Operations Research: The TransfORmative Discipline for the 21st Century

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Acknowledgments

Many thanks to Sociedad Mexicana de Investigación de Operaciones (SMIO) for the invitation and the opportunity to speak to you today in beautiful Mexico City.

It is a great honor!

Outline

- Background and Inspiration
- Network Systems and the Braess Paradox
- Representation of Supply Chains as Networks
- Supply Chain Networks from Healthcare to Food
- Network Models and Disaster Relief
- Cybercrime and Cybersecurity
- Envisioning a New Kind of Internet
- The Global Supply Chain Network with TRQs
- A Case Study on Avocados
- Concluding Thoughts

Background and Inspiration

For the Love of **OR**

When were you first captivated by OR?

From my first course at Brown University on the subject to my first projects in industry - working in the high tech defense sector on naval submarines in Newport, Rhode Island, I was drawn to the power of the subject, especially when combined with computing.

Off to Grad School for a PhD

Very soon I realized that I did not like having a boss!

Dr. Stella Dafermos was the only female professor at the time in either Engineering or Applied Mathematics at Brown University. **I** became her first PhD student.

EQUILIBRIUM MODELING, ANALYSIS AND COMPUTATION: THE CONTRIBUTIONS OF STELLA DAFERMOS

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(Received June 1990; accepted August 1990)

This memorial tribute to the late Stella Dafermos summarizes her contributions to equilibrium modeling, analysis, and computation, and provides a list of her published papers.

On April 5, 1990, with the death at 49 of Stella Dafermos, Professor of Applied Mathematics and Engineering at Brown University, Providence, Rhode Island, the operations research community lost one of its early woman doctorates. Throughout her quarter-century career she dedicated herself to developing rigorous mathematical formalisms for modeling, analyzing and making computations related to competitive equilibrium systems that spanned applications from congested urban transportation networks to multicommodity trade. Beginning with her 1968 doctoral dissertation, ''Traffic Assignment and Resource Allocation in Transportation Networks,'' directed by F. T. Sparrow at Johns Hopkins University, which focused on the study of system-optimized and user-optimized transportation networks, she initiated a theme of advancement of methodologies by which the behavior of complex systems could be captured and studied.

EQUILIBRIUM MODELING

In her first paper, based on her thesis and published in 1969, she proposed convergent equilibration algorithms that simulated the adjustment behavior of travelers on a congested network operating in their own self-interest in choosing their routes. The governing equilibrium conditions, due to Wardrop, reflected that only the minimum cost routes connecting each origin/destination pair would be used. These algorithms took advantage of the problem structure and were later extended in papers published in 1971 and 1972 to network models that allowed for interaction among users of the system via the link cost functions. In her 1969 paper she also focused on stability issues, which began the theme of qualitative analysis of equilibrium patterns that was also to pervade her scholarly work.

These network equilibrium models, as well as the integrated models that allowed for both location and route choice, developed in her paper of 1976, were formulated as optimization problems, with the observation that the equilibrium conditions governing these problems were actually the Kuhn-Tucker conditions of an appropriately constructed optimization problem. Interestingly, parallel to these developments in nonlinear networks, the economics community was reformulating spatial price equilibrium problems, in which commodities are produced, consumed and traded, subject to transportation or transaction costs, as optimization problems. However, the assumption required for such a transformation—that of *symmetry*, in which cross-effects of various interactions had to be identical—precluded the realistic modeling of multiple modes of transportation and different classes of users of a given system, as well as multiple commodities. Moreover, the objective function thus constructed, although convenient and essential given the state-of-the-art at the time, was artificial. Furthermore, equilibrium problems, by their very nature, involve more than a single agent and objective function, with interactions among the agents, and, hence, the objective functions being the rule rather than the exception. To overcome such shortcomings, a methodological advance was needed.

In 1980 Stella made a fundamental discovery by observing that the equilibrium conditions of the traffic assignment problem actually had the structure of a variational inequality problem. Although the theory of variational inequalities had been introduced over a decade earlier for the study of partial differential equations, the emphasis there was on infinite-dimensional problems arising in mechanics, and its use as a powerful tool for equilibrium analysis in operations research was left unrealized. Stella's identification of network equilibrium conditions with a variational inequality problem opened up new horizons for mathematical modeling, analysis and the efficient computation of more general equilibrium systems than had heretofore been possible. With this

Subject classifications: Economics: solution of equilibrium problems. Networks/graphs: equilibrium modeling and computation. Transportation: formulation and solution of multimodal problems.

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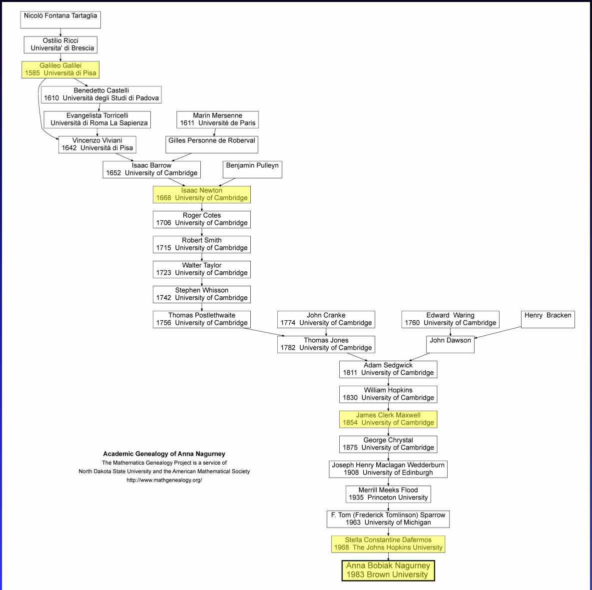
Stella was only the second female to have received a PhD in OR and that was at Johns Hopkins University.

On the Shoulders of Giants - Academic Genealogy



Our Fabulous **OR** Community

After I received my PhD, I met **Professor George Dantzig of Stanford University**, the developer of the simplex method and a Father of OR! He came to the first presentation that I ever gave at a conference, post PhD, and it was at the Mathematical Programming Symposium at MIT.

A Few Quotes

Philip M. Morse in his 1977 book, "In at the Beginnings" on page 318 writes:

The delights of research in O/R (he used the slash) are multiple. To me the pleasure coming from understanding how traffic behaves is as great as that coming from understanding how two atoms combine. In addition, **the practical applications of O/R theory are often immediate and satisfying***.*

Morse ends his book with the following:

For those who like exploration, immersion in scientific research is not unsocial, is not dehumanizing; in fact, **it is a lot of fun***. And, in the end,* **if one is willing to grasp the opportunities, it can enable one to contribute something to human welfare**.

OR - Our Profession

The founders of OR would be delighted to the see the growth of our discipline and profession with the discovery of and wide use of novel methodologies and innovative applications that they could not have envisioned in: industry, government, defense, healthcare, consultancies, and even, increasingly, in nonprofit organizations.

And, importantly, **students are drawn to Operations Research** because of its scope and great job opportunities!

Network Systems and the Braess Paradox

I Work on the Modeling of Network Systems

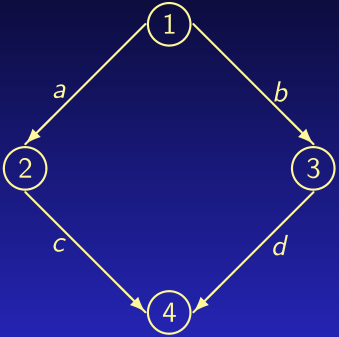
And utilize optimization, game theory, and also dynamical systems to gain insights as to the behavior of stakeholders.

Importance of Capturing Behavior on Networks - The Braess (1968) Paradox and User-Optimizing (U-O) Behavior

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



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

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

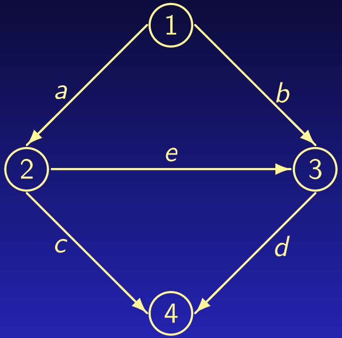
Adding a Link Increases Travel Cost for All!

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:

"On a Paradox of Traffic Planning,"

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

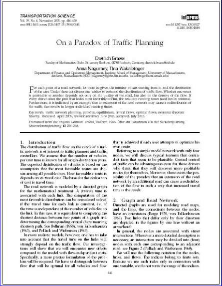
1. Einleitung

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.



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On a Paradox of Traffic Planning

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

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

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

1. Introduction

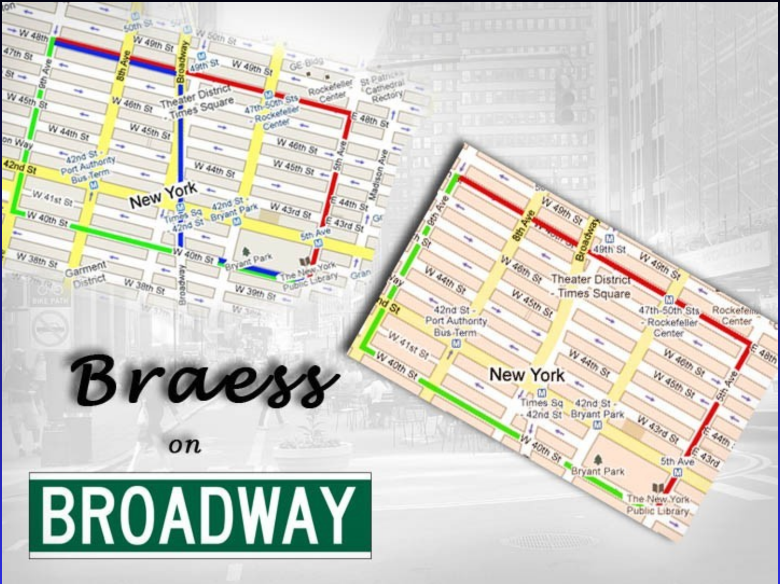
The distribution of traffic flow on the roads of a traffic network is of interest to traffic planners and traffic controllers. We assume that the number of vehicles per unit time is known for all origin-destination pairs. The expected distribution of vehicles is based on the assumption that the most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

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.

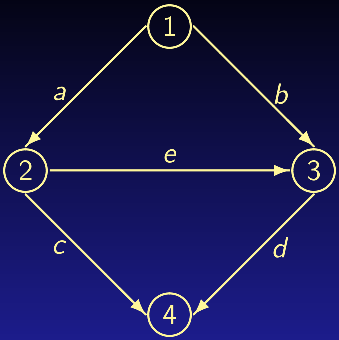
2002 - Seoul, Korea - A 6 lane road built over the Cheonggyecheon River that carried 160,000 cars per day and was perpetually jammed was torn down to improve traffic flow.


Braess
on
BROADWAY
New York
Theater District - Times Square
Bryant Park
The New York Public Library
W 40th St
W 49th St
Broadway
8th Ave
9th Ave
5th Ave

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?

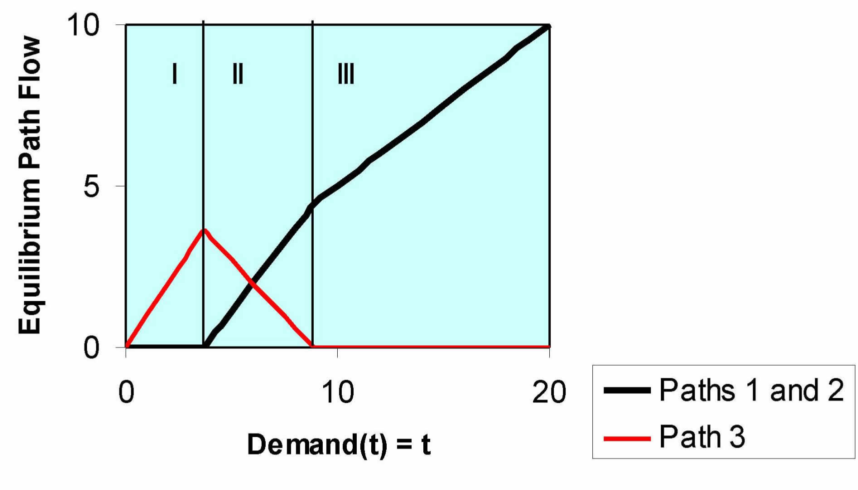
For Networks with Time-Dependent Demands

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

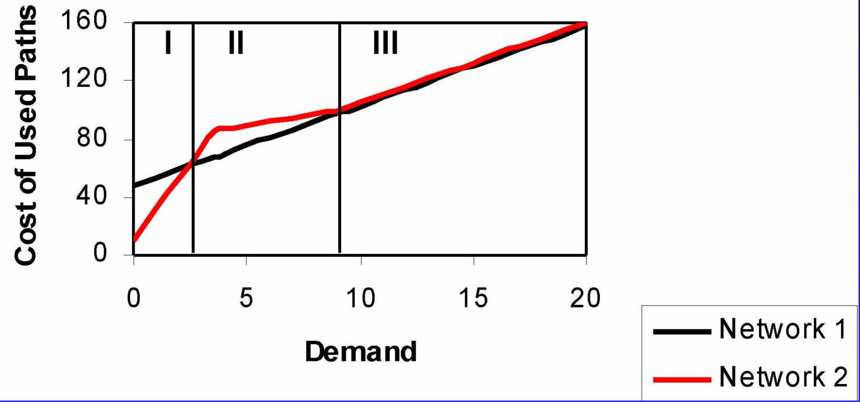
The U-O Solution of the Braess Network with Added Link (Path) and Time-Varying Demands Solved as an *Evolutionary Variational Inequality* (Nagurney, Daniele, and Parkes, *Computational Management Science* **4** (2007), pp 355-375).



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

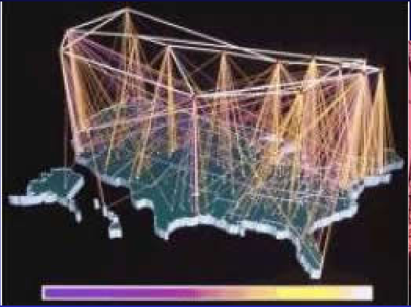
In Demand Regime II, the travel demand lies in the range [2.58, 8.89], and *the Addition of a New Link (Path) Makes Everyone Worse Off*!

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!

Representation of Supply Chains as Networks

Much of My Recent Research Had Been on 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*.

Representation of Supply Chains as Networks

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• build meaningful extensions using the graphical/network conceptualization.

Some of My Books

Methodology - The Variational Inequality Problem

We utilize the theory of variational inequalities for the formulation, analysis, and solution of numerous 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*.*

The vector X consists of the decision variables – typically, the flows (products, prices, investments, security levels, 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.

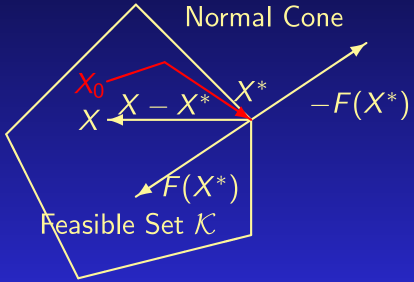
The variational inequality problem contains, as special cases, such mathematical programming problems as:

- 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*, 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

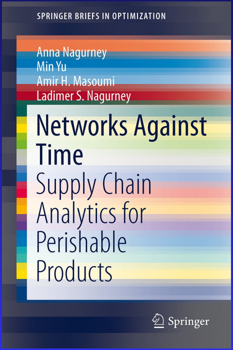
even *neuroscience* (Girard et al. (2008)

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

Supply Chain Networks from Healthcare to Food

A Multidisciplinary Approach

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 healthcare products such as blood, medical nucleotides, and pharmaceuticals to food.



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.

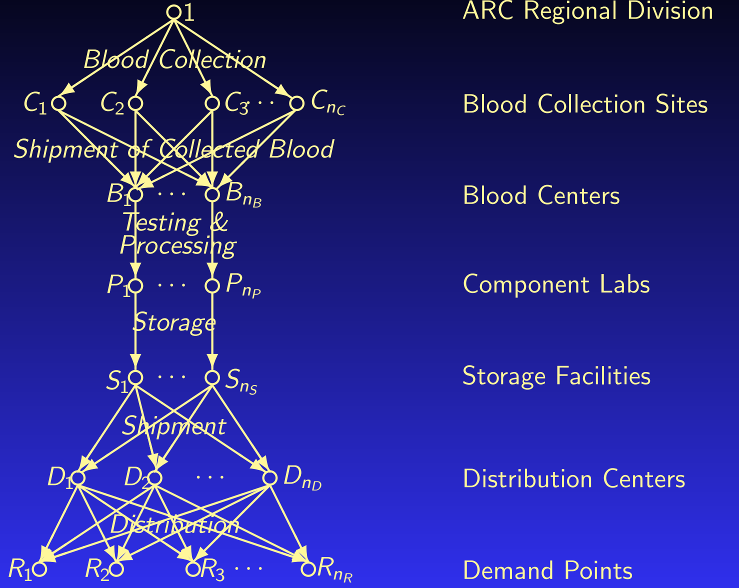
Blood Supply Chains for the Red Cross

The American Red Cross is the major supplier of blood products to hospitals and medical centers satisfying about 40% of the demand for blood components nationally.

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.

Supply Chain Network Topology for a Regionalized Blood Bank



Blood Supply Chains for the Red Cross

Our blood supply chain network optimization model for the management of the procurement, testing and processing, and distribution has such novel features as:

- 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.

Supply Chain Networks – Game Theory Models

Game Theory

There are many game theory problems and tools for solving them. There is noncooperative game theory, in which the players or decision-makers compete with one anther, and cooperative game theory, in which players cooperate with one another.

John F. Nash

In noncooperative games, the governing concept is that of Nash equilibrium. In cooperative games, we can apply Nash bargaining theory.

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.

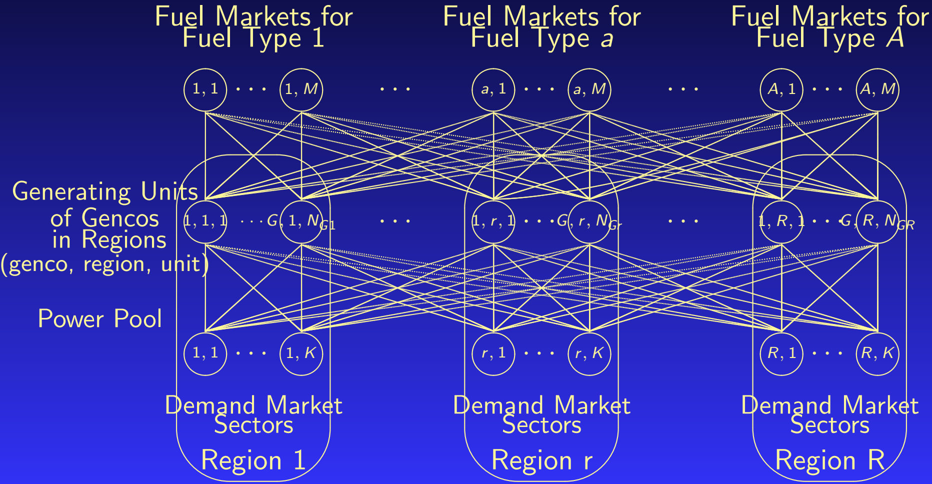
An Empirical Example of an Electric Power Supply Chain for New England

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

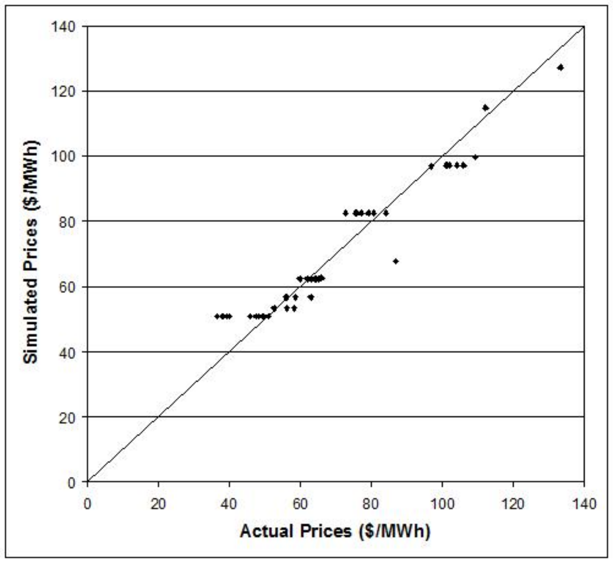
The Electric Power Supply Chain Network with Fuel Supply Markets



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)



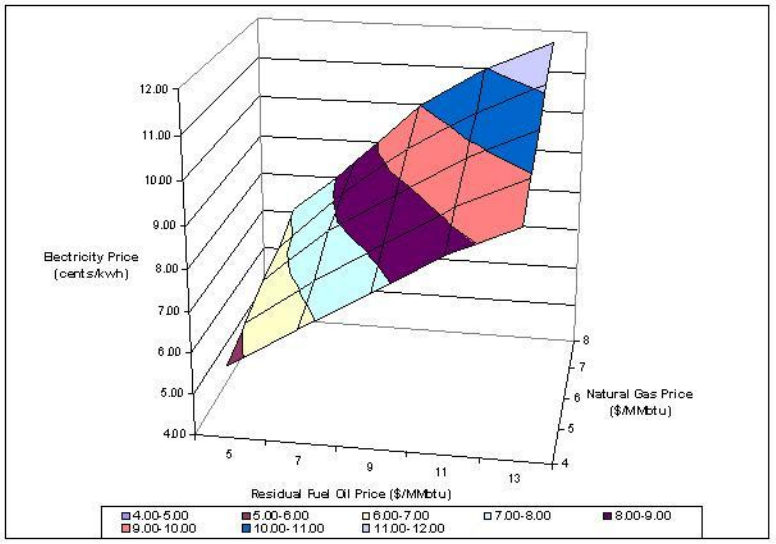
Sensitivity Analysis

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



Food Supply Chains

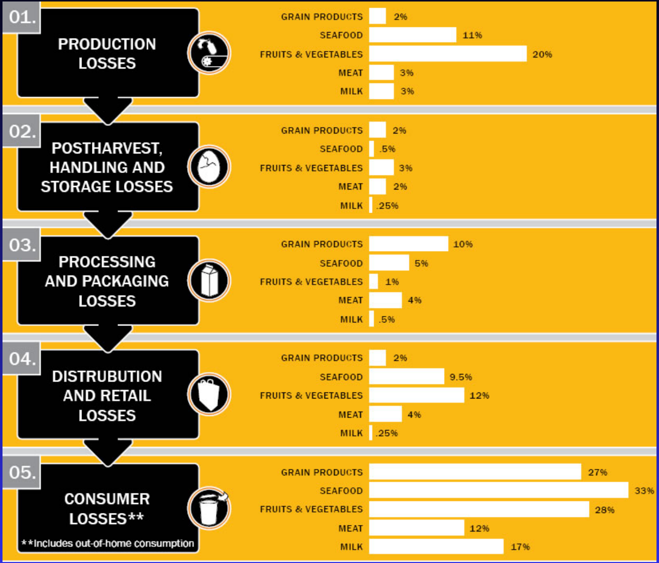
Food is something anyone can relate to.

Fascinating Facts About Food Perishability

THE SHELF LIFE OF FOOD

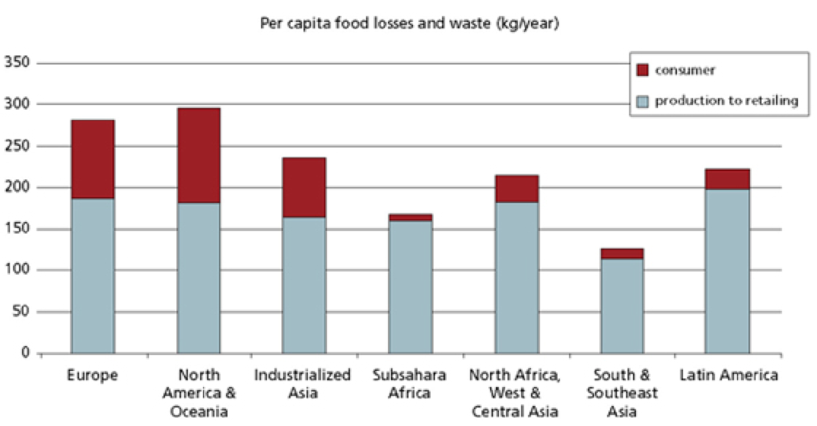
Foods unopened, uncut or uncooked unless stated otherwise	COUNTER/PANTRY (1 DAY ← → 1 MONTH)	REFRIGERATOR (1 DAY ← → 3 MONTHS)	FREEZER (1 MONTH ← → 1 YEAR)
APPLES	2-4 weeks	1-2 months	8-12 months
BANANAS	2-7 days	5-9 days	2-3 months
CANTALOUPE	Until ripe	1 week	8-12 months
CARROTS	Up to 4 days	4-5 weeks	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 of the United Nations 2011

Wasting of Food



Source: Food and Agriculture Organization of the United Nations 2018

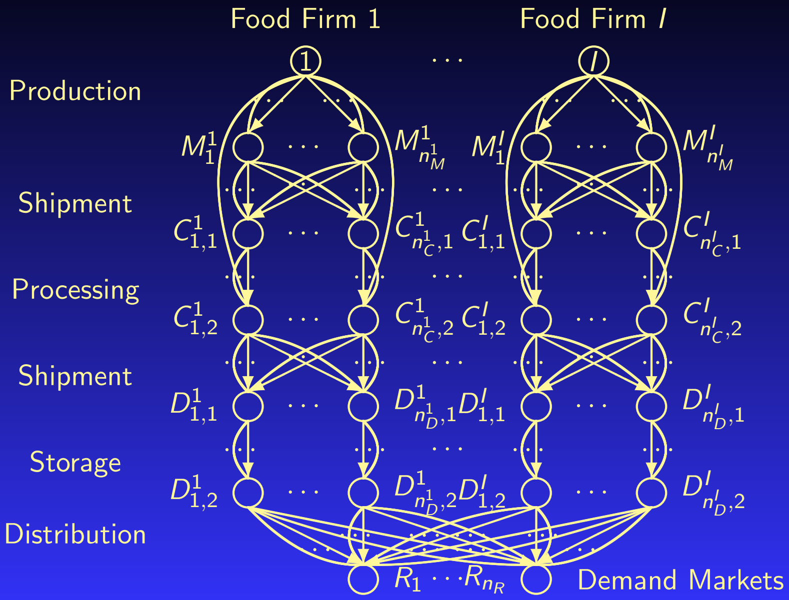
Fresh Produce Food Supply Chains

Our fresh produce supply chain network oligopoly model:

1. captures the deterioration of fresh food along the entire supply chain from a network perspective;
2. handles the 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," M. Yu and A. Nagurney, *European Journal of Operational Research* **224(2)** (2013), pp 273-282.

Fresh Produce Food Supply Chains



Fresh Produce Food Supply Chains

Food products also deteriorate over time and especially fresh produce. According to Nahmias (1982), each unit has a probability of $e^{\lambda t_a}$ of surviving t_a units of time where λ is the decay rate. Hence, arc multipliers can be constructed in a similar manner as those for the medical nuclear supply chain:

$$\alpha_a = e^{-\lambda t_a}$$

where λ is the decay rate for the food.

In rare cases, food deterioration follows the zero order reactions with linear decay (see Tijskens and Polderdijk (1996) and Rong, Akkerman, and Grunow (2011)). Then,

$$\alpha_a = 1 - \lambda t_a$$

for a post-production link.

Pharmaceutical Supply Chains

The supply chain generalized network oligopoly model has the following novel features:

1. it handles the perishability of the pharmaceutical product through the introduction of arc multipliers;

2. it allows each firm to minimize the discarding cost of waste / perished medicine;

3. it captures product differentiation under oligopolistic competition through the branding of drugs, which can also include generics as distinct brands.

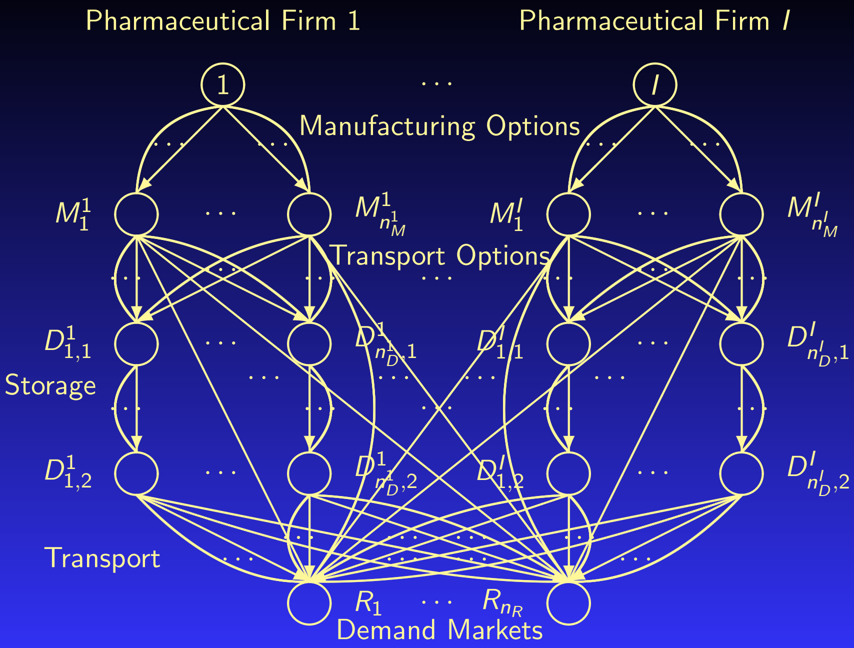
References can be found in our paper, "A Supply Chain Generalized Network Oligopoly Model for Pharmaceuticals Under Brand Differentiation and Perishability," A.H. Masoumi, M. Yu, and A. Nagurney, *Transportation Research E* **48** (2012), pp 762-780.

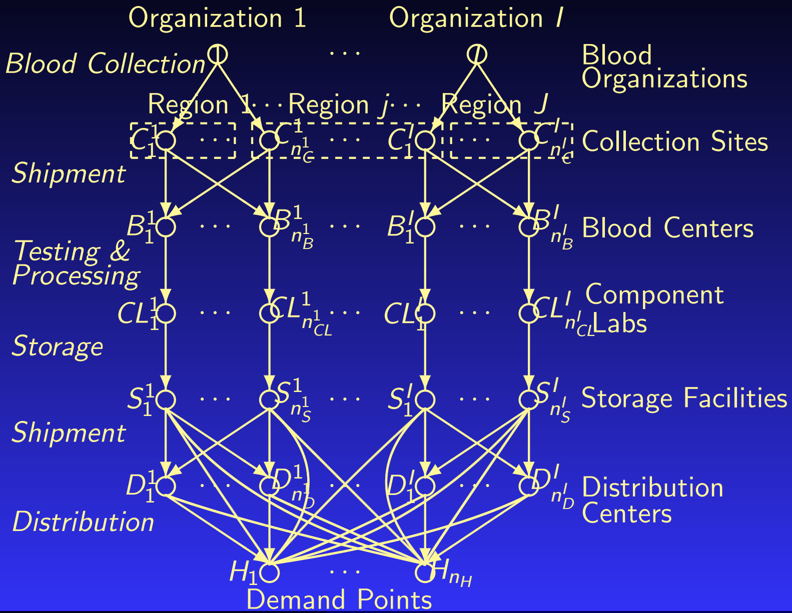
Pharmaceutical Supply Chains

We consider I pharmaceutical firms, with a typical firm denoted by i.

The firms compete non-cooperatively, in an oligopolistic manner, and the consumers can differentiate among the products of the pharmaceutical firms through their individual product brands.

The supply chain network activities include manufacturing, shipment, storage, and, ultimately, the distribution of the brand name drugs to the demand markets.


Pharmaceutical Firm 1
Pharmaceutical Firm I
1
I
Manufacturing Options
M_1^1
$M_{n_M^1}^1$
M_1^I
$M_{n_M^I}^I$
Transport Options
$D_{1,1}^1$
$D_{n_D^1,1}^1$
$D_{1,1}^I$
$D_{n_D^I,1}^I$
Storage
$D_{1,2}^1$
$D_{n_D^1,2}^1$
$D_{1,2}^I$
$D_{n_D^I,2}^I$
Transport
R_1
R_{n_R}
Demand Markets


Organization 1
Organization I
Blood Collection
1
I
Blood Organizations
Region 1
Region j
Region J
C_1^1
$C_{n_C^1}^1$
C_1^I
$C_{n_C^I}^I$
Collection Sites
Shipment
B_1^1
$B_{n_B^1}^1$
B_1^I
$B_{n_B^I}^I$
Blood Centers
Testing & Processing
CL_1^1
$CL_{n_{CL}^1}^1$
CL_1^I
$CL_{n_{CL}^I}^I$
Component Labs
Storage
S_1^1
$S_{n_S^1}^1$
S_1^I
$S_{n_S^I}^I$
Storage Facilities
Shipment
D_1^1
$D_{n_D^1}^1$
D_1^I
$D_{n_D^I}^I$
Distribution Centers
Distribution
H_1
H_{n_H}
Demand Points

Network Models and Disaster Relief

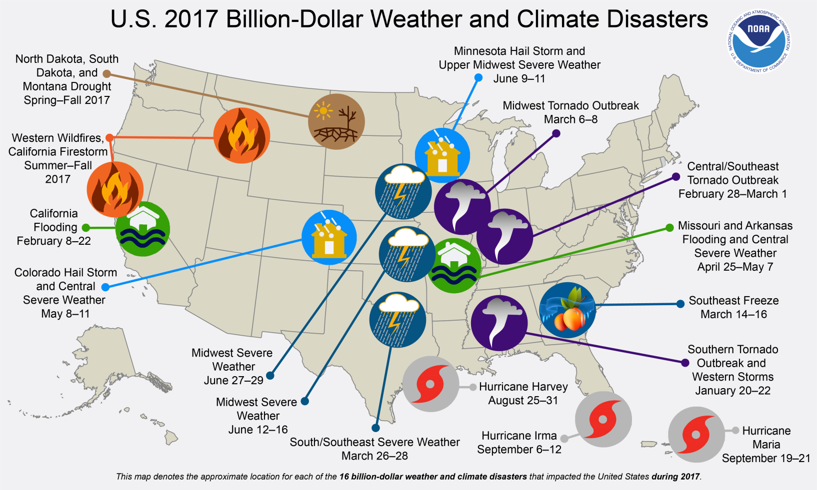
Network Models Are Also Very Useful in Disaster Relief

Examples of Some Disasters

- The biggest blackout in North America, August 14, 2003;
- The Indonesian tsunami (and earthquake), December 26, 2004;
- Hurricane Katrina, August 23, 2005;
- 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;
- Hurricanes Harvey, Irma, and Maria that struck in 2017 and Hurricanes Florence and Michael in 2018.

Hurricane Katrina, Fukushima, and Superstorm Sandy

Billion Dollar Disasters in the United States in 2017



2017 Set a Record for Losses in the US from Natural Disasters

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

Natural Disasters and Mexico

- According to the United Nations (2011), **Mexico is ranked as one of the worlds thirty most exposed countries to three or more types of natural disasters, notably, storms, hurricanes, floods, as well as earthquakes, and droughts**.

- The International Bank for Reconstruction and Development/The World Bank (2012), reported that **41% of Mexico's national territory is exposed to storms, hurricanes, and floods; 27% to earthquakes, and 29% to droughts**. The hurricanes can come from the Atlantic or Pacific oceans or the Caribbean.

- **The single most costly disaster in Mexico were the 1985 earthquakes**, followed by the floods in the southern state of Tabasco in 2007, with damages of more than 3.1 billion U.S. dollars. More recently, two high-magnitude earthquakes struck Mexico in September 2017, leading to significant damage of public infrastructure and buildings, more than 340 deaths, and economic losses amounting to approximately $2.5 billion.

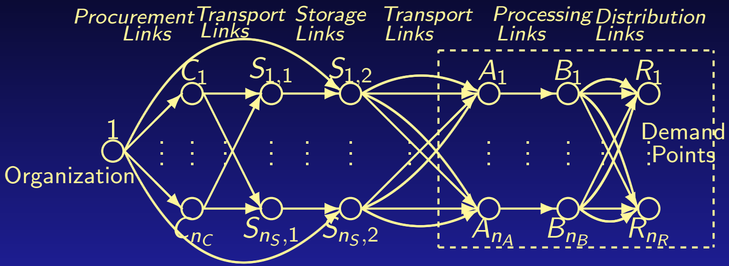
Natural Disasters and Mexico

- According to the GFDRR, **Mexico has taken steps to manage its natural hazard risk and improve recovery after disaster events. The National System for Civil Protection (SINAPROC) was formed in 1986** following the devastating earthquake that hit Mexico City the previous year.

- Under the framework of SINAPROC, **the government established Mexicos Fund for Natural Disasters (FONDEN) in 1996** to support the rapid reconstruction of federal and state infrastructure affected by natural hazard events.

- **Now the focus has moved toward building a comprehensive disaster risk management (DRM) system.**

Time in Disaster Relief



Network Topology of the Integrated Disaster Relief Supply Chain

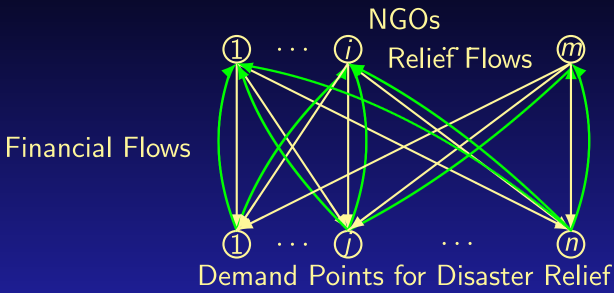
A. Nagurney, A.H. Masoumi, and M. Yu, "An Integrated Disaster Relief Supply Chain Network Model with Time Targets and Demand Uncertainty." In: *Regional Science Matters: Studies Dedicated to Walter Isard*, P. Nijkamp, A. Rose, and K. Kourtit, Editors, Springer International Publishing Switzerland (2015),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

Game Theory and Disaster Relief

We developed the first Generalized Nash Equilibrium (GNE) model for post-disaster humanitarian relief, which contains both a financial component and a supply chain component. The Generalized Nash Equilibrium problem is a generalization of the Nash Equilibrium problem (cf. Nash (1950, 1951)).

"A Generalized Nash Equilibrium Network Model for Post-Disaster Humanitarian Relief," Anna Nagurney, Emilio Alvarez Flores, and Ceren Soylu, *Transportation Research E* **95** (2016), pp 1-18.

A Game Theory Disaster Relief Model



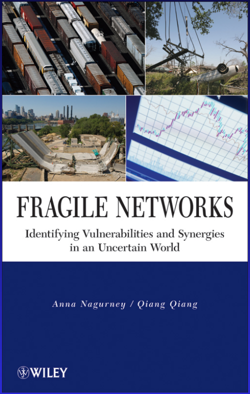
The Network Structure of an Integrated Game Theory Model

A. Nagurney et al., "A Variational Equilibrium Network Framework for Humanitarian Organizations in Disaster Relief: Effective Product Delivery Under Competition for Financial Funds." In: *Dynamics of Disasters: Algorithmic Approaches and Applications*, I.S. Kotsireas, A. Nagurney, and P.M. Pardalos, Editors, Springer International Publishers Switzerland (2018), pp 109-133.

Cybercrime and Cybersecurity

How I Became Interested in Cybersecurity

One of my books, written with a UMass Amherst PhD alum, was "hacked" and digital copies of it posted on websites around the globe.



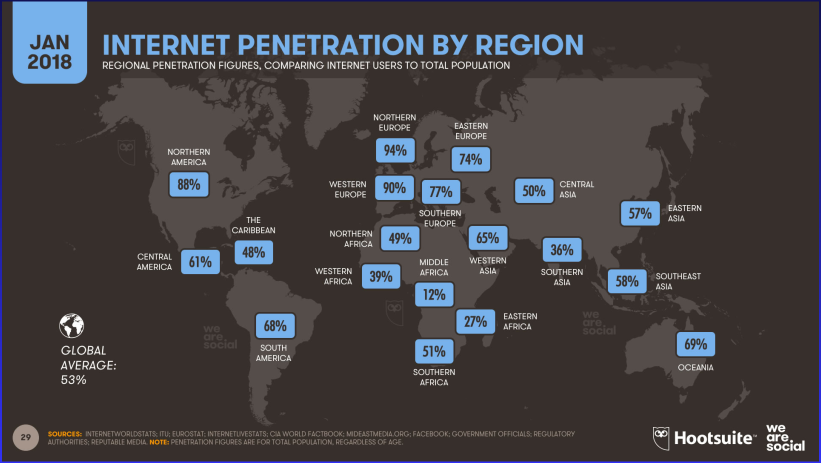
In a sense, this may be viewed as a compliment since clearly someone had determined that it has some sort of *value*.

The publisher John Wiley & Sons was notified and lawyers got involved but how do you contact and then influence those responsible for postings on rather anonymous websites?

About the same time news about cyberattacks was getting prominent attention in the media and there were those interested in working with us on related research on cybersecurity.

The Internet has transformed the ways in which individuals, groups, organizations communicate, obtain information, access entertainment, and conduct their economic and social activities.

In 2012, there were over 2.4 billion users. In 2019, the number of Internet users surpassed 4.3 billion users, more than half of the world's population.



Some Recent Major Cyberattacks

• **Equifax**: In September 2017, it was revealed that names, SSNs, birthdates, drivers' license information, and credit card numbers on about 143 million U.S. consumers was compromised in a cybersecurity breach that began in mid-May and was discovered only on July 29, 2017 (Bloomberg (2017)). In late February 2018, Equifax disclosed that it had discovered that an additional 2.4 million U.S. consumers were affected by the cyberattack (Reuters (2018)).

• **"WannaCry" ransomware**: Began in mid-May 2017. It crippled National Health Services (NHS) hospitals in the UK, hobbling emergency rooms, delaying vital medical procedures, and creating chaos (WIRED (2017)).

Some Recent Major Cyberattacks

• **Banks:** The Carbanak group, also known as Anunak, was exposed in 2015 after supposedly stealing upwards of $1 billion from more than 100 banks across 30 countries (The New York Times (2015)).

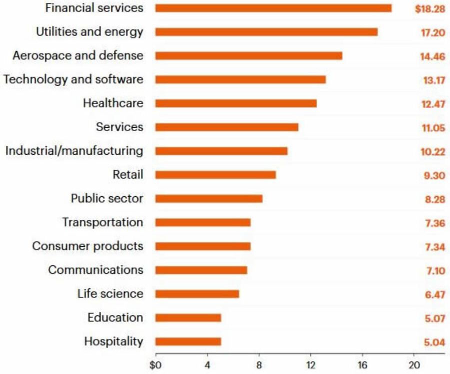
• **US Office of Personnel Management:** In June 2015, OPM discovered that sensitive information, including SSNs of 21.5 million federal employees was stolen (WIRED (2016)).

• **Sony Pictures Entertainment** The attack on Sony in 2014 destroyed data on more than 3,000 computers and disclosed prerelease films and embarrassing emails of executives (Fortune (2015)).

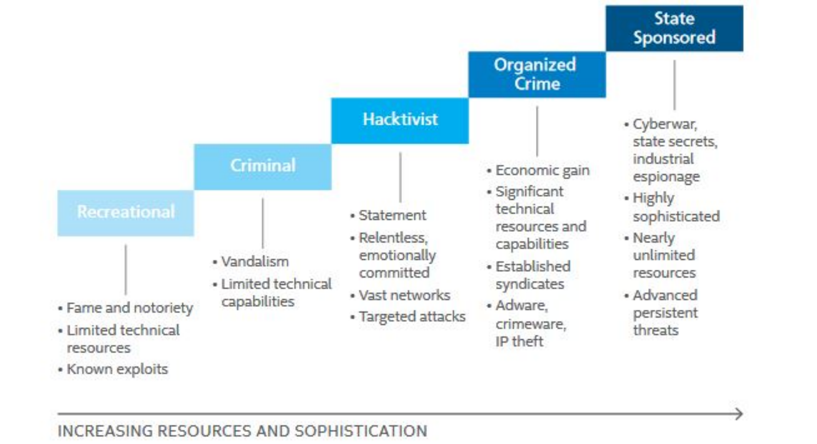
• **Target, Home Depot, Michaels Stores, Staples, and eBay:** These were breached in 2014 - card data and personal information of millions of customers were stolen (The New York Times (2015)).

Cost of Cybercrime

- **Cybercrimes are costly for organizations.** According to Forbes (2017), cybercrime will cost the world about $6 trillion per year on average through 2021. All industries fall victim to cybercrime, but to different degrees. **Average annual costs per company caused by global cybercrime as of 2017 by sector (in million US$) (Ponemon(2017))**



Changing Attacker Profiles

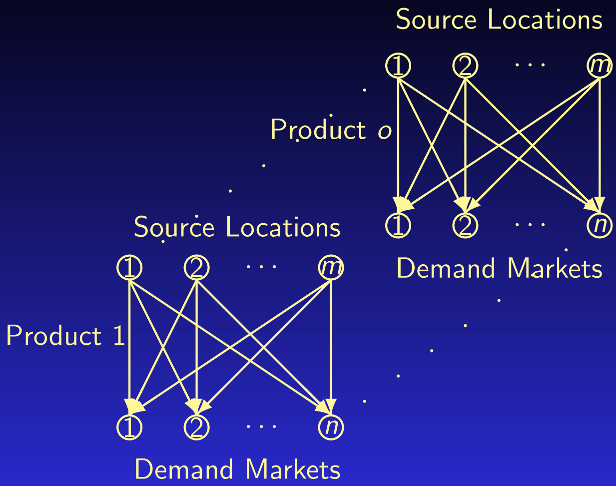


McAfee Labs Threats Report, August 2015

Cybercrime

Clearly, hackers go where there is money.

Perishability and Cybercrime in Financial Products



The model is constructed in the paper, "A Multiproduct Network Economic Model of Cybercrime in Financial Services," A. Nagurney, *Service Science* **7(1)** (2015), pp 70-81.

Cybersecurity and Supply Chains

Supply chains are also vulnerable to cyberattacks and can serve as entre points

Some Other Examples of Our Recent Cybersecurity Work

"Multifirm Models of Cybersecurity Investment Competition vs. Cooperation and Network Vulnerability," A. Nagurney and S. Shukla, *European Journal of Operational Research* **260(2)** (2017), pp 588-600.

"A Supply Chain Network Game Theory Model of Cybersecurity Investments with Nonlinear Budget Constraints," A. Nagurney, P. Daniele, and S. Shukla, *Annals of Operations Research* **248(1)** (2017), pp 405-427.

"Cybersecurity Investments with Nonlinear Budget Constraints: Analysis of the Marginal Expected Utilities," P. Daniele, A. Maugeri, and A. Nagurney. In: *Operations Research, Engineering, and Cyber Security*, Th.M. Rassias and N.J. Daras (Eds.), Springer International Publishing Switzerland (2017), pp 117-134.

Envisioning a New Kind of Internet – ChoiceNet

Envisioning a New Kind of Internet – ChoiceNet

We were one of five teams funded by NSF as part of the Future Internet Architecture (FIA) project. Our project: *Network Innovation Through Choice* and the envisioned architecture is *ChoiceNet*.

Team:

- University of Kentucky: Jim Griffioen, Ken Calvert
- North Carolina State University: Rudra Dutta, George Rouskas
- RENCI/UNC: Ilya Baldin
- University of Massachusetts Amherst: Tilman Wolf, Anna Nagurney

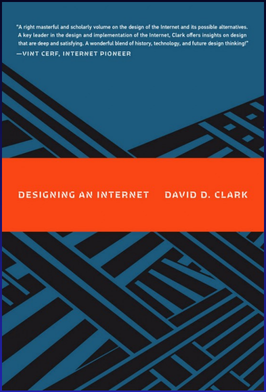
Network Economic Conundrums and Operations Research to the Rescue

- **New architectures are focusing on networking technology, and not on economic interactions. Also, they lack in mechanisms to introduce competition and market forces.**

- Existing economic models cannot be deployed in today's Internet: **no mechanisms in order to create and discover contracts with any provider and to do so on short-time scales, and time-scales of different lengths**.

- We have developed multitiered network economic game theory models using **novel operations research methodologies**, including that of *projected dynamical systems* to study ChoiceNet and to explore the evolution of prices and flows among content and service providers.

Designing an Internet



The new book by Clark, a developer of the Internet, cites our paper: "ChoiceNet: Toward an Economy Plane for the Internet," Wolf, Griffioen, Calvert, Dutta, Rouskas, Baldin, and Nagurney, *ACM SIGCOMM Computer Communication Review* **44(3)** (2018), pp 58-65.

Supply Chains Are Essential to Global Trade

- **Global supply chain networks** have made possible the wide distribution of goods, from agricultural products to textiles and apparel as well as aluminum and steel.
- Nations engage in trade **to increase their productivity levels, employment rates, and general economic welfare**.
- The increased level of world trade has also garnered **the attention of government policy makers**.
- Governments may attempt to protect their domestic firms from the possible effects of the **highly competitive** global arena.

Some of the Biggest Agricultural Exports of Mexico

Credit: 2012 - 2018 Food and Agricultural Atlas in Mexico. SAGARPA - Ministry of Agriculture, Livestock, Rural Development, Fishing and Food.

Global Trade Policies

Examples of policy instruments that have been applied by governments to modify trade patterns included: **tariffs**, **quotas**, and a combination thereof - **tariff rate quotas**.

Tariffs Are in the News Every Day!

The imposition of tariffs by certain countries is leading to retaliation by other countries with ramifications across multiple supply chains, and a **trade war**.

With Higher Tariffs, China Retaliates Against the U.S.

The Yangshan Deep Water Port in Shanghai, China. The Chinese government said on Monday that it would raise tariffs on goods from the United States as of June 1, giving negotiators from the two countries time to strike a deal. Aly Song/Reuters

The New York Times, May 13, 2019

Global Trade Policies

Our research community needs to construct **computable operational mathematical models** that enable the assessment of the impacts of trade policy instruments such as tariff rate quotas on consumer prices, trade flows, as well as on the profits of producers/firms.

However, this is very challenging research!

How Our Journey Began

In the early 1990s, we were contacted by Charles E. Nicholson and Phillip M. Bishop of of the Department of Agricultural, Resource and Managerial Economics at Cornell University, who were interested in modeling ad valorem tariffs associated with the dairy industry and Mexico and were faced with challenges.

We had been doing a lot of research on spatial price equilibrium modeling:

- A. Nagurney, T. Takayama, and D. Zhang (1995), Massively parallel computation of spatial price equilibria as dynamical systems, *Journal of Economic Dynamics and Control* **19(1-2)**, 3-37.
- A. Nagurney, S. Thore, and J. Pan (1996), Spatial market policy modeling with goal targets, *Operations Research* **44(2)**, 393-406.
- A. Nagurney and L. Zhao (1991), A network equilibrium formulation of market disequilibrium and variational inequalities, *Networks* **21**, 109-132.

How Our Journey Began

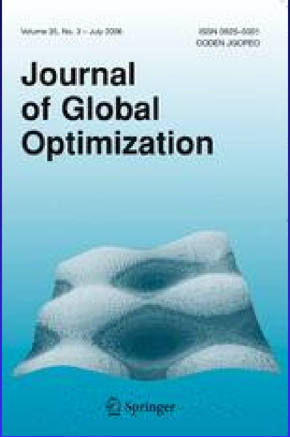
We ended up publishing a series of papers, including:

A. Nagurney, C.F. Nicholson, and P.M. Bishop (1996), Massively parallel computation of large-scale spatial price equilibrium models with discriminatory ad valorem tariffs, *Annals of Operations Research* **68(2)**, 281-300.

The Global Supply Chain Network Model with TRQs

This part of the presentation is based on the paper:

A. Nagurney, D. Besik, and L.S. Nagurney (2019), Global supply chain networks and tariff tate quotas: Equilibrium analysis with application to agricultural products, *Journal of Global Optimization* **75**, pp 439-460.



Motivation

- A tariff rate quota (TRQ) is a **two-tiered tariff**, in which a lower **in-quota tariff** is applied to imports until a quota is attained and then a higher **over-quota tariff** is applied to all subsequent imports.
- The Uruguay Round in 1996 induced the creation of more than 1,300 new TRQs. Currently, **43 World Trade Organization members have a total of 1,425 tariff quotas in their commitments**. TRQs are widely utilized especially in agricultural trade for products such as: milk and dairy products, bananas, chocolate, sugar, beef, peanuts, eggs, poultry, soybeans, potatoes, among others.
- **The world's four most important food crops: rice, wheat, corn, and bananas have all been subject to tariff rate quotas.**

Literature Review

Perfect Competition

- Tariff rate quotas (TRQs) have been deemed challenging to formulate; models have focused almost exclusively on **spatial price equilibrium**.
- Spatial price equilibrium models are perfectly competitive models with numerous producers (Samuelson (1964), Takayama and Judge (1964, 1971)).
- For more recent applications of spatial price equilibrium models, utilizing variational inequality theory, see Nagurney (1999, 2006), Daniele (2004), Li, Nagurney, and Yu (2018)).
- For the inclusion of tariff rate quotas into spatial price equilibrium models using variational inequality theory, see the EJOR paper by Nagurney, Besik, and Dong (2019).

Literature Review

A. Nagurney, D. Besik, and J. Dong (2019), Tariffs and quotas in world trade: A unified variational inequality framework, *European Journal of Operational Research* **275(1)**, 347-360.

Imperfect Competition

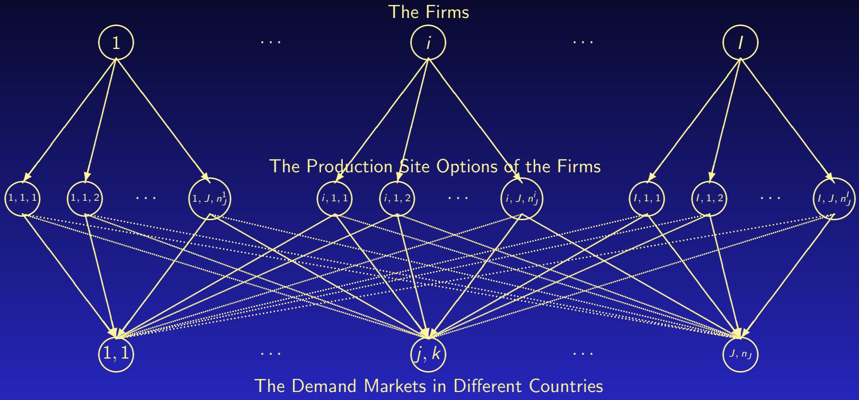
- In many industrial sectors, the more appropriate framework is that of imperfect competition, as in the case of **oligopolistic competition**.
- Shono (2001) relaxed the assumption of perfect competition, and incorporated TRQs, under oligopolistic competition and that the computable framework consisted of linear functions.
- Maeda, Suzuki, and Kaiser (2001, 2005) considered oligopolistic competition and TRQs but assumed that there is a single producer in each country.

The Global Supply Chain Network Model with TRQs

Specifically, we:

- Introduce **the global supply chain network model** consisting of firms that seek to maximize their profits by determining how much of the product to manufacture/produce at the production sites, which can be located in multiple countries;
- **Incorporate tariff rate quotas** into the supply chain network equilibrium model, and
- Provide **a case study on the agricultural product of avocados**, a very popular fruit in the United States, with growing consumer demand even in China.

The Global Supply Chain Network Model with TRQs



Notation Related to Tariff Rate Quotas

- The groups G_g; $g = 1, \ldots, n_G$, consist of the middle tier nodes $\{h\}$ corresponding to the production sites in the countries from which imports are to be restricted under the tariff quota regime and the demand markets $\{l\}$ in the country that is imposing the tariff rate quota.
- Associated with each group G_g is an under-quota tariff $\tau^u_{G_g}$.
- Associated with each group G_g is an over-quota tariff $\tau^o_{G_g}$, where $\tau^u_{G_g} < \tau^o_{G_g}$.

The Variables

Q_{ihl}**:** denotes the volume of the product manufactured/produced by firm i at production site $h \in \mathcal{J}_i$ and then shipped to demand market l for consumption.

Q_i**:** is the vector of nonnegative product flows, where $Q_i = \{Q_{ihl}; h \in \mathcal{J}_i, l \in \mathcal{K}\}$.

Q is then the vector of all the Q_is.

λ_{G_g}: denotes the quota rent equivalent for G_g.

The Global Supply Chain Network Model with TRQs

The Production Cost Functions

Each firm i; $i = 1, \ldots, I$, is faced with a production cost function f_{ih} associated with manufacturing the product at h such that:

$$f_{ih} = f_{ih}(Q), \quad \forall h \in \mathcal{J}_i. \tag{1}$$

The Transportation Cost Functions

Each firm i; $i = 1, \ldots, I$, encumbers a transportation cost c_{ihl} associated with transporting the product from production site node h to demand market node l:

$$c_{ihl} = c_{ihl}(Q), \quad \forall h \in \mathcal{J}_i, \forall l \in \mathcal{K}. \tag{2}$$

The Conservation of Flow Equations

The demand at each demand node l; $\forall l \in \mathcal{K}$, is denoted by d_l, and satisfies:

$$\sum_{i=1}^{I} \sum_{h \in \mathcal{J}_i} Q_{ihl} = d_l. \tag{3}$$

The Demand Price Functions

The consumers, located at the demand markets, reflect their willingness to pay for the product through the demand price functions ρ_l, $\forall l \in \mathcal{K}$, with these functions being expressed as:

$$\rho_l = \rho_l(d), \tag{4a}$$

where d is the vector of all the demands.

In view of (3), we can redefine the demand price functions (4a) as follows:

$$\hat{\rho}_l = \hat{\rho}_l(Q) \equiv \rho_l(d), \quad \forall l \in \mathcal{K}. \tag{4b}$$

The Utility Function for a Firm Under a TRQ

For a firm i affected by a TRQ, we define the utility function U_i^G as

$$U_i^G \equiv \sum_{h\in\mathcal{J}_i}\sum_{l\in\mathcal{K}}\hat{\rho}_l(Q)Q_{ihl} - \sum_{h\in\mathcal{J}_i} f_{ih}(Q) - \sum_{h\in\mathcal{J}_i}\sum_{l\in\mathcal{K}} c_{ihl}(Q)$$

$$- \sum_{G_g\in\mathcal{I}^i}(\tau^u_{G_g}+\lambda^*_{G_g})\sum_{(h,l)\in G_g} Q_{ihl} \qquad (5a)$$

where $\lambda^*_{G_g}$ is the equilibrium economic rent equivalent for group G_g, assuming values as in Definition 1 below. We group the $\lambda^*_{G_g}$s into the vector λ^*.

The Utility Function for a Firm Not Under A TRQ

For any other firm i, we define its utility function U_i, as

$$U_i \equiv \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} \hat{\rho}_l(Q) Q_{ihl} - \sum_{h \in \mathcal{J}_i} f_{ih}(Q) - \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} c_{ihl}(Q). \quad (5b)$$

We then define $\hat{U}_i \equiv U_i^G$ for all firms i with plants associated with groups and $\hat{U}_i \equiv U_i$ for all firms without plants in countries subject to tariff rate quotas.

Also, we define the feasible sets: $K_i \equiv \{Q_i | Q_i \in R_+^{\sum_{j=1}^{J} Kn_j^i}\}$, $\forall i$.

We assume that the utility functions are concave and continuously differentiable.

Definition 1: Global Supply Chain Network Equilibrium Under TRQs

A product flow pattern Q^* and quota rent equivalent λ^* is a global supply chain network equilibrium under tariff rate quotas if, for each firm i; $i = 1, \ldots, I$, the following conditions hold:

$$\hat{U}_i(Q_i^*, Q_{-i}^*, \lambda^*) \geq \hat{U}_i(Q_i, Q_{-i}^*, \lambda^*), \quad \forall Q_i \in K_i, \tag{6}$$

where $Q_{-i}^* \equiv (Q_1^*, \ldots, Q_{i-1}^*, Q_{i+1}^*, \ldots, Q_I^*)$, and for all groups G_g:

$$\lambda_{G_g}^* \begin{cases} = \tau_{G_g}^o - \tau_{G_g}^u, & \text{if} \quad \sum_{i=1}^I \sum_{(h,l) \in G_g} Q_{ihl}^* > \bar{Q}_{G_g}, \\ \leq \tau_{G_g}^o - \tau_{G_g}^u, & \text{if} \quad \sum_{i=1}^I \sum_{(h,l) \in G_g} Q_{ihl}^* = \bar{Q}_{G_g}, \\ = 0, & \text{if} \quad \sum_{i=1}^I \sum_{(h,l) \in G_g} Q_{ihl}^* < \bar{Q}_{G_g}. \end{cases} \tag{7}$$

Variational Inequality Formulation

Theorem 1: Variational Inequality Formulation of the Global Supply Chain Network Equilibrium Under TRQs

Under the assumption that the utility functions are concave and continuously differentiable, the product flow and quota rent equivalent pattern $(Q^*, \lambda^*) \in \mathcal{H}$ is a global supply chain network equilibrium under tariff rate quotas according to Definition 1 if and only if it satisfies the variational inequality (VI):

$$-\sum_{i=1}^{I} \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} \frac{\partial \hat{U}_i(Q^*, \lambda^*)}{\partial Q_{ihl}} \times (Q_{ihl} - Q^*_{ihl})$$

$$+ \sum_{g} \left[\bar{Q}_{G_g} - \sum_{i=1}^{I} \sum_{(h,l) \in G_g} Q^*_{ihl} \right] \times \left[\lambda_{G_g} - \lambda^*_{G_g} \right] \geq 0, \quad \forall (Q, \lambda) \in \mathcal{H}, \tag{8}$$

where $\mathcal{H} \equiv \{(Q,\lambda) | Q \in \bar{K}, \lambda \in R^{n_G}_{+} | 0 \leq \lambda_{G_g} \leq \tau^o_{G_g} - \tau^u_{G_g}, \forall g\}$.

Corollary 1: Variational Inequality Formulation for the Global Supply Chain Network Without TRQs

In the absence of tariff rate quotas, the equilibrium of the resulting global supply chain network model collapses to the solution of the VI: determine $Q^* \in \bar{K}$, *satisfying:*

$$-\sum_{i=1}^{I} \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} \frac{\partial U_i(Q^*)}{\partial Q_{ihl}} \times (Q_{ihl} - Q^*_{ihl}) \geq 0, \quad \forall Q \in \bar{K}, \tag{9}$$

where $\bar{K} \equiv \prod_{i=1}^{I} K_i$.

Unit Tariffs

The framework can be adapted to handle the simpler trade policy of unit tariffs with an appended term: $-\sum_{h\in\mathcal{J}_i}\sum_{l\in\mathcal{K}}\tau_{hl}Q_{ihl}$, where τ_{hl} denotes the unit tariff assessed on a product flow from h to l, with $\tau_{hl}=0$, if h,l corresponds to a production site and demand market pair in countries not under a tariff.

Strict Quotas

If there is a strict quota regime, for those firms i that are affected, the utility function U_i^G in (5a) is modified to U_i^Q as:

$$U_i^Q = \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} \hat{\rho}_l(Q) Q_{ihl} - \sum_{h \in \mathcal{J}_i} f_{ih}(Q) - \sum_{h \in \mathcal{J}_i} \sum_{l \in \mathcal{K}} c_{ihl}(Q)$$

$$- \sum_{G_g \in \mathcal{I}^i} \lambda^*_{G_g} \sum_{(h,l) \in G_g} Q_{ihl}, \tag{10}$$

where the groups G_g, $\forall g$, now correspond to those node pairs under strict quotas.

The Nash Equilibrium conditions (6) are still relevant but the system (7) is replaced with the system below: for all groups G_g:

$$\bar{Q}_{G_g} - \sum_{i=1}^{I} \sum_{(h,l) \in G_g} Q^*_{ihl} \begin{cases} = 0, & \text{if} \quad \lambda^*_{G_g} > 0, \\ \geq 0, & \text{if} \quad \lambda_{G_g} = 0. \end{cases} \tag{11}$$

The Standard Variational Inequality Form

We now put variational inequality (8) into standard form (cf. Nagurney (1999)): determine $X^* \in \mathcal{L} \subset R^{\mathcal{N}}$, such that

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

where X and $F(X)$ are $\mathcal{N}$-dimensional vectors, $\mathcal{L}$ is a closed, convex set, and F is a given continuous function from $\mathcal{L}$ to $R^{\mathcal{N}}$.

Indeed, we can define $X \equiv (Q, \lambda)$ and $F(X) \equiv (F_1(X), F_2(X))$, where $F_1(X)$ consists of $\sum_{i=1}^{I} \sum_{j=1}^{J} Kn_j^i$ elements: $-\frac{\partial \hat{U}_i(Q,\lambda)}{\partial Q_{ihl}}$ for all i, h, l, and $F_2(X)$ consists of n_G elements, with the g-th element given by: $\left[\bar{Q}_{G_g} - \sum_{i=1}^{I} \sum_{(h,l)\in G_g} Q_{ihl}\right]$. Also, here $\mathcal{N} = \sum_{i=1}^{I} \sum_{j=1}^{J} Kn_j^i + n_G$ and $\mathcal{L} \equiv \mathcal{H}$.

Theorem 2: Existence of a Solution X^* to (12)
Existence of a solution X^* to the variational inequality governing the global supply chain network model with tariff rate quotas given by (12); equivalently, (8), is guaranteed.

Proposition 1: Monotonicity of $F(X)$ in (12)
$F(X)$ in (12) is monotone, that is,

$$\langle F(X^1) - F(X^2), X^1 - X^2 \rangle \geq 0, \quad \forall X^1, X^2 \in \mathcal{L}, \tag{13}$$

if and only if $\hat{F}(X)$ is monotone, where the (i,h,l)-component of $\hat{F}(X)$, $\forall i, h, l$, consists of

$$\left[\sum_{j \in \mathcal{J}_i} \frac{\partial f_{ij}(Q)}{\partial Q_{ihl}} + \sum_{j \in \mathcal{J}_i} \sum_{k \in \mathcal{K}} \frac{\partial c_{ijk}(Q)}{\partial Q_{ihl}} - \hat{\rho}_l(Q) - \sum_{j \in \mathcal{J}_i} \sum_{k \in \mathcal{K}} \frac{\partial \hat{\rho}_k(Q)}{\partial Q_{ihl}} Q_{ijk} \right]. \tag{14}$$

The Algorithm: The Modified Projection Method

Step 0: Initialization

Initialize with $X^0 \in \mathcal{L}$. Set $t := 1$ and select β, such that $0 < \beta \leq \frac{1}{L}$, where L is the Lipschitz constant for function F in the variational inequality problem.

Step 1: Construction and Computation

Compute $\bar{X}^t$ by solving the VI subproblem:

$$\langle \bar{X}^t + \beta F(X^{t-1}) - X^{t-1}, X - \bar{X}^t \rangle \geq 0, \quad \forall X \in \mathcal{L}. \tag{15}$$

Step 2: Adaptation

Compute X^t by solving the VI subproblem:

$$\langle X^t + \beta F(\bar{X}^t) - X^{t-1}, X - X^t \rangle \geq 0, \quad \forall X \in \mathcal{L}. \tag{16}$$

Step 3: Convergence Verification

If $|X^t - X^{t-1}| \leq \epsilon$, for $\epsilon > 0$, a specified tolerance, then, stop; otherwise, set $t := t + 1$ and go to Step 1.

The Algorithm: The Modified Projection Method

Explicit formulae for our model for Step 1.

Path Flows

For each Q_{ihl} with (h,l) **associated with a group** G_g, $\forall g$:

$$\bar{Q}^t_{ihl} = \max\{0, \beta(-\sum_{j \in \mathcal{J}_i} \frac{\partial f_{ij}(Q^{t-1})}{\partial Q_{ihl}} - \sum_{j \in \mathcal{J}_i} \sum_{k \in \mathcal{K}} \frac{\partial c_{ijk}(Q^{t-1})}{\partial Q_{ihl}} + \hat{\rho}_l(Q^{t-1})$$

$$+ \sum_{j \in \mathcal{J}_i} \sum_{k \in \mathcal{K}} \frac{\partial \hat{\rho}_k(Q^{t-1})}{\partial Q_{ihl}} Q^{t-1}_{ijk} - \tau^u_{G_g} - \lambda^{t-1}_{G_g}) + Q^{t-1}_{ihl}\}, \quad (17)$$

and for each Q_{ihl} with (h,l) **not associated with a TRQ**:

$$\bar{Q}^t_{ihl} = \max\{0, \beta(-\sum_{j \in \mathcal{J}_i} \frac{\partial f_{ij}(Q^{t-1})}{\partial Q_{ihl}} - \sum_{j \in \mathcal{J}_i} \sum_{k \in \mathcal{K}} \frac{\partial c_{ijk}(Q^{t-1})}{\partial Q_{ihl}} + \hat{\rho}_l(Q^{t-1})$$

$$+ \sum_{j \in \mathcal{J}_i} \sum_{k \in \mathcal{K}} \frac{\partial \hat{\rho}_k(Q^{t-1})}{\partial Q_{ihl}} Q^{t-1}_{ijk}) + Q^{t-1}_{ihl}\}. \quad (18)$$

The Quota Rent Equivalents

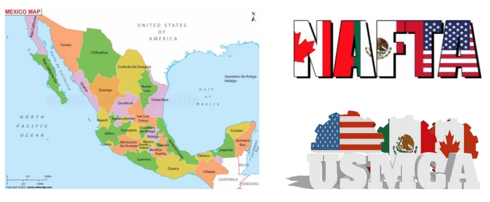
The closed form expression for the quota rent equivalent for group G_g; $g = 1, \ldots, n_G$, is:

$$\bar{\lambda}^t_{G_g} = \max\{0, \min\{\beta(\sum_{i=1}^{I} \sum_{(h,l)\in G_g} Q^{t-1}_{ihl} - \bar{Q}_{G_g}) + \lambda^{t-1}_{G_g}, \tau^o_{G_g} - \tau^u_{G_g}\}\}. \quad (19)$$

A Case Study on Avocados

A Case Study on Avocados

- Mexico produces more avocados than any other country in the world, about **a third of the global total**.
- **In 2017, Mexico exported more than 1.7 billion pounds of Haas avocados to the US.**
- With about 90% of the avocados imported from Mexico to the United States coming from Michoacan.
- The Mexican state of Jalisco, the second-largest avocado-producing state in Mexico, accounts for about 6 percent of total Mexican production.



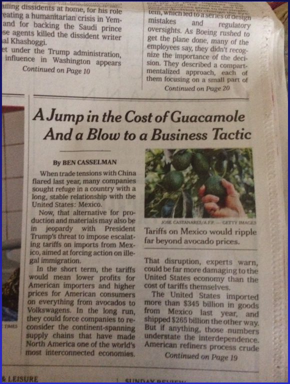
A Case Study on Avocados

- The volume of avocado imports into the United States has surpassed even the volume by weight of bananas imported into the US.

- US domestic avocado consumption has risen to approximately 6.5 pounds per person annually, as compared to only 1.4 in 1990.
- The US is among the world's top ten avocado producers, producing between 160,000 and 270,000 tons of avocados a year.
- In terms of other major demand markets, Mexico was the largest supplier of avocados to China until 2017.

A Case Study on Avocados

The United States' recent imposition of a variety of tariffs, in turn, has resulted in retaliatory tariffs by multiple countries, notably, by Mexico and China and on agricultural products produced in the US.



ailing dissidents at home, for his role eating a humanitarian crisis in Yem- and for backing the Saudi prince se agents killed the dissident writer al Khashoggi.

et under the Trump administration, influence in Washington appears

Continued on Page 10

tem, which led to a series of design mistakes and regulatory oversights. As Boeing rushed to get the plane done, many of the employees say, they didn't recognize the importance of the decision. They described a compartmentalized approach, each of them focusing on a small part of

Continued on Page 20

A Jump in the Cost of Guacamole And a Blow to a Business Tactic

By BEN CASSELMAN

When trade tensions with China flared last year, many companies sought refuge in a country with a long, stable relationship with the United States: Mexico.

Now, that alternative for production and materials may also be in jeopardy with President Trump's threat to impose escalating tariffs on imports from Mexico, aimed at forcing action on illegal immigration.

In the short term, the tariffs would mean lower profits for American importers and higher prices for American consumers on everything from avocados to Volkswagens. In the long run, they could force companies to reconsider the continent-spanning supply chains that have made North America one of the world's most interconnected economies.

JOSE CASTANARES/A.F.P. — GETTY IMAGES

Tariffs on Mexico would ripple far beyond avocado prices.

That disruption, experts warn, could be far more damaging to the United States economy than the cost of tariffs themselves.

The United States imported more than $345 billion in goods from Mexico last year, and shipped $265 billion the other way. But if anything, those numbers understate the interdependence. American refiners process crude

Continued on Page 19

& LEISURE

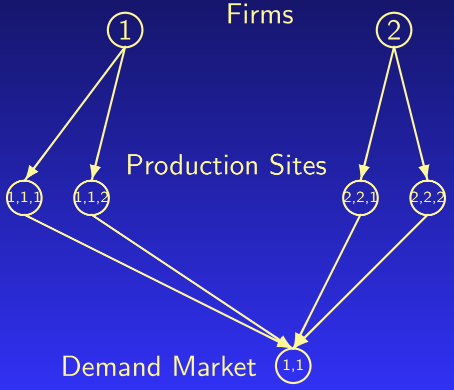
Figure 2: Front page of *The New York Times*, June 2, 2019

A Case Study on Avocados

Example 1: Baseline Example Without Tariff Rate Quotas

Firm 1 has two US production sites: one in San Diego county, and the other in San Luis Obispo in California. Firm 2 also has two production sites available, but located in Mexico, in Michoacan and Jalisco. There is a single demand market in this example, located in the US.

We are interested in determining the equilibrium product flows: Q^*_{111}, Q^*_{121}, Q^*_{231}, and Q^*_{241}.



Example 1: Baseline Example Without Tariff Rate Quotas

The production cost functions faced by Firm 1 at its two production sites are:

$$f_{11}(Q) = .005Q_{111}^2 + .8Q_{111}, \quad f_{12}(Q) = .01Q_{121}^2 + 1.1Q_{121}.$$

The transportation cost functions associated with Firm 1 transporting the avocados to the demand market are:

$$c_{111}(Q) = .1Q_{111}^2 + .5Q_{111}, \quad c_{121}(Q) = .1Q_{121}^2 + .4Q_{121}.$$

The production cost functions faced by Firm 2, with the production sites at the two locations in Mexico, are:

$$f_{23}(Q) = .0005Q_{231}^2 + .15Q_{231}, \quad f_{24}(Q) = .0005Q_{241}^2 + .5Q_{241},$$

and its transportation costs to the demand market are:

$$c_{231}(Q) = .04Q_{231}^2 + .5Q_{231}, \quad c_{241}(Q) = .045Q_{241}^2 + .5Q_{241}.$$

The demand price function is: $\rho_1(d) = -.01d_1 + 3$.

Equilibrium Product Flows, Demand Prices, and Profits

We consider the time horizon of a week and the quantities of avocados are reported in millions of pounds. The currency is US dollars.

- The modified projection method yielded the equilibrium avocado product flow pattern:

$$Q^*_{111} = 5.63, \quad Q^*_{121} = 4.52, \quad Q^*_{231} = 20.75, \quad Q^*_{241} = 15.24.$$

- Demand price per pound of avocados is $\rho_1 = 2.54$.
- Firm 1 achieves a utility (profit) of **6.09 in millions of dollars** whereas Firm 2 enjoys a utility (profit) of **34.63 in millions** of dollars.

Since consumers in the United States consume about 80% of their avocados from Mexico and about 20% from the US, the above results are very reasonable and also correspond well to the weekly consumption of avocados by US consumers.

Example 2: Tariff Rate Quotas on Avocados from Mexico

The United States assigns the tariff rate quota on group G_1, which consists of the Mexican production sites that ship to the United States, and the demand market.

In this example, $\bar{Q}_1 = 30$, $\tau^u_{G_1} = .25$, and $\tau^o_{G_1} = .50$.

- The equilibrium avocado product trade flow and economic rent equivalent patterns are:

$$Q^*_{111} = 5.88, \quad Q^*_{121} = 4.76, \quad Q^*_{231} = 17.60, \quad Q^*_{241} = 12.40,$$

$$\lambda^*_{G_1} = .09.$$

- The demand market price per pound of avocados is: $\rho_1 = 2.59$.
- The utility (profit) of Firm 1 is: 6.69 in millions of dollars and that of Firm 2: 24.18 in millions of dollars.
- The US government acquires tariff payments of 10.24 in millions of dollars.

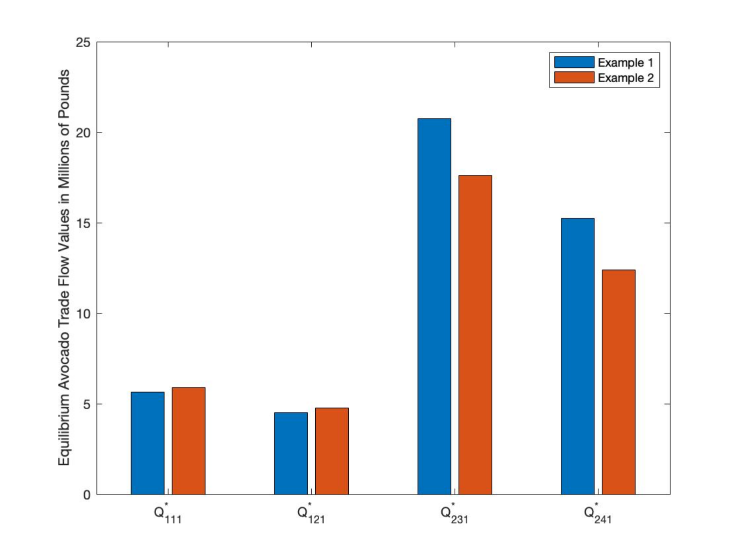
Example 2: Tariff Rate Quotas on Avocados from Mexico

Since the demand market price per pound of avocados ρ_1 is now 2.59, the consumers are faced with a higher price.

Observe that the imports from Mexico to the United States are precisely equal to the imposed quota.

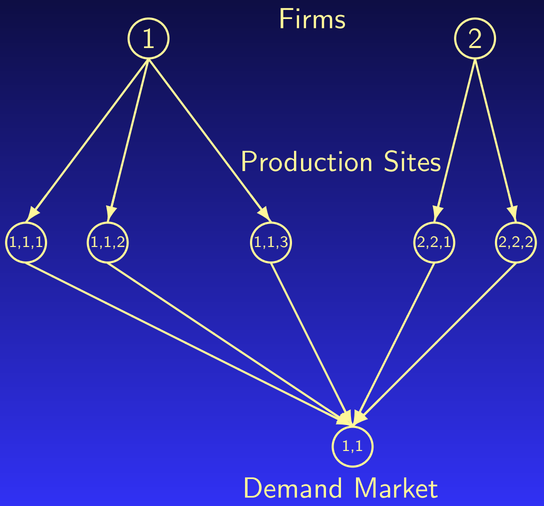
The imposition of the TRQs increases the profit of the US firm by about 10% and **decreases the profit of the Mexican firm by about 33%**.

Equilibrium Avocado Trade Flows in Examples 1 and 2



Example 3: Addition of a New Production Site in the US

Example 3 has the same data as Example 2 except that now Firm 1 has added a production site in Florida.



Example 3: Addition of a New Production Site in the US

- The new computed equilibrium avocado product flow pattern is:

$$Q^*_{111} = 5.57, \quad Q^*_{121} = 4.45, \quad Q^*_{151} = 7.56, \quad Q^*_{231} = 17.60,$$

$$Q^*_{241} = 12.40.$$

- The volume of imports from Mexico remain at the quota $\bar{G}_1 = 30$ million pounds and the equilibrium $\lambda^*_{G_1} = .02$.
- The utility (profit) of Firm 1 is now 12.36 in millions of dollars and 24.18 for Firm 2 in millions of dollars.
- The US government now acquires tariff payments of 8.10 in millions of dollars.

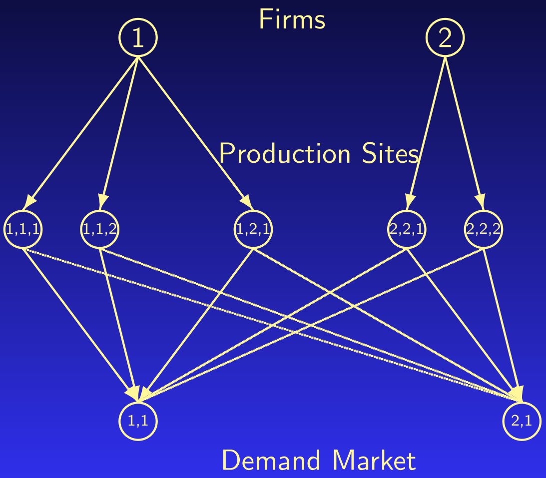
Example 3: Addition of a New Production Site in the US

The almost doubling of profits for Firm 1 in this example signals that it should expand the number of its production sites.

Consumers also benefit since the demand market price decreases to 2.52.

Example 4: Addition of a New Demand Market in China

There has been growing interest among consumers in China for avocados.



Example 4: Addition of a New Demand Market in China

- The new computed equilibrium avocado product flow pattern is:

$$Q^*_{111} = 5.03, \quad Q^*_{112} = 13.33, \quad Q^*_{121} = 3.48, \quad Q^*_{122} = 11.96,$$
$$Q^*_{151} = 7.60, \quad Q^*_{152} = 1.07,$$
$$Q^*_{231} = 17.51, \quad Q^*_{232} = 40.09, \quad Q^*_{241} = 12.49, \quad Q^*_{242} = 21.82.$$

- The incurred demand market prices at the equilibrium in the United States and China are $\rho_1 = 2.54$ and $\rho_2 = 6.12$, respectively.
- The utility (profit) of Firm 1 is now 68.35 and that of Firm 2: 174.97.
- The imports from Mexico to the United States are at the quota with $\lambda^*_{G_1} = .01$.
- The US government income from tariff payments is now: 7.8 in millions of dollars.

Example 4: Addition of a New Demand Market in China

With the opening of a major new market for avocados, the utilities (profits) of both firms increase significantly, with those of Firm 1 more than five-fold, and those of Firm 2 about seven-fold.

The price of avocados in the US, however, increases, albeit only slightly.

The price per pound of avocados in China is very reasonable and reflects reality.

Example 5: Tariff Rate Quota Imposed by China on Imports from the US

- G_2 consists of the production sites corresponding to the United States and the demand market in China.
- The added data are: $\bar{Q}_{G_2} = 15$, $\tau^u_{G_2} = 1$ and $\tau^o_{G_2} = 2$.
- The modified projection method yielded the following equilibrium avocado product flow pattern:

$$Q^*_{111} = 5.25, \quad Q^*_{112} = 7.80, \quad Q^*_{121} = 3.92, \quad Q^*_{122} = 6.58,$$

$$Q^*_{151} = 7.58, \quad Q^*_{152} = .63,$$

$$Q^*_{231} = 17.50, \quad Q^*_{232} = 40.99, \quad Q^*_{241} = 12.48, \quad Q^*_{242} = 22.30.$$

- The demand prices are: $\rho_1 = 2.53$ for a pound of avocados in the United States and $\rho_2 = 6.22$ for a pound of avocados in China.
- The equilibrium economic rents are: $\lambda^*_{G_1} = 0.00$ and $\lambda^*_{G_2} = .87$.

The US government gathers 7.49 million in tariff payments, whereas the Chinese government gains 28.05 million dollars in tariff payments.

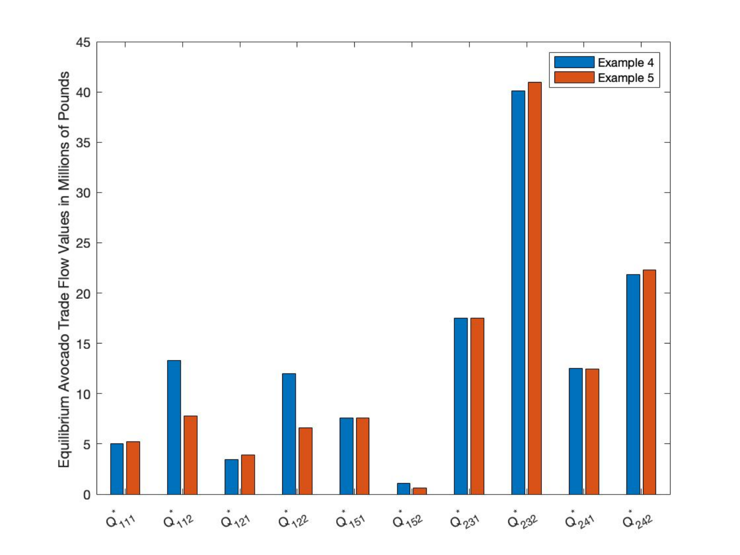
Example 5: Tariff Rate Quota Imposed by China on Imports from the US

Firm 1 now has a reduced utility (profit) of 30.60 in millions of dollars, whereas Firm 2 has a utility (profit) of 181.67 in millions of dollars.

Under the tariff quota regime imposed by China on the United States, **Firm 1 experiences a drop in profits of over 50% as compared to Example 4**, whereas **Firm 2 enjoys a small increase in profits**.

The Chinese government clearly benefits from the imposition of the tariff rate quota against the United States; however, **consumers in China must pay a higher price**.

Equilibrium Avocado Trade Flows in Examples 4 and 5

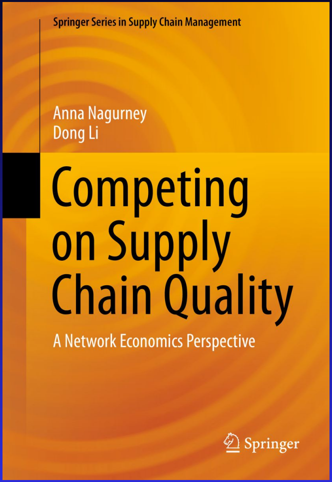


Findings

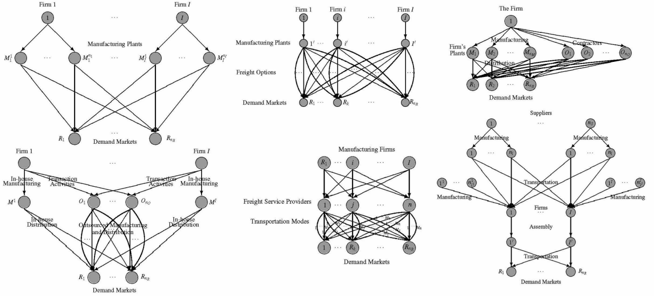
- To-date, there has been limited modeling work of imperfectly competitive firms in supply chain network, in the presence of trade policies such as TRQs, which have been challenging to model.
- The theory of variational inequalities is very useful for the formulation, analysis, and solution of oligopolistic supply chain network equilibrium problems under TRQs.
- The numerical examples that comprise the case study quantify impacts of tariff rate quotas on consumer prices, on product flows, as well as on the firms' profits.
- **The results demonstrate that TRQs can be effective in reducing product flows from countries on which they are imposed but at the expense of the consumers in terms of prices.**

Concluding Thoughts

Our Research on Quality



In the book, we present supply chain network models and tools to investigate information asymmetry, impacts of outsourcing on quality, minimum quality standards, applications to industries such as pharma and high tech, freight services and quality.



Also, relevant is the paper, D. Li and A. Nagurney (2017), Supply chain performance assessment and supplier and component importance identification in a general competitive multitiered supply chain network model, *Journal of Global Optimization* **67(1)**, 223-250.

Food and Product Quality

Consumers are increasingly demanding quality in the food)fresh produce) that they eat as well as many other products.

Supply Chain Network Models with Quality Under Strict Quotas or Tariffs

Now we turn to research on the incorporation of quality as a strategic variable and the exploration of the relationship between strict quotas and tariffs.

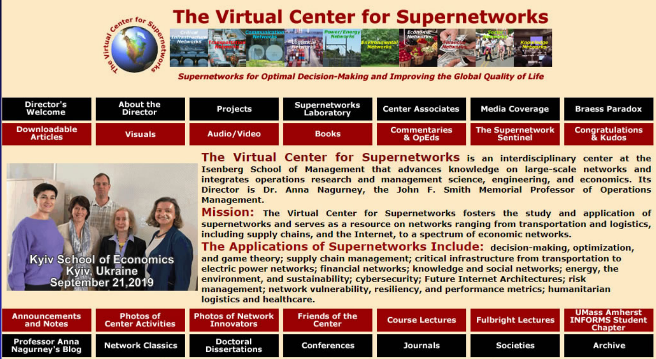
Specifically, we are interested in the impact of tariffs or strict quotas on consumer welfare.

A. Nagurney, D. Besik, and D. Li (2019), Strict quotas or tariffs? Implications for product quality and consumer welfare in differentiated product supply chains, *Transportation Research E* **29**, pp 136-161.

We see at this Congress the fabulous OR tools and applications that are transforming transportation, logistics, finance, and agriculture, among other areas!

Congratulations to all and keep up the great work!

THANK YOU!



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