Operations Management and Supply Chain Network Theory

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Course Outline of Topics

- Introduction to Operations Management
- Overview of Networks of Relevance to Supply Chains
- Supply Chain Network Theory and Applications
- Other Issues That Have Been Explored Using Supply Chain Network Theory

Introduction to Operations Management

Introduction to Operations Management

In this course segment we will cover the following:

- What is Operations Management?
- A Brief History of Operations Management
  - Goods versus Services
- What Do Operations Managers Do?
- Issues Facing Operations Managers.

What is Operations Management?

Operations

Operations consist of the jobs or tasks composed of one or more elements or subtasks, performed typically in one location.

Operations **transform** *resource or data inputs into desired goods, services, or results, and create and deliver value to the customers.*

Two or more connected operations constitute a **process**.

Operations **are essential to any organization** and, hence, so is operations management.

What is Operations Management?

Operations management is the design, improvement, and the management of the transformation processes that create value by converting inputs, such as raw materials, labor, and/or customers into outputs, such as goods or services.

Operations managers solicit feedback at each stage of the transformation processes.

What is Operations Management?

Operations management is concerned about Systems and how to make them operate Better, whether more efficiently, more effectively, at a higher level of quality, at reduced cost, and/or at lower environmental emissions, using the appropriate criterion or criteria determined by the organization.

Operations Management (OM) is one of the major functions of *any* **organization (Finance, Marketing, Operations Management).**

Examples of Some Systems and the Transformation Processes

System	Inputs	Components	Primary Transformation Function(s)	Typical Desired Output
Hospital	Patients, medical supplies	MDs, nurses, equipment	Health care (physiological)	Healthy individuals
Restaurant	Hungry customers, food	Chef, waitstaff, environment	Well-prepared food, well served; agreeable environment (physical and exchange)	Satisfied customers
Automobile factory	Sheet steel, engine parts	Tools, equipment, workers	Fabrication and assembly of cars (physical)	High-quality cars
College or university	High school graduates, books	Teachers, classrooms	Developing knowledge and skills (informational)	Educated individuals
Department store	Shoppers, stock of goods	Displays, salesclerks	Attract shoppers, promote products, fill orders (exchange)	Sales to satisfied customers
Distribution center	Stockkeeping units (SKUs)	Storage bins, stockpickers	Storage and redistribution	Fast delivery, availability of SKUs

Properties of Transformation Processes

The transformation processes may be:

- **Physical:** as in the manufacturing operations;
- **Locational:** as in transportation and distribution operations;
- **Exchange:** as in retail operations;
- **Physical:** as in healthcare operations;
- **Informational**: as in communications and education;
- **Psychological**: as in entertainment.

A Brief History of Operations Management

A Brief History of Operations Management

Pre-18th century — Agriculture was the predominant industry.

Industrial Revolution (1770-1830) — Economy based on manual labor was replaced by one dominated by industry and the manufacture of machinery.

• The development of all-metal machine tools in the first two decades of the 19th century facilitated the manufacture of more production machines powered by steam or water (Watt 1785).

A Brief History of Operations Management

Second Industrial Revolution (around 1850) — The development of steam-powered ships, railways, and later in the nineteenth century with the internal combustion engine and electrical power generation revolutionized industry.

• The introduction of Frederick W. Taylor's systematic approach to scientific management at the beginning of the twentieth century (1911).

• Henry Ford, the father of the moving assembly line, in 1920, brought the world into an age centered around the mass production of goods.

A Brief History of Operations Management

Post World War II

• Leveraging of management science techniques that were developed in the war – Techniques such as linear programming, queuing theory, decision theory, and simulation continue to be developed. Nonlinear programming and game theory followed.

• Growth in the power of computers – algorithms can be implemented and larger problems solved.

• Japanese Production System based on the principles:
  Quality — Continuous Improvement — Elimination of Waste.

A Brief History of Operations Management

1950s and early 1960s

• Evolution of operations research/management science/industrial engineering into production management.

• Production management becomes a professional field as well as an academic discipline – now more commonly referred to as *Operations Management* with *Supply Chain Management* playing a major role.

More recently: World economies evolving into the service arena:

- Service jobs outnumber manufacturing jobs.

- Productivity increases much more difficult to achieve.

- Operations management techniques begin to be incorporated into services - the term production/operations management comes into use.

Goods versus Services

Goods versus Services

Characteristics of Goods

- Tangible product
- Consistent product definition
- Production usually separate from consumption
- Can be stored/inventoried.

Goods versus Services

Characteristics of Services

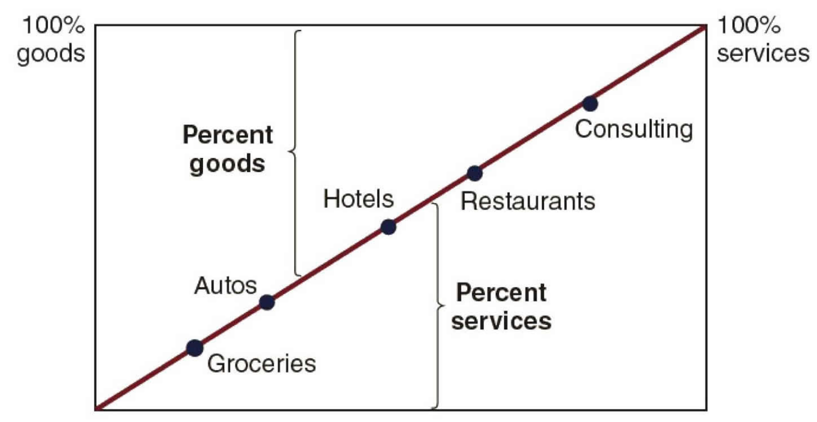
- Intangible product
- Inconsistent product definition
- Produced and consumed essentially at the same time
- Often unique
- High customer interaction
- Often knowledge-based.

Services

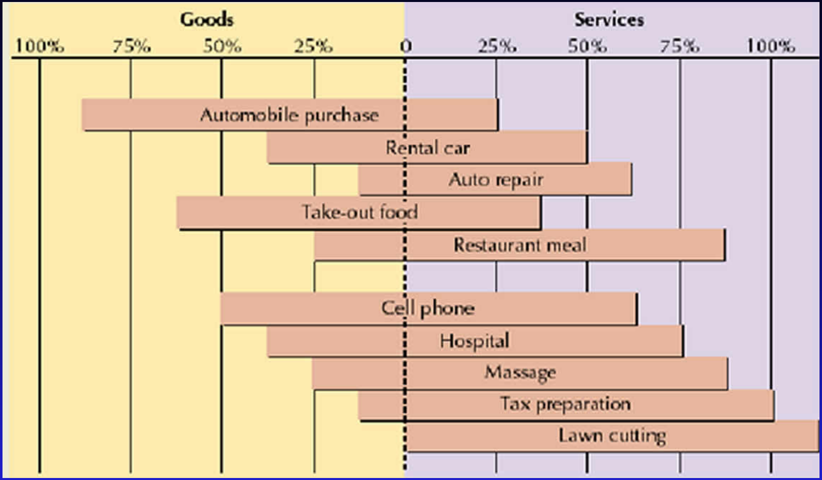
Services as a percentage of Gross Domestic Product (GDP) – World Factbook 2000:

Country	Services as a Percent of GDP
Industrialized Countries:	
United States	80%
United Kingdom	73%
France	70%
Canada	66%
Japan	63%
Lesser Developed Countries:	
Brazil	50%
Thailand	49%
Peru	45%
India	45%
Ghana	30%

Many Products are a Composition or Bundle of Goods and Services



A Continuum of Goods to Services



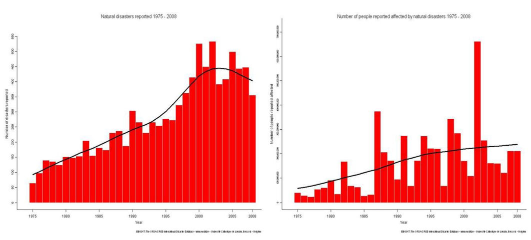
Source: Sasser, Olsen, and Wyckoff, *Management of Service Operations*, 1978, Allyn & Bacon, Boston, Massachusetts.

A Brief History Of Operations Management

More recently:

- Globalization and Outsourcing

- Just in Case versus Just in Time because the number of disasters is growing as well as the people affected by them.



A Brief History Of Operations Management

Today: More Environmental and Social Awareness
Corporate Social Responsibility – CSR

What Do Operations Managers Do?

What Do Operations Managers Do?

Strategic (Long Term) Level

Decisions about:

- What to make (product development)?
- How to make it (process and layout decisions) or should we buy it?
- Where to make it (site location)?
- How much capacity is needed (high level capacity decisions)?

What Do Operations Managers Do?

Tactical (Intermediate Term) Level

Addresses the material and labor resources within the constraints, for example:

- How many workers are needed and when (labour planning)?
- What level of stock is required and when should it be delivered (inventory and replenishment planning)?
- How many shifts needed for work? Whether overtime or subcontractors are required (detailed capacity planning)

What Do Operations Managers Do?

Operational (Short Term (daily/weekly/monthly) Level)

Planning, execution and control decisions, such as, for example:

- What to process and when (scheduling)?
- What is the order to process requirements (sequencing)?
- How does the work utilize the resources (loading)?
- Who does the work (assignments)?

Issues Facing Operations Managers

Issues Facing Operations Managers

The Major Issues Are:

- Environmental sustainability, recycling, reuse
- Counter terrorism / risk management
- Globalization of supply and demand
- Reducing the time to market
- Achieving and sustaining high quality while controlling costs
- Integrating new technologies and control systems into existing processes
- Obtaining, training, and keeping qualified workers
- Working effectively with other functions (especially finance and marketing) to accomplish the goals
- Integrating production and service activities at multiple sites
- Working effectively with suppliers and customers.

These are relevant issues to research as well as to practice.

Some of the Quantitative / Analytical Methodologies in Operations Management

Some of the quantitative / analytical methods that have been successfully applied to operations management problems include:

- decision theory
- project planning (network planning techniques such as CPM (Critical Path Method) and PERT (Project Evaluation and Review Technique)
- quality management and statistical control
- optimization theory and, more recently, game theory
- linear programming (part of optimization) and specializations such as the classical transportation problem
- queuing theory
- inventory theory
- facility planning and location theory
- simulation.

Overview of Networks of Relevance to Supply Chains

Overview of Networks of Relevance to Supply Chains

In this course segment we will cover the following:

- A New Era of Decision-Making
- From Operations Management to Supply Chain Management
- Organizations/Firms as Part of Supply Chains
- Supply Chains and Networks
- Characteristics of Networks Today
- Representation of Supply Chains as Networks
- Why Behavior Matters and Paradoxes
- User-Optimization (U-O) and System-Optimizatin (S-O)
- The Braess Paradox.

A New Era of Decision-Making

A New Era of Decision-Making

We are in a new era of decision-making characterized by:

- *complex interactions* among decision-makers in organizations;
- *alternative and, at times, conflicting criteria* used in decision-making;
- *constraints on resources*: human, financial, natural, time, etc.;
- *global reach* of many decisions;
- *high impact* of many decisions;
- *increasing risk and uncertainty*;
- the *importance of dynamics* and realizing a timely response to evolving events.

A New Era of Decision-Making

We are in an Era of *Networks of Networks* or *Supernetworks*, with examples of networks in the world around us illustrated by:

- *multimodal transportation networks*;
- *complex logistical networks consisting of manufacturers, shippers and carriers, distributors, and retailers*;
- *electric power generation and distribution networks*,
- *multitiered financial networks*, and
- *social network platforms such as Facebook and Twitter*, along with the Internet itself.

Supply chains are also networks of networks and, hence, the underlying theory needs to be built on network theory and to draw from advances made in other network systems.

From Operations Management to Supply Chain Management

From Operations Management to Supply Chain Management

A fundamental and critical aspect of operations in the modern world is that of formulating, analyzing, and managing supply chains.

Hence, in order to fully comprehend the scope of operations and operations management and to be able to advance theory and practice, we must consider supply chains.

It is also important to emphasize the synergies between practice and the development of theory in operations management and in supply chain management.

From Operations Management to Supply Chain Management

Operations management, typically, focuses on improving processes within an organization, whereas supply chain management uses and advances theory, tools, and practice for operations across organizations.

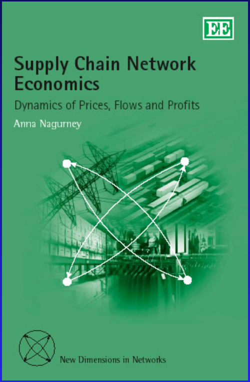
Of course, many of the methodologies of relevance and application in operations management can be transferred to supply chain management.

Organizations/Firms as Part of Supply Chains

Organizations/Firms as Part of Supply Chains

Most organizations and firms function as part of *supply chains*.

According to Nagurney (2006): *Supply chains are the critical infrastructure for the production, distribution, and consumption of goods as well as services in our globalized Network Economy.*



Organizations/Firms as Part of Supply Chains

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.

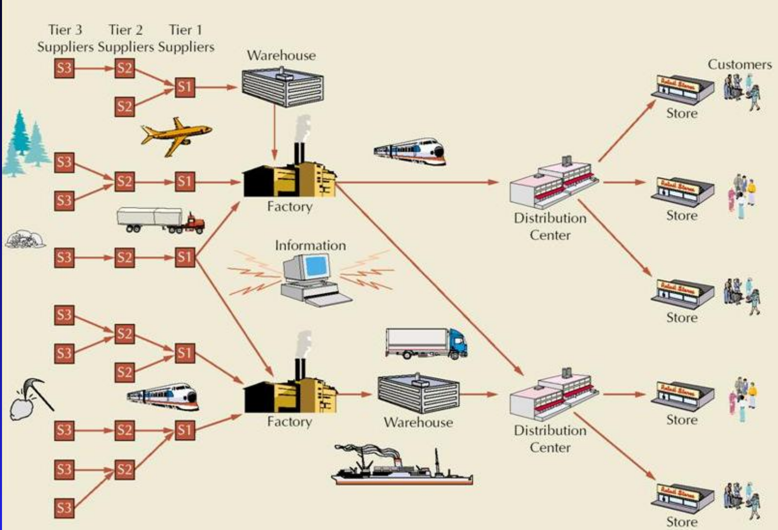
Organizations/Firms as Part of Supply Chains

Changes in the availability of supplies, price shocks, as well as disruptions to transportation modes or telecommunications may have effects 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, may provide new opportunities for profit maximization for manufacturers, distributors, as well as retailers, and new linkages that were not previously possible.

Supply Chains and Networks

A General Supply Chain



Supply Chains and Networks

Supply chains are characterized by either centralized or decentralized decision-making associated with the different economic agents and 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.

Supply Chains and Networks

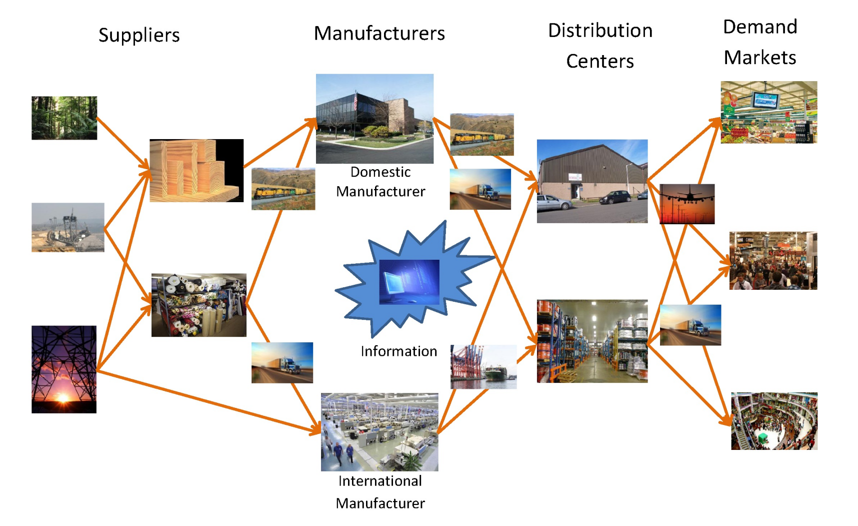
The reality of supply chain networks today includes not only competition but also cooperation since decision-makers in the supply chains must interact not only in terms of the product flows but also in terms of pricing in order to satisfy the consumers.

At the same time, decision-makers in supply chains are characterized by their individualized objectives, which may include not only profit maximization, but also risk minimization, as well as the incorporation of environmentally conscious objectives, to various degrees.

The concept of supply chain networks is as applicable to services as it is to goods.

Multimodal Transportation

Complex Logistical Networks



Electric Power Generation and Distribution Networks

Financial Networks

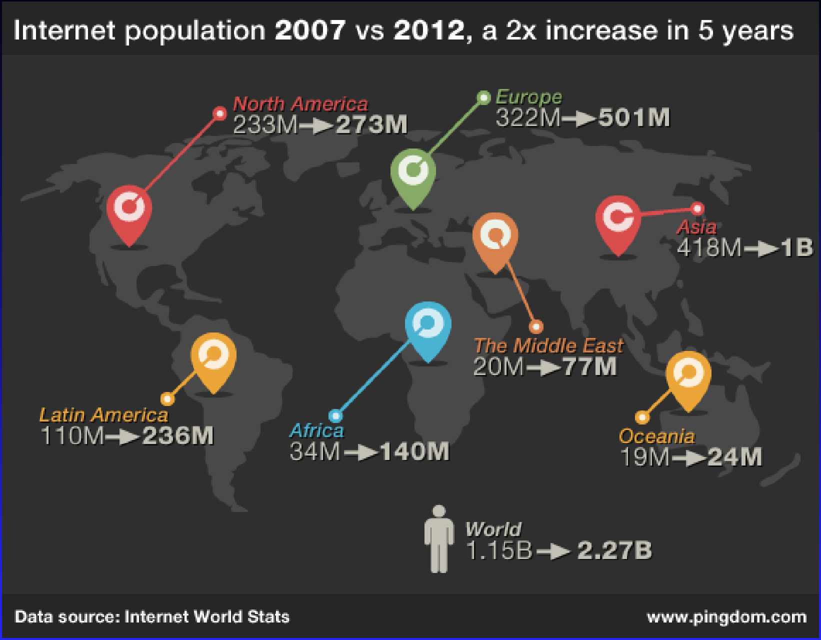
Social Networks

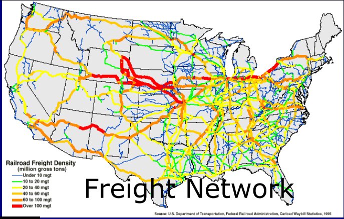
Characteristics of Networks Today

Characteristics of Networks Today

- *large-scale nature* and complexity of network topology;
- *congestion*, which leads to nonlinearities;
- *alternative behavior of users of the networks*, which may lead to paradoxical phenomena;
- *possibly conflicting criteria associated with optimization*;
- *interactions among the underlying networks themselves*, such as the Internet with electric power, financial, 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*.

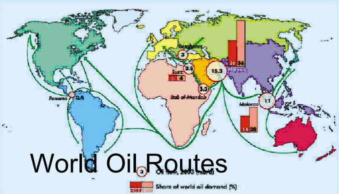
In the case of the Internet, in 2010, there were *1.8 billion users*

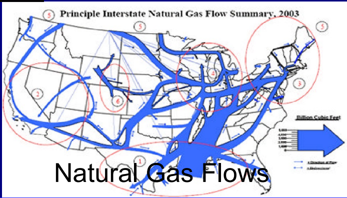




Network

Systems

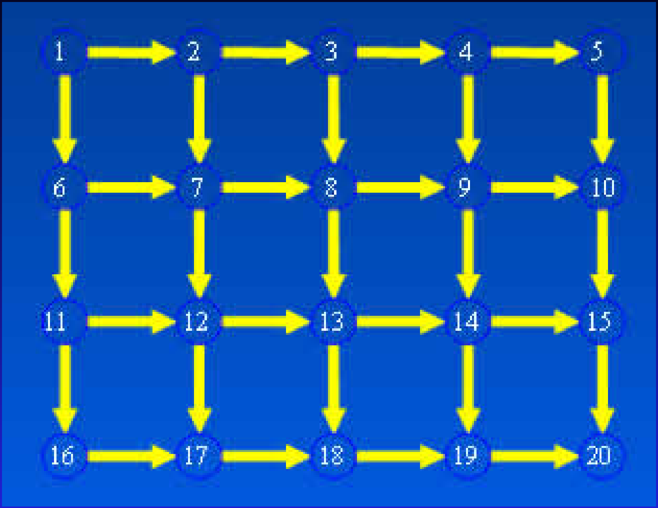




Components of Common Physical Networks

Network System	Nodes	Links	Flows
Transportation	Intersections, Homes, Workplaces, Airports, Railyards	Roads, Airline Routes, Railroad Track	Automobiles, Trains, and Planes,
Manufacturing and logistics	Workstations, Distribution Points	Processing, Shipment	Components, Finished Goods
Communication	Computers, Satellites, Telephone Exchanges	Fiber Optic Cables Radio Links	Voice, Data, Video
Energy	Pumping Stations, Plants	Pipelines, Transmission Lines	Water, Gas, Oil, Electricity

Network Components



The components of networks as a theoretical (modeling, analysis, and solution) construct include: nodes, links, and flows.

An Example

In Chicago's Regional Transportation Network, there are *12,982 nodes, 39,018 links, and 2,297,945 origin/destination (O/D) pairs*, whereas in the Southern California Association of Governments model there are *3,217 origins and/or destinations, 25,428 nodes, and 99,240 links, plus 6 distinct classes of users*.

Network Components

It is important to realize that there may be systems that, at first glance, do not seem to be networks, but, after further though and creativity, one may be able to represent the system as a network!

The advantages of doing so are many:

• One can then see similarities and differences in structure across different problem domains.

• One can avail oneself of powerful network-based analytical tools.

• One can represent what may be an extremely complex problem graphically through a network, which can suggest further insights and extensions.

Representation of Supply Chains as Networks

Representation of Supply Chains as Networks

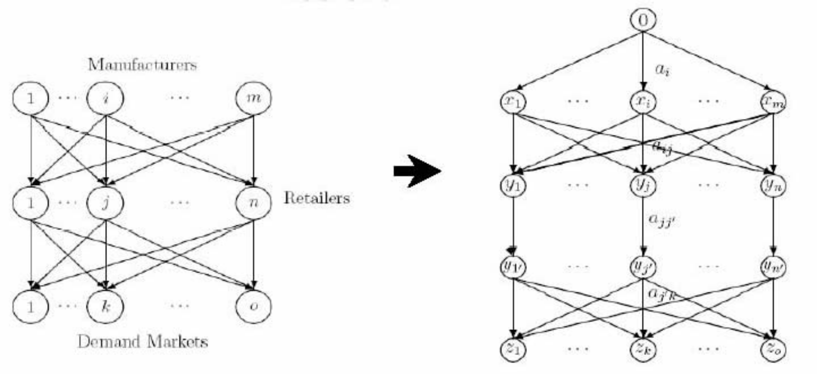
By depicting supply chains as networks, consisting of nodes, links, flows (and also associated functions and behavior) we can:

- see commonalities and differences among different supply chain problems and even other network problems;

- avail ourselves, once the underlying functions (cost, profit, demand, etc.), flows (product, informational, financial, relationship levels, etc.), and constraints (nonnegativity, demand, budget, etc.), and the behavior of the decision-makers is identified, of powerful methodological network tools for modeling, analysis, and computations;

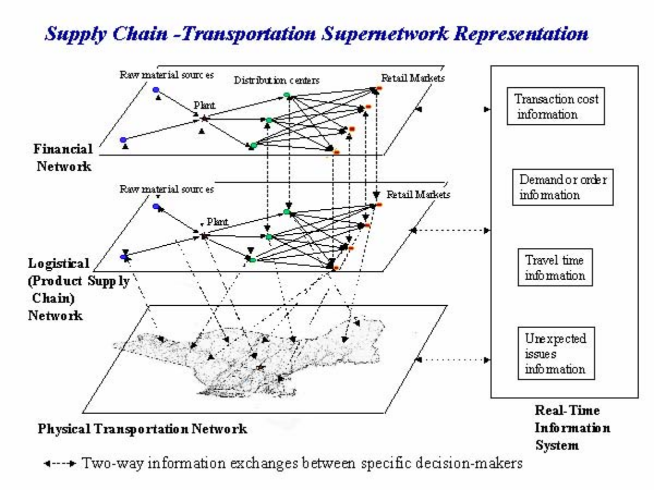
- build powerful extensions using the graphical/network conceptualization.

Representation of Supply Chains as Networks



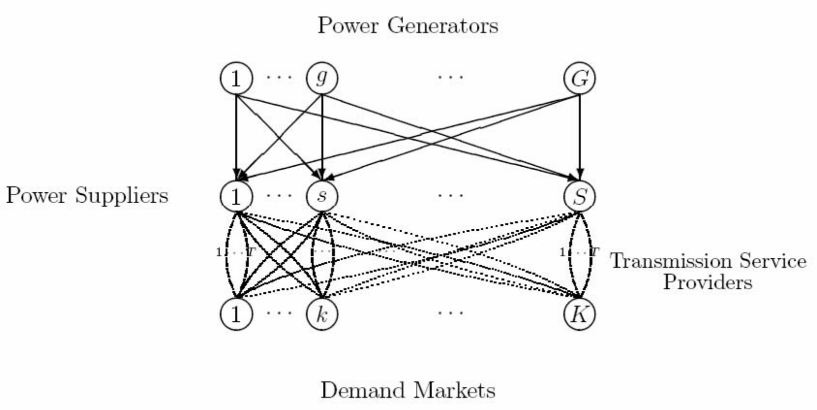
The equivalence between supply chains and transportation networks established in Nagurney, *Transportation Research E* 42 (2006), pp 293-316.

Representation of Supply Chains as Networks



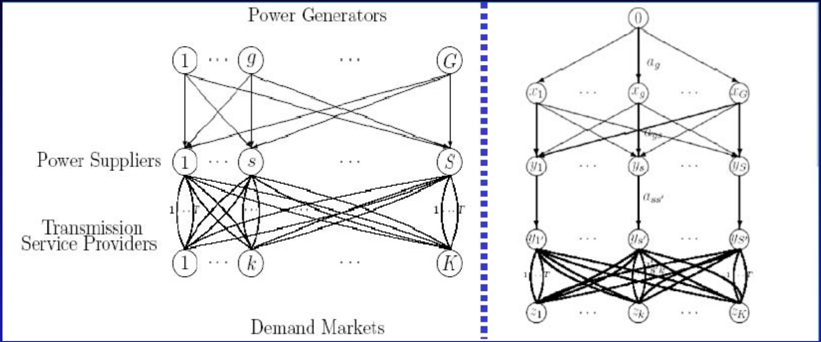
Multilevel supply chain established by Nagurney, Ke, Cruz, Hancock, and Southworth in *Environment & Planning B* 29 (2002), pp 795-818.

Representation of Supply Chains as Networks



Model by Nagurney and Matsypura, *Proceedings of the CCCT* (2004).

Representation of Supply Chains as Networks



The transportation network equilibrium reformulation of electric power supply chain networks by Nagurney, Liu, Cojocaru, and Daniele, *Transportation Research E* 43 (2007), pp 624-646.

Why Behavior Matters and Paradoxes

Network Models from Analysis to Design Must Capture the Behavior of Users

Behavior on Congested Networks

Decision-makers select their cost-minimizing routes.

				User-Optimized or Equilibrium
Decentralized		Selfish		U–O
vs.	⇔	vs.	⇔	vs.
Centralized		Unselfish		S–O
				System-Optimized

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

User-Optimization (U-O) and System-Optimization (S-O)

Two fundamental principles of flow (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 Braess Paradox Illustrates

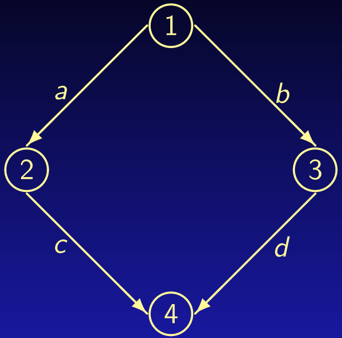
Why Behavior on Networks is Important

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 $C_{p_1} = C_{p_2} = 83$.



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

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

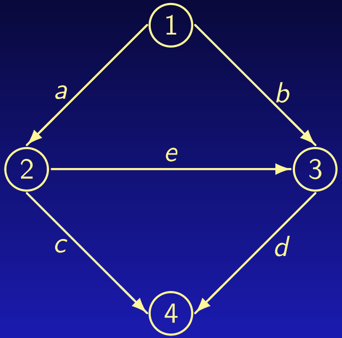
Adding a Link Increases Travel Cost for All!

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



$$c_e(f_e) = f_e + 10$$

Under S-O behavior, the total cost in the network is minimized, and the new route p_3, under the same demand of 6, would not be used.

The Braess paradox never occurs in S-O networks.

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.

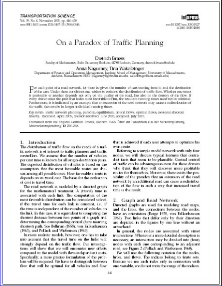
1. Einleitung

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
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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 depends on its travel cost. The basis for the evaluation of cost is travel time.

The road network is modeled by a directed graph for the mathematical treatment. A (travel) time is associated with each link. The computation of the most favorable distribution can be considered solved if the travel time for each link is constant, i.e., if the time is independent of the number of vehicles on the link. In this case, it is equivalent to computing the shortest distance between two points of a graph and determining the corresponding critical (here meaning shortest) path. See Bellman (1958), von Falkenhausen (1963), and Pollack and Wiebenson (1960).

In more realistic models, however, one has to take into account that the travel time on the links will strongly depend on the traffic flow. Our investigations will show that we will encounter new effects compared to the model with flow-independent costs. Specifically, a more precise formulation of the problem will be required. We have to distinguish between flow that will be optimal for all vehicles and flow 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 of the paradox that an extension of the road network by an additional road can cause a redistribution of the flow in such a way that increased travel time is the result.

2. Graph and Road Network

Directed graphs are used for modeling road maps, and the links, the connections between the nodes, have an orientation (Berge 1958, von Falkenhausen 1966). Two links that differ only by their direction are depicted in the figures by one line without an arrowhead.

In general, the nodes are associated with street intersections. Whenever a more detailed description is necessary, an intersection may be divided into (four) nodes with each one corresponding to an adjacent road; see Figure 2 (Pollack and Wiebenson 1960).

We will use the following notation for the nodes, links, and flows. The indices belong to finite sets. Because we use each index only in connection with one variable, we do not write the range of the indices.

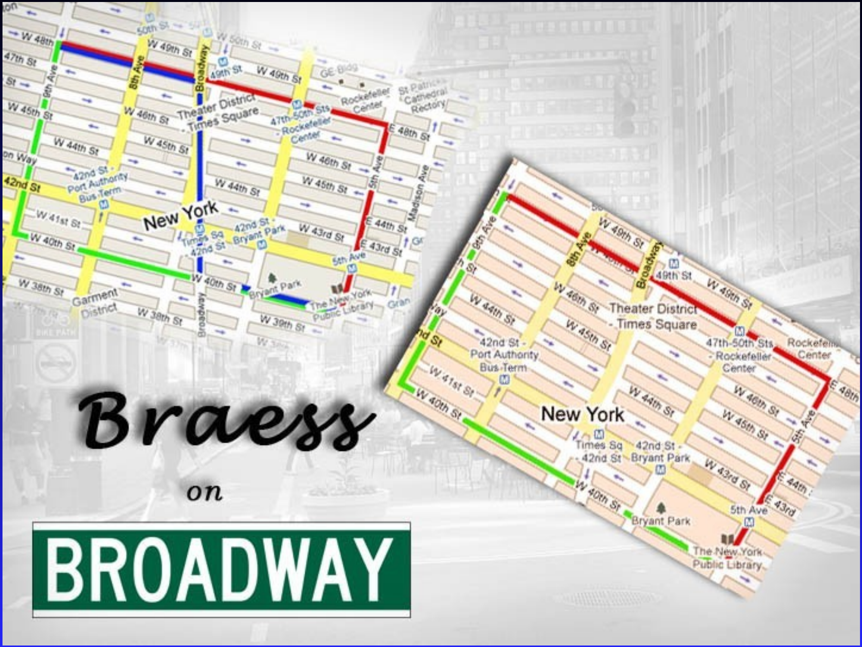
446

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

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

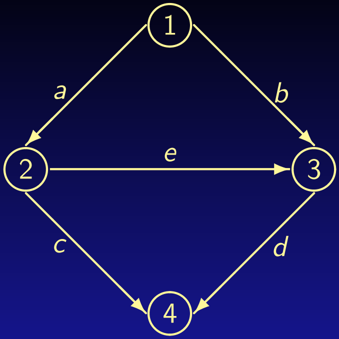
Question: When does the U-O solution coincide with the S-O solution?

Answer: In a general network, when the user link cost functions are given by:

$$c_a(f_a) = c_a^0 f_a^\beta,$$

for all links, with $c_a^0 \geq 0$, and $\beta \geq 0$.

In particular, if $c_a(f_a) = c_a^0$, that is, in the case of *uncongested networks*, this result always holds.



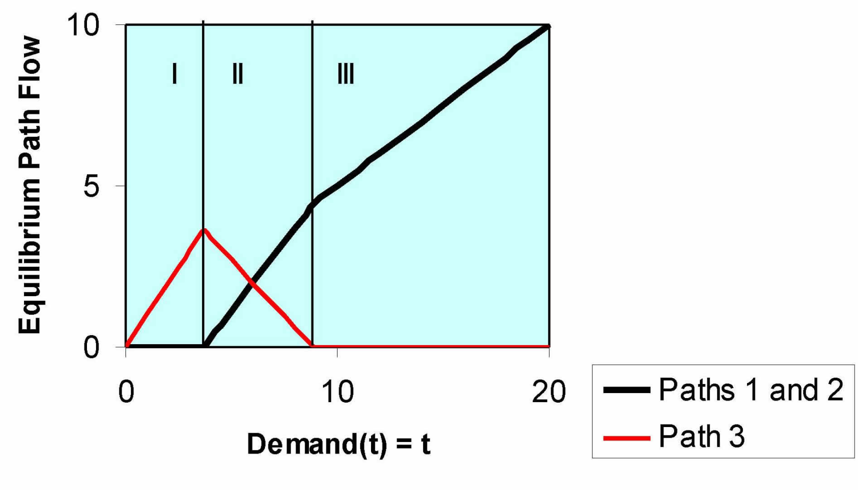
Recall the Braess network with the added link e.

What happens as the demand increases?

For Networks with Time-Dependent Demands

We Use Evolutionary Variational Inequalities

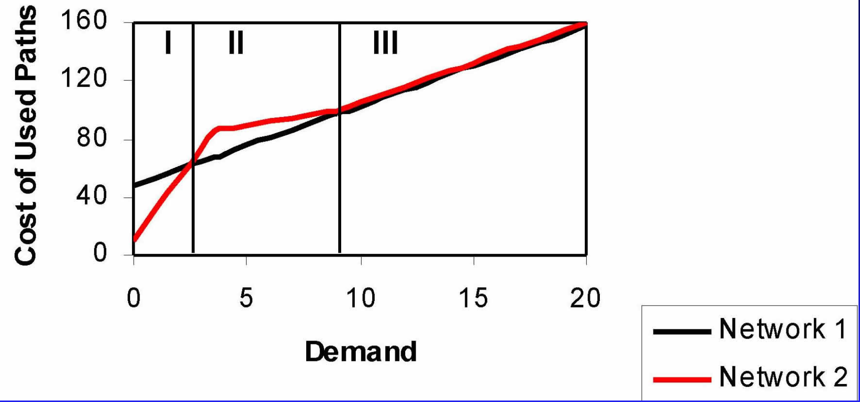
The U-O Solution of the Braess Network with Added Link (Path) and Time-Varying Demands Solved as an *Evolutionary Variational Inequality* (Nagurney, Daniele, and Parkes (2007)).



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

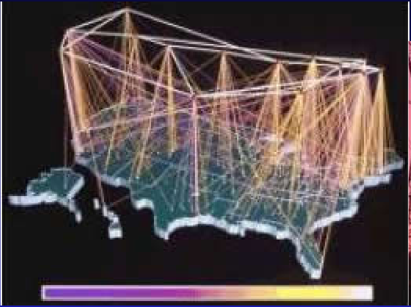
In Demand Regime II, the travel demand lies in the range [2.58, 8.89], and *the Addition of a New Link (Path) Makes Everyone Worse Off*!

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, electric power networks, and even multitiered financial networks and supply chain networks!

Supply Chain Network Theory and Applications

Supply Chain Network Theory and Applications

In this course segment we will cover the following:

- What is Theory and What Makes Good Theory
- Supply Chain Network Theory
- Methodology – The Variational Inequality Problem
- Variational Inequalities and Optimization Theory
- Variational Inequalities and Game Theory
- Supply Chain Networks and Optimization Models
- Supply Chain Networks and Game Theory Models
- A Full Model and Application – Sustainable Fashion Supply Chains.

What is Theory and What Makes Good Theory

Theory

By definition, theory must have four basic criteria:

- conceptual definitions
- domain limitations
- relationship-building
- predictions (factual claims).

Theory is important because it provides a framework for analysis, facilitates the efficient development of the field, and is needed for the applicability to practical real world problems.

Reference: "A Definition of Theory: Research Guidelines for Different Theory-Building Research Methods in Operations Management," John G. Wecker, *Journal of Operations Management* **16** (1998), pp 361-385.

Use of theory is also important for managers seeking to achieve measurable results.

According to A. H. Van de Ven, *Academy of Management Review* **14** (1989), pp 486-489:

Good theory is practical precisely because it advances knowledge in a scientific discipline, guides research toward crucial questions, and enlightens the profession of management.

The *analytical mathematical research methodology* is, by-far, the most prevalent in Operations Management and also in the study of Supply Chains.

Theory

Many of the relevant issues that we highlighted regarding Operations Management are also directly relevant to Supply Chains and, hence, to Supply Chain Management.

Hence, an appropriate theoretical framework should be able to address such important issues as:

- competition versus cooperation
- globalization
- outsourcing
- pricing
- mergers and acquisitions
- different criteria and objective functions
- distinct supply chain structures
- realities such as vertical integration
- fundamental decision-making such as "'buy or make," where to locate, the frequency of production and deliveries, the level of quality, capturing uncertainty and risk, etc.

Key Features of Good Theory and Why They Are Important

The virtues of ‘good’ theory: key features and why they are important to ‘good’ theory development

Virtue	Key feature	Why important for ‘good’ theory and for the development of the field
Uniqueness	The uniqueness virtue means that one theory must be differentiated from another.	If two theories are identical, they should be considered a single theory. Although it applies to all criteria for theory, this virtue directly applies to definitions since definitions are the most elemental of building blocks for theory.
Conservatism	A current theory cannot be replaced unless the new theory is superior in its virtues.	Therefore, current theory is not rejected for the sake of change. This criteria is needed so that when a new theory is proposed, there is a good reason to believe all other theories are lacking in some virtue (Quine and Ullian, 1980; Kuhn, 1980; Popper, 1957).
Generalizability	The more areas that a theory can be applied to makes the theory a better theory.	If one theory can be applied to one type of environment and another theory can be applied to many environments, then the second theory is a more virtuous theory since it can be more widely applied. Some authors call this virtue the utility of the theory since those theories that have wider application have more importance.
Fecundity	A theory which is more fertile in generating new models and hypotheses is better than a theory that has fewer hypotheses	Theories which expand the area of investigation into new conceptual areas are considered superior to theories which investigate established research areas. This means
Theory parsimony theory simplicity, theory efficiency Occum’s razor	The parsimony virtue states, other things being equal, the fewer the assumptions the better.	If two theories are equal in all other aspects, the one with fewer assumptions and the fewer definitions is more virtuous. This virtue also includes the notion that the simpler the explanation, the better the theory. This virtue keeps theories from becoming too complex and incomprehensible.

Reference: John G. Wacker, *Journal of Operations Management* **16** (1998), pp 361-385.

Key Features of Good Theory and Why They Are Important

Internal consistency	Internal consistency means the theory has identified all relationships and gives adequate explanation.	Internal consistency refutation means that the theory *logically* explains the relationships between variables. The more *logically* the theory explains the variables and predicts the subsequent event, the better the theory is. This *internal consistency* virtue means that the theory's entities and relationships must be *internally compatible* using symbolic logic or mathematics. This *internal consistency* means that the concepts and relationships are logically *compatible with* each other.
Empirical riskiness	Any empirical test of a theory should be risky. Refutation must be very possible if theory is to be considered a 'good' theory.	If there are two competing theories, the theory that predicts the most unlikely event is considered the superior theory. In the opposite case, if the theory predicts a very likely event then it is not seen as being a very valuable theory. This criteria is sometimes put in a different way: ''Every good theory has at least one prohibition; it prohibits certain things from happening'' (Popper, 1957).
Abstraction	The abstraction level of theory means it is independent of time and space. It achieves this independence by including more relationships.	The abstraction level means it is better to integrate many relationships and variables into a larger theory. If one of two competing theories integrates more internally consistent concepts, it is more virtuous than a theory that integrates fewer internally consistent relationships.

Reference: John G. Wacker, *Journal of Operations Management* **16** (1998), pp 361-385.

A General Procedure for Theory Building and the Empirical Support for Theory

A general procedure for theory-building and the empirical support for theory

	Purpose of this step	Common question	'Good' theory virtues emphasized
Definitions of variables	Defines who and what are included and what is specifically excluded in the definition.	Who? What?	Uniqueness, conservation
Limiting the domain	Observes and limits the conditions by when (antecedent event) and where the subsequent event are expected to occur.	When? Where?	Generalizability
Relationship (model) building	Logically assembles the reasoning for each relationship for internal consistency.	Why? How?	Parsimony, fecundity, internal consistency, abstractness
Theory predictions and empirical support	Gives specific predictions. Important for setting conditions where a theory predicts. Tests model by criteria to give empirical verification for the theory. The riskiness of the test is an important consideration.	Could the event occur? Should the event occur? Would the event occur?	Empirical tests refutability

Reference: John G. Wacker, *Journal of Operations Management* **16** (1998), pp 361-385.

Supply Chain Network Theory

Supply Chain Network Theory

Supply chain network theory is an integrated theory that includes:

- *network theory* – in order to identify the structure of the supply chain and relationships
- *optimization theory* – in order to capture the decision-maker's criteria in the form of objective functions, the decision variables that they control, and the underlying recourse constraints, and
- *game theory* – so that cooperation, if appropriate, as well as the reality of competition can be modeled.

For full background, see the book: Anna Nagurney, *Supply Chain Network Economics: Dynamics of Prices, Flows, and Profits*, Edward Elgar Publishing, Cheltenham, England (2006).
The fundamental methodology that we utilize for the integration is that of *Variational Inequality Theory*.

Methodology - The Variational Inequality Problem

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

Definition: The Variational Inequality Problem

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

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

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

Methodology - The Variational Inequality Problem

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

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

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

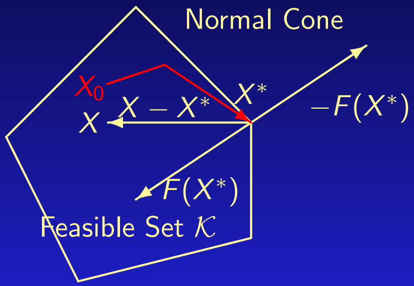
The variational inequality problem contains, as special cases, such mathematical programming problems as:

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

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

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

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.

Variational Inequalities and Optimization Theory

Optimization problems, including constrained and unconstrained, can be formulated as variational inequality problems (see Nagurney (1999)). The relationship between variational inequalities and optimization problems is as follows.

Proposition

Let X^* be a solution to the optimization problem:

$$\textit{Minimize} \quad f(X)$$

subject to:

$$X \in \mathcal{K},$$

where f is continuously differentiable and $\mathcal{K}$ is closed and convex. Then X^* is a solution of the variational inequality problem: determine $X^* \in \mathcal{K}$, such that

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

where $\nabla f(X)$ is the gradient vector of f with respect to X.

Proposition

If $f(X)$ is a convex function and X^* is a solution to $\mathrm{VI}(\nabla f, \mathcal{K})$, then X^* is a solution to the optimization problem:

$$\textit{Minimize} \quad f(X)$$

subject to:

$$X \in \mathcal{K}.$$

In the case that the feasible set $\mathcal{K} = R^n$, then the unconstrained optimization problem is also a variational inequality problem.

The variational inequality problem can be reformulated as an optimization problem under certain symmetry conditions. The definitions of positive semidefiniteness, positive definiteness, and strongly positive definiteness are presented next, followed by stating the above relationship in a theorem.

Optimization and Supply Chain Networks

The types of optimization problems that are of relevance to supply chain networks, include:

- the minimization of costs,
- the maximization of profits,
- the minimization of risk, the minimization of pollution emissions,
- the minimization of delay,
- or a combination thereof, subject to the constraints being met.

Variational Inequalities and Game Theory

The Nobel laureate John Nash (1950, 1951) developed noncooperative game theory, involving multiple players, each of whom acts in his/her own interest.

In particular, consider a game with m players, each player i having a strategy vector $X_i = \{X_{i1}, ..., X_{in}\}$ selected from a closed, convex set $\mathcal{K}^i \subset R^n$. Each player i seeks to maximize his/her own utility function, U_i: $\mathcal{K} \rightarrow R$, where $\mathcal{K} = \mathcal{K}^1 \times \mathcal{K}^2 \times \ldots \times \mathcal{K}^m \subset R^{mn}$.

The utility of player i, U_i, depends not only on his/her own strategy vector, X_i, but also on the strategy vectors of all the other players, $(X_1, \ldots, X_{i-1}, X_{i+1}, \ldots, X_m)$.

An equilibrium is achieved if no one can increase his/her utility by unilaterally altering the value of its strategy vector. The formal definition of Nash equilibrium is:

Definition: Nash Equilibrium
A Nash equilibrium is a strategy vector

$$X^* = (X_1^*, \dots, X_m^*) \in \mathcal{K},$$

such that

$$U_i(X_i^*, \hat{X}_i^*) \geq U_i(X_i, \hat{X}_i^*), \quad \forall X_i \in \mathcal{K}^i, \forall i,$$

where $\hat{X}_i^* = (X_1^*, \dots, X_{i-1}^*, X_{i+1}^*, \dots, X_m^*)$.

In other words, under Nash equilibrium, no unilateral deviation in strategy by any single player is profitable for that player.

Variational Inequalities and Game Theory

Given continuously differentiable and concave utility functions, U_i, $\forall i$, the Nash equilibrium problem can be formulated as a variational inequality problem defined on $\mathcal{K}$ (cf. Hartman and Stampacchia (1966), Gabay and Moulin (1980), and Nagurney (1999)).

Theorem: Variational Inequality Formulation of Nash Equilibrium

Under the assumption that each utility function U_i is continuously differentiable and concave, X^* is a Nash equilibrium if and only if $X^* \in \mathcal{K}$ is a solution of the variational inequality

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

where $F(X) \equiv (-\nabla_{X_1} U_1(X), \ldots, -\nabla_{X_m} U_m(X))$ and $\nabla_{X_i} U_i(X) = (\frac{\partial U_i(X)}{\partial X_{i1}}, \ldots, \frac{\partial U_i(X)}{\partial X_{in}})$.

Game Theory and Supply Chain Networks

In game theory models of supply chain networks, each decision-maker (such as a firm) has his/her own objective function and constraints.

In the case of oligopolies, for example, the objective functions could be profits and the strategic variables the product flows.

Examples of oligopolies are:

- airlines
- freight carriers
- automobile manufacturers
- oil companies
- beer / beverage companies
- wireless communications
- fast fashion brands
- certain financial institutions.

Supply Chain Networks – Optimization Models

Blood Supply Chains for the Red Cross

A. Nagurney, A. Masoumi, and M. Yu, "Supply Chain Network Operations Management of a Blood Banking System with Cost and Risk Minimization," *Computational Management Science* **9(2)** (2012), pp 205-231.

Blood Supply Chains for the Red Cross

- Over 39,000 donations are needed everyday in the United States, and the blood supply is frequently reported to be just 2 days away from running out (American Red Cross (2010)).
- Hospitals with as many days of surgical delays due to blood shortage as 120 a year have been observed (Whitaker et al. (2007)).
- The national estimate for the number of units blood products outdated by blood centers and hospitals was 1,276,000 out of 15,688,000 units (Whitaker et al. (2007)).

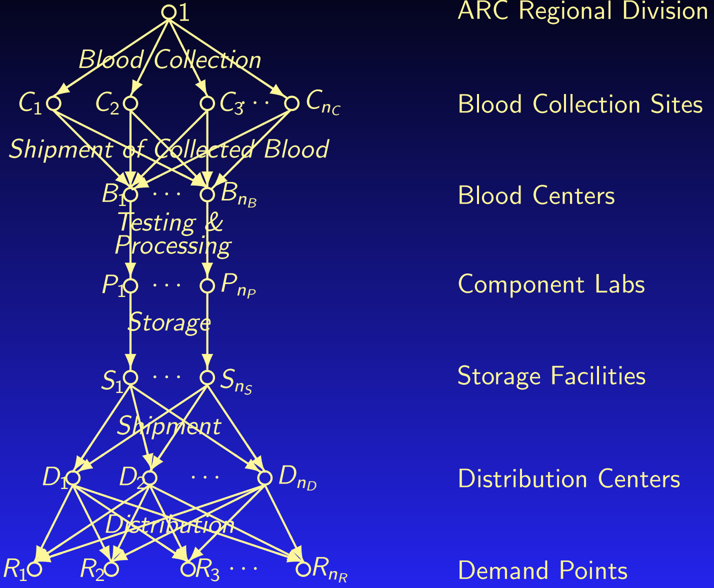
The American Red Cross is the major supplier of blood products to hospitals and medical centers satisfying over 45% of the demand for blood components nationally (Walker (2010)).

Background and Motivation

The hospital cost of a unit of red blood cells in the US had a 6.4% increase from 2005 to 2007.

In the US, this criticality has become more of an issue in the Northeastern and Southwestern states since this cost is meaningfully higher compared to that of the Southeastern and Central states.

Supply Chain Network Topology for a Regionalized Blood Bank



Blood Supply Chains for the Red Cross

We developed a supply chain network optimization model for the management of the procurement, testing and processing, and distribution of a perishable product – that of human blood.

Novel features of the model include:

- It captures *perishability of this life-saving product* through the use of arc multipliers;
- It contains *discarding costs* associated with waste/disposal;
- It handles *uncertainty* associated with demand points;
- It assesses *costs associated with shortages/surpluses at the demand points*, and
- It quantifies the *supply-side risk* associated with procurement.

Medical Nuclear Supply Chains

Medical nuclear supply chains are essential supply chains in healthcare and provide the conduits for products used in nuclear medical imaging, which is routinely utilized by physicians for diagnostic analysis for both cancer and cardiac problems.

Such supply chains have unique features and characteristics due to the products' time-sensitivity, along with their hazardous nature.

Salient Features:

- complexity
- economic aspects
- underlying physics of radioactive decay
- importance of considering both waste management and risk management.

Medical Nuclear Supply Chains

We developed a medical nuclear supply chain network design model which captures the decay of the radioisotope molybdenum.

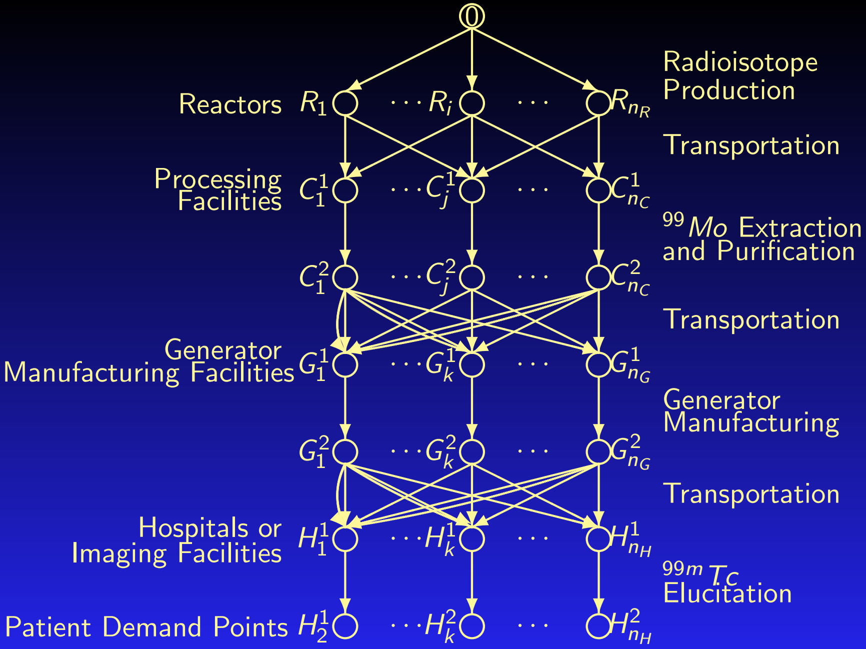


Figure: The Medical Nuclear Supply Chain Network Topology

Supply Chain Networks – Game Theory Models

Electric Power Supply Chains

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

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

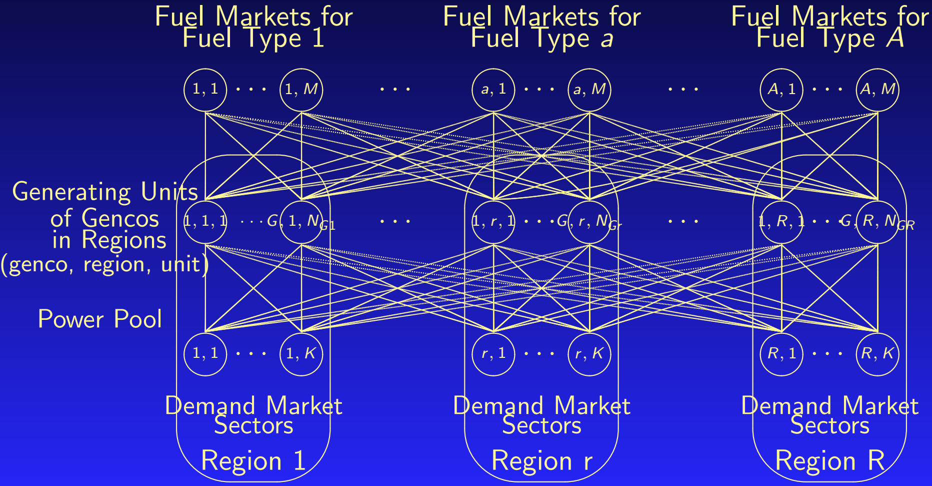
An Empirical Example of an Electric Power Supply Chain for New England

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

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

Graphic of New England

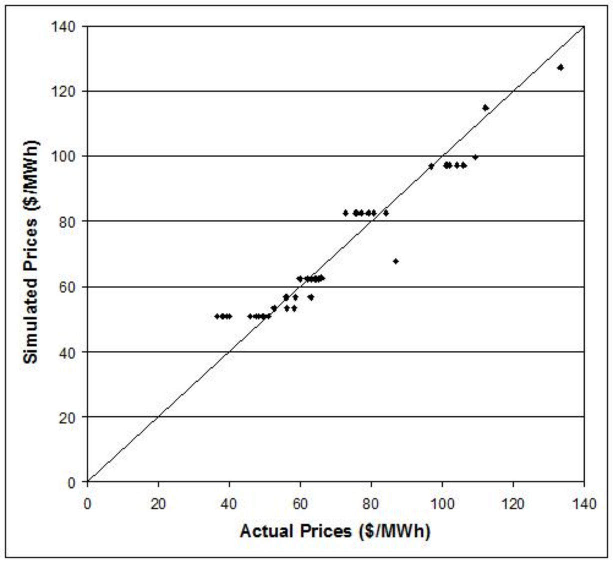
The Electric Power Supply Chain Network with Fuel Supply Markets



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



Food Supply Chains

Food is something anyone can elate to.

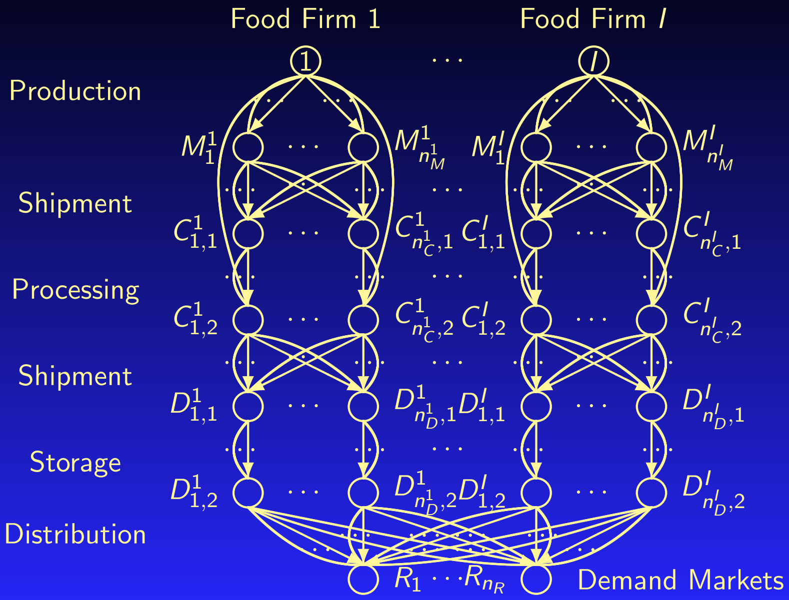
Fresh Produce Food Supply Chains

We developed a fresh produce supply chain network oligopoly model that

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

Reference: "Competitive Food Supply Chain Networks with Application to Fresh Produce," Min Yu and Anna Nagurney, in press in the *European Journal of Operational Research*.

Fresh Produce Food Supply Chains



A Full Model
and
Application to Sustainable Fashion Supply Chains

This part of the course segment is based on the paper:

Anna Nagurney and Min Yu (2012), "Sustainable Fashion Supply Chain Management Under Oligopolistic Competition and Brand Differentiation," *International Journal of Production Economics* **135**, Special Issue on Green Manufacturing and Distribution in the Fashion and Apparel Industries, pp 532-540.

Outline – A Full Model and Application to Sustainable Fashion Supply Chains

- Background and Motivation
- An Overview of the Relevant Literature
- The Sustainable Fashion Supply Chain Network Oligopoly Model
- The Algorithm
- Case Study with Managerial Insights
- Summary and Conclusions

Background and Motivation

The fashion and apparel industry is facing vast challenges in terms of the environmental impacts.

Background and Motivation

Organizations such as the Natural Resources Defense Council (NRDC) are now increasingly emphasizing that this industry's reduction of its environmental impacts will require that brands and retailers reexamine their supply chains way back to the inputs into their production processes and take more responsibility even for the fabric utilized (cf. Tucker (2010)).

Background and Motivation

- According to the Natural Resources Defense Council (NRDC), textile manufacturing pollutes as much as 200 tons of water per ton of fabric.
- In China, a textile factory may also burn about 7 tons of carbon emitting coal per ton of fabric produced (see Tucker (2010)).

Background and Motivation

- According to the Natural Resources Defense Council (NRDC), textile manufacturing pollutes as much as 200 tons of water per ton of fabric.
- In China, a textile factory may also burn about 7 tons of carbon emitting coal per ton of fabric produced (see Tucker (2010)).
- Polyester is a man-made fiber whose demand from the fashion industry has doubled in the past 15 years. Its manufacture requires petroleum and releases emissions into the air and the water (see Claudio (2007)).

Background and Motivation

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- Polyester is a man-made fiber whose demand from the fashion industry has doubled in the past 15 years. Its manufacture requires petroleum and releases emissions into the air and the water (see Claudio (2007)).
- The production of cotton accounts for a quarter of all the pesticides used in the United States, which is the largest exporter of cotton in the world (see Claudio (2007)).

Background and Motivation

In the last three decades, there has been a migration of clothing manufacturers from developed to developing countries.

- Whereas in 1992 about 49% of all retail apparel sold in the United States was actually made there, by 1999 the proportion had fallen to just 12% (Rabon (2001)).
- Between 1990 and 2000, the value of apparel imports to the US increased from $25 billion to $64 billion.

Background and Motivation

In the last three decades, there has been a migration of clothing manufacturers from developed to developing countries.

- Whereas in 1992 about 49% of all retail apparel sold in the United States was actually made there, by 1999 the proportion had fallen to just 12% (Rabon (2001)).
- Between 1990 and 2000, the value of apparel imports to the US increased from $25 billion to $64 billion.

Lower production cost is not the only reason for the globalization of apparel manufacturing. Some firms may be taking advantage of a looser environmental regulatory system and/or lower environmental impact awareness in developing nations (see Allwood et al. (2006)).

Xintang, the 'Jeans Capital' of the World

Background and Motivation

Given its global dimensions, it is crucial to realize the seriousness of emissions generated along the entire supply chains associated with the fashion and apparel industry, include emissions generated in the transportation and distribution of the products across oceans and vast tracts of land.

The demand to minimize the environmental pollution is coming not only from **consumers** but, more recently, even from **fashion firms** that wish to enhance or to maintain a positive brand identity (see, e.g., Claudio (2007), Glausiusz (2008), Rosenbloom (2010), Tucker (2010), and Zeller Jr. (2011)).

Background and Motivation

H&M has identified that 51% of its carbon imprint in 2009 was due to transportation. In order to reduce the associated emissions, it began more direct shipments that avoided intermediate warehouses, decreased the volumes shipped by ocean and air by 40% and increased the volume of products shipped by rail, resulting in an over 700 ton decrease in the amount of carbon dioxide emitted. (H&M (2010)).

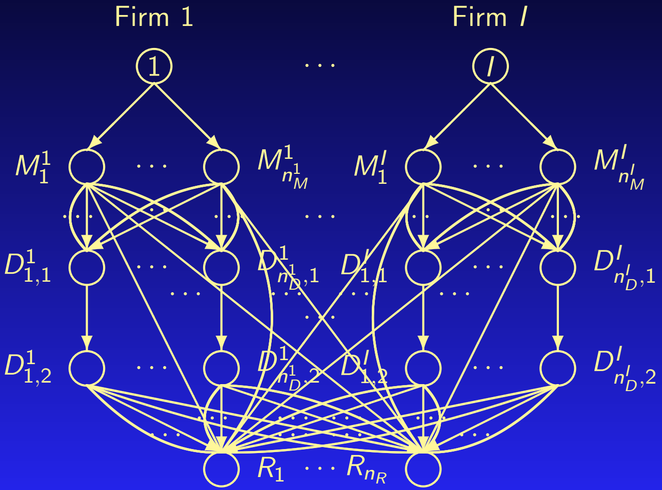
Relevant Literature

- Sustainable Supply Chains
  - Yeung et al. (2008) claimed that social compliance is one of the influentials of operational performance in the clothing manufacturing industry, especially for imported fashion products.
  - Beamon (1999), Sarkis (2003), Corbett and Kleindorfer (2003), Nagurney and Toyasaki (2003, 2005), Sheu, Chou, and Hu (2005), Kleindorfer, Singhal, and van Wassenhove (2005), Nagurney, Liu, and Woolley (2007), Linton, Klassen, and Jayaraman (2007), Piplani, Pujawan, and Ray (2008), Nagurney and Nagurney (2010), and Nagurney and Woolley (2010)
  - Wu et al. (2006), Nagurney, Liu, and Woolley (2006), and Chaabane, Ramudhin, and Paquet (2010)

The Sustainable Fashion Supply Chain Network Oligopoly Model

We consider a finite number of I fashion firms, with a typical firm denoted by i, who are involved in the production, storage, and distribution of a fashion product and who compete noncooperatively in an oligopolistic manner. Each firm corresponds to an individual brand representing the product that it produces.

The Fashion Supply Chain Network Topology of the Oligopoly



Demands, Path Flows, and Link Flows

Let d_{ik} denote the demand for fashion firm i's product at demand market k. The products of all these fashion firms are not homogeneous but are differentiated by *brand*.

Let x_p denote the nonnegative flow on path p joining (origin) node i; $i = 1, \ldots, I$ with a (destination) demand market node. Let f_a denote the flow on link a.

The Conservation of Flow Equations

$$\sum_{p \in P_k^i} x_p = d_{ik}, \quad k = 1, \ldots, n_R; \; i = 1, \ldots, I. \tag{1}$$

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

The demand price of fashion firm i's product at demand market R_k is denoted by ρ_{ik} and the demand price functions are assumed to be continuous, continuously differentiable and monotone decreasing.

$$\rho_{ik} = \rho_{ik}(d), \quad k = 1, \ldots, n_R; \; i = 1, \ldots, I. \tag{3}$$

The total operational cost on a link is assumed to be a function of the product flows on all the links, that is,

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

The total cost on each link is assumed to be convex and is continuously differentiable.
The profit function π_i of firm i; $i = 1, \ldots, I$, is:

$$\pi_i = \sum_{k=1}^{n_R} \rho_{ik}(d) \sum_{p \in P_k^i} x_p - \sum_{a \in L^i} \hat{c}_a(f). \tag{5}$$

The emission-generation function associated with link a, denoted by $\hat{e}_a$, is assumed to be a function of the product flow on that link, that is,

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

These functions are assumed to be convex and continuously differentiable.

Each fashion firm aims to minimize the total amount of emissions generated in the manufacture, storage, and shipment of its product.

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

The Sustainable Fashion Supply Chain Network Oligopoly Model

The multicriteria decision-making problem faced by fashion firm i; $i = 1, \ldots, I$, is:

$$U_i = \sum_{k=1}^{n_R} \rho_{ik}(d) \sum_{p \in P_k^i} x_p - \sum_{a \in L^i} \hat{c}_a(f) - \omega_i \sum_{a \in L^i} \hat{e}_a(f_a), \qquad (8)$$

where the term ω_i is assumed to be the price that firm i would be willing to pay for each unit of emission on each of its links, representing the environmental concern of firm i.

In view of (1)-(8),

$$U = U(X), \qquad (9)$$

where U is the I-dimensional vector of all the firms' utilities.

Definition: Supply Chain Network Cournot-Nash Equilibrium

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

$$U_i(X_i^*, \hat{X}_i^*) \geq U_i(X_i, \hat{X}_i^*), \quad \forall X_i \in K_i, \tag{10}$$

where
$\hat{X}_i^* \equiv (X_1^*, \ldots, X_{i-1}^*, X_{i+1}^*, \ldots, X_I^*)$ *and* $K_i \equiv \{X_i | X_i \in R_+^{n_{P^i}}\}$.

Theorem: Variational Inequality Formulation

Assume that for each fashion firm i; $i = 1, \ldots, I$, the utility function $U_i(X)$ is concave with respect to the variables in X_i, and is continuously differentiable. Then $X^* \in K$ is a sustainable fashion supply chain network Cournot-Nash equilibrium if and only if it satisfies the variational inequality:

$$-\sum_{i=1}^{I} \langle \nabla_{X_i} U_i(X^*), X_i - X_i^* \rangle \geq 0, \quad \forall X \in K, \tag{11}$$

where $\langle \cdot, \cdot \rangle$ denotes the inner product in the corresponding Euclidean space and $\nabla_{X_i} U_i(X)$ denotes the gradient of $U_i(X)$ with respect to X_i.

Variational Inequality Formulation in Path Flows

The solution of variational inequality (11) is equivalent to the solution of the variational inequality: determine $x^* \in K^1$ satisfying:

$$\sum_{i=1}^{I}\sum_{k=1}^{n_R}\sum_{p\in P_k^i}\left[\frac{\partial \hat{C}_p(x^*)}{\partial x_p}+\omega_i\frac{\partial \hat{E}_p(x^*)}{\partial x_p}-\rho_{ik}(x^*)-\sum_{l=1}^{n_R}\frac{\partial \rho_{il}(x^*)}{\partial d_{ik}}\sum_{p\in P_l^i}x_p^*\right]$$

$$\times[x_p-x_p^*]\geq 0,\ \forall x\in K^1, \tag{12}$$

where $K^1 \equiv \{x|x\in R_+^{n_P}\}$, $\frac{\partial \hat{C}_p(x)}{\partial x_p}\equiv \sum_{b\in L^i}\sum_{a\in L^i}\frac{\partial \hat{c}_b(f)}{\partial f_a}\delta_{ap}$ *and* $\frac{\partial \hat{E}_p(x)}{\partial x_p}\equiv \sum_{a\in L^i}\frac{\partial \hat{e}_a(f_a)}{\partial f_a}\delta_{ap}$.

In addition, (12) can be re-expressed in terms of link flows as: determine the vector of equilibrium link flows and the vector of equilibrium demands $(f^*, d^*) \in K^2$, such that:

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

$$+ \sum_{i=1}^{I} \sum_{k=1}^{n_R} \left[-\rho_{ik}(d^*) - \sum_{l=1}^{n_R} \frac{\partial \rho_{il}(d^*)}{\partial d_{ik}} d_{il}^* \right] \times [d_{ik} - d_{ik}^*] \geq 0, \quad \forall (f, d) \in K^2, \tag{13}$$

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

Theorem: Existence

There exists at least one Nash Equilibrium, equivalently, at least one solution to variational inequality (12) (equivalently, (13)), since in the light of the demand price functions (3), there exists a $b > 0$*, such that variational inequality*

$$\langle F(X^b), X - X^b \rangle \geq 0, \quad \forall X \in \mathcal{K}_b, \tag{14}$$

admits a solution in $\mathcal{K}_b \equiv \{x | 0 \leq x \leq b\}$ *with*

$$x^b \leq b. \tag{15}$$

Theorem: Uniqueness

Variational inequality (13) admits at least one solution. Moreover, if the function $F(X)$ of variational inequality (13), is strictly monotone on $\mathcal{K} \equiv K^2$, that is,

$$\langle (F(X^1) - F(X^2)), X^1 - X^2 \rangle > 0, \quad \forall X^1, X^2 \in \mathcal{K}, \; X^1 \neq X^2. \quad (16)$$

then the solution to variational inequality (13) is unique, that is, the equilibrium link flow pattern and the equilibrium demand pattern are unique.

The Algorithm – The Euler Method

At an iteration τ of the Euler method (see Dupuis and Nagurney (1993) and Nagurney and Zhang (1996)) one computes:

$$X^{\tau+1} = P_{\mathcal{K}}(X^{\tau} - a_{\tau} F(X^{\tau})), \tag{17}$$

where $P_{\mathcal{K}}$ is the projection on the feasible set $\mathcal{K}$ and F is the function that enters the variational inequality problem: determine $X^* \in \mathcal{K}$ such that

$$\langle F(X^*), X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{K}, \tag{18}$$

where $\langle \cdot, \cdot \rangle$ is the inner product in n-dimensional Euclidean space, $X \in R^n$, and $F(X)$ is an n-dimensional function from $\mathcal{K}$ to R^n, with $F(X)$ being continuous.

The sequence $\{a_{\tau}\}$ must satisfy: $\sum_{\tau=0}^{\infty} a_{\tau} = \infty$, $a_{\tau} > 0$, $a_{\tau} \rightarrow 0$, as $\tau \rightarrow \infty$.

Explicit Formulae for the Euler Method Applied to the Sustainable Fashion Supply Chain Network Oligopoly Variational Inequality (12)

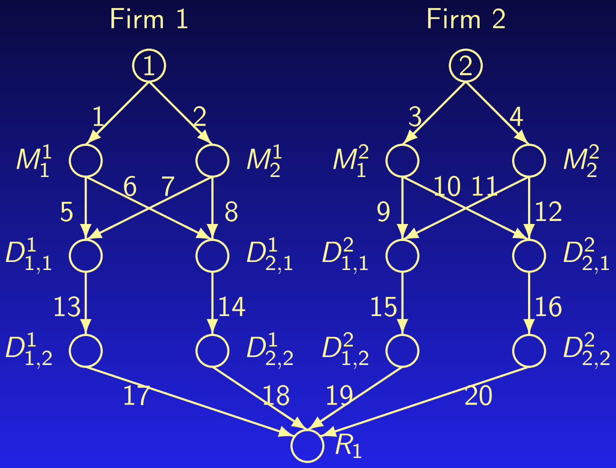
$$x_p^{\tau+1} = \max\{0, x_p^{\tau} + a_{\tau}(\rho_{ik}(x^{\tau}) + \sum_{l=1}^{n_R} \frac{\partial \rho_{il}(x^{\tau})}{\partial d_{ik}} \sum_{p \in P_l^i} x_p^{\tau}$$

$$-\frac{\partial \hat{C}_p(x^{\tau})}{\partial x_p} - \omega_i \frac{\partial \hat{E}_p(x^{\tau})}{\partial x_p})\}, \quad \forall p \in P_k^i, \forall k, \forall i. \qquad (19)$$

Case Study

There are two fashion firms, Firm 1 and Firm 2, each of which is involved in the production, storage, and distribution of a single fashion product, which is differentiated by its brand. Each firm has, at its disposal, two manufacturing plants, two distribution centers, and serves a single demand market. The manufacturing plants M_1^1 and M_1^2 are located in the United States, whereas the manufacturing plants M_2^1 and M_2^2 are located off-shore with lower operational costs. However, the demand market is in the United States as are the distribution centers.

The Fashion Supply Chain Network Topology for the Case Study



Problem Set 1

Fashion Firm 1 cares about the emissions that it generates much more than Firm 2 does, which is indicated by the respective values of ω_1 and ω_2, where $\omega_1 = 5$ and $\omega_2 = 1$. In addition, Firm 1 utilizes more advanced technologies in its supply chain activities in order to lower the emissions that it generates, but at relatively higher costs.

Total Cost and Total Emission Functions

Link a	$\hat{c}_a(f)$	$\hat{e}_a(f_a)$
1	$10f_1^2 + 10f_1$	$.05f_1^2 + .5f_1$
2	$f_2^2 + 7f_2$	$.1f_2^2 + .8f_2$
3	$10f_3^2 + 7f_3$	$.1f_3^2 + f_3$
4	$f_4^2 + 5f_4$	$.15f_4^2 + 1.2f_4$
5	$f_5^2 + 4f_5$	$.08f_5^2 + f_5$
6	$f_6^2 + 6f_6$	$.1f_6^2 + f_6$
7	$2f_7^2 + 30f_7$	$.15f_7^2 + 1.2f_7$
8	$2f_8^2 + 20f_8$	$.15f_8^2 + f_8$
9	$f_9^2 + 3f_9$	$.25f_9^2 + f_9$
10	$f_{10}^2 + 4f_{10}$	$.25f_{10}^2 + 2f_{10}$
11	$1.5f_{11}^2 + 30f_{11}$	$.4f_{11}^2 + 1.5f_{11}$
12	$1.5f_{12}^2 + 20f_{12}$	$.45f_{12}^2 + f_{12}$
13	$f_{13}^2 + 3f_{13}$	$.01f_{13}^2 + .1f_{13}$
14	$f_{14}^2 + 2f_{14}$	$.01f_{14}^2 + .15f_{14}$
15	$f_{15}^2 + 1.8f_{15}$	$.05f_{15}^2 + .3f_{15}$
16	$f_{16}^2 + 1.5f_{16}$	$.08f_{16}^2 + .5f_{16}$
17	$2f_{17}^2 + f_{17}$	$.08f_{17}^2 + f_{17}$
18	$f_{18}^2 + 4f_{18}$	$.1f_{18}^2 + .8f_{18}$
19	$f_{19}^2 + 5f_{19}$	$.3f_{19}^2 + 1.2f_{19}$
20	$1.5f_{20}^2 + f_{20}$	$.35f_{20}^2 + 1.2f_{20}$

Example 1

$$\rho_{11}(d) = -d_{11} - .2d_{21} + 300, \quad \rho_{21}(d) = -2d_{21} - .5d_{11} + 300.$$

Example 2

$$\rho_{21}(d) = -3d_{21} - .5d_{11} + 300.$$

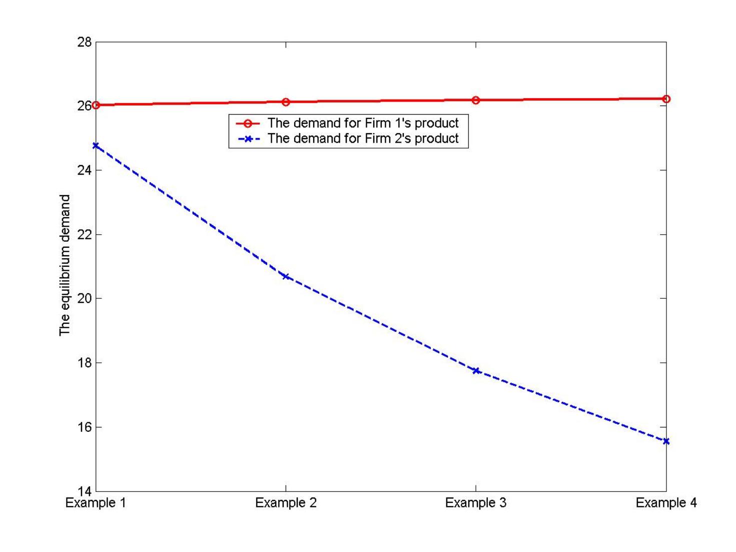
Example 3

$$\rho_{21}(d) = -4d_{21} - .5d_{11} + 300.$$

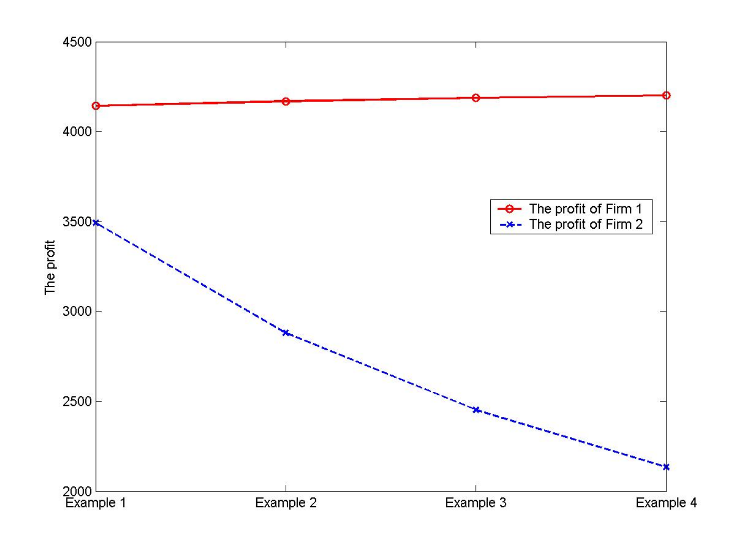
Example 4

$$\rho_{21}(d) = -5d_{21} - .5d_{11} + 300.$$

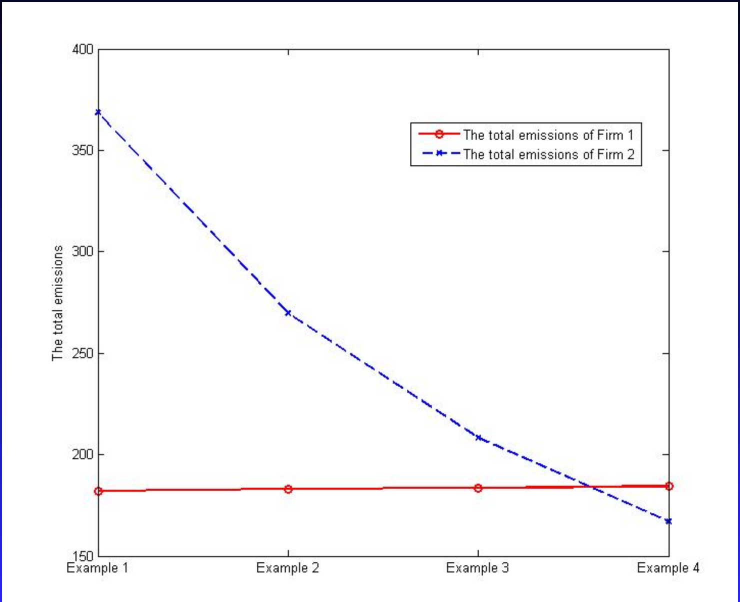
The Equilibrium Demands as ρ_{21} Varies



The Equilibrium Profits as ρ_{21} Varies



The Equilibrium Total Emissions as ρ_{21} Varies

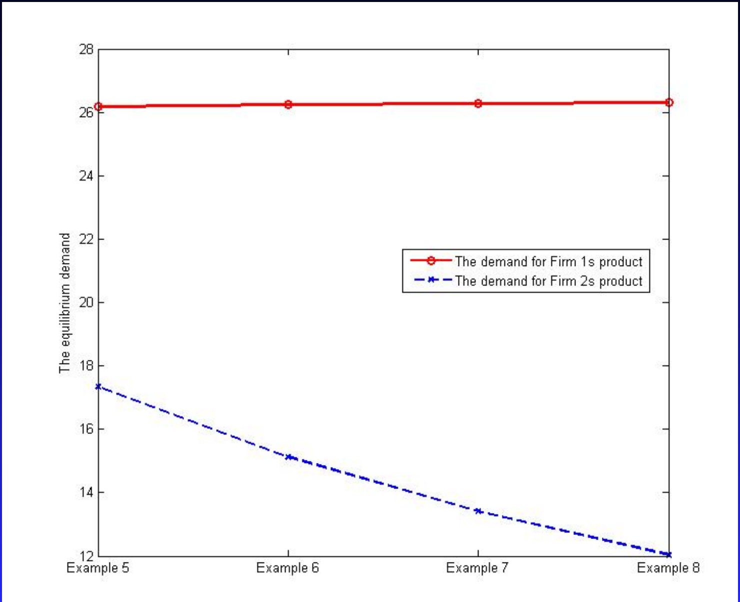


Problem Set 2

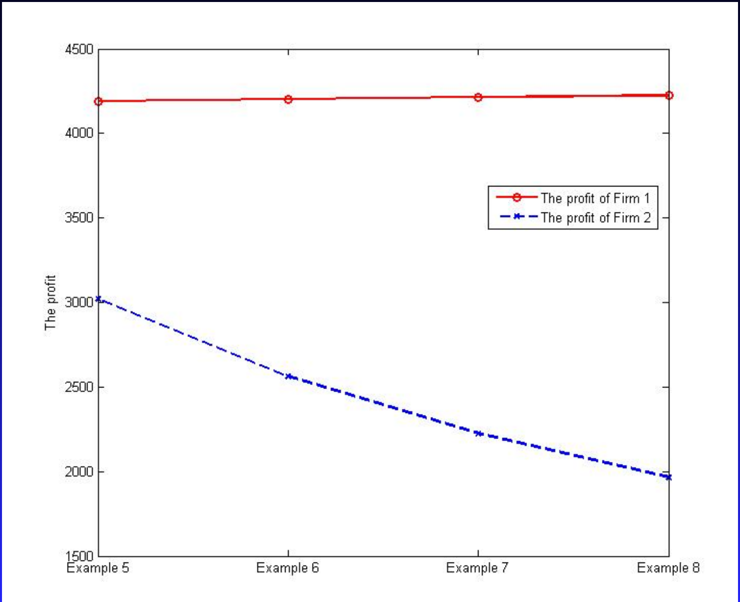
Firm 2 was now more environmentally conscious and raised ω_2 from 1 to 5. Hence, in this set of examples, Firm 1 and Firm 2 both had their ω weights equal to 5. Examples 5 through 8 had their data identical to the data in Examples 1 through 4, respectively, except for the larger value of ω_2.

The weights, the ω_is, may also be interpreted as *taxes* in that a governmental authority may impose a tax associated with carbon emissions, for example, that each firm must pay.

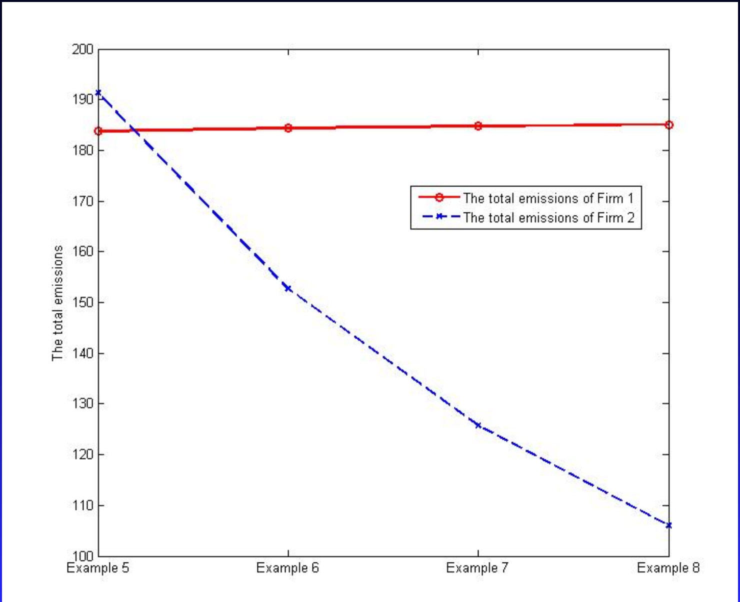
The Equilibrium Demands as ρ_{21} Varies



The Equilibrium Profits as ρ_{21} Varies



The Equilibrium Total Emissions as ρ_{21} Varies



We varied both the total cost functions and the total emission functions of Firm 2. Example 9

$$\hat{c}_3(f) = 10f_3^2 + 10f_3, \quad \hat{c}_4(f) = f_4^2 + 7f_4,$$

$$\hat{e}_3(f_3) = .05f_3^2 + .5f_3, \quad \hat{e}_4(f_4) = .1f_4^2 + .8f_4.$$

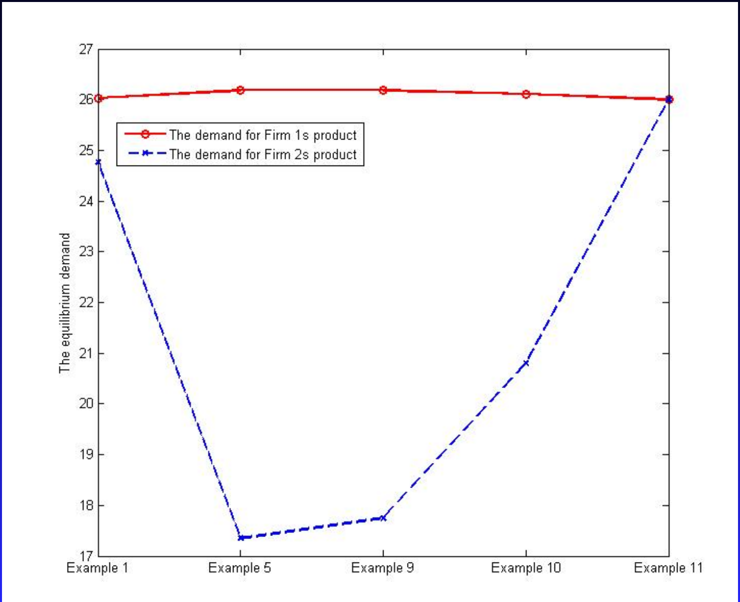
Example 10 Fashion Firm 2 made even a greater effort to lower its emissions, not only focusing on its manufacturing processes, but also on all other supply chain activities.
Example 11 Firm 1 and 2 were *identical*.

$$\rho_{11}(d) = -d_{11} - .2d_{21} + 300, \quad \rho_{21}(d) = -d_{21} - .2d_{11} + 300.$$

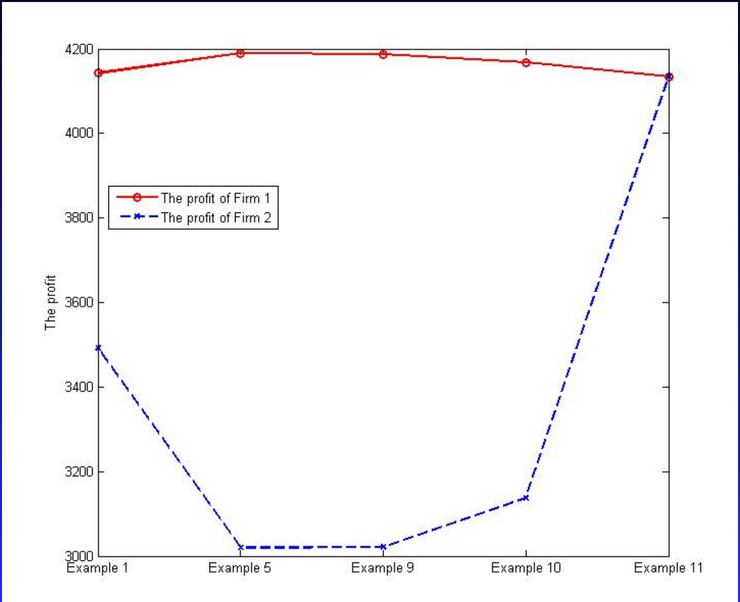
Total Cost and Total Emission Functions for Example 10

Link a	$\hat{c}_a(f)$	$\hat{e}_a(f_a)$
1	$10f_1^2 + 10f_1$	$.05f_1^2 + .5f_1$
2	$f_2^2 + 7f_2$	$.1f_2^2 + .8f_2$
3	$10f_3^2 + 10f_3$	$.05f_3^2 + .5f_3$
4	$f_4^2 + 7f_4$	$.1f_4^2 + .8f_4$
5	$f_5^2 + 4f_5$	$.08f_5^2 + f_5$
6	$f_6^2 + 6f_6$	$.1f_6^2 + f_6$
7	$2f_7^2 + 30f_7$	$.15f_7^2 + 1.2f_7$
8	$2f_8^2 + 20f_8$	$.15f_8^2 + f_8$
9	$f_9^2 + 4f_9$	$.08f_9^2 + f_9$
10	$f_{10}^2 + 6f_{10}$	$.1f_{10}^2 + f_{10}$
11	$2f_{11}^2 + 30f_{11}$	$.15f_{11}^2 + 1.2f_{11}$
12	$2f_{12}^2 + 20f_{12}$	$.15f_{12}^2 + f_{12}$
13	$f_{13}^2 + 3f_{13}$	$.01f_{13}^2 + .1f_{13}$
14	$f_{14}^2 + 2f_{14}$	$.01f_{14}^2 + .15f_{14}$
15	$f_{15}^2 + 3f_{15}$	$.01f_{15}^2 + .1f_{15}$
16	$f_{16}^2 + 2f_{16}$	$.01f_{16}^2 + .15f_{16}$
17	$2f_{17}^2 + f_{17}$	$.08f_{17}^2 + f_{17}$
18	$f_{18}^2 + 4f_{18}$	$.1f_{18}^2 + .8f_{18}$
19	$2f_{19}^2 + f_{19}$	$.08f_{19}^2 + f_{19}$
20	$f_{20}^2 + 4f_{20}$	$.1f_{20}^2 + .8f_{20}$

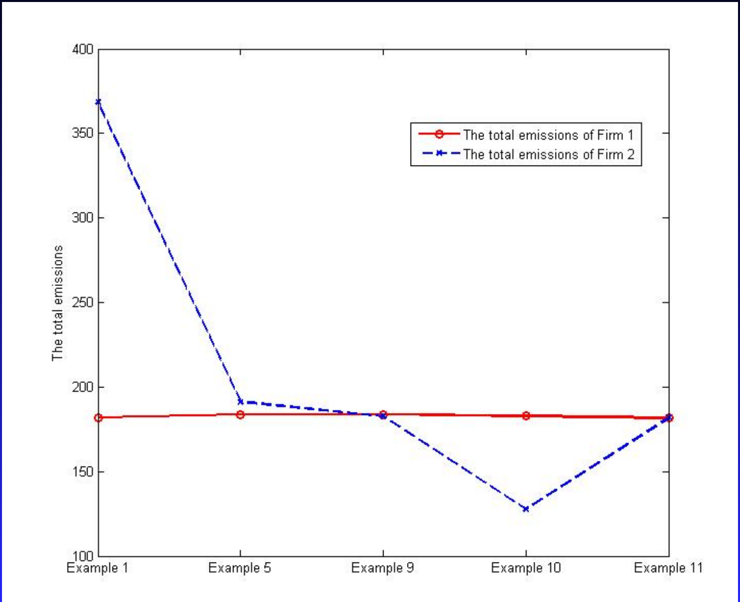
Comparison of the Equilibrium Demands



Comparison of the Equilibrium Profits



Comparison of the Equilibrium Total Emissions



Case Study

- Consumers' environmental consciousness can be a valuable incentive to spur fashion companies to reexamine their supply chains so as to reduce their environmental pollution, which can, in turn, help such companies to obtain competitive advantages and increased profits.
- The development of a positive image for a firm in terms of its environmental consciousness and concern may also be an effective marketing strategy for fashion firms.

Summary and Conclusions

- We developed a competitive supply chain network model, using variational inequality theory, that captures oligopolistic competition with fashion product brand differentiation.
  - The model captures competition through brand differentiation.
  - The model allows for each firm to individually weight its concern for the environment.
  - Alternatives such as multiple modes of transportation can be investigated.

Summary and Conclusions

- We presented a case study, to demonstrate the effects of changes in the demand price functions, the total cost and total emission functions, and the weights associated with the environmental criterion on the equilibrium product demands, the product prices, profits, and utilities.
  - The environmental weights could also be interpreted as taxes and, thus, in exploring different values an authority such as the government could assess a priori the effects on the firms' emissions and profits.
  - The case study also demonstrated that consumers can have a major impact, through their environmental consciousness, on the level of profits of firms in their favoring of firms that adopt environmental pollution-abatement technologies for their supply chain activities.

Other Issues That Have Been Explored Using Supply Chain Network Theory

Outline – Other Issues that Have Been Explored Using Supply Chain Network Theory

In this course segment we will cover the following:

- Mergers & Acquisitions
- Integration of Social Networks with Supply Chains and with Financial Networks
- Supply Chain Networks for Rescue, Recovery and Reconstruction in Disasters
- The Nagurney-Qiang (N-Q) Network Efficiency / Performance Measure
- Design of Supply Chains for Critical Needs Products
- Summary, Conclusions, and Suggestions for Future Research

Mergers & Acquisitions

Merger & Acquisition Activity

M&As totaled over $2 trillion in 2009, down 32% from full-year 2008 and down 53% from the record high in 2007, according to data from Thomson Reuters.

Mergers announced in October 2010 include Bain Capital / Gymboree, at $1.789 billion and Dynamex / Greenbriar Equity Group ($207 million).

Some of the most visible recent mergers have occurred in the airline industry with Delta and Northwest completing their merger in October 2008 and United and Continental closing on the formation of United Continental Holdings Oct. 1, 2010.

Merger & Acquisition Activity

Global 2010 M&A activity is estimated to rise as much as 35% from 2009 figures (Sanford C. Bernstein research firm).

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)).

Mergers and Acquisitions and Network Synergies

A successful merger depends on the ability to measure the anticipated synergy of the proposed merger (cf. Chang (1988)) .

- A. Nagurney, "A System-Optimization Perspective for Supply Chain Network Integration: The Horizontal Merger Case," *Transportation Research E* (2009) **45**, pp 1-15.

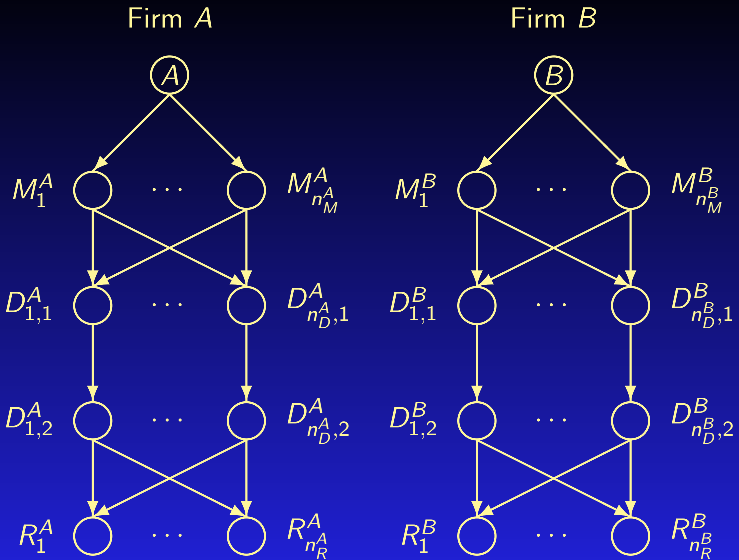


Figure: Case 0: Firms A and B Prior to Horizontal Merger

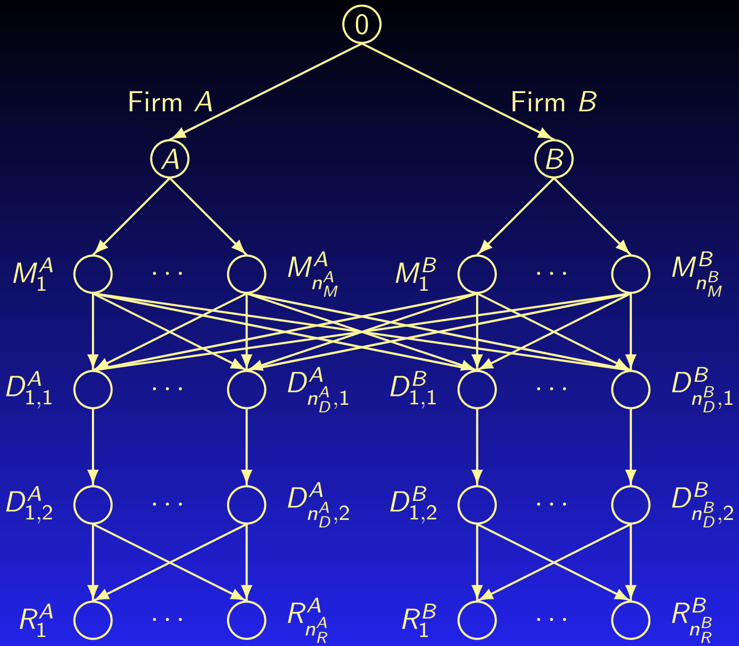


Figure: Case 1: Firms A and B Merge

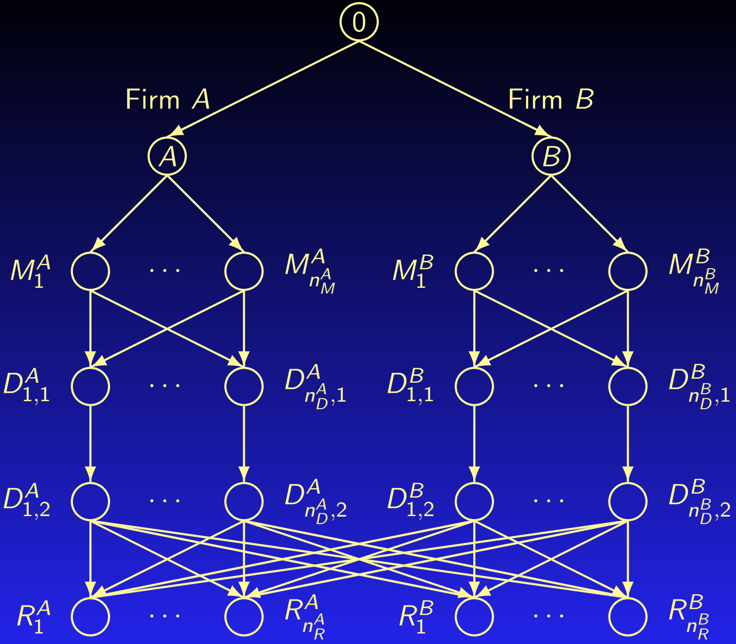


Figure: Case 2: Firms A and B Merge

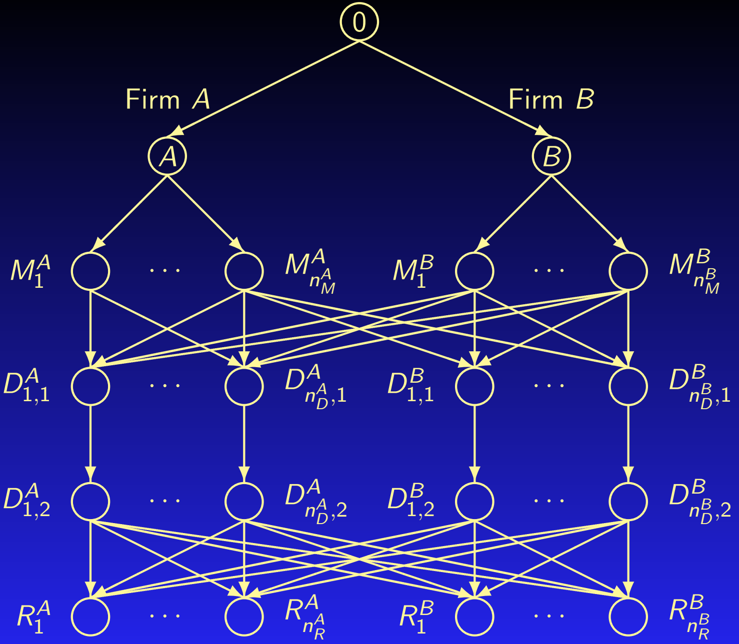


Figure: Case 3: Firms A and B Merge

Synergy Measure

The measure that we utilized in Nagurney (2009) to capture the gains, if any, associated with a horizontal merger Case i; $i = 1, 2, 3$ is as follows:

$$\mathcal{S}^i = \left[\frac{TC^0 - TC^i}{TC^0} \right] \times 100\%,$$

where TC^i is the total cost associated with the value of the objective function $\sum_{a \in L^i} \hat{c}_a(f_a)$ for $i = 0, 1, 2, 3$ evaluated at the optimal solution for Case i. Note that $\mathcal{S}^i$; $i = 1, 2, 3$ may also be interpreted as *synergy*.

This model can also be applied to the teaming of organizations in the case of humanitarian operations.

Bellagio Conference on Humanitarian Logistics

See: http://hlogistics.isenberg.umass.edu/

The Supply Chain Network Oligopoly Model

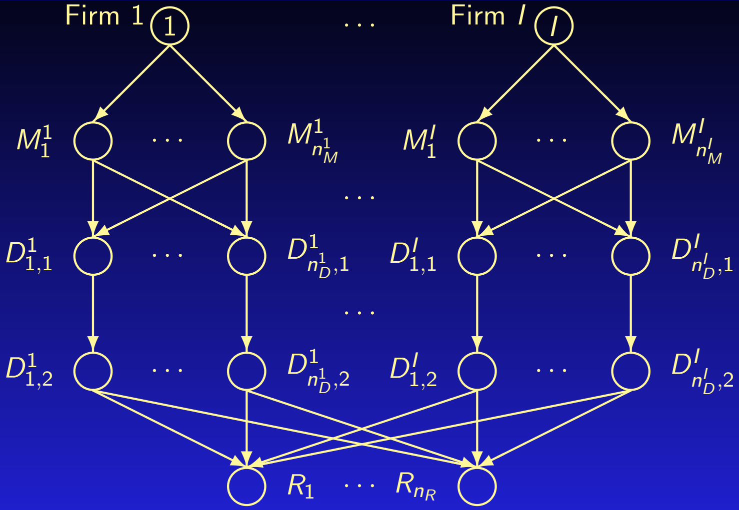


Figure: Supply Chain Network Structure of the Oligopoly

Nagurney *Computational Management Science* (2010) **7**, pp 377-401.

Mergers Through Coalition Formation

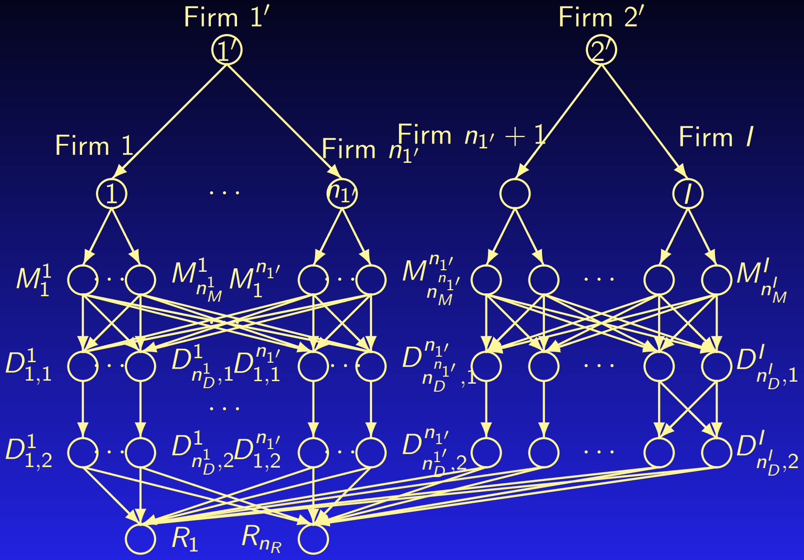


Figure: Mergers of the First $n_{1'}$ Firms and the Next $n_{2'}$ Firms

Integration of Social Networks with Supply Chains and with Financial Networks

Integration of Social Networks with Supply Chains and with Financial Networks

Two References:

A. Nagurney, T. Wakolbinger, and L. Zhao (2006) "The Evolution and Emergence of Integrated Social and Financial Networks with Electronic Transactions: A Dynamic Supernetwork Theory for the Modeling, Analysis, and Computation of Financial Flows and Relationship Levels," *Computational Economics* **27**, pp 353-393.

J. M. Cruz, A. Nagurney, and T. Wakolbinger (2006) "Financial Engineering of the Integration of Global Supply Chain Networks and Social Networks with Risk Management," *Naval Research Logistics* **53**, pp 674-696.

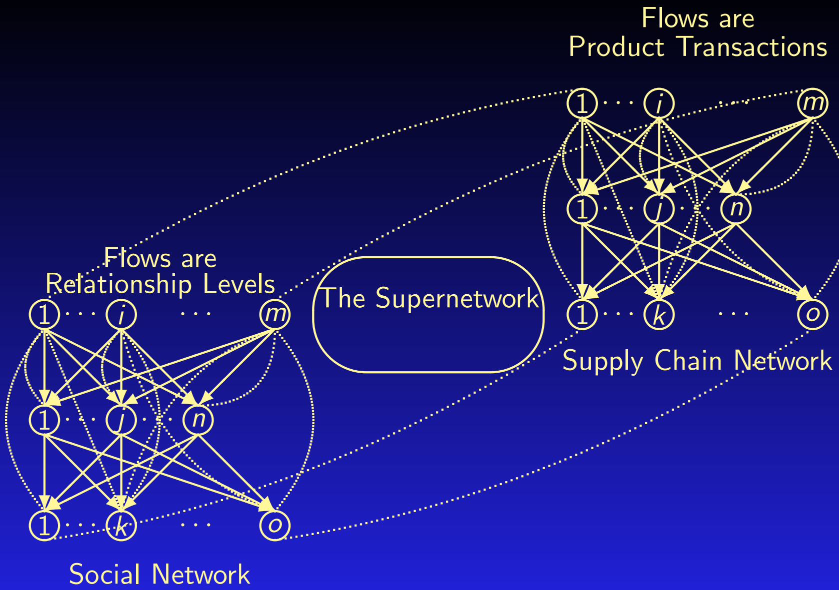


Figure: The Multilevel Supernetwork Structure of the Integrated Supply Chain / Social Network System

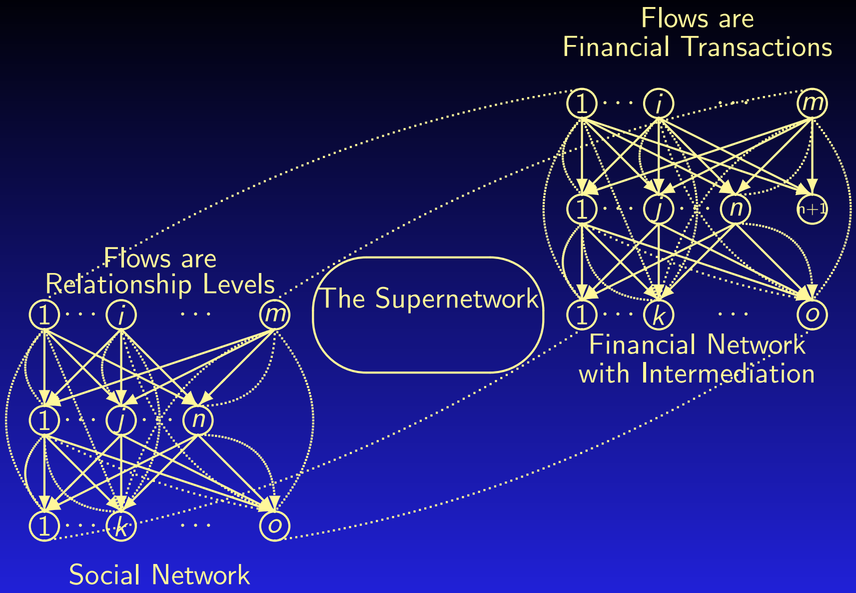


Figure: The Multilevel Supernetwork Structure of the Integrated Financial Network / Social Network System

Supply Chain Networks
for
Rescue, Recovery and Reconstruction in Disasters

Supply chains are the *fundamental critical infrastructure* for the production and distribution of goods and services in our globalized *Network Economy*.

Supply chain networks also serve as the primary conduit for *rescue, recovery, and reconstruction in disasters.*

Recent disasters have vividly demonstrated the importance and vulnerability of our transportation and critical infrastructure systems

- The biggest blackout in North America, August 14, 2003;
- Two significant power outages in September 2003 – one in the UK and the other in Italy and Switzerland;
- The Indonesian tsunami (and earthquake), December 26, 2004;
- Hurricane Katrina, August 23, 2005;
- The Minneapolis I35 Bridge collapse, August 1, 2007;
- The Mediterranean cable destruction, January 30, 2008;
- The Sichuan earthquake on May 12, 2008;
- The Haiti earthquake that struck on January 12, 2010 and the Chilean one on February 27, 2010;
- The triple disaster in Japan on March 11, 2011.

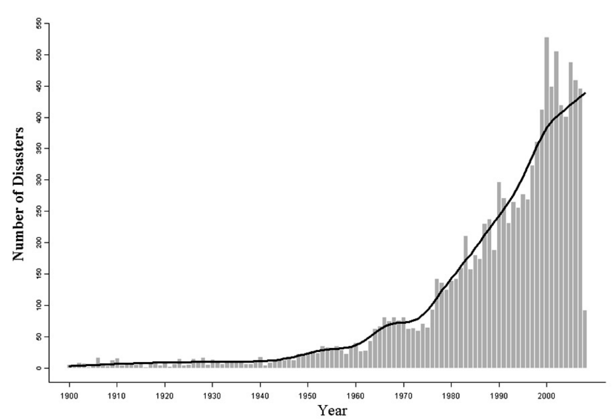
Hurricane Katrina in 2005

Hurricane Katrina has been called an *"American tragedy,"* in which essential services failed completely.

The Haitian and Chilean Earthquakes

The Triple Disaster in Japan on March 11, 2011

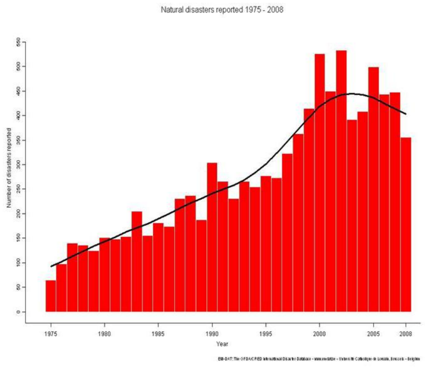
Disasters have brought an unprecedented impact on human lives in the 21st century and the number of disasters is growing. From January to October 2005, *an estimated 97,490 people were killed in disasters globally; 88,117 of them because of natural disasters*.

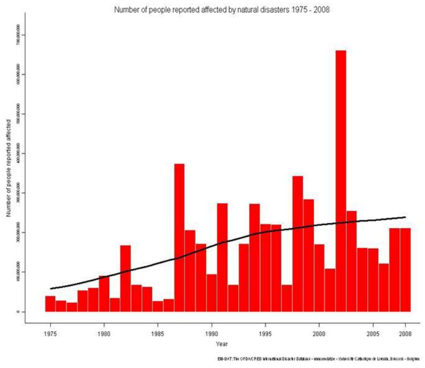


Frequency of disasters [Source: Emergency Events Database (2008)]

Disasters have a catastrophic effect on human lives and a region's or even a nation's resources.

Natural Disasters (1975–2008)





Which Nodes and Links Really Matter?

Nagurney-Qiang (N-Q) Network Efficiency / Performance Mea

The Nagurney and Qiang (N-Q) Network Efficiency / Performance Measure

Definition: A Unified Network Performance Measure

The network performance/efficiency measure, $\mathcal{E}(\mathcal{G}, d)$, for a given network topology $\mathcal{G}$ and the equilibrium (or fixed) demand vector d, is:

$$\mathcal{E} = \mathcal{E}(\mathcal{G}, d) = \frac{\sum_{w \in W} \frac{d_w}{\lambda_w}}{n_W},$$

where recall that n_W is the number of O/D pairs in the network, and d_w and λ_w denote, for simplicity, the equilibrium (or fixed) demand and the equilibrium disutility for O/D pair w, respectively.

Definition: Importance of a Network Component

The importance of a network component $g \in \mathcal{G}$, $I(g)$, is measured by the relative network efficiency drop after g is removed from the network:

$$I(g) = \frac{\triangle \mathcal{E}}{\mathcal{E}} = \frac{\mathcal{E}(\mathcal{G}, d) - \mathcal{E}(\mathcal{G} - g, d)}{\mathcal{E}(\mathcal{G}, d)}$$

where $\mathcal{G} - g$ is the resulting network after component g is removed from network $\mathcal{G}$.

The Approach to Identifying the Importance of Network Components

The elimination of a link is treated in the N-Q network efficiency measure by removing that link while the removal of a node is managed by removing the links entering and exiting that node.

In the case that the removal results in no path connecting an O/D pair, we simply assign the demand for that O/D pair to an abstract path with a cost of infinity.

The N-Q measure is well-defined even in the case of disconnected networks.

The Advantages of the N-Q Network Efficiency Measure

- The measure captures *demands, flows, costs, and behavior of users*, in addition to network topology.

- The resulting importance definition of network components is applicable and *well-defined even in the case of disconnected networks*.

- It can be used to identify the *importance (and ranking) of either nodes, or links, or both*.

- It can be applied to *assess the efficiency/performance of a wide range of network systems, including financial systems and supply chains under risk and uncertainty*.

- It is applicable also to *elastic demand networks*.

- It is *applicable to dynamic networks*, *including the Internet*.

Some Applications of the N-Q Measure

The Sioux Falls Network

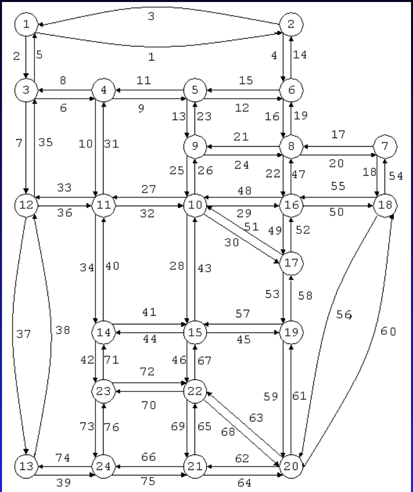


Figure: The Sioux Falls network with 24 nodes, 76 links, and 528 O/D pairs of nodes.

Importance of Links in the Sioux Falls Network

The computed network efficiency measure $\mathcal{E}$ for the Sioux Falls network is $\mathcal{E} = 47.6092$. Links 27, 26, 1, and 2 are the most important links, and hence special attention should be paid to protect these links accordingly, while the removal of links 13, 14, 15, and 17 would cause the least efficiency loss.

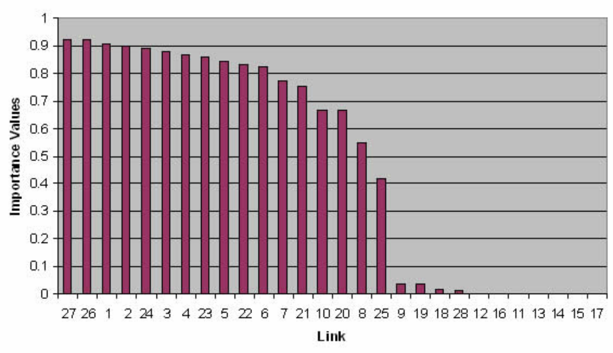


Figure: The Sioux Falls network link importance rankings

According to the European Environment Agency (2004), *since 1990, the annual number of extreme weather and climate related events has doubled, in comparison to the previous decade*. These events account for approximately 80% of all economic losses caused by catastrophic events. In the course of climate change, catastrophic events are projected to occur more frequently (see Schulz (2007)).

Schulz (2007) applied *N-Q network efficiency measure to a German highway system in order to identify the critical road elements* and found that this measure provided more reasonable results than the measure of Taylor and DEste (2007).

The N-Q measure can also be used to assess which links should be added to improve efficiency. *This measure was used for the evaluation of the proposed North Dublin (Ireland) Metro system* (October 2009 Issue of *ERCIM News*).

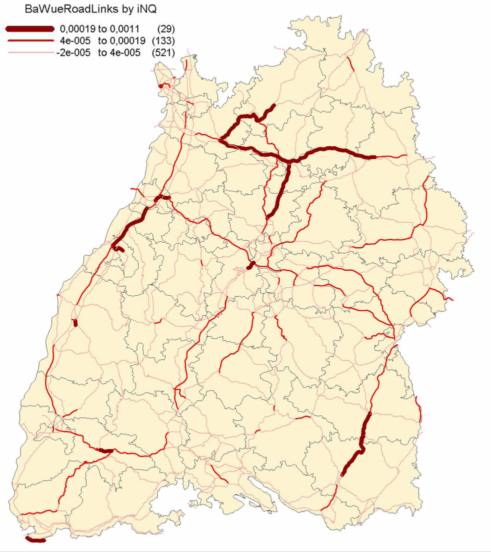


Figure: Comparative Importance of the links for the Baden - Wurttemberg Network – Modelling and analysis of transportation networks in earthquake prone areas via the N-Q measure, Tyagunov et al.

What About Disaster Relief?

The period between 2000-2004 experienced an average annual number of disasters that was 55% higher than the period of 1995-1999 with 33% more people affected in the more recent period.

Humanitarian Relief

Humanitarian Supply Chains

The supply chain is a critical component not only of corporations but also of humanitarian organizations and their logistical operations.

At least 50 cents of each dollar's worth of food aid is spent on transport, storage and administrative costs.

Vulnerability of Humanitarian Supply Chains

Extremely poor logistical infrastructures: Modes of transportation include trucks, barges, donkeys in Afghanistan, and elephants in Cambodia.

To ship the humanitarian goods to the affected area in the first 72 hours after disasters is crucial. The successful execution is not just a question of money but a difference between life and death.

Corporations expertise with logistics could help public response efforts for nonprofit organizations.

In the humanitarian sector, organizations are 15 to 20 years behind, as compared to the commercial arena, regarding supply chain network development.

Illustrations of Supply Chain Risk

It is clear that better-designed supply chain networks in which transportation plays a pivotal role would have facilitated and enhanced various emergency preparedness and relief efforts and would have resulted in less suffering and lives lost.

Design of Supply Chains for Critical Needs Products

Critical Needs Products

Critical needs products are those that are *essential to the survival of the population*, and can include, for example, vaccines, medicine, food, water, etc., depending upon the particular application.

The demand for the product should be met as nearly as possible since otherwise there may be additional loss of life.

In times of crises, a *system-optimization* approach is mandated since the demands for critical supplies should be met (as nearly as possible) at minimal total cost.

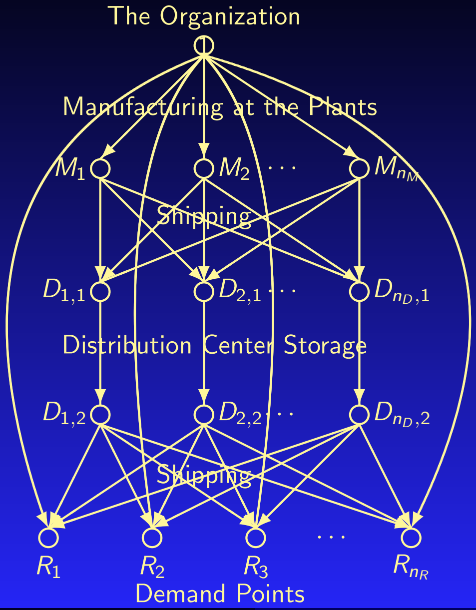
We have now developed a framework for the optimal design of critical needs product supply chains:

"Supply Chain Network Design for Critical Needs with Outsourcing,"

A. Nagurney, M. Yu, and Q. Qiang, *Papers in Regional Science* (2011), **90**, 123-142,

where additional background as well as references can be found.

Supply Chain Network Topology with Outsourcing



Applications to Vaccine Production

By applying the general theoretical model to the company's data, the firm can determine whether it needs to expand its facilities (or not), how much of the vaccine to produce where, how much to store where, and how much to have shipped to the various demand points. Also, it can determine whether it should outsource any of its vaccine production and at what level.

The firm by solving the model with its company-relevant data can then ensure *that the price that it receives for its vaccine production and delivery is appropriate* and that it recovers its incurred costs and obtains, if negotiated correctly, an equitable profit.

Applications to Emergencies

A company can, using the model, prepare and plan for an emergency such as a natural disaster in the form of a hurricane and identify where to store a necessary product (such as food packets, for example) so that the items can be delivered to the demand points in a timely manner and at minimal total cost.

Summary, Conclusions, and Suggestions for Future Research

- We discussed the *new era of networks of networks*.
- We emphasized the *importance of capturing behavior* in network modeling, analysis, and design and various paradoxes.
- We noted a *variety of supply chain network issues*: the addition of links; the integration of networks as in mergers and acquisitions; disaster relief issues.
- We presented the *Nagurney-Qiang network performance / efficiency measure* and how it has been applied to identify the importance and rankings of nodes and links along with various applications.

- We noted an *integrated framework for the design of supply chain networks for critical products* with outsourcing and discussed humanitarian operations applications.
- Our recent research in network design has also considered oligopolistic markets.
- In addition, we have been heaving involved in *constructing mathematical models that capture the impacts of foreign exchange risk and competition intensity* on supply chain companies who are involved in offshore outsourcing activities.
- Our research in supply chain networks has also led us to other time-sensitive products, such as *fast fashion*, and
- Finally, we are now working on modeling *disequilibrium dynamics and equilibrium states in ecological predator-prey networks*, that is, supply chains in nature.

- We expect that future research will include supply chain network design for robustness and resiliency.

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THANK YOU!

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