Environment and Resources: From Theory to Practice of Network Optimization in Supply Chains

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Outline

Motivation: scarce resources

A farmer kneeling on his cracked land, Los Angeles, 2014

Congolese soldiers guarding suspected rebel fighters over the conflict of rare earth elements (cobalt, copper, and coltan) near the eastern town of Goma, 2013

Yemenis presenting documents in order to receive food rations provided by a local charity, in Sanaa, Yemmen, 2017

Some empty shelves in a grocery store in the US during COVID-19 pandemic, 2020

A notice covering an empty shelf at an Oakland CVS store in February, 2020

How climate change may impact energy usage: 2080-2099

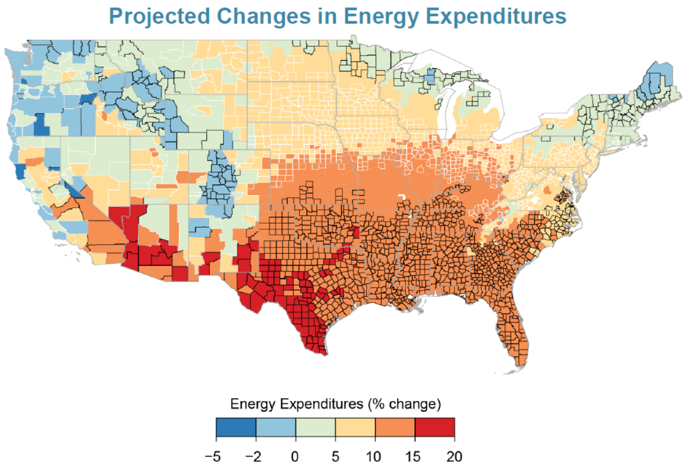


Figure 4.2: This figure shows county-level median projected increases in energy expenditures for average 2080–2099 impacts under the higher scenario (RCP8.5). Impacts are changes relative to no additional change in climate. Color indicates the magnitude of increases in energy expenditures in median projection; outline color indicates level of agreement across model projections (thin white outline, inner 66% of projections disagree in sign; no outline, more than 83% of projections agree in sign; black outline, more than 95% agree in sign; thick gray outline, state borders). Data were unavailable for Alaska, Hawai'i and the U.S.-Affiliated Pacific Islands, and the U.S. Caribbean regions. Source: Hsiang et al. 2017.[14]

Scarce Resource

What are considered scarce resource?

(Rosenberg, 1973; Krautkraemer, 2005)

- Natural resources: agricultural crops, fisheries, wildlife, forests, petroleum, metals, minerals, even air, soil, water, etc
- Non-renewable resources: rare earth elements, fossil fuels
- Commodities in high demand during a short period of time: PPE during COVID-19 pandemic.

Characters of scarce resource

(Pfeffer and Salancik, 1978; Cannon and Perreault, 1999; Pfeffer and Salancik, 2003; Caniëls and Gelderman, 2007; Hunt, 2000)

- Abundance means power
- Heterogeneous
- Interdependent with one another

Some causes of resource scarcity

- Growing population and demand
- Climate change
- Geopolitical shift, trade wars
- Rising risk of crises such as pandemics

A complex system: interdependent resources, affected by climate

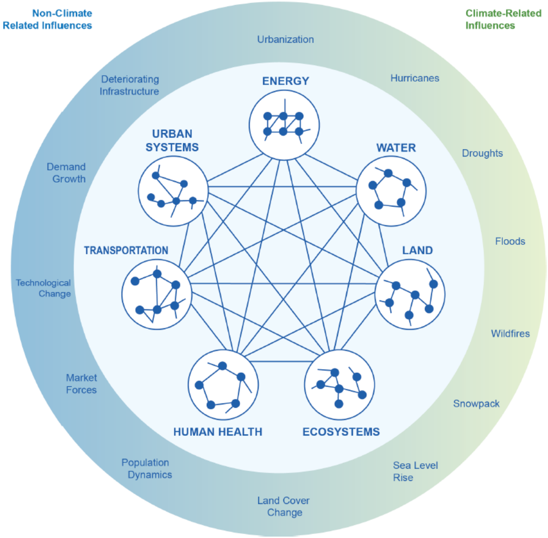


Figure 1: Sources: Pacific Northwest Nat'l Lab, Arizona State, Cornell University

Research Objectives

Research questions

1. How can a scarce resource supply chain be represented by a general network?
2. For **resource producing firms**, how do they benefit from an incentive scheme? How does a specific incentive impact demands, prices, and profits? Under a certain environmental policy, how should firms adjust their business strategies in order to be more profitable and competitive?
3. For **consumers** at different demand markets, how do they benefit from a producer "stimulus package"?
4. For **resources owners**, what happens when conflict emerges? What could alleviate it?
5. For **policy makers**, how does social welfare respond to policy instruments? Who is the winner? During supply chain overload, who should get the stimulus when budget is limited? To relieve a critical resource shortage crisis, what might be a better incentive structure?

Research agenda

1. Develop a general network model to represent the scarce resource supply chain.
2. Formulate the model using finite-dimensional variational inequalities, for their elegant representation, inherent connection to a variety classes of problems, and well-developed theoretical and solution framework.
3. Evaluate production activities, consumer prices, ownership conflicts, and social welfare.
4. Incorporate a new theoretical property to characterize the supply chain network equilibrium.
5. Provide managerial insights for firms and advice for policy-makers.
6. Assess Carbon Dividend Act of 2019.

Scholarly Landmarks

Some history of games and networks

Year	Name	Event
1929	Harold Hotelling	Spatial (location) model
1940s	John von Neumann	Minimax, game theory (w/ Morgenstern)
1951	John Nash	Nash equilibrium
1952	John Nash	Nash equilibrium: n-person game
1951	Lloyd Shapley	Shapley value was introduced to characterize how important each player is to a cooperative game (eg., a coalition).
1952	Debreu	Generalized Nash equilibrium problems
1950s-1960s	Enke; P. Samuelson; Takayama and Judge	Spatial Price equilibrium and linear programming
1960s	D. Friedman	Evolutionary games
1965	J. Ben Rosen	Existence and uniqueness of equilibrium for concave n-person games
1980s	Robinson; Rutherford	Newton based computational methods; convergence; sensitivity; generalized methods
2014	Yann Bramoullé	Lowest eigenvalue for strategic complements or substitute in network games

Some history of O.R. and network optimization

Year	Name	Event
Early 1900s - 1949	Caratheodory, Minkowski, Steinitz, Farkas	Pre-history: Properties of convex sets and functions
1930s	-	Operational Research was used to describe the process of evaluation of radar in the air defense of Britain
1940s-1950s	Werner Fenchel	Duality theory.
1940s	John von Neumann	Minimax, game theory (w/ Morgenstern)
1944	Haskell Curry	Gradient descent method: unconstrained smooth optimization
1946–1947		Operational Research Quarterly: The first OR journal
1950s	George B. Dantzig	linear programming and simplex method
1951	K.K.T.	Karush–Kuhn–Tucker conditions
1956	Marguerite Frank and Philip Wolfe	Frank–Wolfe algorithm for constrained convex optimization
1960s-1980s	R. Tyrrell Rockafellar	Differentiability, Lagrange multipliers and optimality, sensitivity of convex and concave.
1960s	Guido Stampacchia	1st theorem of existence and uniqueness of VI solution
1964	Richard W. Cottle	NCP identified (as Dantzig's student)
1970s	W. Hogan	PIES: a VI/CP based market eq. sytem model by USDOE
1960s-1970s	S. Dafermos; D. Braess	Traffic eq. problem in VI; Braess's paradox
1980	Gabay and Moulin	Equivalence of VI and Optimization problem
1980s	Robinson; Rutherford	Newton based computational methods; convergence; sensitivity; generalized methods
1990s	-	Pre 1990s: LP-NLP. Post 1990s: Convex-Nonconvex (Rockafellar)
1990s-2000s	S. Dafermos; A. Nagurney	Equivalence of traffic and supply chain eq. problem; super-networks
1995	Michael Ferris	GAMS PATH solver, a Newton method based algorithm, for equilibrium problems
1995-	Facchinei; Kanzow	semi-smooth Newton method: improvement, extension, testing

Building Blocks of the Research

Laws in resource usage, ownership, and enforcement

I examine the roles that the focused resources play, in legal conflicts, and the lessons from the (ruling of the) cases.

Some famous resource related supreme court cases

- WYOMING HEREFORD RANCH v. HAMMOND PACKING CO., Supreme court of Wyoming, 1952. (PRIOR APPROPRIATION)
- HARRIS v. BROOKS, Supreme Court of Arkansas 1955. (RIPARIAN RIGHTS)
- COMMONWEALTH OF MASSACHUSETTS et al. v. ENVIRONMENTAL PROTECTION AGENCY, the U.S. Supreme Court, 2007. (EPA's authority on CAA of 1963)

"A judge should not be influenced by the weather of the day. They will inevitably be influenced by the climate of the era."

- RBG, when asked if public opinions should affect a judge's vote in a particular case.

Related literature I: variational inequality (VI) thoery

The variational inequality provides a unifying, elegant framework for equilibrium problems, with well-developed algorithmic solution schemes.

- VI theory: Kinderlehrer and Stampacchia (1980); Harker and Pang (1990); Facchinei and Pang (2003)
- GNEP/QVI: Debreu (1952); Arrow and Debreu (1954); Harker (1991); Facchinei and Kanzow (2007); Kulkarni and Shanbhag (2012); Dreves (2016)
- Theoretical and algorithmic procedure for VI: Korpelevich (1976); Nagurney (1999); Hogan (1992); Chao and Peck (1996); Wu et al. (1996); Conejo and Prieto (2001); Contreras et al. (2004); Nagurney (2006a); Schweppe et al. (2013)

Related literature II: network optimization

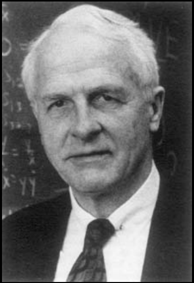
Convexity/concavity is the "backbone" of this research - it's a favorable condition that allows for NP-hard problems to be "solved".

- Convex optimization theory: Bertsekas and Tsitsiklis (1989); Boyd and Vandenberghe (2004)

VI formulation solves important optimization problem.

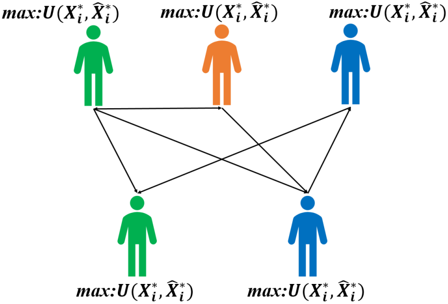
- Equivalence of VI and optimization problems: Eaves (1971); Gabay and Moulin (1980); Dafermos and Nagurney (1987); Bazaraa et al. (1993); Nagurney (1999)

"The great **watershed in optimization** isn't between linearity and nonlinearity, but **convexity and nonconvexity**"



- Tyrrell Rockafellar

Network games and Nash equilibrium



DEFINITION:
A network game is a game in which a player's payoff depends on its own strategy AND the neighbors' strategies.

Nash equilibrium (Nash, 1950, 1951)

For an m-person game, a Nash equilibrium is a strategy vector

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

such that,

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

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

Related literature III: games theory and networks

The foundation of competitions is the non-cooperative behaviors. Network game is a class of (classic) prisoner-dilemma kind of game theory.

- Classic Cournot-Nash: Cournot (1838); Nash (1950, 1951)

The theoretical study of Network game is a new avenue of research. It was revived from the earlier research that deals with existence, uniqueness, sensitivity, convergence, and approximation.

- Network games theory (existence, uniqueness, sensitivity): Rosen (1965); Jackson and Zenou (2015); Parise and Ozdaglar (2017); Melo (2018)
- Emerging trend: scalar quantity (eigenvalue of game Jacobians): Bramoullé et al. (2014); Naghizadeh and Liu (2017); Melo (2018)

Related literature IV: applications of network games/VI

- Spatial price equilibrium (SPE) - a transportation network: Enke (1951); Samuelson (1952); Takayama and Judge (1964)
- SPE in VI: Dafermos and Nagurney (1984, 1987)
- General supply chain: Nagurney et al. (2002); Zhang (2006); Nagurney (2006b)
- Scare resources supply chain: power supply (Nagurney et al., 2006; Nagurney and Matsypura, 2007; Wu et al., 2006); blood donation (Nagurney and Dutta, 2019); fresh produce (Besik and Nagurney, 2017); pharmaceuticals (Masoumi et al., 2012).
- Policy intervention: taxation (Nagurney et al., 2006; Wu et al., 2006; Yu et al., 2018); pollution control (Nagurney and Dhanda, 2000; Yu et al., 2018); subsidy (Wu et al., 2019)

Related literature V: resources in complex system with game-theoretic models

This study is also inherent to the research that aims to understand the interconnected physical resources and their ability to adapt to external stressors in a competitive environment.

- Agriculture and fuels: Wang et al. (2013); Lim and Ouyang (2016); Bai et al. (2016, 2012); Luo and Miller (2013); Bajgiran et al. (2019)
- Energies and water: Zhang and Vesselinov (2016); Hamoud and Jang (2020)
- Water and agriculture: Bakker et al. (2018)

Literature gaps

1. There is no general model that can represent a typical scarce resource supply chain.
2. Only a few paper examined the efficacy of incentives in stylized models, but not in general models.
3. No one has used λ_{min} to characterize a variational inequality-based network structure in a supply chain setting.
4. No one has examined or assessed a combination of incentive and taxation policies in one supply chain network.
5. There are very few supply chain models as general Nash equilibrium problem (GNEP) in the literature to-date.

A Technical Preliminary: Variational Inequality Theories

A modeling technique: Variational Inequalities (VI)

The variational Inequality provides a powerful, unifying framework to model and solve network games.

Definition: Variational Inequality Problem (Facchinei and Pang, 2003)

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

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

where F is a given smooth 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 n dimensional Euclidean space.

The variational inequality (VI) problem: geometry

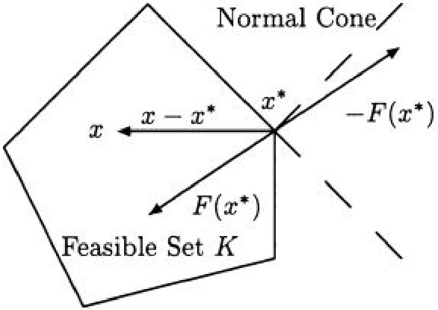


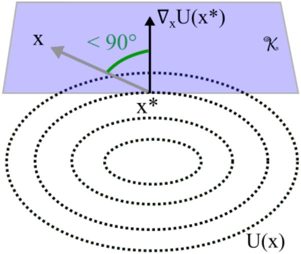
Figure 2: The VI states that $F(x^*)^T$ is "orthogonal" to the feasible set K at the point x^*. (Nagurney, 1999)

The relationship between VI and convex optimization problem

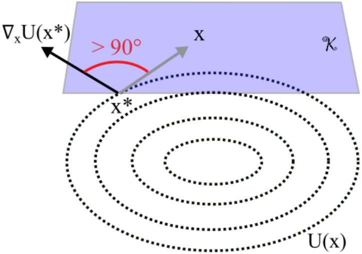
An equivalence (Eaves, 1971; Gabay and Moulin, 1980)

If $\mathcal{K}$ closed and convex, $F(X) = \nabla_X U(X)$ for $U(X)$ convex.

$$\nabla U(X^*)^T (X - X^*) \geq 0, \ \forall X \in \mathcal{K} \quad \Leftrightarrow \quad X^* \in arg \min_{X \in \mathcal{K}} U(X)$$

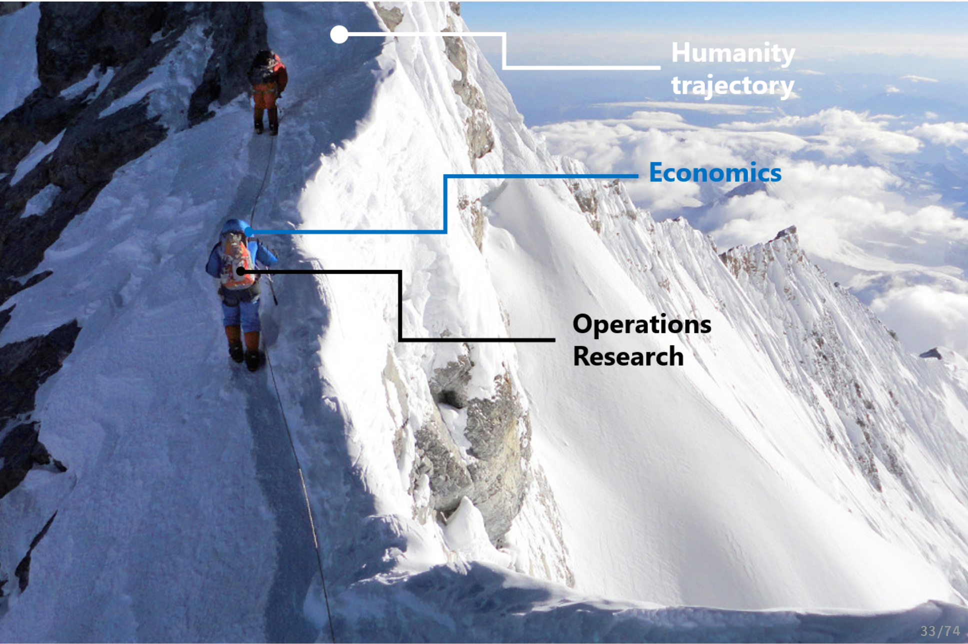


x* is a solution



x* is not a solution

Resource, climate: a humanity trajectory



Proposed Model:
A General Scarce Resource Supply Chain Network with Fiscal/Monetary Schemes

The general scarce resource supply chain network model

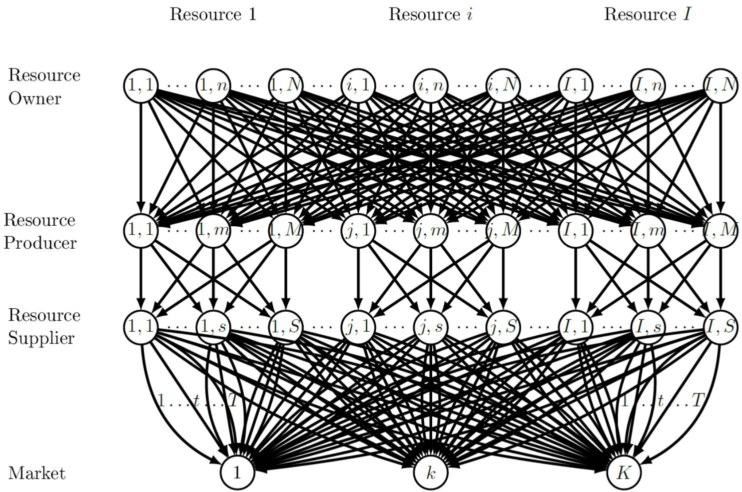


Figure 3: A Scarce Resource Supply Chain Network topology

Some highlights of the model

- It represents multiple resources.
- It considers the features of scarcity.
- It is the first general scarce resource supply chain network model (as opposed to stylized models).
- It is one of the few decentralized supply chains that consider a unified fiscal/monetary scheme (on resource owners and producers).
- The shared resource pools of owners are inspired by the conflicts in resource law cases.
- The model embodies the interdependence of the scarce resources.

The incentive scheme

A_g: cutoff bracket of the incentives, $g = 1, ...G$.
δ_g: the excess of output quantity within bracket A_g. Assume linear.

The general incentive payment function

$$\alpha_0(x) + \sum_{g=1}^{G} \alpha_g(\delta_g), \tag{1}$$

where, $\delta_g = [x - A_g^{in}]_+, \quad g = 1, ..., G$.

Note: this scheme can also be used as a general taxation scheme.

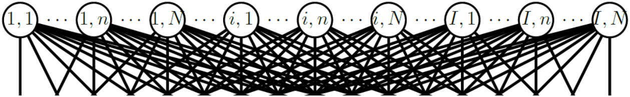
E.g.: the US Economic Impact Payments of COVID-19 (aka, the stimulus checks) is:

$$1200 - 0.05(\delta_1), \tag{2}$$

where, $\delta_1 = [x - 75000]_+$, $\delta_2 = [x - 99000]_+$.

Resource owner's problem (1 of 2)

Resource Owner



$$max : \sum_{j=1}^{I}\sum_{m=1}^{M} \rho_{0jm}^{in} x_{jm}^{in} - f^{in}(x^{in}) - \sum_{j=1}^{I}\sum_{m=1}^{M} c_{jm}^{in}(x_{jm}^{in}) + \alpha_0(\sum_{j=1}^{I}\sum_{m=1}^{M} x_{jm}^{in}) + \sum_{g=1}^{G} \alpha_g(\delta_g^{in})$$

$$s.t. : \sum_{j=1}^{I}\sum_{m=1}^{M} x_{jm}^{in} \leq U_{in},$$

$$\sum_{j=1}^{I}\sum_{m=1}^{M} x_{jm}^{in} - \delta_g^{in} \leq A_g^{in}, \quad \forall g,$$

$$x_{jm}^{in} \geq 0, \quad \forall j, m,$$

$$\delta_g^{in} \geq 0, \quad \forall g.$$

Resource owner's problem (2 of 2)

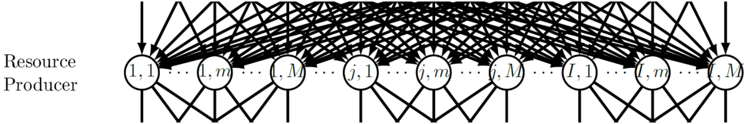
Reformulate the previous optimization problem into VI problem:

Resource owner's optimality condition

$$\sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{j=1}^{I}\sum_{m=1}^{M}\left[\frac{\partial f^{in}(x^{in*})}{\partial x_{jm}^{in}}+\frac{\partial c_{jm}^{in}(x_{jm}^{in*})}{\partial x_{jm}^{in}}-\rho_{0jm}^{in*}-\frac{\partial \alpha_0(x_{jm}^{in*})}{\partial x_{jm}^{in}}\right.$$
$$\left.+\lambda_{in}^{0*}+\sum_{g=1}^{G}\mu_{ing}^{0*}\right]\times(x_{jm}^{in}-x_{jm}^{in*})$$
$$+\sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{g=1}^{G}\left[-\frac{\partial \alpha_g(\delta_g^{in*})}{\partial \delta_g^{in}}\right]\times(\delta_g^{in}-\delta_g^{in*})$$
$$+\sum_{i=1}^{I}\sum_{n=1}^{N}\left[U_{in}-\sum_{j=1}^{I}\sum_{m=1}^{M}x_{jm}^{in*}\right]\times(\lambda_{in}^{0}-\lambda_{in}^{0*})$$
$$+\sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{g=1}^{G}\left[A_g^{in}-\sum_{j=1}^{I}\sum_{m=1}^{M}x_{jm}^{in*}+\delta_g^{in*}\right]\times(\mu_{ing}^{0}-\mu_{ing}^{0*})\geq 0,$$
$$\forall(Q^0,\mathfrak{d}^0,\lambda^0,\mu^0)\in\mathcal{K}^1,$$

where, $\mathcal{K}^1\equiv\{(Q^0,\mathfrak{d}^0,\lambda^0,\mu^0)|(Q^0,\mathfrak{d}^0,\lambda^0,\mu^0)\in R_+^{I^2MN+2ING+IN}\}$.

Resource producer's problem (1 of 2)



$$max : \sum_{s=1}^{S} \rho_{1s}^{jm*} x_s^{jm} - \sum_{j=1}^{I} \sum_{n=1}^{N} \rho_{0jm}^{in*} x_{jm}^{in} - f^{jm}(x_{jm}) - \sum_{s=1}^{S} c_s^{jm}(x_s^{jm})$$

$$+ \beta_0 (\sum_{s=1}^{S} x_s^{jm}) + \sum_{g=1}^{G} \beta_g (\delta_g^{jm})$$

$$s.t. : \sum_{i=1}^{I} \sum_{n=1}^{N} x_{jm}^{in} \cdot \psi_{jm}^{in} \leq \sum_{s=1}^{S} x_s^{jm},$$

$$\sum_{s=1}^{S} x_s^{jm} - \delta_g^{jm} \leq B_g^{jm}, \quad \forall g,$$

$$x_s^{jm} \geq 0, \quad \forall s,$$

$$\delta_g^{jm} \geq 0, \quad \forall g.$$

Resource producer's problem (2 of 2)

Resource producer's optimality condition

$$\sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{j=1}^{I}\sum_{m=1}^{M}\left[\frac{\partial f^{jm}(x_{jm}^{*})}{\partial x_{jm}^{in}}+\rho_{0jm}^{in*}+\psi_{jm}^{in}\lambda_{jm}^{1*}\right]\times(x_{jm}^{in}-x_{jm}^{in*})$$

$$+\sum_{j=1}^{I}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{s}^{jm}(x_{s}^{jm*})}{\partial x_{s}^{jm}}-\rho_{1s}^{jm*}-\frac{\partial\beta_{0}(x_{s}^{jm*})}{\partial x_{s}^{jm}}-\lambda_{jm}^{1*}+\sum_{g=1}^{G}\mu_{jmg}^{1*}\right]\times(x_{s}^{jm}-x_{s}^{jm*})$$

$$+\sum_{j=1}^{I}\sum_{m=1}^{M}\sum_{g=1}^{G}\left[-\frac{\partial\beta_{g}(\delta_{g}^{jm*})}{\partial\delta_{g}^{jm}}\right]\times(\delta_{g}^{jm}-\delta_{g}^{jm*})$$

$$+\sum_{j=1}^{I}\sum_{m=1}^{M}\left[\sum_{s=1}^{S}x_{s}^{jm*}-\sum_{i=1}^{I}\sum_{n=1}^{N}x_{jm}^{in*}\cdot\psi_{jm}^{in}\right]\times(\lambda_{jm}^{1}-\lambda_{jm}^{1*})$$

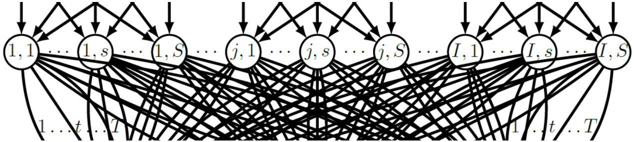
$$+\sum_{j=1}^{I}\sum_{m=1}^{M}\sum_{g=1}^{G}\left[B_{g}^{jm}-\sum_{s=1}^{S}x_{s}^{jm*}+\delta_{g}^{jm*}\right]\times(\mu_{jmg}^{1}-\mu_{jmg}^{1*})\geq 0,$$

$$\forall(Q^{0},Q^{1},\mathfrak{d}^{1},\lambda^{1},\mu^{1})\in\mathcal{K}^{2},$$

where, $\mathcal{K}^{2}\equiv\{(Q^{0},Q^{1},\mathfrak{d}^{1},\lambda^{1},\mu^{1})|(Q^{0},Q^{1},\mathfrak{d}^{1},\lambda^{1},\mu^{1})\in R_{+}^{I^{2}MN+IMS+2IMG+IM}\}$.

Resource supplier's problem (1 of 2)

Resource
Supplier



$$max: \sum_{t=1}^{T}\sum_{k=1}^{K}\rho_{2tk}^{js*}x_{tk}^{js} - \sum_{j=1}^{I}\sum_{m=1}^{M}\rho_{1s}^{jm*}x_{s}^{jm} - f^{js}(x^{js}) - \sum_{t=1}^{T}\sum_{k=1}^{K}c_{tk}^{js}(x_{tk}^{js})$$

$$S.t.: \quad \sum_{k=1}^{K}\sum_{t=1}^{T}x_{tk}^{js} \leq \sum_{m=1}^{M}x_{s}^{jm},$$

$$x_{tk}^{js} \geq 0, \quad \forall t, k.$$

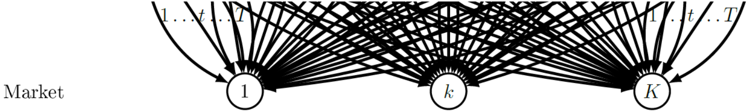
Resource supplier's problem (2 of 2)

Resource supplier's optimality condition

$$\sum_{j=I}^{I}\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{k=1}^{K}\left[\frac{\partial f^{js}(x^{js*})}{\partial x_{tk}^{js}}+\frac{\partial c_{tk}^{js}(x_{tk}^{js*})}{\partial x_{tk}^{js}}-\rho_{2tk}^{js*}+\lambda_{js}^{2*}\right]\times(x_{tk}^{js}-x_{tk}^{js*})$$
$$+\sum_{j=1}^{I}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\rho_{1s}^{jm*}-\lambda_{js}^{2*}\right]\times(x_{s}^{jm}-x_{s}^{jm*})$$
$$+\sum_{j=I}^{I}\sum_{s=1}^{S}\left[\sum_{m=1}^{M}x_{s}^{jm*}-\sum_{k=1}^{K}\sum_{t=1}^{T}x_{tk}^{js*}\right]\times(\lambda_{js}^{2}-\lambda_{js}^{2*})\geq 0,$$
$$\forall(Q^1,Q^2,\lambda^2)\in\mathcal{K}^3,$$

where, $\mathcal{K}^3\equiv\{(Q^1,Q^2,\lambda^2)|(Q^1,Q^2,\lambda^2)\in R_{+}^{IMS+ISTK+IS}\}$.

Demand market's problem (1 of 2)



The spatial price equilibrium condition is given by

$$\rho_{2tk}^{js*} + \hat{c}_{tk}^{js*}(x_{tk}^{js*}) \begin{cases} = \rho_{3k}^{j}(d^*) & \text{if} \quad x_{tk}^{js*} > 0 \\ > \rho_{3k}^{j}(d^*) & \text{if} \quad x_{tk}^{js*} = 0 \end{cases} \quad \forall j, s, t, k.$$

Demand market's problem (2 of 2)

Demand market's optimality condition

$$\sum_{j=1}^{I}\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{k=1}^{K}[\rho_{2tk}^{js*}+\hat{c}_{tk}^{js}(x_{tk}^{js*})]\times(x_{tk}^{js}-x_{tk}^{js*})-\sum_{j=1}^{I}\sum_{k=1}^{K}\rho_{3k}^{j}(d^*)\times(d-d^*)\geq 0,$$
$$\forall(Q^2,d)\in\mathcal{K}^4,$$

where, $\mathcal{K}^4\equiv\{(Q^2,d)|Q^2\in R_+^{ISTK},\ d\in R_+^{IK}\}$.

The equilibrium

Theorem: The equilibrium conditions governing the cross-sector multi-product scarce resource supply chain network are equivalent to the solution to the following variational inequalities:

Determine $(Q^{0}, Q^{1}, Q^{2}, \eth^{0}, \eth^{1}, d, \lambda^{0}, \lambda^{1}, \lambda^{2}, \mu^{0}, \mu^{1}) \in \mathcal{K}$, satisfying

$$
\begin{aligned}
&\sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{j=1}^{I}\sum_{m=1}^{M}\left[\frac{\partial f^{in}(x^{in*})}{\partial x^{in}_{jm}}+\frac{\partial f^{jm}(x^{*}_{jm})}{\partial x^{in}_{jm}}+\frac{\partial c^{in}_{jm}(x^{in*}_{jm})}{\partial x^{in}_{jm}}-\frac{\partial \alpha_{0}(x^{in*}_{jm})}{\partial x^{in}_{jm}}+\lambda^{0*}_{in}+\psi^{in}_{jm}\lambda^{1*}_{jm}+\sum_{g=1}^{G}\mu^{0*}_{ing}\right]\times(x^{in}_{jm}-x^{in*}_{jm})\\
&+\sum_{j=1}^{I}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c^{jm}_{s}(x^{jm*}_{s})}{\partial x^{jm}_{s}}-\frac{\partial \beta_{0}(x^{jm*}_{s})}{\partial x^{jm}_{s}}-\lambda^{1*}_{jm}-\lambda^{2*}_{js}+\sum_{g=1}^{G}\mu^{1*}_{jmg}\right]\times(x^{jm}_{s}-x^{jm*}_{s})\\
&+\sum_{j=I}^{I}\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{k=1}^{K}\left[\frac{\partial f^{js}(x^{js*})}{\partial x^{js}_{tk}}+\frac{\partial c^{js}_{tk}(x^{js*}_{tk})}{\partial x^{js}_{tk}}+\hat{c}^{js}_{tk}(x^{js*}_{tk})+\lambda^{2*}_{js}\right]\times(x^{js}_{tk}-x^{js*}_{tk})\\
&-\sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{g=1}^{G}\frac{\partial \alpha_{g}(\delta^{in*}_{g})}{\partial \delta^{in}_{g}}\times(\delta^{in}_{g}-\delta^{in*}_{g})-\sum_{j=1}^{I}\sum_{m=1}^{M}\sum_{g=1}^{G}\frac{\partial \beta_{g}(\delta^{jm*}_{g})}{\partial \delta^{jm}_{g}}\times(\delta^{jm}_{g}-\delta^{jm*}_{g})\\
&-\sum_{j=1}^{I}\sum_{k=1}^{K}\rho^{j}_{3k}(d^{*})\times(d-d^{*})+\sum_{i=1}^{I}\sum_{n=1}^{N}\left[U_{in}-\sum_{j=1}^{I}\sum_{m=1}^{M}x^{in*}_{jm}\right]\times(\lambda^{0}_{in}-\lambda^{0*}_{in})\\
&+\sum_{j=1}^{I}\sum_{m=1}^{M}\left[\sum_{s=1}^{S}x^{jm*}_{s}-\sum_{i=1}^{I}\sum_{n=1}^{N}x^{in*}_{jm}\cdot\psi^{in}_{jm}\right]\times(\lambda^{1}_{jm}-\lambda^{1*}_{jm})+\sum_{j=I}^{I}\sum_{s=1}^{S}\left[\sum_{m=1}^{M}x^{jm*}_{s}-\sum_{k=1}^{K}\sum_{t=1}^{T}x^{js*}_{tk}\right]\times(\lambda^{2}_{js}-\lambda^{2*}_{js})\\
&+\sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{g=1}^{G}\left[A^{in}_{g}-\sum_{j=1}^{I}\sum_{m=1}^{M}x^{in*}_{jm}+\delta^{in*}_{g}\right]\times(\mu^{0}_{ing}-\mu^{0*}_{ing})\\
&+\sum_{j=1}^{I}\sum_{m=1}^{M}\sum_{g=1}^{G}\left[B^{jm}_{g}-\sum_{s=1}^{S}x^{jm*}_{s}+\delta^{jm*}_{g}\right]\times(\mu^{1}_{jmg}-\mu^{1*}_{jmg})\geq 0,\\
&\forall(Q^{0}, Q^{1}, Q^{2}, \eth^{0}, \eth^{1}, d, \lambda^{0}, \lambda^{1}, \lambda^{2}, \mu^{0}, \mu^{1})\in R_{+}^{2(I^{2}MN+ING+IMG+IMS+ISTK)+I(N+M+S+K)},
\end{aligned}
\tag{3}
$$

Standard form and solution schemes

Rewrite equation (3) as the standard form

$$\langle F(X^*),\ X - X^* \rangle \geq 0, \quad \forall X^* \in \mathcal{K}, \tag{4}$$

where, $X \equiv (Q^0, Q^1, Q^2, \mathfrak{d}^0, \mathfrak{d}^1, d, \lambda^0, \lambda^1, \lambda^2, \mu^0, \mu^1)$,

$$F(X) \equiv (F_{Q^0}, F_{Q^1}, F_{Q^2}, F_{\mathfrak{d}^0}, F_{\mathfrak{d}^1}, F_d, F_{\lambda^0}, F_{\lambda^1}, F_{\lambda^2}, F_{\mu^0}, F_{\mu^1}),$$

$$\mathcal{K} \equiv R_+^{2(I^2 MN + ING + IMG + IMS + ISTK) + I(N+M+S+K)}.$$

Algorithms

- Lemke-Howson algorithm (Lemke and Howson Jr, 1964; Eaves, 1978)
- Newton-based (Newton, Quasi-Newton, linearized Jacobi, projection) methods (Cottle, 1966; Korpelevich, 1976; Pang and Chan, 1982)
- Fixed-point method (Scarf, 1967)
- Euler method (Dupuis and Nagurney, 1993; Zhang and Nagurney, 1995).

Theoretical properties: existence and uniqueness

In VI literature, theoretical properties often refer to the equilibrium solution's existence, uniqueness, stability, and approximation, etc.

This study establishes *existence* and perhaps *uniqueness*.

Existence: (Rosen, 1965)

Conditions required: convex, compact (or closed) $\mathcal{K}$; continuous F.

Uniqueness

1. F's monotonicity via (a) coercivity, or, (b) semidefinteness of game Jacobians, or (c) smallest eigenvalue of game Jacobians.
2. Monotonicity of different "strengths".

Existence

Challenge

While F in (4) is continuous, the feasible set $\mathcal{K}$ is not compact. This results the existence condition of (3) not readily available.

Impose a weak condition to guarantee the existence of a solution pattern. Following Kinderlehrer and Stampacchia (1980), I impose bounds b on strategic variables:
Let

$$\begin{aligned} \mathcal{K}_b \equiv \big\{(Q^0, Q^1, Q^2, \mathfrak{d}^0, \mathfrak{d}^1, d, \lambda^0, \lambda^1, \lambda^2, \mu^0, \mu^1) \mid 0 \leq Q^0 \leq b_1, \\ 0 \leq Q^1 \leq b_2, 0 \leq Q^2 \leq b_3, 0 \leq \mathfrak{d}^0 \leq b_4, 0 \leq \mathfrak{d}^1 \leq b_5, 0 \leq d \leq b_6, \\ 0 \leq \lambda^0 \leq b_7, 0 \leq \lambda^1 \leq b_8, 0 \leq \lambda^2 \leq b_9, 0 \leq \mu^0 \leq b_{10}, 0 \leq \mu^1 \leq b_{11}\big\}, \end{aligned} \tag{5}$$

where $b = (b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8, b_9, b_{10}, b_{11}) \geq 0$.

$$\langle F(X^b),\ X - X^b \rangle \geq 0, \quad \forall X^b \in \mathcal{K}_b \tag{6}$$

Existence

Theorem (Harker and Pang, 1990):

Let $\mathcal{K}$ be a nonempty , compact and convex subset of R^n and let F be a continuous mapping from $\mathcal{K}$ into R^n. Then there exists a solution to the problem $VI(\mathcal{K}, F)$.

$$\Downarrow$$

Theorem: existence

The variational inequality problem (3) admits a least one solution in $\mathcal{K}_b$.

Sketch Proof: One can verify that $\mathcal{K}_b$ is non-empty, compact, and convex, and that the mapping F representing (3) is continuous. $\square$

Research Plans

Plan I: Construction of a general scarce resource SC model

- The model features multiple fiscal/monetary policy instruments.
- The equilibrium conditions that govern the solution is established by using variational inequalities.
- The model embodies the conflict of resource ownership relating to the ruling at the court of law.
- Considers the characters of scarcity.

Plan II: Managerial insights and policy suggestions

- Numerical studies will be conducted by implementing the model in Matlab/GAMS.
- The managerial insights will be distilled to provide governments, resource owners, and firms associated with the respected supply chains, invaluable advice in expansion, cost restructuring, business strategies, coping with SC stressors, handling competition and collaboration, and post-crisis stimulation.

Plan III: Theoretical properties

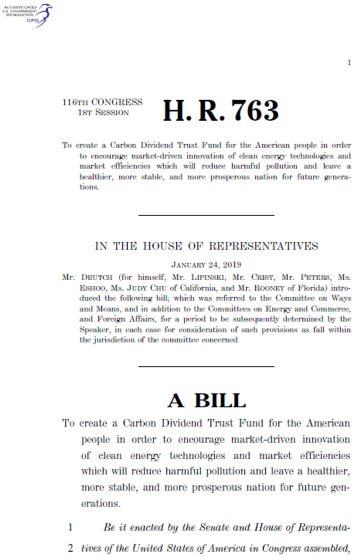
Using λ_{min}, the smallest eigenvalue of the game Jacobian, a scalar property from the latest breakthrough since Bramoullé et al. (2014), to characterize the network equilibrium.

- In literature, the theoretical properties of the network equilibrium are dominated by monotonicity of the F function, semidefiniteness of the game Jacobian, i.e., the Hessian matrix of the utility function.
- Because of the latest finding of the role of λ_{min}, there emerges an opportunity (Parise and Ozdaglar, 2017; Melo, 2018) that such property, under certain favorable conditions, can be used to characterize network games, e.g., uniqueness, substitute/complement network.

Plan IV: A (2nd) general model linking to climate effect

- In addition to the "scarce resource" model (Plan I), to incorporate a loop-like supply chain structure, and a component of "bads" (as opposed to "goods"), e.g., GHG, a new model is needed.
- Such model will bring in "government" as a key player in a supply chain network model, and will better assess the efficacy of a given environmental policy prescribed by the government.

Plan V: Case study
- Energy Innovation and Carbon Dividend Act of 2019



I

116TH CONGRESS
1ST SESSION

H. R. 763

To create a Carbon Dividend Trust Fund for the American people in order to encourage market-driven innovation of clean energy technologies and market efficiencies which will reduce harmful pollution and leave a healthier, more stable, and more prosperous nation for future generations.

IN THE HOUSE OF REPRESENTATIVES

JANUARY 24, 2019

Mr. DEUTCH (for himself, Mr. LIPINSKI, Mr. CRIST, Mr. PETERS, Ms. ESHOO, Ms. JUDY CHU of California, and Mr. ROONEY of Florida) introduced the following bill; which was referred to the Committee on Ways and Means, and in addition to the Committees on Energy and Commerce, and Foreign Affairs, for a period to be subsequently determined by the Speaker, in each case for consideration of such provisions as fall within the jurisdiction of the committee concerned

A BILL

To create a Carbon Dividend Trust Fund for the American people in order to encourage market-driven innovation of clean energy technologies and market efficiencies which will reduce harmful pollution and leave a healthier, more stable, and more prosperous nation for future generations.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

This bill imposes a fee on the carbon content of fuels that will be used so as to emit greenhouse gases into the atmosphere. The fee is imposed on the producers or importers of the fuels.

- Carbon Fee
- Carbon Dividend
- Border Carbon Adjustment
- Regulatory Adjustment

A lobbying infographic

Plan V: Case study - Energy Innovation and Carbon Dividend Act of 2019

The 2nd model (described in Plan IV) can be used to attest such law bill as a case. The case study will include the following components.

- A vertical supply chain that contains carbon-carrying resources' excavators, importers, producers, suppliers, shipments, and consumers including residential and industrial.
- A governmental entity that administers carbon dividend, charging carbon taxes to excavators, importers, distributing carbon dividend to residential consumers.
- Production activities, market prices, and welfare are to be examined.

Contributions and significance (1 of 2)

1. The construction of the first general (with multiple commodities) decentralized scarce resource supply chain network equilibrium models with strategic variables of quantities that incorporate multiple fiscal/monetary policy instruments;
2. The utility of this model is not limited to scarce resource supply chain, but also extends to the supply chains of any resource that pertains the characters of the aforementioned scarce resource.
3. A rigorous formulation of all the models as variational inequality problems, including a piece-wise policy instrument. The establishment of the equivalence of VI problem with GNEP. There are very few GNEP supply chain models in the literature to date.

Contributions and significance (2 of 2)

4. The construction of a formula for the evaluation of welfare, under a fiscal/monetary policy, in competitive supply chain networks;
5. The establishment of a set of novel theoretical conditions that characterize the feature (e.g., existence, uniqueness, stability, etc) of the (network equilibrium) solution, in addition to the popular theoretical properties in literature by monotonicity of the F function, semidefiniteness of the game Jacobian (i.e., the Hessian of the payoff function);
6. The managerial insights that provide governments, resource owners, and firms associated with the respective supply chains, invaluable advice.


Thanks!

Appendix

The relationship between VI and Convex Optimization Problem

Proposition (Nagurney, 1999):

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

$$\begin{aligned} min:\ & f(x) \\ s.t.:\ & x \in \mathcal{K} \end{aligned}$$

where f is continuously differentiable and K is closed and convex. Then x^* is a solution of the VI problem:

$$\nabla f(x^*)^T \cdot (x - x^*) \geq 0, \quad \forall x \subset \mathcal{K}. \tag{7}$$

Proof:
Let $\phi(t) = f(x^* + t(x - x^*)), for\ t \in [0,1]$.
Since $\phi(t)$ achieves its minimum at $t = 0$, $0 \leq \phi'(0) = \nabla f(x^*)^T \cdot (x - x^*)$,
that is, x^* is a solution to (7).

Game theory example: A curious case of inventory in supply chain (Hu et al., 2020)

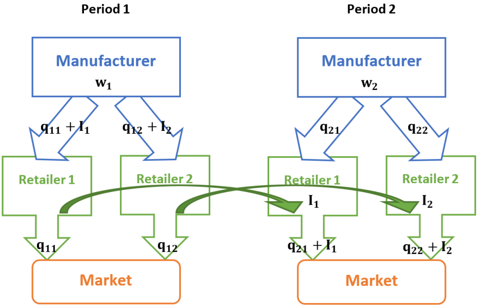


Figure 4: Strategic Inventory in a SC with Cournot Duopoly

A paradox: buying before the dip?!

To defy the manufacturer, retailers carry inventories between periods when the wholesale prices are dropping (w1>w2)!
- *A phenomenon that classic reasons to carry inventory fail to explain.*

Incentives for US switchgrass ethanol supply chains (Luo and Miller, 2013)

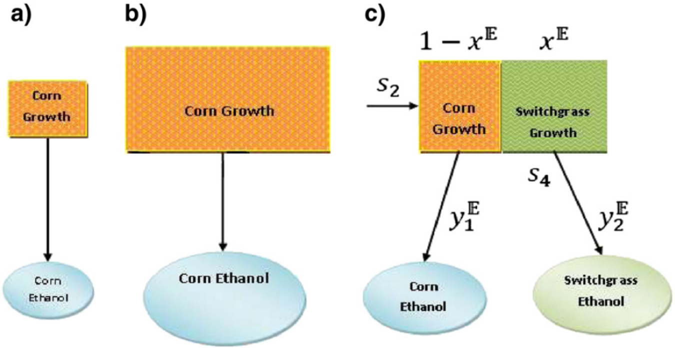


Figure 5: The evolution of biofuel supply chain. (a) Without monetary incentives at current time; (b) a "dummy case" without monetary incentives; and (c) the realization of the RFS with the incentives in place.

A biofuel supply chain with subsidy (Bajgiran et al., 2019)

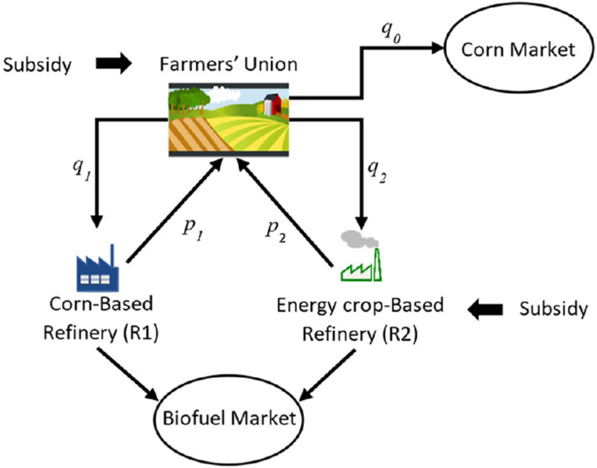


Figure 6: A biofuel supply chain equilibrium analysis with subsidy consideration

Coordinating pricing and marketing decisions in a three-echelon supply chain (Naimi Sadigh et al., 2016)

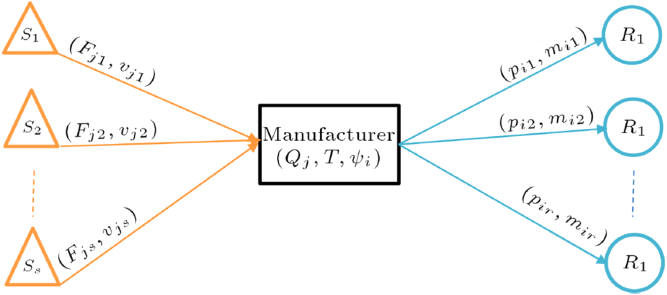


Figure 7: Game-theoretic analysis of coordinating pricing and marketing decisions in a multi-product multi-echelon supply chain

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