimize the total cost to society.

Two fundamental principles of travel behavior, due to Wardrop (1952), with terms coined by Dafermos and Sparrow (1969).

User-optimized (U-O) (network equilibrium) Problem – each user determines his/her cost minimizing route of travel between an origin/destination, until an equilibrium is reached, in which no user can decrease his/her cost of travel by unilateral action (in the sense of Nash).

System-optimized (S-O) Problem – users are allocated among the routes so as to minimize the total cost in the system, where the total cost is equal to the sum over all the links of the link's user cost times its flow.

The U-O problems, under certain simplifying assumptions, possesses optimization reformulations. But now we can handle cost asymmetries, multiple modes of transport, and different classes of travelers, without such assumptions.

We Can State These Conditions Mathematically!

The U-O and S-O Conditions

Definition: U-O or Network Equilibrium – Fixed Demands

A path flow pattern x^*, with nonnegative path flows and O/D pair demand satisfaction, is said to be U-O or in equilibrium, if the following condition holds for each O/D pair $w \in W$ and each path $p \in P_w$:

$$C_p(x^*) \begin{cases} = \lambda_w, & \text{if} \quad x_p^* > 0, \\ \geq \lambda_w, & \text{if} \quad x_p^* = 0. \end{cases}$$

Definition: S-O Conditions

A path flow pattern x with nonnegative path flows and O/D pair demand satisfaction, is said to be S-O, if for each O/D pair $w \in W$ and each path $p \in P_w$:

$$\hat{C}'_p(x) \begin{cases} = \mu_w, & \text{if} \quad x_p > 0, \\ \geq \mu_w, & \text{if} \quad x_p = 0, \end{cases}$$

where $\hat{C}'_p(x) = \sum_{a \in \mathcal{L}} \frac{\partial \hat{c}_a(f_a)}{\partial f_a} \delta_{ap}$, and μ_w is a Lagrange multiplier.

The importance of behavior will now be illustrated through a famous example known as the Braess paradox which demonstrates what can happen under *U-O* as opposed to *S-O* behavior.

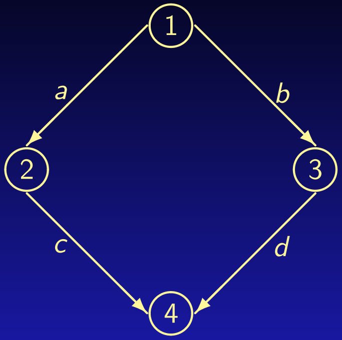
Although the paradox was presented in the context of transportation networks, it is relevant to other network systems in which decision-makers act in a noncooperative (competitive) manner.

The Braess (1968) Paradox

Assume a network with a single O/D pair (1,4). There are 2 paths available to travelers: $p_1 = (a, c)$ and $p_2 = (b, d)$.

For a travel demand of **6**, the equilibrium path flows are $x^*_{p_1} = x^*_{p_2} = 3$ and

The equilibrium path travel cost is $C_{p_1} = C_{p_2} = 83$.



$$c_a(f_a) = 10f_a, \quad c_b(f_b) = f_b + 50,$$

$$c_c(f_c) = f_c + 50, \quad c_d(f_d) = 10f_d.$$

Adding a Link Increases Travel Cost for All!

Adding a new link creates a new path $p_3 = (a, e, d)$.

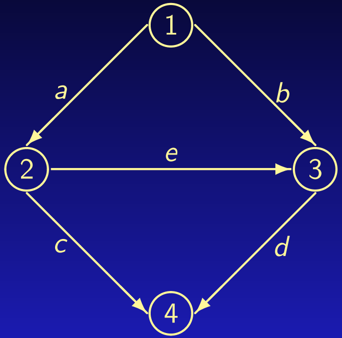
The original flow distribution pattern is no longer an equilibrium pattern, since at this level of flow the cost on path p_3, $C_{p_3} = 70$.

The new equilibrium flow pattern network is

$x^*_{p_1} = x^*_{p_2} = x^*_{p_3} = 2.$

The equilibrium path travel cost:

$C_{p_1} = C_{p_2} = C_{p_3} = 92.$



$c_e(f_e) = f_e + 10$

The 1968 Braess article has been translated from German to English and appears as:

"On a Paradox of Traffic Planning,"

D. Braess, A. Nagurney, and T. Wakolbinger (2005) Transportation Science **39**, 446-450.

Über ein Paradoxon aus der Verkehrsplanung

Von D. Braess, Münster [1])

Eingegangen am 28. März 1968

Zusammenfassung: Für die Straßenverkehrsplanung möchte man den Verkehrsfluß auf den einzelnen Straßen des Netzes abschätzen, wenn die Zahl der Fahrzeuge bekannt ist, die zwischen den einzelnen Punkten des Straßennetzes verkehren. Welche Wege am günstigsten sind, hängt nun nicht nur von der Beschaffenheit der Straße ab, sondern auch von der Verkehrsdichte. Es ergeben sich nicht immer optimale Fahrzeiten, wenn jeder Fahrer nur für sich den günstigsten Weg heraussucht. In einigen Fällen kann sich durch Erweiterung des Netzes der Verkehrsfluß sogar so umlagern, daß größere Fahrzeiten erforderlich werden.

Summary: For each point of a road network let be given the number of cars starting from it, and the destination of the cars. Under these conditions one wishes to estimate the distribution of the traffic flow. Whether a street is preferable to another one depends not only upon the quality of the road but also upon the density of the flow. If every driver takes that path which looks most favorable to him, the resultant running times need not be minimal. Furthermore it is indicated by an example that an extension of the road network may cause a redistribution of the traffic which results in longer individual running times.

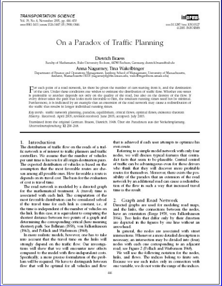
1. Einleitung

Für die Verkehrsplanung und Verkehrssteuerung interessiert, wie sich der Fahrzeugstrom auf die einzelnen Straßen des Verkehrsnetzes verteilt. Bekannt sei dabei die Anzahl der Fahrzeuge für alle Ausgangs- und Zielpunkte. Bei der Berechnung wird davon ausgegangen, daß von den möglichen Wegen jeweils der günstigste gewählt wird. Wie günstig ein Weg ist, richtet sich nach dem Aufwand, der zum Durchfahren nötig ist. Die Grundlage für die Bewertung des Aufwandes bildet die Fahrzeit.

Für die mathematische Behandlung wird das Straßennetz durch einen gerichteten Graphen beschrieben. Zur Charakterisierung der Bögen gehört die Angabe des Zeitaufwandes. Die Bestimmung der günstigen Stromverteilungen kann als gelöst betrachtet werden, wenn die Bewertung konstant ist, d. h., wenn die Fahrzeiten unabhängig von der Größe des Verkehrsflusses sind. Sie ist dann äquivalent mit der bekannten Aufgabe, den kürzesten Abstand zweier Punkte eines Graphen und den zugehörigen kritischen Pfad zu bestimmen [1], [5], [7].

Will man das Modell aber realistischer gestalten, ist zu berücksichtigen, daß die benötigte Zeit stark von der Stärke des Verkehrs abhängt. Wie die folgenden Untersuchungen zeigen, ergeben sich dann gegenüber dem Modell mit konstanter (belastungsunabhängiger) Bewertung z. T. völlig neue Aspekte. Dabei erweist sich schon eine Präzisierung der Problemstellung als notwendig; denn es ist zwischen dem Strom zu unterscheiden, der für alle am günstigsten ist,, und dem, der sich einstellt, wenn jeder Fahrer nur seinen eigenen Weg optimalisiert.

[1]) Priv.-Doz. Dr. Dietrich Braess, Institut für numerische und instrumentelle Mathematik, 44 Münster, Hüfferstr. 3 a.



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On a Paradox of Traffic Planning

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For each point of a road network, let there be given the number of cars starting from it, and the destination of the cars. Under these conditions one wishes to estimate the distribution of traffic flow. Whether one street is preferable to another depends not only on the quality of the road, but also on the density of the flow. If every driver takes the path that looks most favorable to him, the resultant running times need not be minimal. Furthermore, it is indicated by an example that an extension of the road network may cause a redistribution of the traffic that results in longer individual running times.

Key words: traffic network planning; paradox; equilibrium; critical flows; optimal flows; existence theorem
History: Received: April 2005; revision received: June 2005; accepted: July 2005.

Translated from the original German: Braess, Dietrich. 1968. Über ein Paradoxon aus der Verkehrsplanung. *Unternehmensforschung* **12** 258–268.

1. Introduction

The distribution of traffic flow on the roads of a traffic network is of interest to traffic planners and traffic controllers. We assume that the number of vehicles per unit time is known for all origin-destination pairs. The expected distribution of vehicles is based on the assumption that the most favorable routes are chosen among all possible ones. How favorable a route is ...

... that is achieved if each user attempts to optimize his own route.

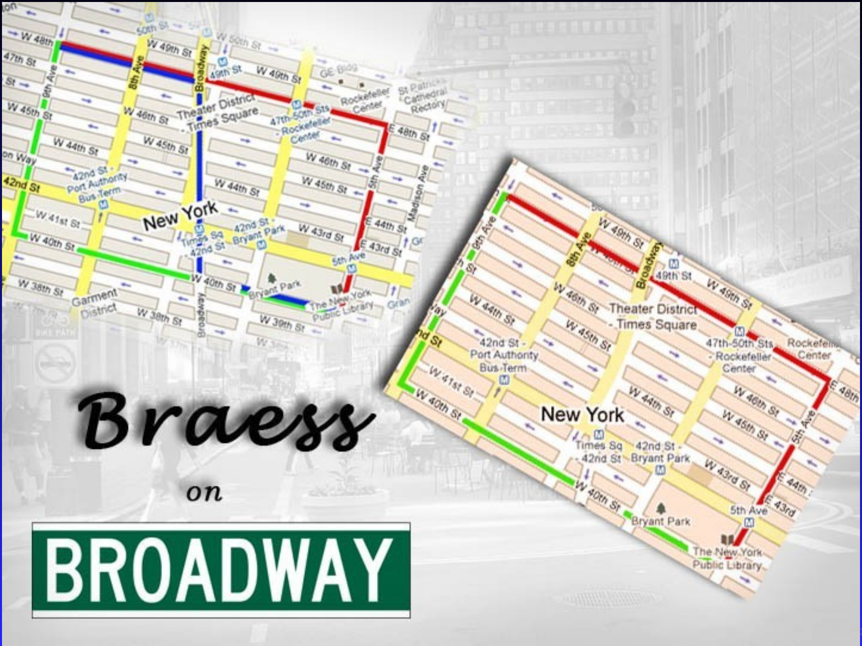
Referring to a simple model network with only four nodes, we will discuss typical features that contradict facts that seem to be plausible. Central control of traffic can be advantageous even for those drivers who think that they will discover more profitable routes for themselves. Moreover, there exists the possibility ...

The Braess Paradox Around the World

1969 - Stuttgart, Germany - The traffic worsened until a newly built road was closed.

1990 - Earth Day - New York City - 42^{nd} Street was closed and traffic flow improved.

2002 - Seoul, Korea - A 6 lane road built over the Cheonggyecheon River that carried 160,000 cars per day and was perpetually jammed was torn down to improve traffic flow.


Braess
on
BROADWAY
New York
Theater District - Times Square
W 49th St
W 46th St
W 45th St
W 44th St
W 43rd St
W 41st St
W 40th St
42nd St - Port Authority Bus Term
47th-50th Sts - Rockefeller Center
Rockefeller Center
Times Sq - 42nd St
42nd St - Bryant Park
Bryant Park
The New York Public Library
5th Ave
8th Ave
Broadway
49th St

Interview on Broadway for *America Revealed* on March 15, 2011

Under S-O behavior, the total cost in the network is minimized, and the new route p_3, under the same demand, would not be used.

The Braess paradox never occurs in S-O networks.

Methodologies for Formulation, Analysis, and Computations

Methodologies Utilized for Our Research in Sustainability

In our research on sustainability we have applied the following methodologies:

- optimization theory,
- network theory,
- game theory,
- risk management, and
- multicriteria decision-making,

with the unifying formalism being the *theory of variational inequalities*.

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:*

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

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*.*

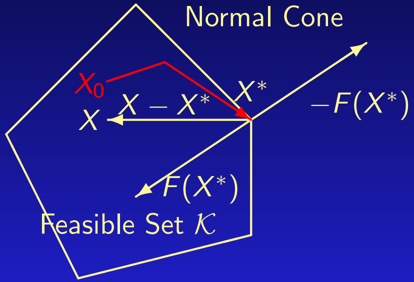
The variational inequality problem contains, as special cases, such mathematical programming problems as:

- systems of equations,
- optimization problems,
- complementarity problems,
- 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 a natural underlying dynamics associated with travel (and other) behavior to the equilibrium.

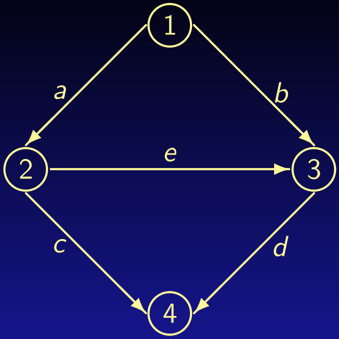
To model the *dynamic behavior of complex networks*, including supply chains, we utilize *projected dynamical systems* (PDSs) advanced by Dupuis and Nagurney (1993) in *Annals of Operations Research* and by Nagurney and Zhang (1996) in their book *Projected Dynamical Systems and Variational Inequalities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

• numerous *energy policy modeling frameworks* (see the work of Matsypura, Nagurney, and Woolley).



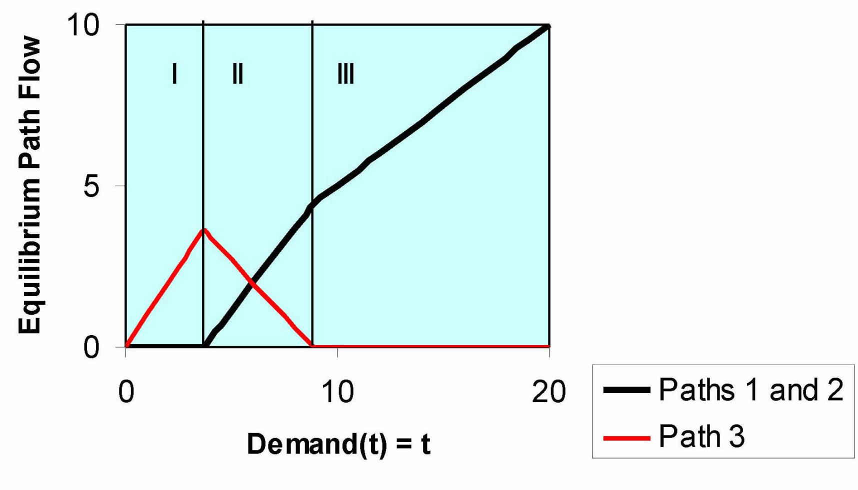
Recall the Braess network with the added link e.

What happens as the demand increases?

For Networks with Time-Dependent Demands

We Use Evolutionary Variational Inequalities

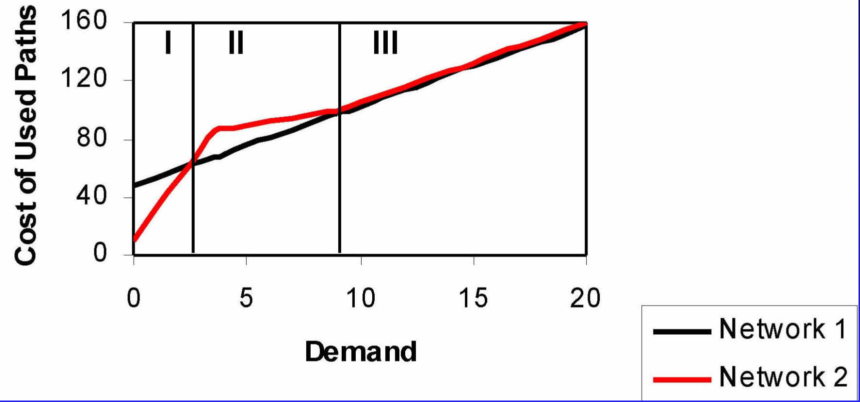
The U-O Solution of the Braess Network with Added Link (Path) and Time-Varying Demands Solved as an *Evolutionary Variational Inequality* (Nagurney, Daniele, and Parkes (2007)).



In Demand Regime I, Only the New Path is Used.

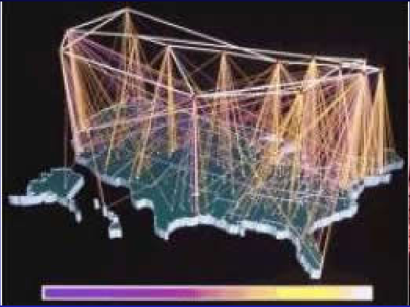
In Demand Regime II, the travel demand lies in the range [2.58, 8.89], and *the Addition of a New Link (Path) Makes Everyone Worse Off*!

In Demand Regime III, when the travel demand exceeds 8.89, *Only the Original Paths are Used!*



The new path is never used, under U-O behavior, when the demand exceeds 8.89, even out to infinity!

Other Networks that Behave like Traffic Networks



The Internet and electric power networks

Electric Power Supply Chains

The U.S. electric power industry: Half a trillion dollars of net assets, $220 billion annual sales, 40% of domestic primary energy (Energy Information Administration (2000, 2005)).

Deregulation:
• Wholesale market • Bilateral contracts • Power pool.

Electric power supply chain networks:
• Generation technologies • Insensitive demands • Transmission congestion.

In 2007, the total transmission congestion cost in New England was about $130 million (ISO New England Annual Market Report, 2007).

Electric Power Supply Chains

We have 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* (2009), **56**, 600-624.

Features of the Model

The model captures both economic transactions and physical transmission constraints.

The model considers the behaviors of all major decision-makers including gencos, consumers and the independent system operator (ISO).

The model considers multiple fuel markets, electricity wholesale markets, and operating reserve markets.

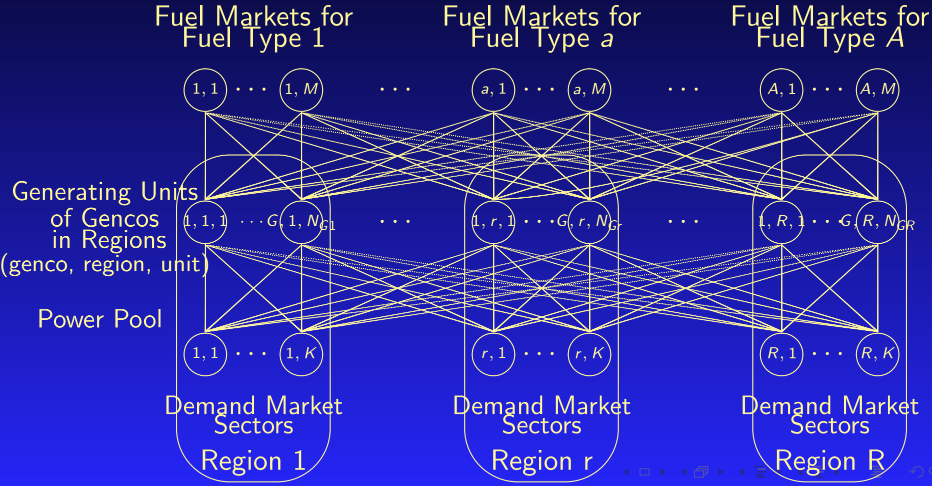
An Empirical Example of an Electric Power Supply Chain for New England

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

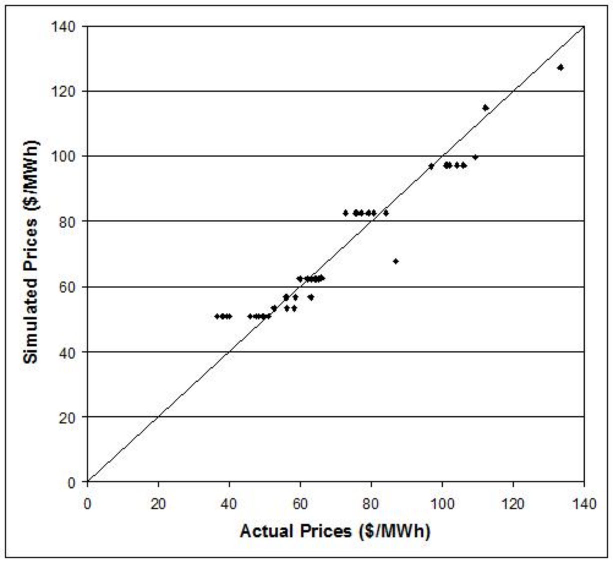
The Electric Power Supply Chain Network with Fuel Supply Markets



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)



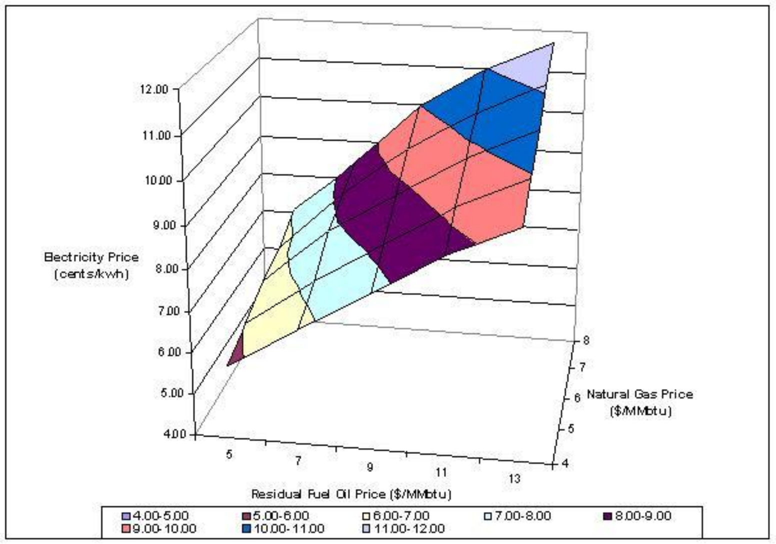
Sensitivity Analysis

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



If the price of one type of fuel is fixed, the electricity price changes less percentage-wise than the other fuel price does.

This is mainly because fuel diversity can mitigate fuel price shocks.

Additional simulation results can be found in our *Naval Research Logistics* paper, including:

• How natural gas prices can be significantly influenced by oil prices through electric power networks and markets.

• How changes in the demand for electricity influence the electric power and fuel markets.

The model and results are useful in determining and quantifying the interactions between electric power flows and prices and the various fuel supply markets.

Such information is important to policy-makers who need to ensure system reliability as well as for the energy asset owners and investors who need to manage risk and to evaluate their assets.

Supply chain network design (and redesign) can be accomplished *through link and node additions (as well as their removals)*.

It can be accomplished *by modifying the link capacities (expanding certain ones and, if applicable, reducing or selling off others)*.

It can also be accomplished *through the integration of networks as in mergers and acquisitions*.

It can be accomplished through the design of the network *from scratch as we shall demonstrate*.

Sustainable Systems

Sustainable Systems

The **design of supply chain networks** is a topic of engineering importance since it involves the determination of both the sites and the levels of operation of its relevant facilities.

Sustainability of supply chains has emerged as a major theme in both research and practice since the impacts of climate change have made both producers and consumers more cognizant of their decision-making and how their decisions affect the environment.

Photos of oil spill crisis in Gulf of Mexico, May 2010

Environmental Effects of Globalization

Businesses, and in particular supply chains, have become increasingly *globalized*.

However, criticism of globalization has increased, specifically by those concerned about the environment on the basis that global free trade may result in the growth of global pollution.

For example, free trade may shift pollution-intensive manufacturing processes from countries with strict environmental regulations to those with less restrictive ones.

An Overview of Some of the Relevant Literature

- M. J. Beckmann, C. B. McGuire, and C. B. Winsten (1956) *Studies in the Economics of Transportation*. Yale University Press, New Haven, Connecticut.

- S. C. Dafermos and F. T. Sparrow (1969) The Traffic Assignment Problem for a General Network. *Journal of Research of the National Bureau of Standards*. 73B: 91-118.

- D. E. Boyce, H. S. Mahmassani, A. Nagurney (2005) A Retrospective on Beckmann, McGuire, and Winsten's *Studies in the Economics of Transportation*. *Papers in Regional Science* 84: 85-103.

- A. Nagurney, and F. Toyasaki (2005) Reverse Supply Chain Management and Electronic Waste Recycling: A Multitiered Network Equilibrium Framework for E-Cycling. *Transportation Research E* 41: 1-28.

- A. Nagurney, Z. Liu, and T. Woolley (2007) Sustainable Supply Chain Networks and Transportation. *International Journal of Sustainable Transportation* 1: 29-51.
- A. Nagurney, Q. Qiang, and L. S. Nagurney (2010) Environmental Impact Assessment of Transportation Networks with Degradable Links in an Era of Climate Change. *International Journal of Sustainable Transportation* 4: 154-171.
- A. Nagurney and T. Woolley (2010) Environmental and Cost Synergy in Supply Chain Network Integration in Mergers and Acquisitions. Sustainable Energy and Transportation Systems. In: *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, pp. 51-78.

The rest of this presentation is based on the paper:

Sustainable Supply Chain Network Design: A Multicriteria Perspective,

A. Nagurney and L. S. Nagurney (2010), *International Journal of Sustainable Engineering* 3: 189-197.

where additional background as well as references can be found.

The Sustainable Supply Chain Network Design Model

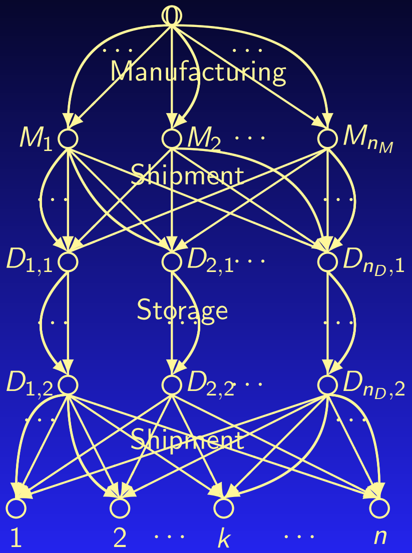
The Sustainable Supply Chain Network Design Model

We assume a *network topology* where the top level (origin) node 0 corresponds to the firm and the bottom level (destination) nodes correspond to the demand sites, which can correspond, for example, to retailers or consumers.

The *paths* joining the origin node to the destination nodes represent sequences of supply chain network activities that ensure that the product is produced and, ultimately, delivered to the demand sites.

Assume we have n_M manufacturing facilities/plants, n_D distribution centers to serve the n demand locations with the respective demands given by: $d_1, d_2, \ldots, d_n$.

Baseline Supply Chain Network Topology



The Sustainable Supply Chain Network Design Model

The links from the top-tiered node 0 are connected to the possible manufacturing nodes of the firm, which are denoted, respectively, by: $M_1, \ldots, M_{n_M}$, and these links represent the *manufacturing* links.

The links from the manufacturing nodes, in turn, are connected to the possible distribution center nodes of the firm which are denoted by $D_{1,1}, \ldots, D_{n_D,1}$. These links correspond to the possible *shipment* links.

The links joining nodes $D_{1,1}, \ldots, D_{n_D,1}$ with nodes $D_{1,2}, \ldots, D_{n_D,2}$ correspond to the possible *storage* links. Finally, there are possible *shipment* links joining the nodes $D_{1,2}, \ldots, D_{n_D,2}$ with the demand nodes: $1, \ldots, n$.

The Sustainable Supply Chain Network Design Model

Multiple alternative manufacturing links correspond to different possible technologies associated with a given manufacturing plant, which may also result in different levels of environmental emissions.

Similarly, for shipments and storage, we may have multiple alternative links which represent different modes of transportation and different storage technologies, respectively.

The Sustainable Supply Chain Network Design Model

Supply chain network consists of the graph $G = [N, L]$, where N denotes the set of nodes and L the set of directed links.

The formalism is that of *optimization*, where the firm wishes to determine which manufacturing plants it should operate (and the corresponding technologies) and at what level; the same for the distribution centers. In addition, the firm seeks to determine the capacity levels of the shipment links and the mode of transportation/shipment used.

The firm seeks to *minimize the total costs* associated with its production, storage, distribution activities, along with the total capital outlays, plus *the total cost of environmental emissions* in order to achieve the activity levels as given by the capacities on its various links, subject to the demand being satisfied at the demand sites.

Notation

- $\hat{c}_a$: the total cost on link a.
- f_a: the flow of the product on link a.
- p: a path in the network joining the origin node to a destination node representing the activities and their sequence associated with producing the product and having it, ultimately, delivered.
- w_k: the pair of origin/destination (O/D) nodes $(0, k)$.
- P_{w_k}: the set of paths, which represent alternative associated possible supply chain network processes, joining $(0, k)$.
- P: the set of all paths joining node 0 to the demand nodes.
- n_P: the number of paths from the origin to the demand markets.
- x_p: the nonnegative flow of the product on path p.
- d_k: the demand, which is assumed to be known and fixed, for the product at demand location k.

Demand satisfaction constraint

$$d_k \equiv \sum_{p \in P_{w_k}} x_p, \quad k = 1, \ldots, n, \tag{1}$$

that is, the demand must be satisfied at each demand site.

Conservation of flow between path flows and link flows

$$f_a = \sum_{p \in P} x_p \delta_{ap}, \quad \forall a \in L, \tag{2}$$

where $\delta_{ap} = 1$, if link a is contained in path p, and $\delta_{ap} = 0$, otherwise.

Path flows nonnegativity constraint

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

Formulation

Total cost functions on links

$$\hat{c}_a = \hat{c}_a(f_a), \quad \forall a \in L. \tag{4}$$

The total cost on a link is assumed to be a function of the flow of the product on the link, which is assumed to be convex and is continuously differentiable.

Total capital cost

$\hat{\pi}_a$: total capital cost of adding capacity u_a on link a:

$$\hat{\pi}_a = \hat{\pi}_a(u_a), \quad \forall a \in L. \tag{5}$$

These functions are also assumed to be convex and continuously differentiable and to have bounded second order partial derivatives.

First Objective Function

The firms seeks to minimize the total cost including the total cost of operating the various links and the total cost of capacity capital investments:

Total cost minimization objective function

$$\text{Minimize} \quad \sum_{a \in L} \hat{c}_a(f_a) + \hat{\pi}_a(u_a). \tag{6}$$

Second Objective Function

- $e_a(f_a)$: emission-generation function associated with link a in the operation phase, which is assumed to be a function of the amount of product flow on the link.
- $\hat{e}_a(u_a)$: emission-generation function associated with link a in the capital investment phase.

These functions are also assumed to be convex and continuously differentiable and to have bounded second order partial derivatives.

Minimization of emissions objective function

$$\text{Minimize} \quad \sum_{a \in L} e_a(f_a) + \hat{e}_a(u_a). \tag{7}$$

The Multicriteria Optimization Formulation

ω: constant nonnegative weight assigned by the firm to the emission-generation criterion (7), or equivalently, a price per unit of emissions that the firm is willing to pay. It can also be interpreted as a tax imposed by the governmental authority.

Multicriteria optimization formulation

$$\text{Minimize} \quad \sum_{a\in L} \hat{c}_a(f_a) + \hat{\pi}_a(u_a) + \omega \left(\sum_{a\in L} e_a(f_a) + \hat{e}_a(u_a) \right). \quad (8)$$

Subject to the constraints: (1), (2), (3), and

$$f_a \leq u_a, \quad \forall a \in L, \quad (9)$$

$$0 \leq u_a, \quad \forall a \in L. \quad (10)$$

Variational Inequality Formulation

Our optimization problem is characterized, under our assumptions, by a convex objective function and a convex feasible set.

β_a: the Lagrange multiplier associated with constraint (9) for each link $a \in L$.

β_a^*: the associated optimal Lagrange multiplier.

These terms may also be interpreted as the price or value of an additional unit of capacity on link a. We group these Lagrange multipliers into the respective vectors β and β^*.

Variational Inequality Formulation

Theorem 1

The optimization problem (8), subject to the constraints (1) – (3) and (9), (10), is equivalent to the variational inequality problem: determine the vectors of link flows, link capacities, and Lagrange multipliers $(f^*, u^*, \beta^*) \in K$, such that:

$$\sum_{a \in L} \left[\frac{\partial \hat{c}_a(f_a^*)}{\partial f_a} + \omega \frac{\partial e_a(f_a^*)}{\partial f_a} + \beta_a^* \right] \times [f_a - f_a^*]$$

$$+ \sum_{a \in L} \left[\frac{\partial \hat{\pi}_a(u_a^*)}{\partial u_a} + \omega \frac{\partial \hat{e}_a(u_a^*)}{\partial u_a} - \beta_a^* \right] \times [u_a - u_a^*]$$

$$+ \sum_{a \in L} [u_a^* - f_a^*] \times [\beta_a - \beta_a^*] \geq 0, \quad \forall (f, u, \beta) \in K, \tag{11}$$

$K \equiv \{(f, u, \beta) | \exists x \geq 0, \text{ and } (1), (2), (3) \text{ and } (10) \text{ hold, and } \beta \geq 0\}$, where f is the vector of link flows, u is the vector of link capacities, and x is the vector of path flows.

Standard form of Variational Inequality Formulation (11)

Determine $X^* \in \mathcal{K}$ such that:

$$\langle F(X^*)^T, X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{K}, \tag{12}$$

where $\langle \cdot, \cdot \rangle$ denotes the inner product in $\mathcal{N}$-dimensional Euclidean space.

If we define the column vectors: $X \equiv (f, u, \beta)$ and $F(X) \equiv (F_1(X), F_2(X), F_3(X))$, such that

$$F_1(X) \equiv \left[\frac{\partial \hat{c}_a(f_a)}{\partial f_a} + \omega \frac{\partial e_a(f_a)}{\partial f_a} + \beta_a; \quad a \in L \right], \tag{13}$$

$$F_2(X) \equiv \left[\frac{\partial \hat{\pi}_a(u_a)}{\partial u_a} + \omega \frac{\partial \hat{e}_a(u_a)}{\partial u_a} - \beta_a; a \in L \right], \tag{14}$$

$$F_3(X) \equiv \left[u_a - f_a; \quad a \in L \right], \tag{15}$$

Solution Method

Variational inequality (11) can be easily solved using the modified projection method.

To solve our numerical examples, we utilize the well-known equilibration algorithm (system-optimization version) of Dafermos and Sparrow (1969), which has been widely applied. Recall that the modified projection method (cf. Korpelevich (1977)) is guaranteed to converge to a solution of a variational inequality problem, provided that the function that enters the variational inequality problem is monotone and Lipschitz continuous and that a solution exists.

The solution (f^*, u^*) to (11) minimizes the objective function (8) associated with the design of the sustainable supply chain network.

Monotonicity and Lipschitz Continuity

Theorem 2

The function $F(X)$ as aforementioned is monotone, that is,

$$\langle (F(X^1) - F(X^2))^T, X^1 - X^2 \rangle \geq 0, \quad \forall X^1, X^2 \in \mathcal{K}. \tag{16}$$

Theorem 3

The function $F(X)$ as defined is Lipschitz continuous, that is,

$$\|F(X^1) - F(X^2)\| \leq \|X^1 - X^2\|, \quad \forall X^1, X^2 \in \mathcal{K}. \tag{17}$$

Convergence

Theorem 4

Assume that the function that enters the variational inequality (11) (or its standard form equivalent (12)) has at least one solution and satisfies the conditions in Theorem 2 and in Theorem 3. Then the modified projection method converges to the solution of the variational inequality (11) (or (12)).

For proofs of Theorems 2, 3 and 4, see the paper.

Numerical Examples

The baseline supply chain network topology for all the examples is as depicted next with the links defined by numbers.

The numerical examples, hence, consisted of a firm faced with 3 possible manufacturing plants, each of which had 2 possible technologies, 2 distribution centers, each of which also had 2 distinct technologies, and the firm had to supply the 3 demand points. There was only a single mode of transportation/shipment available between each manufacturing plant and each distribution center and between each distribution center at a given demand point.

The common input data for the three examples is reported in Table 1.

Baseline Supply Chain Network Topology for the Examples

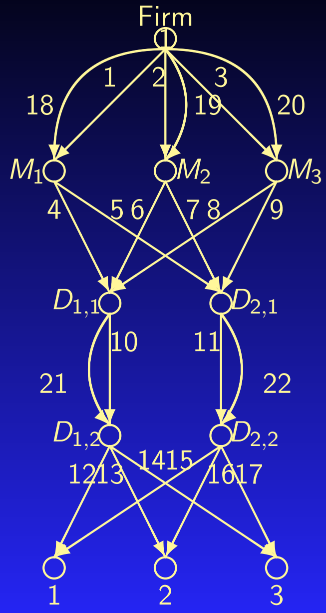


Table 1: Total Cost and Emission Functions for the Numerical Examples

Link a	$\hat{c}_a(f_a)$	$\hat{\pi}_a(u_a)$	$e_a(f_a)$	$\hat{e}_a(u_a)$
1	$f_1^2 + 2f_1$	$.5u_1^2 + u_1$	$.05f_1^2 + f_1$	$1.5u_1^2 + 2u_1$
2	$.5f_2^2 + f_2$	$2.5u_2^2 + u_2$	$.1f_2^2 + f_2$	$2u_2^2 + 2u_2$
3	$.5f_3^2 + f_3$	$u_3^2 + 2u_3$	$.15f_3^2 + 2f_3$	$2.5u_3^2 + u_3$
4	$1.5f_4^2 + 2f_4$	$u_4^2 + u_4$	$.05f_4^2 + .1f_4$	$.1u_4^2 + .2u_4$
5	$f_5^2 + 3f_5$	$2.5u_5^2 + 2u_5$	$.05f_5^2 + .1f_5$	$.05u_5^2 + .1u_5$
6	$f_6^2 + 2f_6$	$.5u_6^2 + u_6$	$.1f_6^2 + .1f_6$	$.05u_6^2 + .1u_6$
7	$.5f_7^2 + 2f_7$	$.5u_7^2 + u_7$	$.05f_7^2 + .2f_7$	$.1u_7^2 + .2u_7$
8	$.5f_8^2 + 2f_8$	$1.5u_8^2 + u_8$	$.05f_8^2 + .1f_8$	$.1u_8^2 + .3u_8$
9	$f_9^2 + 5f_9$	$2u_9^2 + 3u_9$	$.05f_9^2 + .1f_9$	$.1u_9^2 + .2u_9$
10	$.5f_{10}^2 + 2f_{10}$	$u_{10}^2 + 5u_{10}$	$.2f_{10}^2 + f_{10}$	$1.5u_{10}^2 + 3u_{10}$
11	$f_{11}^2 + f_{11}$	$.5u_{11}^2 + 3u_{11}$	$.25f_{11}^2 + 3f_{11}$	$2u_{11}^2 + 3u_{11}$

Table 1 (continued)

Link a	$\hat{c}_a(f_a)$	$\hat{\pi}_a(u_a)$	$e_a(f_a)$	$\hat{e}_a(u_a)$
12	$.5f_{12}^2 + 2f_{12}$	$.5u_{12}^2 + u_{12}$	$.05f_{12}^2 + .1f_{12}$	$.1u_{12}^2 + .2u_{12}$
13	$.5f_{13}^2 + 5f_{13}$	$.5u_{13}^2 + u_{13}$	$.1f_{13}^2 + .1f_{13}$	$.05u_{13}^2 + .1u_{13}$
14	$f_{14}^2 + 7f_{14}$	$2u_{14}^2 + 5u_{14}$	$.15f_{14}^2 + .2f_{14}$	$.1u_{14}^2 + .1u_{14}$
15	$f_{15}^2 + 2f_{15}$	$.5u_{15}^2 + u_{15}$	$.05f_{15}^2 + .3f_{15}$	$.1u_{15}^2 + .2u_{15}$
16	$.5f_{16}^2 + 3f_{16}$	$u_{16}^2 + u_{16}$	$.05f_{16}^2 + .1f_{16}$	$.1u_{16}^2 + .1u_{16}$
17	$.5f_{17}^2 + 2f_{17}$	$.5u_{17}^2 + u_{17}$	$.15f_{17}^2 + .3f_{17}$	$.05u_{17}^2 + .1u_{17}$
18	$.5f_{18}^2 + f_{18}$	$u_{18}^2 + 2u_{18}$	$.2f_{18}^2 + 2f_{18}$	$2u_{18}^2 + 3u_{18}$
19	$.5f_{19}^2 + 2f_{19}$	$u_{19}^2 + u_{19}$	$.25f_{19}^2 + 3f_{19}$	$3u_{19}^2 + 4u_{19}$
20	$1.5f_{20}^2 + f_{20}$	$u_{20}^2 + u_{20}$	$.3f_{20}^2 + 3f_{20}$	$2.5u_{20}^2 + 5u_{20}$
21	$.5f_{21}^2 + 2f_{21}$	$u_{21}^2 + 3u_{21}$	$.1f_{21}^2 + 3f_{21}$	$1.5u_{21}^2 + 4u_{21}$
22	$f_{22}^2 + 3f_{22}$	$.5u_{22}^2 + 2u_{22}$	$.2f_{22}^2 + 4f_{22}$	$2.5u_{22}^2 + 4u_{22}$

Solution Method for Numerical Examples

The modified projected method was implemented in FORTRAN, and a Unix system at the University of Massachusetts Amherst was used for all the computations.

We initialized the algorithm by equally distributing the demand at each demand site among all the paths joining the firm node 0 to the demand node. All other variables, that is, the link capacities and the Lagrange multipliers, were initialized to zero.

Example 1

Demands at destination points:

$$d_1 = 45, \quad d_2 = 35, \quad d_3 = 5.$$

In this example, we assumed that the firm did not care about the emissions generated in its supply chain design, thus, $\omega = 0$. The computed solution is reported in Table 2.
The total cost was: 10,716.33.
The total emissions generated were: 8,630.45.
The value of the objective function (8) was 10,716.33.

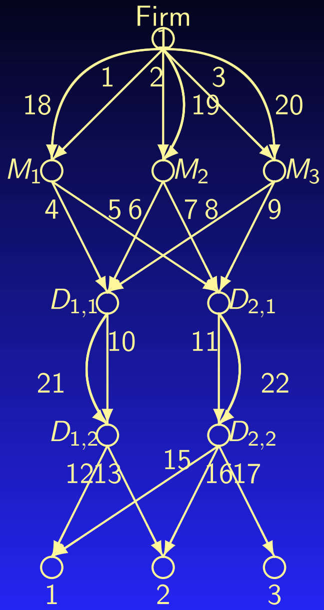
Note that link 14 has zero capacity and, thus, zero flow. Therefore, the final optimal sustainable supply chain network topology for this problem is the baseline network but with link 14 removed.

Table 2: Example 1 Solution

Link a	f_a^*	u_a^*	β_a^*
1	12.43	12.43	13.43
2	11.67	11.67	59.33
3	15.81	15.81	33.62
4	14.69	14.69	30.39
5	10.16	10.16	52.82
6	13.94	13.94	14.94
7	20.70	20.70	12.70
8	15.83	15.83	48.50
9	9.66	9.66	41.66
10	21.90	21.90	48.80
11	20.43	20.43	23.43

Link a	f_a^*	u_a^*	β_a^*
12	25.44	25.44	26.44
13	19.03	19.03	20.03
14	0.00	0.00	3.85
15	19.56	19.56	20.56
16	15.97	15.97	32.93
17	5.00	5.00	6.00
18	12.43	12.43	26.86
19	22.98	22.98	46.95
20	9.69	9.69	20.37
21	22.57	22.57	48.14
22	20.10	20.10	22.10

Optimal Supply Chain Network Topology for Example 1



Example 2

Identical data as in Example 1 except that the firm now was more concerned about the environment with $\omega = 5$. The new computed solution is given in Table 3.

The total cost was now: 11,285.04.
The total emissions generated were now: 7,759.35.
The value of the objective function (8) was 50,081.77.
Decreased number of emissions due to the higher weight on the total emissions generated; in contrast, higher total cost. Note that now all the links have positive capacity and positive flows.

Observe that whereas links 1 and 18 had the same product flows in Example 1, in Example 2, the production shifted from link 18 to link 1 at about a 50% increase, since link 1 corresponded to more environmentally-friendly technology. Similar behavior occurred with links 2 and 19.

Table 3: Example 2 Solution

Link a	f_a^*	u_a^*	β_a^*
1	19.32	19.32	320.17
2	15.69	15.69	403.10
3	13.45	13.45	370.17
4	19.43	19.43	60.29
5	13.80	13.80	78.38
6	13.75	13.75	22.12
7	13.28	13.28	28.55
8	15.73	15.73	65.43
9	9.02	9.02	49.09
10	24.03	24.03	428.53
11	19.71	19.71	431.81

Link a	f_a^*	u_a^*	β_a^*
12	26.62	26.62	55.23
13	20.62	20.62	32.43
14	1.67	1.67	13.87
15	18.38	18.38	38.77
16	14.38	14.38	44.65
17	3.33	3.33	6.49
18	13.90	13.90	322.79
19	11.34	11.34	383.79
20	11.30	11.30	331.01
21	24.88	24.88	445.88
22	16.38	16.38	447.95

Example 3

The same data as Examples 1 and 2 but now the firm was even more concerned about the environment with $\omega = 10$. The new solution is given in Table 4.

The total cost was: 11,414.07.
The total emissions generated were now: 7,739.32.
The value of the objective function (8) was 88,807.30.

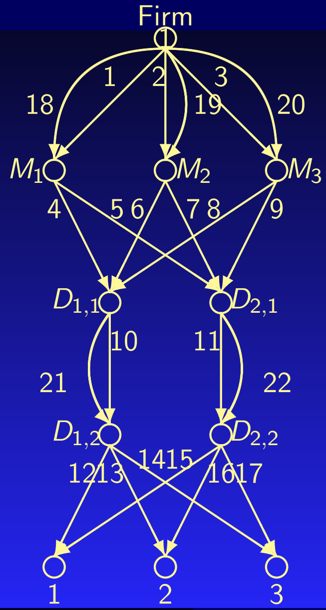
As in Example 2, all links have positive capacity and positive product flow at the optimal solution.

Table 4: Example 3 Solution

Link a	f_a^*	u_a^*	β_a^*
1	20.16	20.16	645.86
2	15.80	15.80	731.98
3	13.10	13.10	693.10
4	19.66	19.66	81.62
5	14.66	14.66	90.97
6	14.37	14.37	30.74
7	11.99	11.99	38.96
8	15.45	15.45	81.25
9	8.88	8.88	58.25
10	24.30	24.30	812.50
11	19.49	19.49	831.78

Link a	f_a^*	u_a^*	β_a^*
12	26.44	26.44	82.33
13	20.63	20.63	43.25
14	2.40	2.40	20.43
15	18.56	18.56	58.67
16	14.37	14.37	59.50
17	2.60	2.60	7.19
18	14.16	14.16	626.55
19	10.55	10.55	695.13
20	11.22	11.22	634.49
21	25.17	25.17	848.48
22	16.04	16.04	859.93

Optimal Supply Chain Network Topology for Examples 2 and 3



Summary, Conclusions, and Suggestions for Future Research

Summary, Conclusions, and Suggestions for Future Research

- We provided an overview of the fundamental methodologies that we utilize in our sustainability research and focused on applications to energy and supply chains.
- We described a sustainable supply chain network design model that allows for the evaluation of environmental multicriteria decision-making. Using the presented formalism, a firm may engineer its supply chain to be not only fiscally cost-effective, but also environmentally-responsible.
- The model utilizes cost minimization within a system-optimization perspective while taking into account the capital investment costs, the operational costs, as well as the total emissions generated.
- The supply chain network design model allows us to determine the optimal capacity for every single activity of the supply chain network.

Summary, Conclusions, and Suggestions for Future Research

- This presentation aimed to provide an overview of some of the highlights of our sustainability research and is by, no means, comprehensive.
- Our recent research has focused on the incorporation of risk and uncertainty and the synthesis of stochastic programming and variational inequality theory.
- Applications of sustainability we have been addressing also in a spectrum of time-sensitive supply chains ranging from humanitarian operations and healthcare to even fast fashion!

Thank You!

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