Perishable Product Supply Chain Networks: The Role of Transportation

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Swiss Transport Research Conference
Monte Verità, Ascona, Switzerland
May 16-18, 2018

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Acknowledgments

Many thanks to Professor Kay Axhausen for the invitation to deliver this keynote lecture at STRC.

Special acknowledgments and thanks to my students and collaborators who have made research and teaching always stimulating and rewarding.

Support for Our Research Has Been Provided by:

National Science Foundation

THE ROCKEFELLER FOUNDATION

Fulbright Scholar Program FULBRIGHT

RADCLIFFE INSTITUTE FOR ADVANCED STUDY
HARVARD UNIVERSITY

AT&T AT&T Foundation

John F. Smith Memorial Fund
University of Massachusetts
Amherst

UNIVERSITY OF GOTHENBURG
SCHOOL OF BUSINESS, ECONOMICS AND LAW

All Souls College
University of Oxford

Outline

- Background and Motivation
- Representation of Supply Chains as Networks
- Why User Behavior Must be Captured in Supply Chain Network Analysis and Design
- Time as a Challenge and Competitive Advantage
- Methodology – The Variational Inequality Problem
- Supply Chain Networks - Optimization Models
  - • Blood and Medical Nuclear Supply Chains
- Supply Chain Networks - Game Theory Models
  - • Electric Power and Food Supply Chains
- A Competitive Food Supply Chain Network Model with Quality as a Strategic Variable
- Some Other Issues in Supply Chain Networks that We Have Explored
- Summary and Conclusions

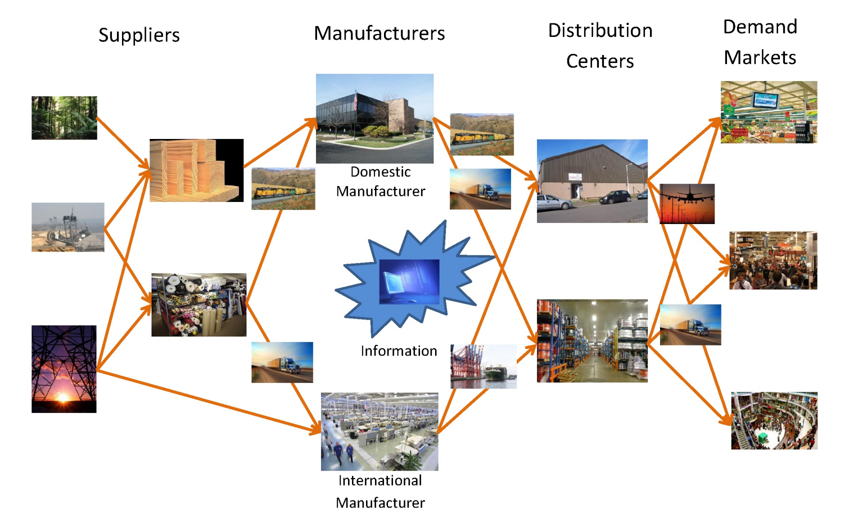
Background and Motivation

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

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

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

A General Supply Chain



Examples of Supply Chains

- food and food products
- high tech products
- automotive
- energy (oil, electric power, etc.)
- clothing and toys
- healthcare supply chains
- humanitarian relief
- supply chains in nature.

Examples of Supply Chains

Characteristics of Supply Chains and Networks Today

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

Supply Chains Are Network Systems

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

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

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

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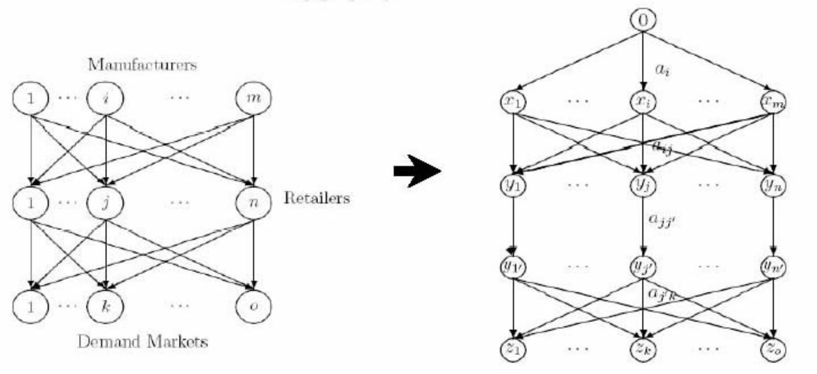
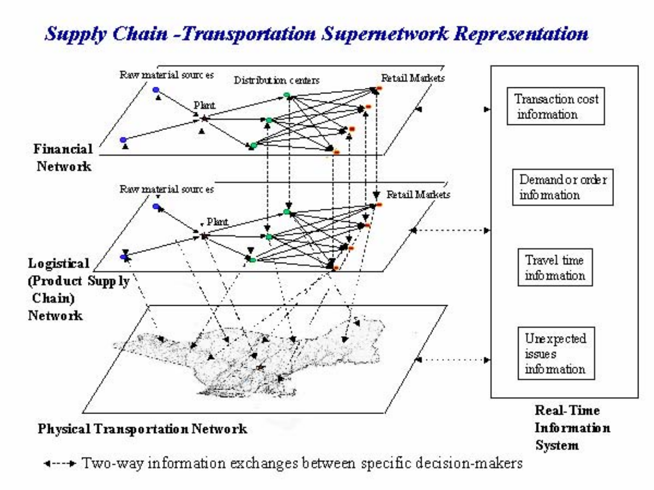
- build meaningful extensions using the graphical/network conceptualization.

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.

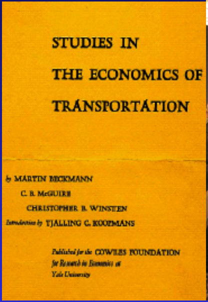
Representation of Supply Chains as Networks



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

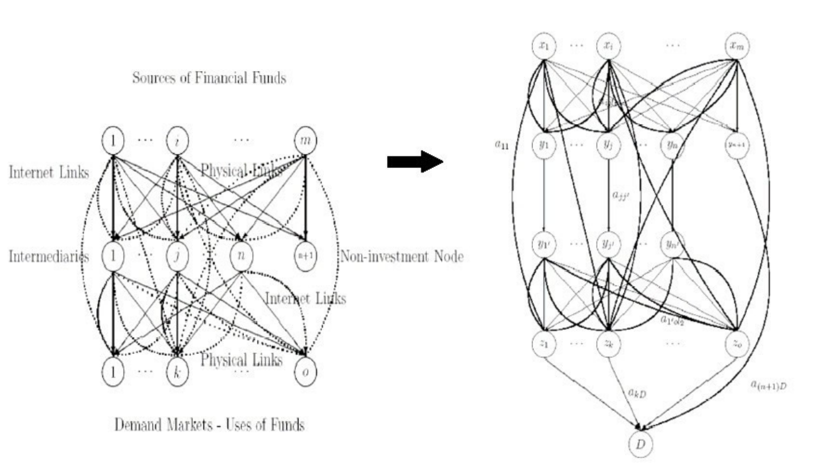
In 1952, Copeland in his book, *A Study of Moneyflows in the United States*, NBER, NY, asked whether money flows like water or electricity?

In 1956, Beckmann, McGuire, and Winsten in *Studies in the Economics of Transportation*, Yale University Press, hypothesized that electric power generation and distribution networks could be transformed into transportation network equilibrium problems.



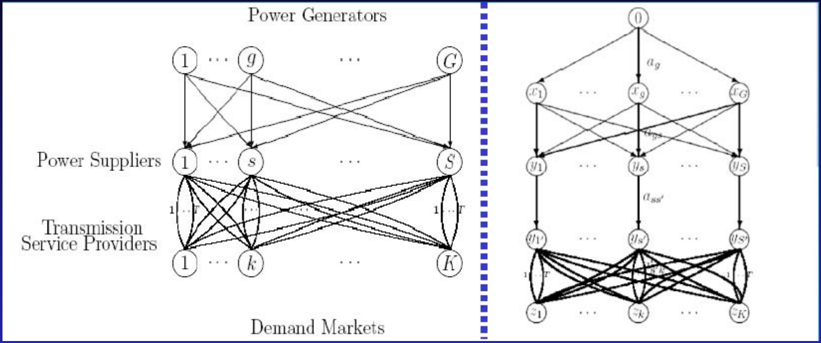
The Cowles Foundation at Yale University, through Dr. Philip Haile, kindly provided plaques and citations for Beckmann and McGuire.

Transportation Network Equilibrium Reformulation of the Financial Network Equilibrium Model with Intermediation



Liu and Nagurney, *Computational Management Science* **4** (2007), pp 243-281

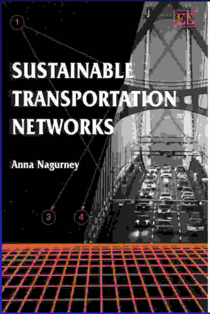
Representation of Supply Chains as Networks

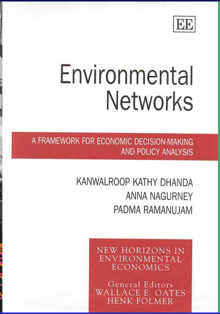


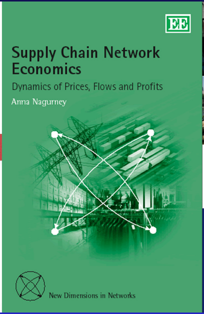
The transportation network equilibrium reformulation of electric power supply chain networks by Nagurney, Liu, Cojocaru, and Daniele, *Transportation Research E* **43** (2007), pp 624-646.

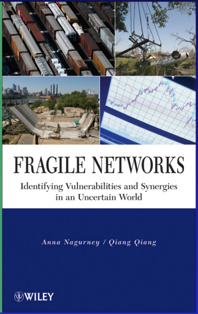
We have shown that both electricity as well as money flow like transportation flows.

Some of Our Books Related to Supply Chain Network Analysis and Design









Why User Behavior Must be Captured in Supply Chain Network Analysis and Design

Supply Chain Network Design Must Capture the Behavior of Users

Decision-makers select their cost-minimizing routes.

		User-Optimized
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.

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

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

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

The U-O problems, under certain simplifying assumptions, possess 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 $p \in P_w$:

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

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

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

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

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

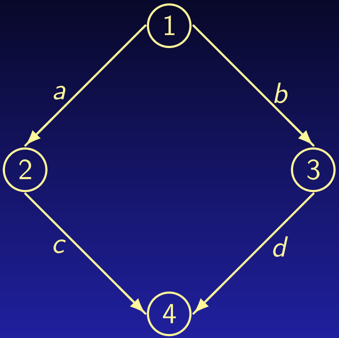
Although the paradox was presented in the context of transportation networks, it is relevant to other network systems in which decision-makers act in a noncooperative (competitive) manner.

The Braess (1968) Paradox

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

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

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



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

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

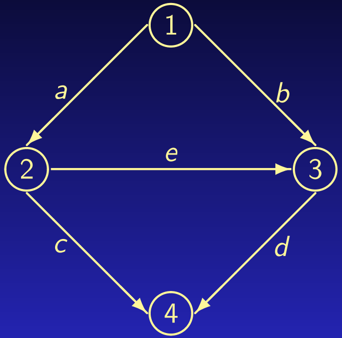
Adding a Link Increases Travel Cost for All!

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

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

The new equilibrium flow pattern network is
$x^*_{p_1} = x^*_{p_2} = x^*_{p_3} = 2$.

The equilibrium path travel cost:
$C_{p_1} = C_{p_2} = C_{p_3} = 92$.



$c_e(f_e) = f_e + 10$

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

"On a Paradox of Traffic Planning,"

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

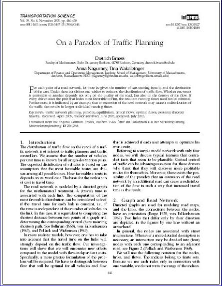
1. Einleitung

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.



TRANSPORTATION SCIENCE
Vol. 39, No. 4, November 2005, pp. 446–450
ISSN 0041-1655 | EISSN 1526-5447 | 05 | 3904 | 0446

DOI 10.1287/TRSC.1050.0127
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On a Paradox of Traffic Planning

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

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

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

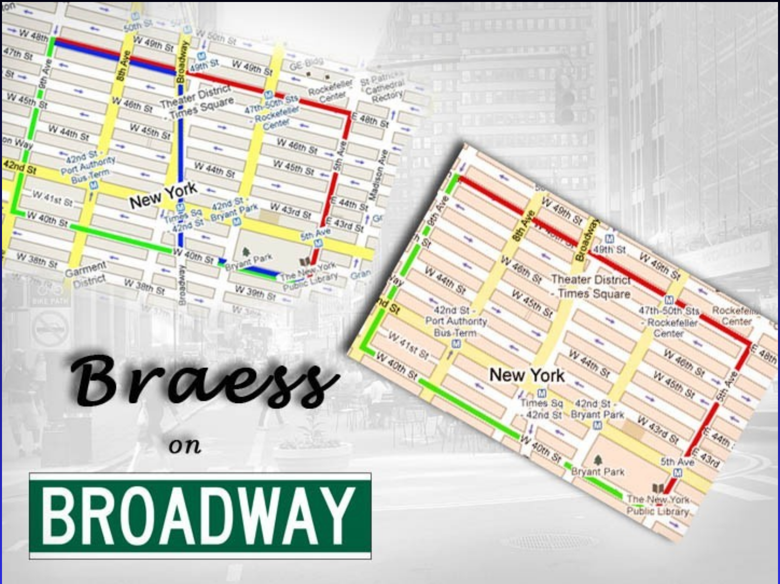
1. Introduction

The 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.

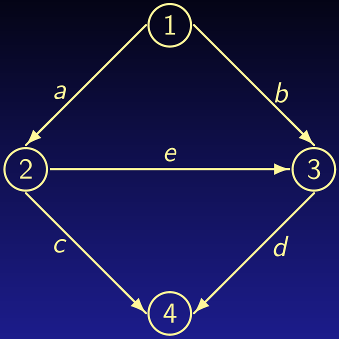
2002 - Seoul, Korea - A 6 lane road built over the Cheonggyecheon River that carried 160,000 cars per day and was perpetually jammed was torn down to improve traffic flow.


Braess
on
BROADWAY
New York
Theater District
- Times Square
Broadway
8th Ave
9th Ave
5th Ave
W 49th St
W 46th St
W 45th St
W 44th St
W 43rd St
W 40th St
Bryant Park
The New York
Public Library
42nd St -
Port Authority
Bus Term
47th-50th Sts
- Rockefeller
Center
Rockefeller
Center

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

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

The Braess paradox never occurs in S-O networks.



Recall the Braess network with the added link e.

What happens as the demand increases?

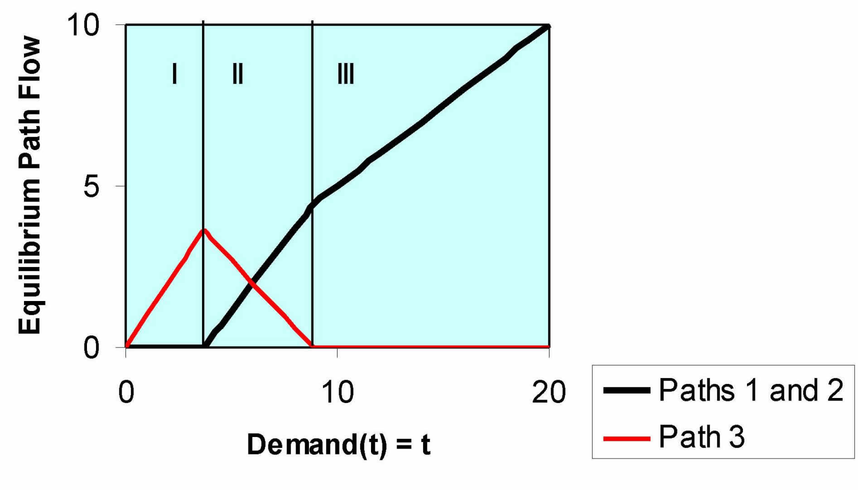
For Networks with Time-Dependent Demands

We Use Evolutionary Variational Inequalities

Radcliffe Institute for Advanced Study – Harvard University 2005-2006

Research with Professor David Parkes of Harvard University and Professor Patrizia Daniele of the University of Catania, Italy

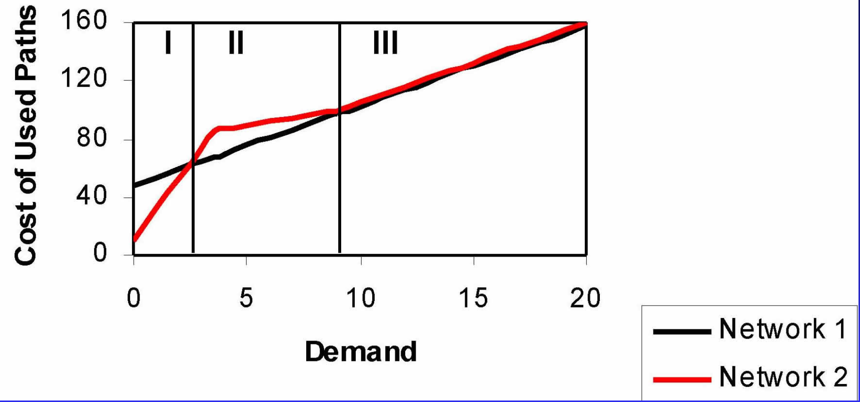
The U-O Solution of the Braess Network with Added Link (Path) and Time-Varying Demands Solved as an *Evolutionary Variational Inequality* (Nagurney, Daniele, and Parkes, *Computational Management Science* **4** (2007), pp 355-375).



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

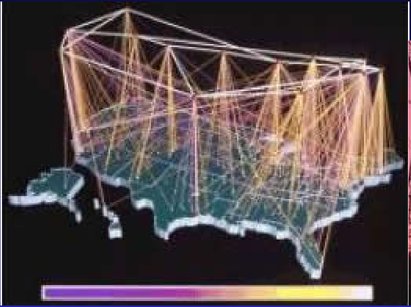
In Demand Regime II, the travel demand lies in the range [2.58, 8.89], and *the Addition of a New Link (Path) Makes Everyone Worse Off*!

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 when the demand goes out to infinity!

Other Networks that Behave like Traffic Networks



The Internet and electric power networks and even supply chains!

Time as a Challenge and Competitive Advantage

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- More knowledgeable (and demanding) consumers are expecting timely deliveries, despite, paradoxically, the great distances that may be involved from the producers to the consumers.

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- More knowledgeable (and demanding) consumers are expecting timely deliveries, despite, paradoxically, the great distances that may be involved from the producers to the consumers.

- Delivery times are becoming a strategy, as important as productivity, quality, and even innovation.

Time as a Challenge and Competitive Advantage

Practitioners realize that speed and consistency of delivery time are two essential components of customer satisfaction, along with price. Amazon Prime members can get deliveries on same day as orders in 16 metropolitan areas and maybe some day via drones.

Stalk, Jr., in his *Harvard Business Review* 1988 article, "Time - The next source of competitive advantage," utilized the term *time-based competition*, to single out time as the major factor for sustained competitive advantage.

Time and Perishable Products

Added challenges arise in the case of *Perishable Products*, which, by definition, are time-sensitive.

Benjamin Franklin wrote in 1748 in his “Advice to a Young Tradesman,” *Remember that Time is Money*.

It may also be said that *time is life*, since time-sensitive products, such as vaccines and medicines, as well as, at the most fundamental level, food and water, are of a life-sustaining, if not, life-saving, nature.

Time and Perishable Products

Classical examples of perishable goods include fresh produce in the form of fruits and vegetables, meat and dairy products, medicines and vaccines, radioisotopes, cut flowers, and even human blood.

We take the broader perspective of products being perishable not only in terms of their characteristics (such as their chemistry and the underlying physics) and *supply* (that is, the manner of procurement/production/processing, storage, transportation, etc.) aspects, but also in terms of the *demand* for the products.

We include, under the *perishable product* umbrella, products that are *discarded* (or replaced) relatively quickly after purchase, because of changing consumer tastes, such as *fast* fashion apparel, or those that become obsolete (as in certain high technology products).

Such an approach follows from Whitin (1957), who considered the deterioration of fashion goods at the end of a prescribed shortage period.

Time and Perishable Products

Supply chain management of perishable products at the strategic, tactical, and operational levels of the decision-making hierarchy is faced with such challenges as:

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- *Safety and environmental impact*: Perished products and the associated waste may be hazardous and may pollute.
- *Demand management*: Demand may be uncertain or known (as in scheduled treatments) and fixed. It may be price-sensitive (fashion apparel, consumer goods and pharma).

Methodology - The Variational Inequality Problem

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

Definition: The Variational Inequality Problem

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

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

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

Methodology - The Variational Inequality Problem

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

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

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

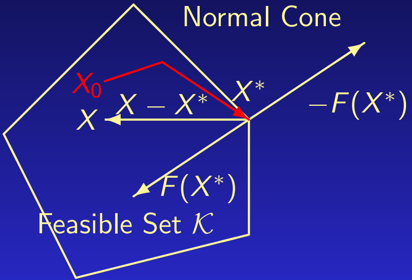
The variational inequality problem contains, as special cases, such mathematical programming problems as:

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

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

Geometric Interpretation of VI($F, \mathcal{K}$) and a Projected Dynamical System (Dupuis and Nagurney, 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 natural underlying dynamics associated with travel (and other) behavior to the equilibrium.

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

Such nonclassical dynamical systems are now being used in

evolutionary games (Sandholm (2005, 2011)),

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

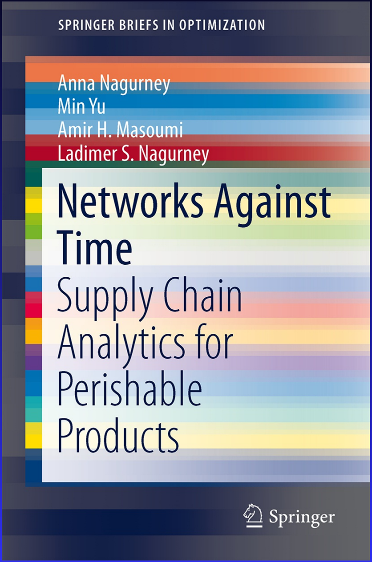
even *neuroscience* (Girard et al. (2008)

dynamic spectrum model for cognitive radio networks (Setoodeh, Haykin, and Moghadam (2012)).

A Multidisciplinary Perspective for Perishable Product Supply Chains

In our research on perishable and time-sensitive product supply chains, we utilize results from physics, chemistry, biology, and medicine in order to capture the perishability of various products over time from food to healthcare products such as blood, medical nucleotides, and pharmaceuticals.

A variety of perishable product supply chain models, computational procedures, and applications can be found in our book:



Supply Chain Networks – Optimization Models

Blood Supply Chains for the Red Cross

A. Nagurney, A. H. 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.

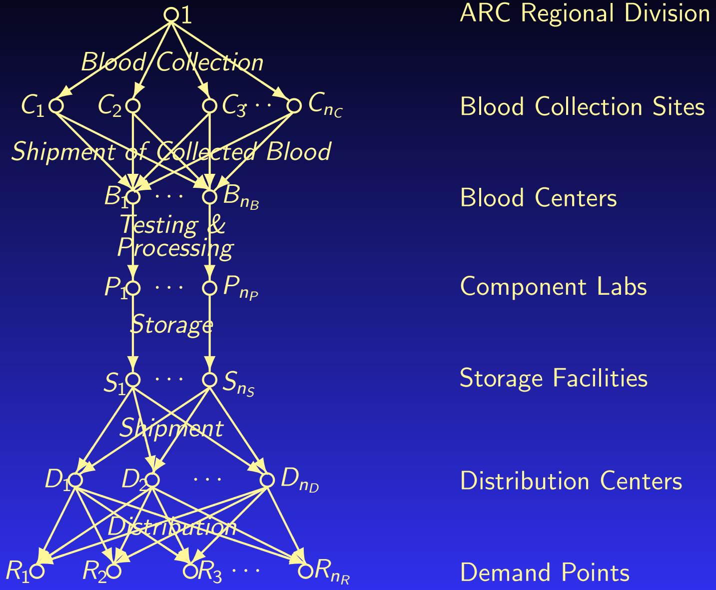
Blood Supply Chains for the Red Cross

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

American Red Cross
Together, we can save a life

Blood Supply Chains for the Red Cross

- The shelf life of platelets is 5 days and of red blood cells is 42.
- Over 39,000 donations are needed everyday in the US.
- Blood is a perishable product that cannot be manufactured but must be donated.
- As of February 1, 2018, the American Red Cross was facing a critical emergency need for blood and platelet donors. Severe winter weather forced the cancellation of hundreds of blood drives, resulting in nearly tens of thousands donations uncollected. In addition, flu in the US was close to epidemic levels.
- There is increasing competition among blood service organizations for donors and, overall, there has been a decrease in demand because of improved medical procedures.


1
Blood Collection
C_1 C_2 C_3 ··· C_{n_C}
Shipment of Collected Blood
B_1 ··· B_{n_B}
Testing &
Processing
P_1 ··· P_{n_P}
Storage
S_1 ··· S_{n_S}
Shipment
D_1 D_2 ··· D_{n_D}
Distribution
R_1 R_2 R_3 ··· R_{n_R}
ARC Regional Division
Blood Collection Sites
Blood Centers
Component Labs
Storage Facilities
Distribution Centers
Demand Points

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

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

"Medical Nuclear Supply Chain Design: A Tractable Network Model and Computational Approach," A. Nagurney and L. S. Nagurney, *International Journal of Production Economics* **140(2)** (2012), pp 865-874.

Medical Nuclear Supply Chains

In our medical nuclear supply chain models we capture the radioactive decay through the use of arc multipliers.

Hence, the framework for both our blood supply chain work and medical nuclear work is that of *generalized* networks.

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

Over 100,000 hospitals in the world use radioisotopes (World Nuclear Association (2011)).

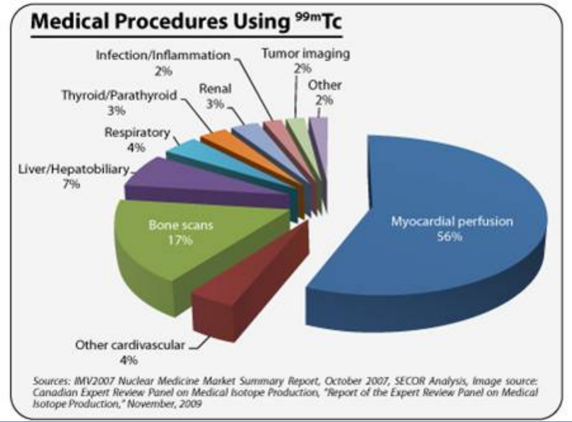
Technetium, ^{99m}Tc, which is a decay product of Molybdenum-99, ^{99}Mo, is the most commonly used medical radioisotope, used in more than 80% of the radioisotope injections, with more than 30 million procedures worldwide each year.

The half-life of Molybdenum-99 is 66 hours.

Each day, 41,000 nuclear medical procedures are performed in the United States using Technetium-99m.

Medical Nuclear Supply Chains

A radioactive isotope is bound to a pharmaceutical that is injected into the patient and travels to the site or organ of interest in order to construct an image for medical diagnostic purposes.



Medical Nuclear Supply Chains

For over two decades, all of the Molybdenum necessary for US-based nuclear medical diagnostic procedures has come from foreign sources.

^{99}Mo Supply Chain Challenges:

- The majority of the reactors are between 40 and 50 years old. Several of the reactors currently used are due to be retired by the end of this decade (Seeverens (2010) and OECD Nuclear Energy Agency (2010a)).

Medical Nuclear Supply Chains

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- The majority of the reactors are between 40 and 50 years old. Several of the reactors currently used are due to be retired by the end of this decade (Seeverens (2010) and OECD Nuclear Energy Agency (2010a)).
- Limitations in processing capabilities make the world critically vulnerable to Molybdenum supply chain disruptions.

Medical Nuclear Supply Chains

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- The number of generator manufacturers is under a dozen (OECD Nuclear Energy Agency (2010b)).

Medical Nuclear Supply Chains

^{99}Mo Supply Chain Challenges:

- The majority of the reactors are between 40 and 50 years old. Several of the reactors currently used are due to be retired by the end of this decade (Seeverens (2010) and OECD Nuclear Energy Agency (2010a)).
- Limitations in processing capabilities make the world critically vulnerable to Molybdenum supply chain disruptions.
- The number of generator manufacturers is under a dozen (OECD Nuclear Energy Agency (2010b)).
- Long-distance transportation of the product raises safety and security risks, and also results in greater decay of the product.

Medical Nuclear Supply Chains

In 2015, NorthStar Medical Radioisotopes LLC has received approval to begin routine production of molybdenum-99 (Mo-99) at the University of Missouri Research Reactor (MURR) facility in Columbia, Missouri. LEU rather than HEU will be used there.

This transitioning of NorthStar's Mo-99 line at MURR from a development process to a routine production process is another significant step toward establishing a domestic source of Mo-99.

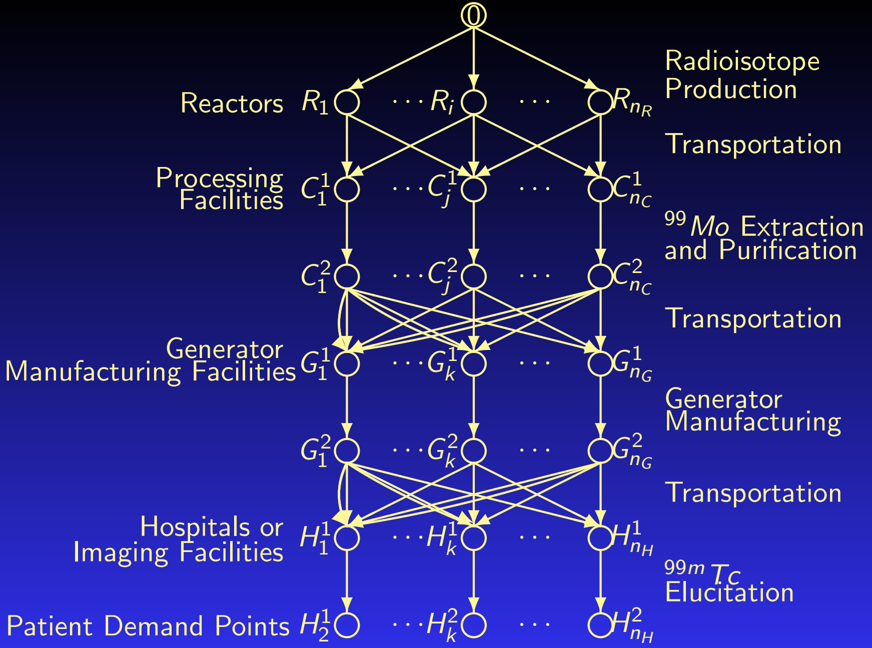


Figure 1: The Medical Nuclear Supply Chain Network Topology

Arc Multipliers

Because of the exponential decay of molybdenum, we have that the quantity of the radioisotope:

$$N(t) = N_0 e^{-\lambda t}$$

so that an arc multiplier on a link a that takes t_a hours of time corresponds to:

$$\alpha_a = e^{-\frac{ln2}{66.7} t_a}.$$

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.

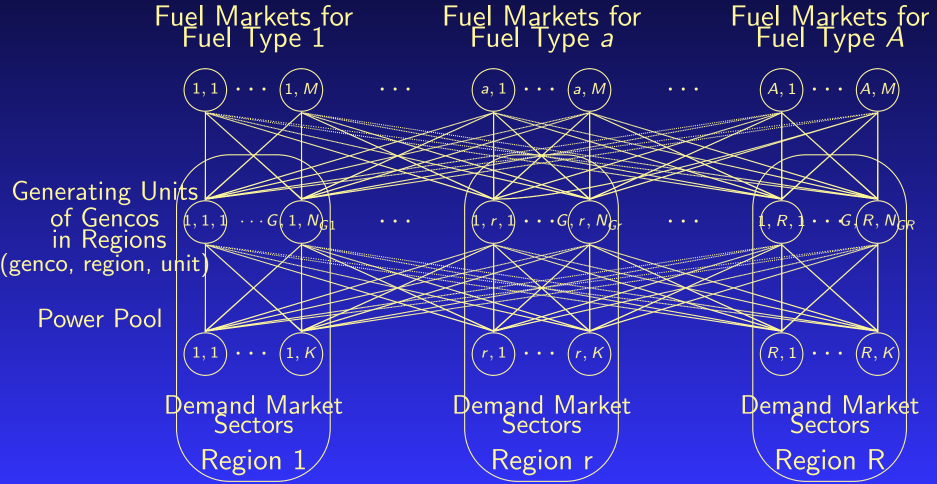
An Empirical Example of an Electric Power Supply Chain for New England

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

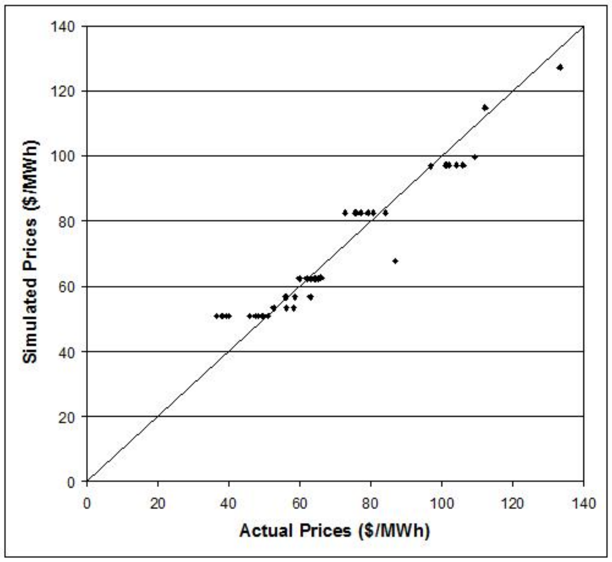
The Electric Power Supply Chain Network with Fuel Supply Markets



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; $w = 2, ..., 6$) and calculated the average regional demands and the average weighted regional prices for each block.

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

Actual Prices Vs. Simulated Prices ($/Mwh)



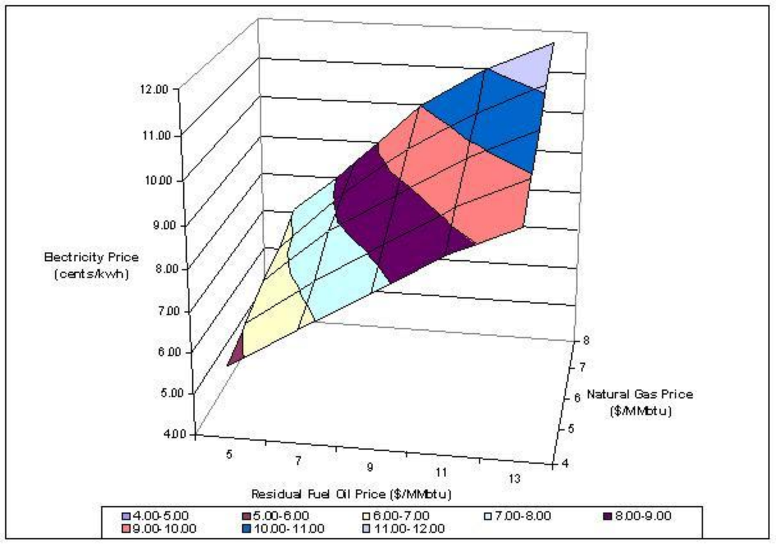
Sensitivity Analysis

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

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

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

Sensitivity Analysis



A Competitive Food Supply Chain Network Model
with
Quality as a Strategic Variable

This part of the lecture is based on the paper:

A. Nagurney, D. Besik, and M. Yu, "Dynamics of Quality as a Strategic Variable in Complex Food Supply Chain Network Competition: The Case of Fresh Produce," *Chaos* **28**, 043124 (2018); doi: 10.1063/1.5023683.

Food Supply Chains

Food is something anyone can relate to.

Fascinating Facts About Food Perishability

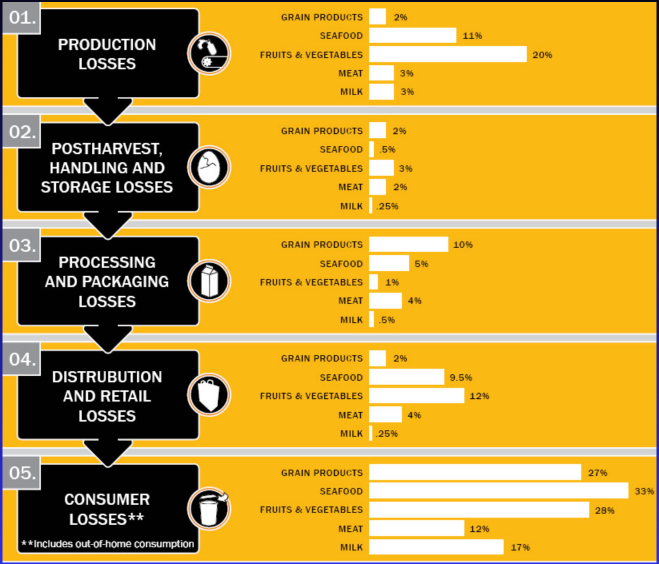
Source: Food and Agriculture Organization 2011

Fascinating Facts About Food Perishability

THE
SHELF LIFE OF FOOD

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

Fascinating Facts About Food Perishability



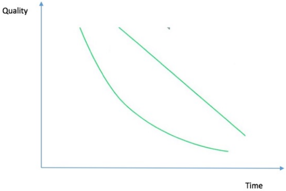
Source: Food and Agriculture Organization 2011

Background and Motivation

- **Food supply chains**, as noted in Yu and Nagurney (2013), are distinct from other product supply chains.
- Fresh produce is exposed to continuous and significant **change in the quality** of food products throughout the entire supply chain from the points of production/harvesting to points of demand/consumption.
- The quality of food products is **decreasing with time**, even with the use of advanced facilities and under the best **processing, handling, storage, and shipment** conditions (Sloof, Tijskens, and Wilkinson (1996) and Zhang, Habenicht, and Spieß (2003)).

Background and Motivation

- It has been discovered that the quality of fresh produce can be determined scientifically using **chemical formulae**, which include both **time** and **temperature**.
- The **initial quality** is also very important and food producers, such as farmers, have significant control over this important **strategic variable** at their production/harvesting sites.
- There are great opportunities for enhanced decision-making in this realm that can be supported by **appropriate models** and **methodological tools**.



Literature Review

- We note that early contributions focused on perishability and, in particular, on **inventory management** (see Ghare and Schrader (1963), Nahmias (1982, 2011) and Silver, Pyke, and Peterson (1998) for reviews).
- More recently, some studies have proposed integrating **more than a single supply chain network activity** (see, e.g., Zhang, Habenicht, and Spieß (2003), Widodo et al. (2006), Ahumada and Villalobos (2011), and Kopanos, Puigjaner, and Georgiadis (2012)).
- Yu and Nagurney (2013) have emphasized the need to bring greater realism to the underlying **economics** and **competition** on food supply chains.
- Additional modeling and methodological contributions in the **food supply chain** and **quality** domain have been made by Blackburn and Scudder (2009) and by Rong, Akkerman, and Grunow (2011).
- Besik and Nagurney (2017) formulating **short fresh produce supply chains** with the inclusion of the **dynamics of quality**, in the context of **farmers' markets**, while also capturing competition.

Contributions

• We construct a competitive supply chain network model for fresh produce under **oligopolistic competition** among the food firms, who are profit-maximizers.

• The firms have, as their **strategic variables**, not only the **product flows** on the pathways of their supply chain networks from the production/harvesting locations to the ultimate points of demand, but also the **initial quality** of the produce that they grow at their production locations.

• The consumers at the retail outlets (demand points), **differentiate the fresh produce** from the distinct firms and reflect their preferences through the **prices** that they are willing to pay which depend on quantities of the produce as well as **the average quality** of the produce associated with the firm and retail outlet pair(s).

• **Quality of the produce** reaching a destination node depends on its **initial quality** and **on the path** that it took with each particular path consisting of specific links, with particular characteristics of physical features of **time, temperature, etc.**.

Preliminaries on Quality

Fresh foods **deteriorate** since they are biological products, and, therefore, **lose quality over time**. The rate of **quality deterioration** can be represented as a function of the microenvironment, the gas composition, the relative humidity, and the temperature (Taoukis and Labuza (1989)).

Labuza (1984) demonstrated that the quality of a food attribute, Q, over time t, which can correspond, depending on the fruit or vegetable, to **the color change**, **the moisture content**, **the amount of nutrition such as vitamin C**, or **the softening of the texture**, can be formulated via the differential equation:

$$\frac{\partial Q}{\partial t} = -kQ^n = -Ae^{(-E/RT)}Q^n, \qquad (1)$$

where k is the reaction rate and is defined by the Arrhenius formula, $Ae^{(-E/RT)}$, A is a pre-exponential constant, T is the temperature, E is the activation energy, and R is the universal gas constant (cf. Arrhenius (1889)).

Preliminaries on Quality

If the reaction order n is zero, that is, $\frac{\partial Q}{\partial t} = -k$, and the **initial quality** is denoted by Q_0, we can quantify the **remaining quality** Q_t at time t (Tijskens and Polderdijk (1996)) according to:

$$Q_t = Q_0 - kt. \tag{2}$$

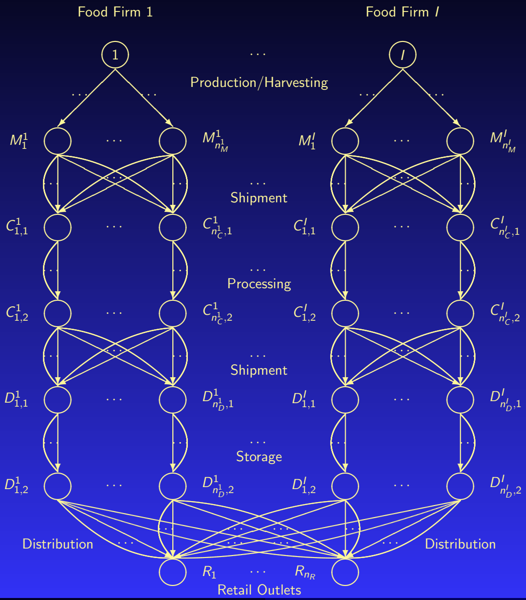
Examples of fresh produce that follow a reaction order of zero include **watermelons** and **spinach**.

If the reaction order is 1, known as a *first order reaction*, the quality decay function is then given by the expression:

$$Q_t = Q_0 e^{-kt}. \tag{3}$$

Popular fruits that follow first order kinetics include **peaches**, and **strawberries**, as well as vegetables such as: **peas, beans**, **carrots**, **avocados**, and **tomatoes**.

The Food Supply Chain Network Topology



Quality Over a Path

Let L^i denote the set of directed links in the supply chain network of food firm i; where $i = 1, \ldots, I$, which consists of **a set of production links**, L_1^i, and **a set of post-harvest links**, L_2^i, that is, $L^i \equiv L_1^i \cup L_2^i$.

Let β_b denote the **quality decay incurred on link** b, for $b \in L_2^i$, which is a factor that depends on the reaction order n, the reaction rate k_b, and the time t_b on link b, according to:

$$\beta_b \equiv \begin{cases} -k_b t_b, , & \text{if } n = 0, \forall b \in L_2^i, \forall i, \\ e^{-k_b t_b}, & \text{if } n = 1, \forall b \in L_2^i, \forall i, \end{cases} \quad (4)$$

where the reaction rate is

$$k_b = Ae^{(-E/RT_b)}, \quad \forall b \in L_2^i, \forall i. \quad (5)$$

Quality Over a Path

We can have **multiple paths** from an origin node i to a destination node k, P^i_k denotes the set of all paths that have origin i and destination k.

The quality q_p, over a path p, joining the origin node i, with a destination node k, with the incorporation of the quality deterioration of the fresh produce, is:

$$q_p \equiv \begin{cases} \mathbf{q^i_{0a}} + \sum_{b \in p \cap L^i_2} \beta_b, & \text{if} \quad n = 0,\ p \in P^i_k,\ \forall i, k, \\ q^i_{0a} \prod_{\mathbf{b} \in \mathbf{p} \cap \mathbf{L^i_2}} \beta_{\mathbf{b}}, & \text{if} \quad n = 1,\ p \in P^i_k,\ \forall i, k. \end{cases} \tag{6}$$

Here q^i_{0a} **is the initial quality** of the fresh produce on a top-most link a from an origin node i and in the path p under consideration.

Nonnegativity of the Path Flows

For each path p, joining an origin node i with a destination node k, the following nonnegativity condition must hold:

$$x_p \geq 0, \quad \forall p \in P_k^i;\ i = 1, \ldots, I;\ k = R_1, \ldots, R_{n_R}. \qquad (7)$$

Nonnegativity of the Initial Quality Levels

The initial quality of the fresh produce on the top-most links a of an origin node i, must be nonnegative, that is:

$$q_{0a}^i \geq 0, \quad \forall a \in L_1^i;\ i = 1, \ldots, I. \qquad (8)$$

Maximum Initial Quality Levels

We assume that the quality is bounded from above by a maximum value; hence, we have that:

$$q_{0a}^i \leq \bar{q}_{0a}^i, \quad \forall a \in L_1^i;\ i = 1, \ldots, I. \qquad (9)$$

Link Flows

The conservation of flow equations that relate the link flows of each food firm i; $i = 1, \ldots, I$, to the path flows are given by:

$$f_l = \sum_{p \in P} x_p \delta_{lp}, \quad \forall l \in L^i; \, i = 1, \ldots, I, \tag{10}$$

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

Link Capacities

Link flows must satisfy capacity constraints:

$$f_l \leq u_l, \quad \forall l \in L. \tag{11}$$

Capacities in Terms of Path Flows

In view of (10), we can rewrite (11) as:

$$\sum_{p \in P} x_p \delta_{lp} \leq u_l, \quad \forall l \in L. \tag{12}$$

The Food Supply Chain Network Model with Quality

Average Quality Levels

The average quality product of firm i, at retail outlet k, is given by:

$$\hat{q}_{ik} = \frac{\sum_{p \in P^i_k} q_p x_p}{\sum_{p \in P^i_k} x_p}, \quad i = 1, \dots, I; \; k = R_1, \dots, R_{n_R}. \tag{13}$$

Demands

The demand for food firm i's fresh food product at retail outlet k, d_{ik}, is equal to the sum of all the fresh produce flows on paths joining (i, k):

$$\sum_{p \in P^i_k} x_p = d_{ik}, \quad i = 1, \dots, I; \; k = R_1, \dots, R_{n_R}. \tag{14}$$

Demand Price Functions

The demand price of food firm i's product at retail outlet k is:

$$\rho_{ik} = \rho_{ik}(d, \hat{q}), \quad i = 1, \dots, I; \; k = R_1, \dots, R_{n_R}. \tag{15}$$

The Food Supply Chain Network Model with Quality

Costs of Production/Harvesting

The cost of production/harvesting at firm i's site a:

$$\hat{z}_a = \hat{z}_a(f_a, q^i_{0a}), \quad \forall a \in L^i_1;\ i = 1, \ldots, I. \tag{16}$$

Operational Cost Functions

The operational cost functions associated with the remaining links in the supply chain network are:

$$\hat{c}_b = \hat{c}_b(f), \quad \forall b \in L^i_2;\ i = 1, \ldots, I. \tag{17}$$

Vector of Path Flow Strategies

The vector of path flows of firm i; $i = 1, \ldots, I$ is:

$$X_i \equiv \{\{x_p\}|p \in P^i\}\} \in R_+^{n_{P^i}}, P^i \equiv \cup_{k=R_1\ldots,R_{n_R}} P^i_k. \tag{18}$$

Vector of Initial Quality Strategies

The vector of initial quality levels of firm i; $i = 1, \ldots, I$ is:

$$q^i_0 \equiv \{\{q^i_{0a}\}|a \in L^i_1\}\} \in R_+^{n_{L^i_1}}. \tag{19}$$

The Food Supply Chain Network Model with Quality

Utility Functions

The utility of firm i; $i = 1, \ldots, I$, is expressed as:

$$U_i = \sum_{k=R_1}^{R_{n_R}} \rho_{ik}(d, \hat{q}) d_{ik} - (\sum_{a \in L_1^i} \hat{z}_a(f_a, q_{0a}^i) + \sum_{b \in L_2^i} \hat{c}_b(f)). \qquad (20)$$

Rewritten Demand Price Functions

In view of (6), (13), and (14), we can rewrite (15) as:

$$\hat{\rho}_{ik}(x, q_0) \equiv \rho_{ik}(d, \hat{q}), \quad i = 1, \ldots, I; \; k = R_1, \ldots, R_{n_R}. \qquad (21)$$

Vector of the Profits

The I-dimensional vector $\hat{U}$ of profits of all firms i; $i = 1, \ldots, I$, is:

$$\hat{U} \equiv \hat{U}(X, q_0). \qquad (22)$$

Definition: Food Supply Chain Network Nash Equilibrium

A fresh produce path flow pattern and initial quality level $(X^*, q_0^*) \in K = \prod_{i=1}^{I} K_i$ constitutes a food supply chain network Nash Equilibrium if for each food firm i; $i = 1, \ldots, I$:

$$\hat{U}_i(X_i^*, X_{-i}^*, q_0^{i*}, q_0^{-i*}) \geq \hat{U}_i(X_i, X_{-i}^*, q_0^i, q_0^{-i*}), \quad \forall (X_i, q_0^i) \in K_i, \tag{23}$$

where $X_{-i}^* \equiv (X_1^*, \ldots, X_{i-1}^*, X_{i+1}^*, \ldots, X_I^*)$,
$q_0^{-i*} \equiv (q_0^{1*}, \ldots, q_0^{i-1*}, q_0^{i+1*}, \ldots, q_0^{I*})$, *and*
$K_i \equiv \{(X_i, q_0^i) | X_i \in R_+^{n_{P^i}}, q_0^i \in R_+^{n_{L_1^i}},$ (9) *and* (12) *hold for* $l \in L^i\}$.

Variational Inequality Formulation

An equilibrium is established if no food firm can unilaterally improve upon its profit by altering its product flows and initial quality at production sites in its supply chain network, given the product flows and initial quality decisions of the other firms.

Theorem: Variational Inequality Formulation

Assume that, for each food firm i; $i = 1, \ldots, I$, the profit function $\hat{U}_i(X, q_0)$ is concave with respect to the variables X_i and q_0^i, and is continuously differentiable. Then $(X^*, q_0^*) \in K$ is a supply chain network Nash Equilibrium according to the Definition if and only if it satisfies the variational inequality:

$$-\sum_{i=1}^{I} \langle \nabla_{X_i} \hat{U}_i(X^*, q_0^*), X_i - X_i^* \rangle - \sum_{i=1}^{I} \langle \nabla_{q_0^i} \hat{U}_i(X^*, q_0^*), q_0^i - q_0^{i*} \rangle \geq 0, \quad \forall (X, q_0) \in K, \qquad (24)$$

where $\langle \cdot, \cdot \rangle$ denotes the inner product in the corresponding Euclidean space and ∇ denotes the gradient.

An Equivalent Variational Inequality Formulation

An equivalent VI is:

Determine $(x^*, q_0^*, \lambda^*, \gamma^*) \in K^1$ *satisfying:*

$$\sum_{i=1}^{I} \sum_{k=R_1}^{R_{n_R}} \sum_{p \in P_k^i} \left[\frac{\partial \hat{Z}^i(x^*, q_0^{i*})}{\partial x_p} + \frac{\partial \hat{C}^i(x^*)}{\partial x_p} + \sum_{l \in L^i} \gamma_l^* \delta_{lp} - \hat{\rho}_{ik}(x^*, q_0^*) - \sum_{j=R_1}^{R_{n_R}} \frac{\partial \hat{\rho}_{ij}(x^*, q_0^*)}{\partial x_p} \sum_{r \in P_j^i} x_r^* \right]$$

$$\times [x_p - x_p^*] + \sum_{i=1}^{I} \sum_{a \in L_1^i} \left[\frac{\partial \hat{Z}^i(x^*, q_0^{i*})}{\partial q_{0a}^i} + \lambda_a^* - \sum_{j=R_1}^{R_{n_R}} \frac{\partial \hat{\rho}_{ij}(x^*, q_0^*)}{\partial q_{0a}^i} \sum_{r \in P_j^i} x_r^* \right] \times [q_{0a}^i - q_{0a}^{i*}]$$

$$+ \sum_{i=1}^{I} \sum_{a \in L_1^i} [\bar{q}_{0a}^i - q_{0a}^{i*}] \times [\lambda_a - \lambda_a^*] + \sum_{i=1}^{I} \sum_{l \in L^i} \left[u_l - \sum_{r \in P} x_r^* \delta_{lr} \right] \times [\gamma_l - \gamma_l^*] \geq 0,$$

$$\forall (x, q_0, \lambda, \gamma) \in K^1, \qquad (25)$$

where $K^1 \equiv \{(x, q_0, \lambda, \gamma) | x \in R_+^{n_P},\ q_0 \in R_+^{n_{L_1}},\ \lambda \in R_+^{n_{L_1}},\ \gamma \in R_+^{n_L}\}$.

An Equivalent Variational Inequality Formulation

For each path p; $p \in P_k^i$; $i = 1, \ldots, I$; $k = R_1, \ldots, R_{n_R}$:

$$\frac{\partial \hat{Z}^i(x, q_0^i)}{\partial x_p} \equiv \sum_{a \in L_1^i} \frac{\partial \hat{z}_a(f_a, q_{0a}^i)}{\partial f_a} \delta_{ap}, \tag{26a}$$

$$\frac{\partial \hat{C}^i(x)}{\partial x_p} \equiv \sum_{b \in L_2^i} \sum_{l \in L^i} \frac{\partial \hat{c}_b(f)}{\partial f_l} \delta_{lp}, \tag{26b}$$

$$\frac{\partial \hat{\rho}_{ij}(x, q_0)}{\partial x_p} \equiv \frac{\partial \rho_{ij}(d, \hat{q})}{\partial d_{ik}} + \frac{\partial \rho_{ij}(d, \hat{q})}{\partial \hat{q}_{ik}} \left(\frac{q_p}{\sum_{r \in P_k^i} x_r} - \frac{\sum_{r \in P_k^i} q_r x_r}{(\sum_{r \in P_k^i} x_r)^2} \right). \tag{26c}$$

For each a; $a \in L_1^i$; $i = 1, \ldots, I$,

$$\frac{\partial \hat{Z}^i(x, q_0^i)}{\partial q_{0a}^i} \equiv \frac{\partial \hat{z}_a(f_a, q_{0a}^i)}{\partial q_{0a}^i}, \tag{26d}$$

$$\frac{\partial \hat{\rho}_{ij}(x, q_0)}{\partial q_{0a}^i} \equiv \sum_{h=R_1}^{R_{n_R}} \sum_{s \in P_h^i} \frac{x_s}{\sum_{r \in P_h^i} x_r} \frac{\partial \rho_{ij}(d, \hat{q})}{\partial \hat{q}_{ih}} \frac{\partial q_s}{\partial q_{0a}^i}. \tag{26e}$$

In particular, if link a is not included in path s, $\frac{\partial q_s}{\partial q_{0a}^i} = 0$; if link a is included in path s, following (6), we have:

$$\frac{\partial q_s}{\partial q_{0a}^i} = \begin{cases} 1, & \text{if } n = 0, \\ \prod_{b \in s \cap L_2^i} \beta_b, & \text{if } n = 1. \end{cases} \tag{26f}$$

Relationship of the Model to Others in the Literature

Relationship of the Model to Others in the Literature

The above model is now related to several models in the literature.

If quality is not a strategic variable and the product is not perishable, then the model is related to the sustainable fashion supply chain network model of Nagurney and Yu in the *International Journal of Production Economics* **135** (2012), pp 532-540. In that model, however, the other criterion, in addition to the profit maximization one, was emission minimization, rather than waste cost minimization, as in the model in this paper.

Relationship of the Model to Others in the Literature

If the demands are fixed, and there is a single organization, but there are additional processing tiers, as well as capacity investments as variables, along with arc multipliers for perishability, then the model is the medical nuclear supply chain design model of Nagurney and Nagurney, *International Journal of Production Economics* (2012).

Relationship of the Model to Others in the Literature

If the demands are fixed, and there is a single organization, but there are additional processing tiers, as well as capacity investments as variables, along with arc multipliers for perishability, then the model is the medical nuclear supply chain design model of Nagurney and Nagurney, *International Journal of Production Economics* (2012).

If there is only a single organization / firm, and the demands are subject to uncertainty, with the inclusion of expected costs due to shortages or excess supplies, the total operational cost functions are separable, and a criterion of risk is added, then the model above is related to the blood supply chain network operations management model of Nagurney, Masoumi, and Yu, *Computational Management Science* (2012).

Relationship of the Model to Others in the Literature

If the product is homogeneous, and there is no quality and associated deterioration, and the total costs are assumed to be separable, then the above model collapses to the supply chain network oligopoly model of Nagurney (2010) in which synergies associated with mergers and acquisitions were assessed.

The Original Supply Chain Network Oligopoly Model

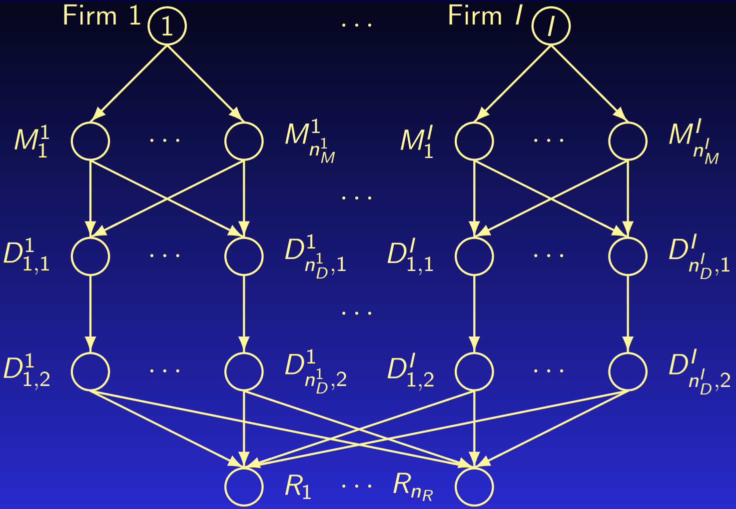


Figure 2: Supply Chain Network Structure of the Oligopoly Without Perishability; Nagurney, *Computational Management Science* **7**(2010), pp 377-401.

Mergers Through Coalition Formation

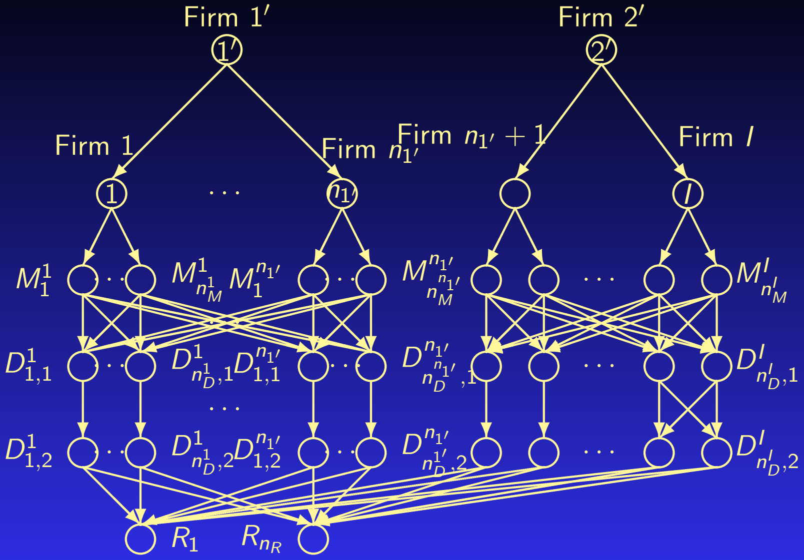


Figure 3: Mergers of the First $n_{1'}$ Firms and the Next $n_{2'}$ Firms

The Algorithm - Euler Method

The Euler method, which is induced by the general iterative scheme of Dupuis and Nagurney (1993), is applied to this model.

Specifically, iteration τ of the Euler method applied to solve the VI problem in standard form is given by:

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

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

The Algorithm

As shown in Dupuis and Nagurney (1993) and Nagurney and Zhang (1996), for convergence of the general iterative scheme, which induces the Euler method, the sequence $\{a_\tau\}$ must satisfy: $\sum_{\tau=0}^{\infty} a_\tau = \infty$, $a_\tau > 0$, $a_\tau \to 0$, as $\tau \to \infty$.

Conditions for convergence of this scheme as well as various applications to the solutions of network oligopolies can be found in Nagurney and Zhang (1996), Nagurney, Dupuis, and Zhang (1994), Nagurney (2010a), and Nagurney and Yu (2011).

The Euler Method Explicit Formulae at Iteration $\tau + 1$

For each path $p \in P^i_j$, $\forall i, j$, compute:

$$x_p^{\tau+1} = \max\{0, x_p^\tau + \alpha_\tau(\hat{\rho}_{ik}(x^\tau, q_0^\tau) + \sum_{j=R_1}^{R_{n_R}} \frac{\partial \hat{\rho}_{ij}(x^\tau, q_0^\tau)}{\partial x_p} \sum_{r \in P^i_j} x_r^\tau$$

$$- \frac{\partial \hat{Z}^i(x^\tau, q_0^{i\tau})}{\partial x_p} - \frac{\partial \hat{C}^i(x^\tau)}{\partial x_p} - \sum_{l \in L^i} \gamma_l^\tau \delta_{lp})\}.$$

For each initial quality level $a \in L^i_1$, $\forall i$, in turn, compute:

$$q_{0a}^{i\tau+1} = \max\{0, q_{0a}^{i\tau} + \alpha_\tau(\sum_{j=R_1}^{R_{n_R}} \frac{\partial \hat{\rho}_{ij}(x^\tau, q_0^\tau)}{\partial q_{0a}^i} \sum_{r \in P^i_j} x_r^\tau - \frac{\partial \hat{Z}^i(x^\tau, q_0^{i\tau})}{\partial q_{0a}^i} - \lambda_a^\tau)\}.$$

The Euler Method Explicit Formulae at Iteration $\tau + 1$

The Lagrange multiplier for each top-most link $a \in L_1^i$; $i = 1, \ldots, I$, associated with the initial quality bounds is computed as:

$$\lambda_a^{\tau+1} = \max\{0, \lambda_a^\tau + \alpha_\tau(q_{0a}^{i\tau} - \bar{q}_{0a}^i)\}.$$

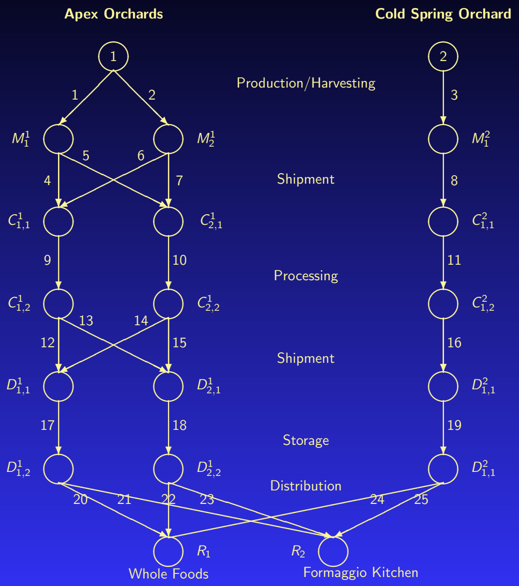
The Lagrange multiplier for each link $l \in L^i$; $i = 1, \ldots, I$, associated with the link capacities is computed according to:

$$\gamma_l^{\tau+1} = \max\{0, \gamma_l^\tau + \alpha_\tau(\sum_{r \in P} x_r^\tau \delta_{lr} - u_l)\}.$$

A Case Study on Peaches

- We focus on the **peach market** in the United States, specifically in **Western Massachusetts**.
- It is noted that, in 2015, the United States peach production was **825,415 tons** in volume, and 606 million dollars in worth (USDA NASS (2016), Zhao et al. (2017)).
- We selected two orchards from Western Massachusetts: **Apex Orchards** and **Cold Spring Orchard**, located, respectively, in Shelburne, MA and Belchertown, MA.
- The orchards sell their peaches to two retailers, **Whole Foods**, located in Hadley, MA, and **Formaggio Kitchen**, located in Cambridge, MA.
- The mode of **transportation** for both of the orchards is **trucks**.
- The **color change attribute** of peaches, in the form of **browning**, follows **a first-order**, that is, an **exponential decay function**.

Supply Chain Network Topology for the Case Study



Parameters for the Calculation of Quality Decay

Link b	Hours	Temperature (Celsius)	β_b ($n = 1$)
4	1	23	0.9961
5	2	23	0.9922
6	2	23	0.9922
7	1	23	0.9961
8	2	27	0.9913
9	3	18	0.9906
10	3	18	0.9906
11	4	25	0.9836
12	1	23	0.9961
13	2	23	0.9922
14	2	23	0.9922
15	1	23	0.9961
16	3	27	0.9870
17	48	1	1.0000
18	72	1	1.0000
19	96	18	0.7397
20	2	27	0.9913
21	4	27	0.9827
22	1	27	0.9956
23	4	27	0.9827
24	0.5	27	0.9978
25	4	27	0.9827

Cost Functions, Capacities and Upper Bounds for the Numerical Examples

Table 1: Total Production / Harvesting Cost Functions, Link Capacities, and Upper Bounds on Initial Quality

Link a	$\hat{z}_a(f_a, q_{0a}^i)$	u_a	$\bar{q}_{0a}^i$
1	$.002f_1^2 + f_1 + 0.7q_{01}^1 + .01(q_{01}^1)^2$	200	98
2	$.002f_2^2 + f_2 + 0.7q_{02}^1 + .01(q_{02}^1)^2$	200	95
3	$.002f_3^2 + f_3 + 0.5q_{03}^2 + .001(q_{03}^1)^2$	150	90

Table 2: Total Operational Link Cost Functions and Link Capacities

Link b	$\hat{c}_b(f)$	u_b
4	$.001f_4^2 + .7f_4$	150
5	$.002f_5^2 + .7f_5$	150
6	$.001_6^2 + .5f_6$	120
7	$.002f_7^2 + .5f_7$	120
8	$.002f_8^2 + .9f_8$	100
9	$.0025f_9^2 + 1.2f_9$	200
10	$.0025f_{10}^2 + 1.2_{10}$	200
11	$.0026f_{11}^2 + 1.5f_{11}$	150
12	$.001f_{12}^2 + .6f_{12}$	150
13	$.002f_{13}^2 + .6f_{13}$	150
14	$.001f_{14}^2 + .6f_{14}$	150
15	$.002f_{15}^2 + .6f_{15}$	150
16	$.002f_{16}^2 + .6f_{16}$	120
17	$.003f_{17}^2 + .5f_{17}$	150
18	$.0037f_{18}^2 + .9f_{18}$	150
19	$.002f_{19}^2 + .7f_{19}$	120
20	$.002f_{20}^2 + .6f_{20}$	150
21	$.003f_{21}^2 + .7f_{21}$	120
22	$.002f_{22}^2 + .6f_{22}$	150
23	$.003f_{23}^2 + .7f_{23}$	100
24	$.002f_{24}^2 + .6f_{24}$	100
25	$.003f_{25}^2 + .7f_{25}$	100

- We report the total **production / harvesting cost functions**,**the upper bounds on the initial quality**, the total operational cost functions, and the link flow capacities.
- The Euler method is implemented in FORTRAN and a Linux system at the University of Massachusetts used for the computations.
- The data is gathered from Sumner and Murdock (2017) and Dris and Jain (2007), in which the authors made a sample cost analysis.
- The **time horizon**, under consideration, is that of **a week**.
- The Euler method is implemented in FORTRAN and a Linux system at the University of Massachusetts used for the computations.
- The sequence is, $a_\tau = \{1, \frac{1}{2}, \frac{1}{2}, \frac{1}{3}, \ldots\}$, with the convergence tolerance being 10^{-7}.

Example 1 - Baseline

- It is known that both retailers sell **high quality food** products, with **Formaggio Kitchen** selling peaches at a higher price due to its emphasis on **quality**.
- Through conversations at the retailers, we concluded that **Apex Orchards** sell their **peaches** at a higher price. Demand Price Functions of Apex Orchards:

$$\rho_{11} = -.02d_{11} - .01d_{21} + 0.008\hat{q}_{11} + 20,$$

$$\rho_{12} = -.02d_{12} - .01d_{22} + 0.01\hat{q}_{12} + 22.$$

Demand Price Functions of Cold Spring Orchard:

$$\rho_{21} = -.02d_{21} - .015d_{11} + 0.008\hat{q}_{21} + 18,$$

$$\rho_{22} = -.02d_{22} - .015d_{12} + 0.01\hat{q}_{22} + 19.$$

Equilibrium Flows, Equilibrium Initial Quality, and the Equilibrium Lagrange Multipliers

Link a	f_a^*	q_{0a}^{i*}	γ_a^*	λ_a^*
1	133.43	97.54	0.00	0.00
2	**166.57**	**95.00**	**0.00**	**0.05**
3	100.00	65.61	0.00	0.00

Table: Equilibrium Link Flows, Equilibrium Initial Quality, and the Equilibrium Production Site Lagrange Multipliers

Table: Equilibrium Link Flows and the Equilibrium Link Lagrange Multipliers

Link b	f_b^*	γ_b^*
4	69.31	0.00
5	64.12	0.00
6	90.33	0.00
7	76.24	0.00
8	**100.00**	**6.53**
9	159.64	0.00
10	140.36	0.00
11	100.00	0.00
12	81.96	0.00
13	77.68	0.00
14	68.04	0.00
15	72.32	0.00
16	100.00	0.00
17	**150.00**	**6.95**
18	**150.00**	**6.19**
19	100.00	0.00
20	64.84	0.00
21	85.16	0.00
22	65.10	0.00
23	84.90	0.00
24	47.80	0.00
25	52.20	0.00

Equilibrium Prices, Demands, Average Quality, and Profits

Equilibrium Prices at the Demand Markets:

$$\rho_{11} = 17.67, \ \boldsymbol{\rho_{12} = 19.00}, \ \rho_{21} = 15.47, \ \rho_{22} = 15.86.$$

Equilibrium Demands:

$$d^*_{11} = 129.95, \ \mathbf{d^*_{12} = 170.05}, \ d^*_{21} = 47.80, \ d^*_{22} = 52.20.$$

Average Quality:

$$\mathbf{\hat{q}_{11} = 93.40}, \ \hat{q}_{12} = 92.56, \ \hat{q}_{21} = 46.60, \ \hat{q}_{22} = 45.90.$$

Profits:

$$\mathbf{U_1 = 3,302.01}, \quad U_2 = 787.65.$$

Sensitivity Analysis and Insights

The orchards may wish to invest in enhancing their capacity with Apex Orchards focusing on the storage facilities and Cold Spring Orchard on its freight shipment capacity.

- **When we raised u_8 to 150, while keeping all the other data as above, the profit of Cold Spring Orchard increased to 921.74** whereas that of Apex Orchards (because of the competition) decreased to 3,272.11.

- **When we raised both u_{17} and u_{18} to 200 and kept all the other data as in Example 1 above, then the profit enjoyed by Apex Orchards increased to 3,884.80** and that of Cold Spring Orchard decreased to 696.87.

Sensitivity Analysis and Insights

- Finally, **we had both orchards make investments so that $u_8 = 150$ and u_{17} and u_{18} were equal to 200. The profit of Apex Orchards was now 3,844.89 and that of Cold Spring: 815.37**. Both firms gain as compared to the profit values in Example 1. The demand prices are now lower but the average quality higher with $\rho_{11} = 16.54$, $\rho_{12} = 17.94$, $\rho_{21} = 14.64$, and $\rho_{22} = 15.10$, and $\hat{q}_{11} = 93.79$, $\hat{q}_{12} = 92.92$, $\hat{q}_{21} = 63.93$, and $\hat{q}_{22} = 67.96$.

By investing in supply chain infrastructure both producers and consumers gain.

Example 2 - Disruption Scenario 1

- We now consider a **disruption scenario** in which a **natural disaster** has significantly affected the **capacity** of the orchard production sites of both orchards.
- Such an incident occurred in **2016 in the Northeast of the United States** when extreme weather in terms of cold temperatures "decimated" the **peach crop**.
- We now have the following capacities on the production/harvesting links:

$$u_1 = 100, \; u_2 = 150, \; u_3 = 80.$$

Link a	f_a^*	q_{0a}^{i*}	γ_a^*	λ_a^*
1	**100.00**	75.54	**8.17**	0.00
2	**150.00**	75.54	**8.18**	0.00
3	**80.00**	11.02	**7.78**	0.00

Table 3: Equilibrium Link Flows, Equilibrium Initial Quality, and the Equilibrium Production Site Lagrange Multipliers

Equilibrium Link Flows and the Equilibrium Link Lagrange Multipliers

Link b	f_b^*	γ_b^*
4	50.28	0.00
5	49.72	0.00
6	82.76	0.00
7	67.24	0.00
8	80.00	0.00
9	133.04	0.00
10	116.96	0.00
11	80.00	0.00
12	80.78	0.00
13	52.25	0.00
14	69.22	0.00
15	47.75	0.00
16	80.00	0.00
17	**150.00**	**0.17**
18	100.00	0.00
19	80.00	0.00
20	67.2	0.00
21	82.79	0.00
22	37.46	0.00
23	62.54	0.00
24	37.67	0.00
25	42.33	0.00

Equilibrium Prices, Demands, Average Quality, and Profits

Equilibrium Prices at the Demand Markets:

$$\rho_{11} = 18.12, \; \boldsymbol{\rho_{12} = 19.40}, \; \rho_{21} = 15.74, \; \rho_{22} = 16.05.$$

Equilibrium Demands:

$$d_{11}^* = 104.67, \; \mathbf{d_{12}^* = 145.33}, \; d_{21}^* = 37.67, \; d_{22}^* = 42.33.$$

Average Quality:

$$\hat{\mathbf{q}}_{11} = \mathbf{73.42}, \; \hat{q}_{12} = 72.68, \; \hat{q}_{21} = 7.83, \; \hat{q}_{22} = 7.71.$$

Profits:

$$\mathbf{U_1 = 2,984.07}, \quad U_2 = 675.72.$$

Insights

Observe from the above equilibrium solution that all the production sites are now at their capacities and, hence, the corresponding link Lagrange multipliers are all positive.

Also, observe that the average quality of each orchard's peaches has decreased at each retailer, as compared to the results for Example 1. The demand prices have increased but more for the peaches of Apex Orchards than those from Cold Spring Orchard.

The profit is reduced for both orchards because of the limitations on how many pecks of peaches they can produce and harvest due to the disruption caused by the natural disaster.

Example 3 - Disruption Scenario 2

- We consider a **disruption** that affects **transportation** in that the links 5 and 6 associated with the supply chain network of **Apex Orchards** are no longer available.
- This can occur and has occurred in western Massachusetts as a result of flooding.
- We now have the following capacities on those links:

$$u_5 = 0, \;\; u_6 = 0.$$

Link a	f_a^*	q_{0a}^{i*}	γ_a^*	λ_a^*
1	150.00	84.50	0.00	0.00
2	120.00	84.50	0.00	0.00
3	100.00	65.59	0.00	0.00

Table 4: Equilibrium Link Flows, Equilibrium Initial Quality, and the Equilibrium Production Site Lagrange Multipliers

Equilibrium Link Flows and the Equilibrium Link Lagrange Multipliers

Link b	f_b^*	γ_b^*
4	150.00	6.94
5	**0.00**	**78.33**
6	**0.00**	**79.92**
7	**120.00**	**7.27**
8	**100.00**	**6.75**
9	150.00	0.00
10	120.00	0.00
11	100.00	0.00
12	85.36	0.00
13	64.64	0.00
14	64.64	0.00
15	55.36	0.00
16	100.00	0.00
17	**150.00**	**0.40**
18	**120.00**	**6.19**
19	100.00	0.00
20	66.22	0.00
21	83.78	0.00
22	48.52	0.00
23	71.48	0.00
24	47.86	0.00
25	52.14	0.00

Equilibrium Prices, Demands, Average Quality, and Profits

Equilibrium Prices at the Demand Markets:

$$\rho_{11} = 17.89, \ \boldsymbol{\rho_{12} = 19.19}, \ \rho_{21} = 15.69, \ \rho_{22} = 16.09.$$

Equilibrium Demands:

$$d^*_{11} = 114.74, \ \mathbf{d^*_{12} = 155.26}, \ d^*_{21} = 47.86, \ d^*_{22} = 52.14.$$

Average Quality:

$$\hat{\mathbf{q}}_{\mathbf{11}} = \mathbf{82.32}, \ \hat{q}_{12} = 81.46, \ \hat{q}_{21} = 46.59, \ \hat{q}_{22} = 45.88.$$

Profits:

$$\mathbf{U_1 = 3,074.72}, \quad U_2 = 811.35.$$

Sensitivity Analysis and Insights

Apex Orchards farm experiences a loss in profits, whereas its competitor, Cold Spring Orchards, garners a higher profit, as compared to the baseline Example 1.

Both orchards raise their prices and the average quality of their produce drops although much more significantly for Apex Orchards, which has suffered a supply chain disruption in terms of transportation/shipment possibilities.

Sensitivity Analysis and Insights

We then addressed the following questions: What would be the impact on profits if only link 5 was restored to its original capacity of 150 (and link 6 remained unavailable)? What would be the impact on profits if only link 6 was restored to its original capacity of 120 (and link 5 remained unavailable)?

The profit of Apex Orchards was 3,272.78 with link 5 restored only and that of Cold Spring Orchard was: 787.64. On the other hand, if link 6 was restored only, then Apex Orchards garnered 3,283.32 in profit and Cold Spring Orchard 787.67 in profit.

Given the choice, Apex Orchards should advocate for restoration of link 6 versus link 5 if only one link restoration is feasible.

Some Other Issues that We Have Explored Using Supply Chain Network Theory

- 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
- Time in Disaster Relief
- Competing on Supply Chain Quality
- Summary, Conclusions, and Suggestions for Future Research

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, "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** (2006), pp 353-393.

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

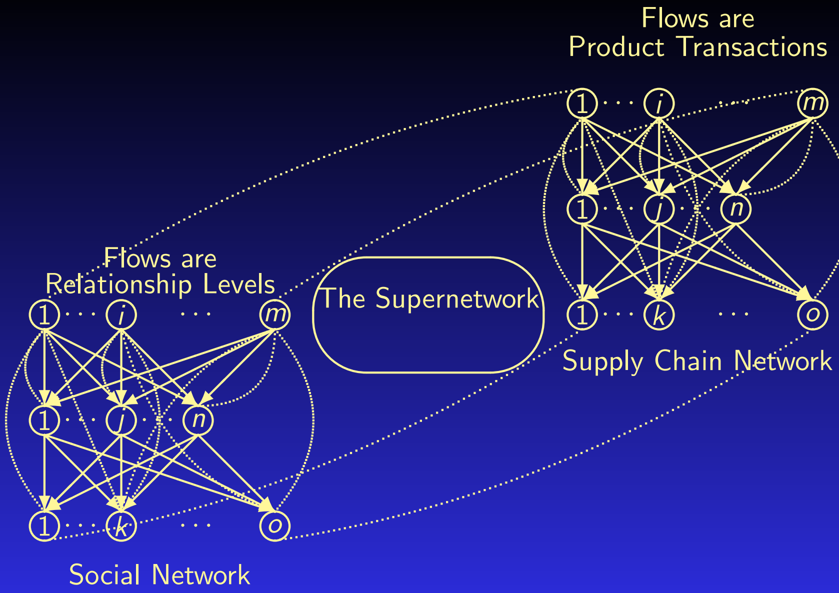


Figure 4: The Multilevel Supernetwork Structure of the Integrated Supply Chain / Social Network System

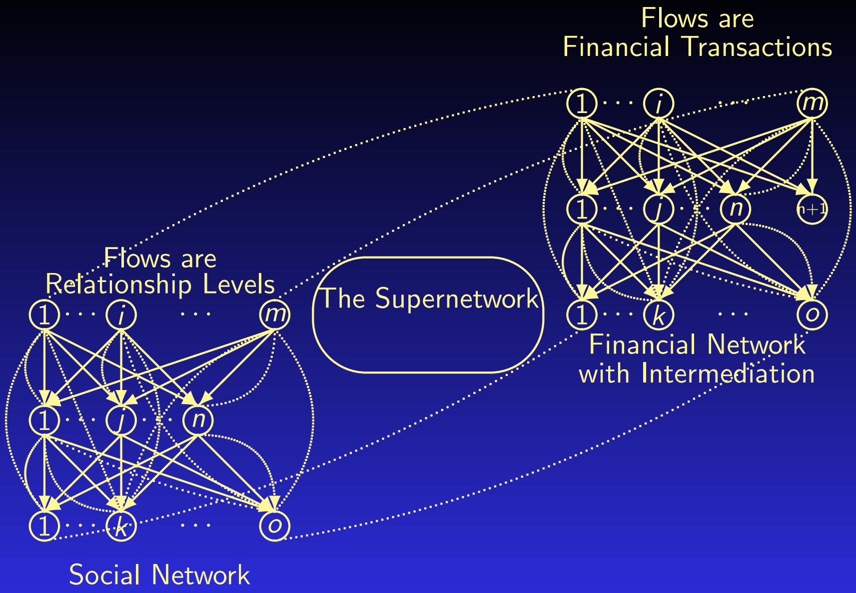


Figure 5: The Multilevel Supernetwork Structure of the Integrated Financial Network / Social Network System

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 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;
- Superstorm Sandy, October 29, 2012.

Hurricane Katrina in 2005

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

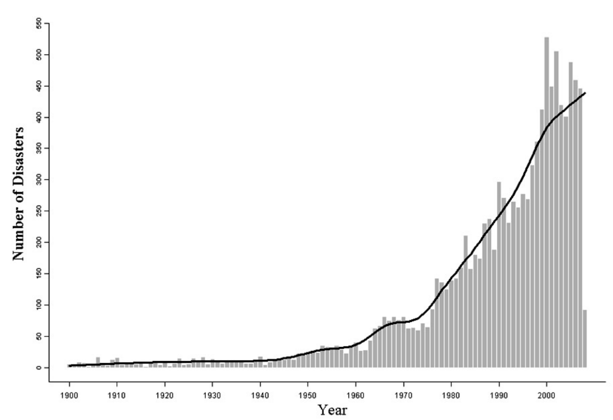
The Haitian and Chilean Earthquakes

The Triple Disaster in Japan on March 11, 2011

Superstorm Sandy and Power Outages

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

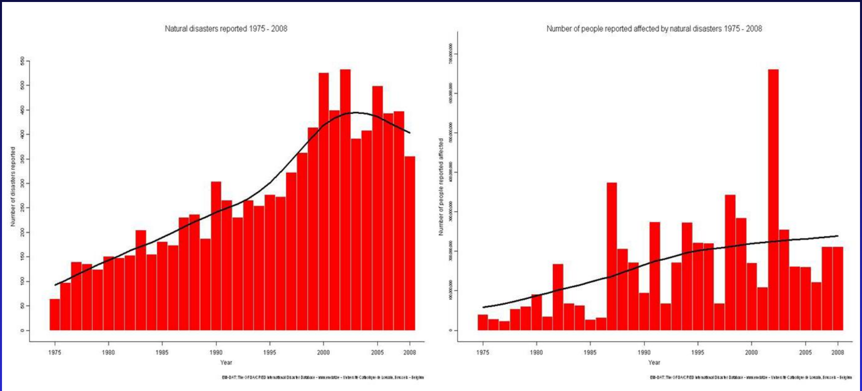
Disasters have brought an unprecedented impact on human lives in the 21st century and the number of disasters is growing. From January to October 2005, *an estimated 97,490 people were killed in disasters globally; 88,117 of them because of natural disasters*.



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)



Some of the Recent Literature on Network Vulnerability

- Latora and Marchiori (2001, 2002, 2004)
- Holme, Kim, Yoon and Han (2002)
- Taylor and Deste (2004)
- Murray-Tuite and Mahmassani (2004)
- Chassin and Posse (2005)
- Barrat, Barthlemy and Vespignani (2005)
- Sheffi (2005)
- DallAsta, Barrat, Barthlemy and Vespignani (2006)
- Jenelius, Petersen and Mattson (2006, 2012)
- Taylor and DEste (2007)
- Nagurney and Qiang (2007, 2008, 2009)
- Qiang and Nagurney (2012)
- Qiang, Nagurney, and Dong (2009)
- Barker, Nicholson, Ramirez-Marquez (2015)

Network Centrality Measures

- Barrat et al. (2004, pp. 3748), The identification of the most central nodes in the system is a major issue in network characterization.
- Centrality Measures for Non-Weighted Networks
  - Degree, betweenness (node and edge), closeness (Freeman (1979), Girvan and Newman (2002))
  - Eigenvector centrality (Bonacich (1972))
  - Flow centrality (Freeman, Borgatti and White (1991))
  - Betweenness centrality using flow (Izquierdo and Hanneman (2006))
  - Random-work betweenness, Current-flow betweenness (Newman and Girvan (2004))
- Centrality Measures for Weighted Networks (Very Few)
  - Weighted betweenness centrality (Dall'Asta et al. (2006))
  - Network efficiency measure (Latora-Marchiori (2001))

Which Nodes and Links Really Matter?

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

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.

The Importance of Nodes and Links

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

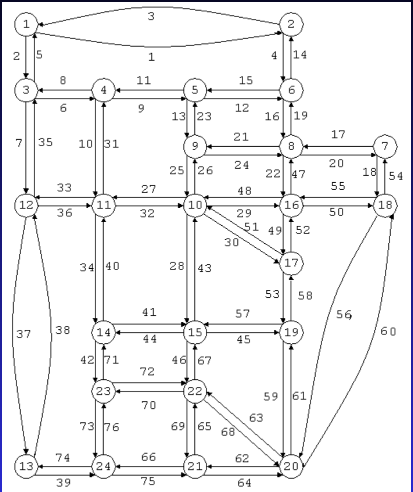


Figure 6: The Sioux Falls network with 24 nodes, 76 links, and 528 O/D pairs of nodes.

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.

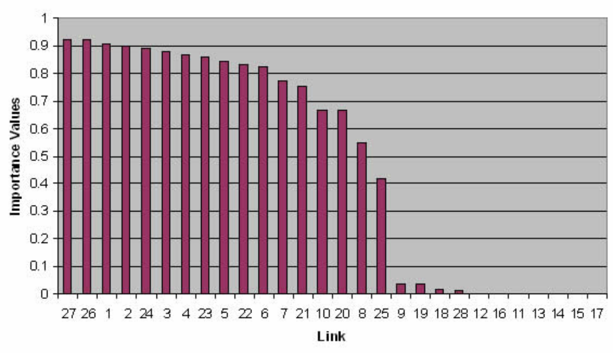


Figure 7: The Sioux Falls network link importance rankings

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 D'Este (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*).

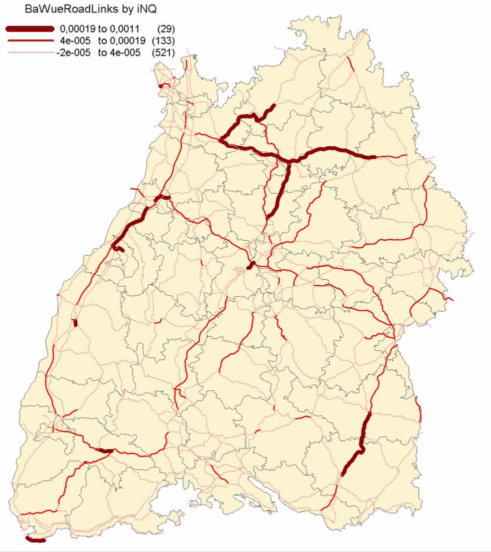
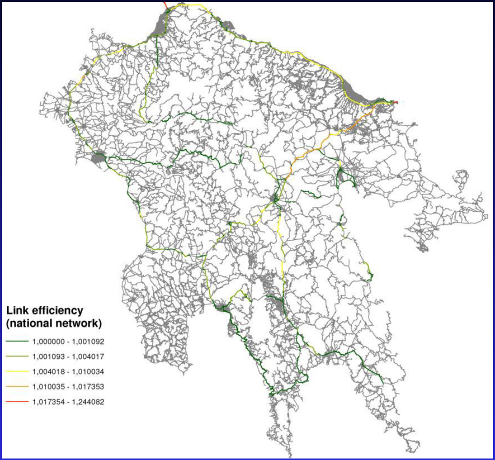


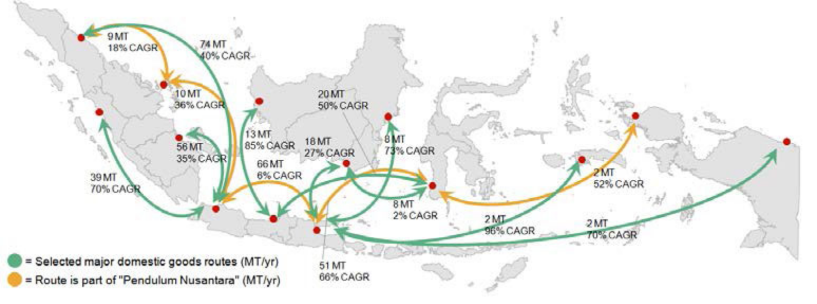
Figure 8: Comparative Importance of the links for the Baden - Wurttemberg Network – Modelling and analysis of transportation networks in earthquake prone areas via the N-Q measure, Tyagunov et al.

Mitsakis et al. (2014) applied the N-Q measure to identify the importance of links in Peloponessus, Greece. The work was inspired by the immense fires that hit this region in 2007.



The N-Q measure is noted in the "Guidebook for Enhancing Resilience of European Road Transport in Extreme Weather Events," 2014.

The N-Q measure has also been used to assess new shipping routes in Indonesia in a report, "State of Logistics - Indonesia 2015."



An Application to the Braess Paradox

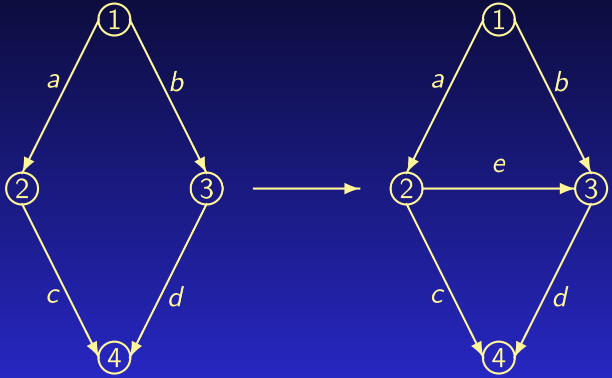


Figure 9: The Braess Network Example

An Application to the Braess Paradox

We now apply the unified network efficiency measure $\mathcal{E}$ to the Braess network with the link e to identify the importance and ranking of nodes and links. The results are reported in the Tables.

Table 5: Link Results for the Braess Network

Link	$\mathcal{E}$ Measure Importance Value	$\mathcal{E}$ Measure Importance Ranking
a	.2069	1
b	.1794	2
c	.1794	2
d	.2069	1
e	-.1084	3

An Application to the Braess Paradox

Table 6: Nodal Results for the Braess Network

Node	$\mathcal{E}$ Measure Importance Value	$\mathcal{E}$ Measure Importance Ranking
1	1.0000	1
2	.2069	2
3	.2069	2
4	1.0000	1

What About Disaster Relief?

Time in Disaster Relief

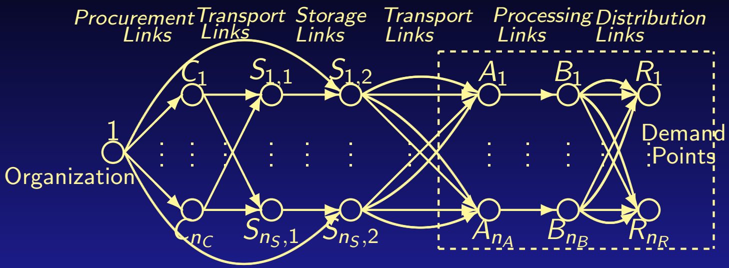
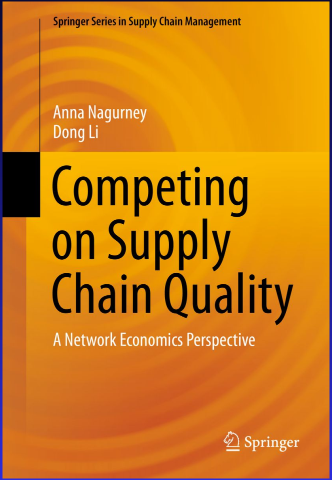


Figure 10: Network Topology of the Integrated Disaster Relief Supply Chain

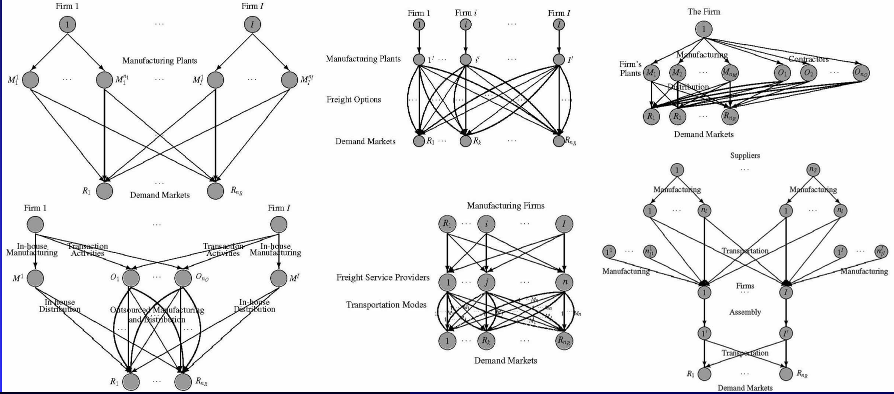
A. Nagurney, A. H. Masoumi, and M. Yu, "An Integrated Disaster Relief Supply Chain Network Model with Time Targets and Demand Uncertainty." In: *Regional Science Matters: Studies Dedicated to Walter Isard*, P. Nijkamp, A. Rose, and K. Kourtit, Editors, Springer International Publishing Switzerland (2015), pp 287-318.

Supply Chain Network Competition in Quality

Research on Quality is Related to That on Perishability



In the book, we present supply chain network models and tools to investigate, amongst other topics, information asymmetry, impacts of outsourcing on quality, minimum quality standards, applications to industries such as pharma and high tech, freight services and quality, and the identification of which suppliers matter the most to both individual firms' supply chains and to that of the supply chain network economy.



Summary and Conclusions

- We emphasized the *importance of product perishability* in a wide range of industries.

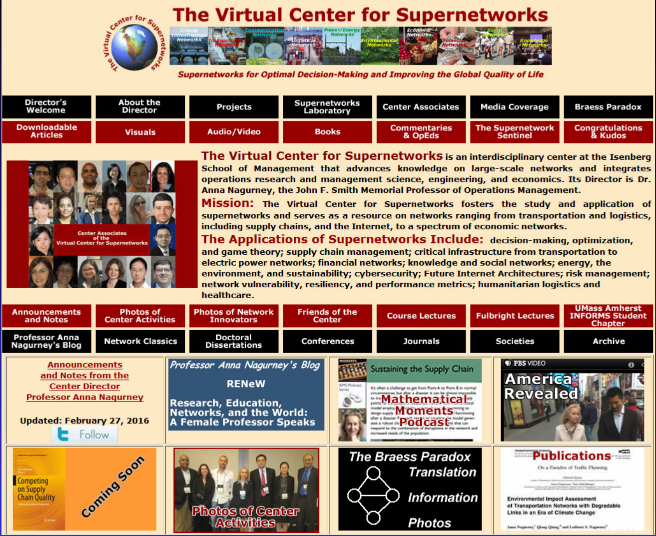
- We developed a *competitive supply chain network model* focused on food with initial quality and path flows as strategic variables and with explicit formulae for quality deterioration.

- The model was formulated and solved as a variational inequality problem.

- We also related the model to several others in the literatures with applications ranging from medical nuclear supply chains to blood supply chains.

- The framework *can be applied in numerous situations*, with some minor modifications, to capture oligopolistic competition for perishable and time-sensitive products.

THANK YOU!



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