A Dynamic Theory for the Integration of Social and Economic Networks with Applications to Supply Chain and Financial Networks

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Outline

- Introduction
  - Research Motivation
  - Literature Review
- Methodologies
- Dynamic Supernetworks for the Integration of Social Networks and Supply Chains
- The Evolution and Emergence of Integrated Social and Financial Networks

Outline

- Financial Engineering of the Integration of Global Supply Chain Networks and Social Networks with Risk Management
- The Co-Evolution and Emergence of Integrated International Financial Networks and Social Networks
- Future Research

Dissertation

- Develops a dynamic supernetwork framework that explicitly integrates social networks with economic networks
  - Contributes to the discussion about how economic actions and social structure are related
  - Captures rigorously the role that non-contractual social relationships play in economic transactions
  - Captures interactions among individual sectors, transaction costs, and risk

Motivation

- Embeddedness Theory (cf. Granovetter (1985)):
  - Rational decision-makers' behavior is embedded in personal relationships and networks of relationships
  - Benefits and costs of economic networks depend on underlying social network

Motivation

- Reasons for impact of social networks on economic networks (cf. Granovetter (2005))
  - Potential to affect flow and quality of information
  - Important source of punishment and reward
  - Trust emerges in context of social relationships

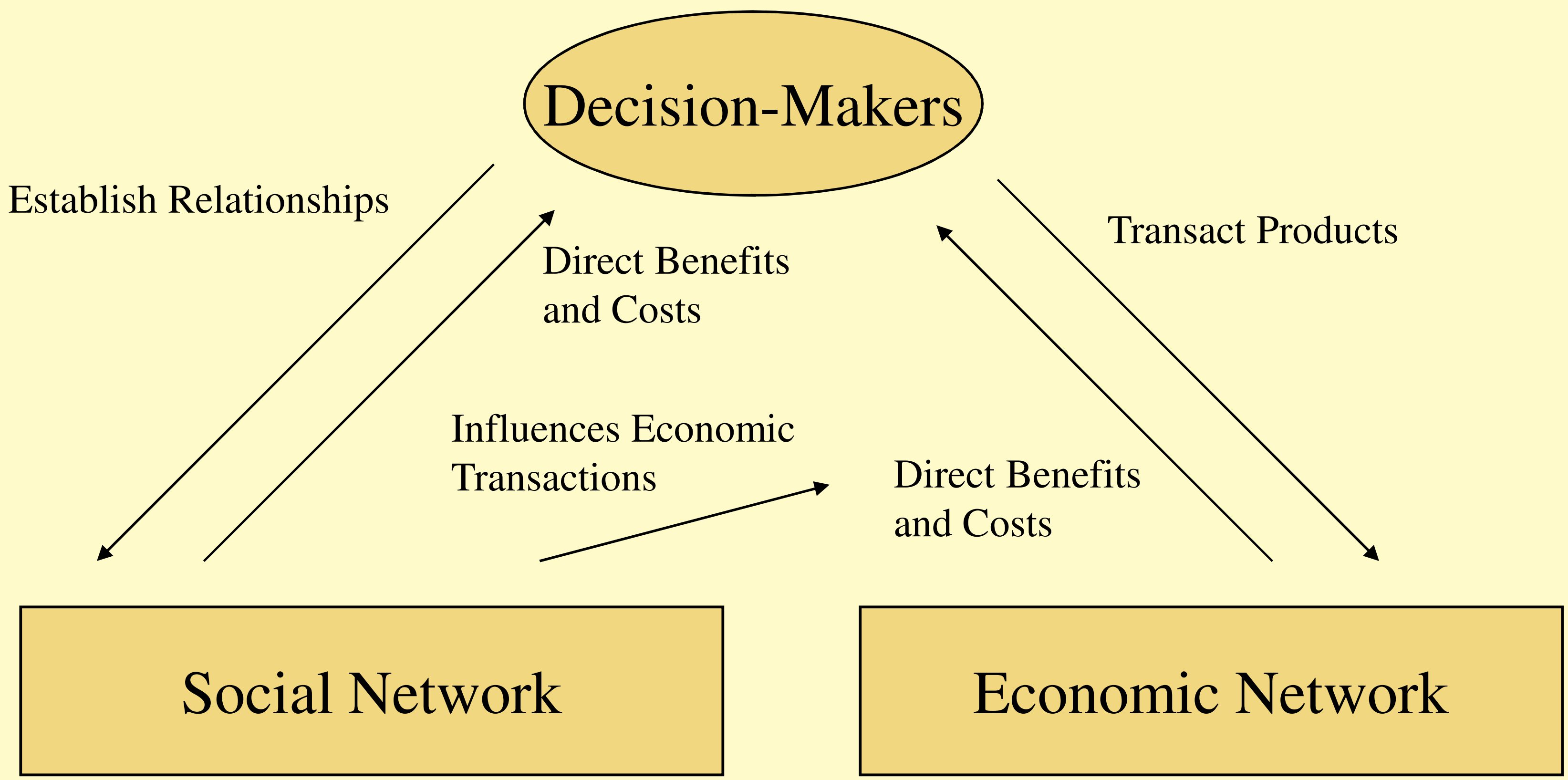
Relationships in Economic Transactions

- Can reduce risk
  - Facilitate cooperation
  - Reduce information asymmetry
  - Reduce opportunism (cf. Baker and Faulkner (2004))
- Can reduce transaction costs
  - Avoid contracting costs, lower the need for monitoring, and facilitate contractual adaptation (cf. Gulati (1995))
  - Allow for simpler governance structures and monitoring systems (cf. Gundlach, Achrol, and Mentzer (1995))

Motivation

- Important role of relationships in supply chain networks
  - Cannon and Perreault (1999), Srivastava, Shervany, and Farhey (1999), Bernardes and Fensterseifer (2004), Baker and Faulkner (2004)
- Important role of relationships in financial transactions
  - Berger and Udell (1995), Anthony (1997), DiMaggio and Louch (1998), Uzzi (1997, 1999), Garmaise and Moskowitz (2004)

Research Framework



Related Supply Chain Literature

- First multitiered model studying supply chains in a network equilibrium context
  - Nagurney, Dong, and Zhang (2002)
- E-commerce in supply chains
  - Cohen and Huchzermeier (1998), Pardalos and Tsitsiringos (2002), Nagurney, Loo, Dong, and Zhang (2002b), Nagurney, Cruz, Dong, and Zhang (2005)

Related Supply Chain Literature

- Risk management in supply chains
  - Johnson (2001), Juttner, Peck, and Christopher (2003), Norrman and Jansson (2004), Nagurney, Cruz, Dong, and Zhang (2005)
- Risk management in global supply chains
  - Huchzermeier and Cohen (1996), Cohen and Mallik (1997), Cohen and Huchzermeier (1998), Nagurney and Matsypura (2005), Nagurney, Cruz, and Dong (2006)

Related Financial Literature

- Representation of financial system as a network
  - Quesnay (1758)
- Risk-return analysis
  - Markowitz (1952, 1959)
- Systems of linked portfolios in credit networks
  - Thore (1969)
- Multi-sector, multi-instrument financial equilibrium
  - Nagurney, Dong, and Hughes (1992)

Related Financial Literature

- Network models with financial intermediation
  - Thore (1980), Nagurney and Ke (2001)
- Electronic finance
  - Claessens, Glaessner, and Klingebiel (2001, 2002), Nagurney and Ke (2003)
- Global financial network
  - Nagurney and Siokos (1997), Nagurney and Cruz (2003, 2004)

Interaction between Social and Economic Networks

- Kranton and Minehart (2000, 2001)
  - Buyers can decide to establish costly relationships to bid in auctions of sellers
  - Buyers can only trade with sellers with whom they have a relationship
  - No relationship value, no relationship strength
- Golicic, Foggin, and Mentzer (2003)
  - Conceptual framework
  - Relationship magnitude influences costs and benefits

Methodologies

- Variational inequality theory
  - To analyze network equilibria
  - Nagurney (1999)

- Projected dynamical systems
  - To analyze the dynamics
  - Dupuis and Nagurney (1993)
  - Nagurney and Zhang (1996a)

Outline of Each Chapter

- Presentation of the supernetwork
  - Supernetwork structure
  - Behavior of individual decision-makers
- Variational inequality formulation
- Dynamics
  - Projected dynamical system
- Algorithm
- Numerical examples

Supernetwork 1

"Dynamic Supernetworks for the Integration of Social Networks and Supply Chains with Electronic Commerce: Modeling and Analysis of Buyer-Seller Relationships with Computations"

Tina Wakolbinger and Anna Nagurney (2004), *Netnomics* 6, 153-185.

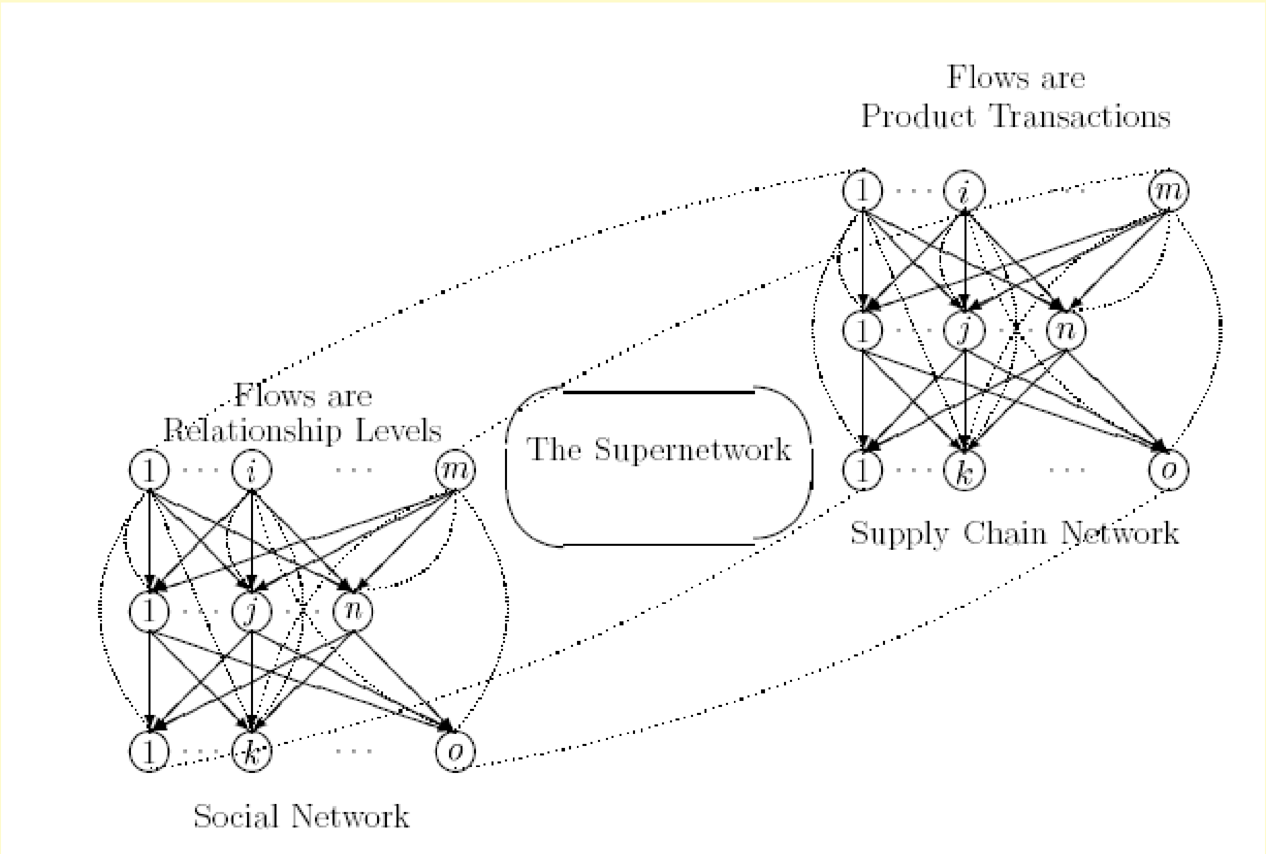
Supernetwork 1

- Models the interaction between a supply chain and a social network
- Captures interactions among individual sectors
- Includes electronic transactions, transaction costs, and risk
- Shows the dynamic evolution of:
  - Product flows and associated prices on the supply chain network
  - Relationship levels on the social network

Motivation

- Many companies form close, collaborative relationships with suppliers and customers (cf. Hogan (2001))
  - Potential for competitive advantage
  - Important to create a portfolio of relationships (cf. Cannon and Perreault (1999), Golicic, Foggin, and Mentzer (2003))
  - Difficult to chose partners with whom relationships should be established
  - Difficult to quantify value of relationships

Supernetwork Structure



Assumptions

- Manufacturers and retailers are multicriteria decision-makers
- Manufacturers and retailers try to
  - Maximize profit
  - Minimize risk
  - Maximize relationship value
  - Individual weights assigned to the different criteria
- Nash equilibrium

Supernetwork 1

- Decision-makers in the network can decide about the amount of product they wish to transact and the relationship levels [0,1] they wish to establish
- Establishing relationship levels incurs some costs
- Relationship levels
  - Influence transaction costs
  - Influence risk
  - Have some additional value ("relationship value")

A Manufacturer's Decision-Making Problem

$$\text{Maximize} \quad \sum_{j=1}^{n}\sum_{l=1}^{2}\rho^*_{1ijl}q_{ijl}+\sum_{k=1}^{o}\rho^*_{1ik}q_{ik}-f_i(Q^1,Q^2)-\sum_{j=1}^{n}\sum_{l=1}^{2}c_{ijl}(q_{ijl},h_{ijl})$$

$$-\sum_{k=1}^{o}c_{ik}(q_{ik},h_{ik})-\sum_{j=1}^{n}\sum_{l=1}^{2}b_{ijl}(h_{ijl})-\sum_{k=1}^{o}b_{ik}(h_{ik})-\alpha_i(\sum_{j=1}^{n}\sum_{l=1}^{2}r_{ijl}(q_{ijl},h_{ijl})$$

$$+\sum_{k=1}^{o}r_{ik}(q_{ik},h_{ik}))+\beta_i(\sum_{j=1}^{n}\sum_{l=1}^{2}v_{ijl}(h_{ijl})+\sum_{k=1}^{o}v_{ik}(h_{ik}))$$

subject to:

$$q_{ijl}\geq 0, \quad \forall j,l, \quad q_{ik}\geq 0, \quad \forall k,$$

$$0\leq h_{ijl}\leq 1, \quad \forall j,l, \quad 0\leq h_{ik}\leq 1, \quad \forall k.$$

A Retailer's Decision-Making Problem

$$\text{Maximize} \quad \rho_{2j}^* \sum_{k=1}^{o} q_{jk} - c_j(Q^1) - \sum_{i=1}^{m}\sum_{l=1}^{2} \hat{c}_{ijl}(q_{ijl}, h_{ijl}) - \sum_{k=1}^{o} c_{jk}(q_{jk}, h_{jk}) -$$

$$\sum_{i=1}^{m}\sum_{l=1}^{2} \rho_{1ijl}^* q_{ijl} - \sum_{i=1}^{m}\sum_{l=1}^{2} \hat{b}_{ijl}(h_{ijl}) - \sum_{k=1}^{o} b_{jk}(h_{jk}) - \delta_j(\sum_{i=1}^{m}\sum_{l=1}^{2} \hat{r}_{ijl}(q_{ijl}, h_{ijl})$$

$$+ \sum_{k=1}^{o} r_{jk}(q_{jk}, h_{jk})) + \gamma_j(\sum_{i=1}^{m}\sum_{l=1}^{2} \hat{v}_{ijl}(h_{ijl}) + \sum_{k=1}^{o} v_{jk}(h_{jk}))$$

subject to:

$$\sum_{k=1}^{o} q_{jk} \leq \sum_{i=1}^{m}\sum_{l=1}^{2} q_{ijl}$$

$$q_{ijl} \geq 0 \quad \forall i, l, \quad q_{jk} \geq 0, \quad \forall k,$$

$$0 \leq h_{ijl} \leq 1, \quad \forall i, l, \quad 0 \leq h_{jk} \leq 1, \quad \forall k.$$

Equilibrium Conditions for Demand Markets

for all retailers: j; $j = 1, ..., n$:

$$\rho_{2j}^* + \hat{c}_{jk}(q_{jk}^*, h_{jk}^*) \begin{cases} = \rho_{3k}^*, & \text{if} \quad q_{jk}^* > 0 \\ \geq \rho_{3k}^*, & \text{if} \quad q_{jk}^* = 0, \end{cases}$$

and for all manufacturers i; $i = 1, \ldots, m$:

$$\rho_{1ik}^* + \hat{c}_{ik}(q_{ik}^*, h_{ik}^*) \begin{cases} = \rho_{3k}^*, & \text{if} \quad q_{ik}^* > 0 \\ \geq \rho_{3k}^*, & \text{if} \quad q_{ik}^* = 0, \end{cases}$$

and

$$d_k(\rho_3^*) \begin{cases} = \sum_{j=1}^{n} q_{jk}^* + \sum_{i=1}^{m} q_{ik}^*, & \text{if} \quad \rho_{3k}^* > 0 \\ \leq \sum_{j=1}^{n} q_{jk}^* + \sum_{i=1}^{m} q_{ik}^*, & \text{if} \quad \rho_{3k}^* = 0. \end{cases}$$

The Equilibrium State

Definition: The equilibrium state of the supernetwork is one where the flows between the tiers of the supernetwork coincide and the product transactions, relationship levels, and prices satisfy the sum of the optimality conditions and the equilibrium conditions.

The equilibrium state is equivalent to a VI of the form:

determine $X^* \in \mathcal{K}$ satisfying

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

The Projected Dynamical System

The dynamic model can be formulated as a projected dynamical system (Dupuis and Nagurney (1993) and Nagurney and Zhang (1996a)) defined by the initial value problem:

$$\dot{X} = \Pi_{\mathcal{K}}(X, -F(X)), \quad X(0) = X_0,$$

where $\Pi_{\mathcal{K}}$ denotes the projection of $-F(X)$ onto $\mathcal{K}$ at X and X_0 is equal to the point corresponding to the initial product transactions, relationship levels, shadow prices, and demand market prices.

The set of stationary points of the projected dynamical system coincides with the set of solutions of the variational inequality problem.

The Disequilibrium Dynamics

The trajectory of the PDS describes the dynamic evolution of:

- Product transactions on the supply chain network
- Relationship levels on the social network
- Demand market prices
- Lagrange multipliers or shadow prices associated with the retailers

Euler Method

Step 0: Initialization

Set $X^0 \in \mathcal{K}$.

Let $\mathcal{T} = 1$ and set the sequence $\{\alpha_\mathcal{T}\}$ so that $\sum_{\mathcal{T}=1}^{\infty} \alpha_\mathcal{T} = \infty$, $\alpha_\mathcal{T} > 0$ for all $\mathcal{T}$, and $\alpha_\mathcal{T} \to 0$ as $\mathcal{T} \to \infty$.

Step 1: Computation

Compute $X^\mathcal{T} \in \mathcal{K}$ by solving the variational inequality subproblem:

$$\langle X^\mathcal{T} + \alpha_\mathcal{T} F(X^{\mathcal{T}-1}) - X^{\mathcal{T}-1}, X - X^\mathcal{T} \rangle \geq 0, \qquad \forall X \in \mathcal{K}$$

Step 2: Convergence Verification

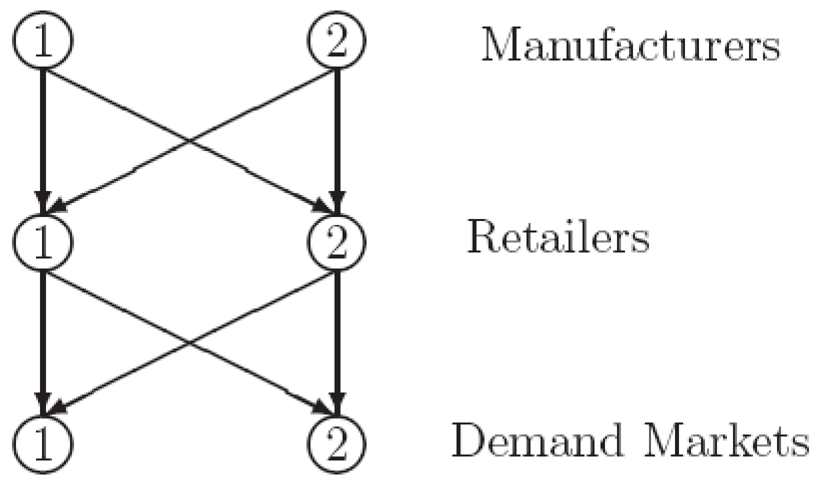
If $|X^\mathcal{T} - X^{\mathcal{T}-1}| \leq \epsilon$, with $\epsilon > 0$, a pre-specified tolerance, then stop; otherwise, set $\mathcal{T} := \mathcal{T} + 1$, and go to Step 1.

Qualitative Properties

I have established

- Existence of a solution to the VI
- Uniqueness of a solution to the VI
- Conditions for the existence of a unique trajectory to the projected dynamical system
- Convergence of the Euler method

Numerical Examples and Sensitivity Analysis



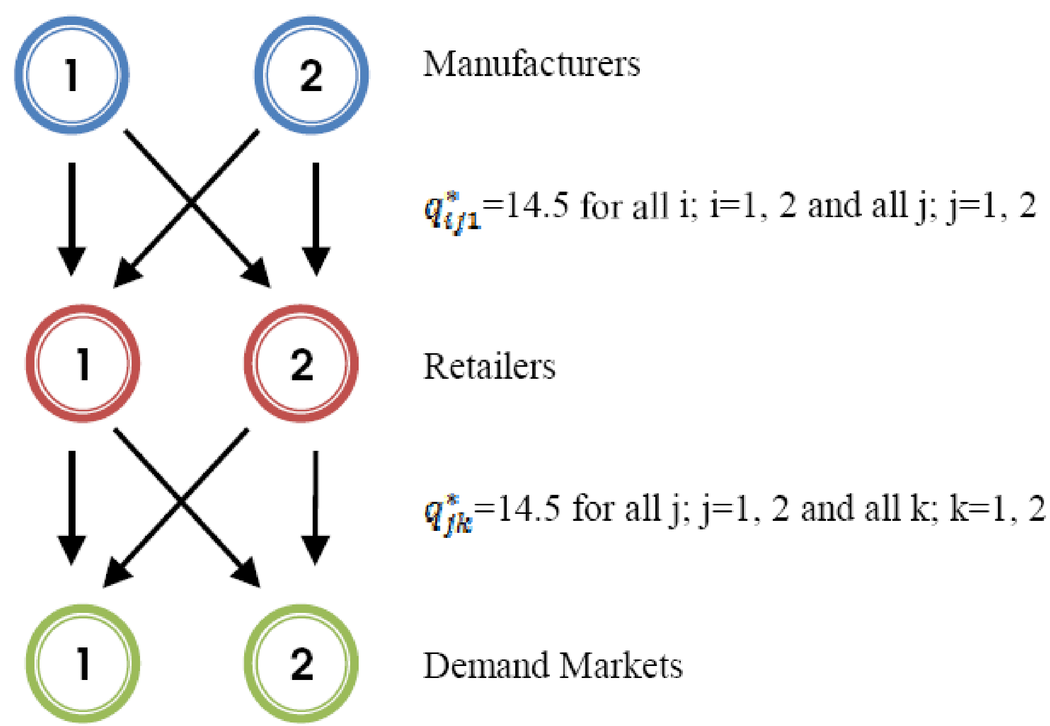
Supply Chain Network

Numerical Examples and Sensitivity Analysis

Table 3.1. Functions for Numerical Example 3.1

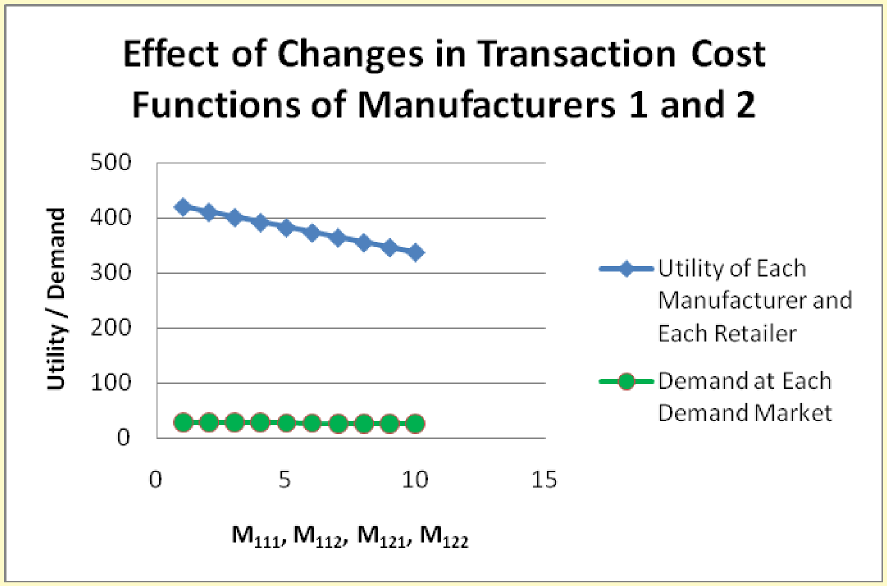
Notation	**Definition**
$f_i(Q^1) = K_i \times (\sum_{j=1}^{2} q_{ij1})$	Production costs faced by manufacturer i; $i = 1, 2$
$d_k(\rho_3) = L_k - R_k \times \rho_{3k}$	Demand at demand market k; $k = 1, 2$
$c_{ij1}(q_{ij1}) = M_{1ij} \times q_{ij1}$	Transaction costs faced by manufacturer i; $i = 1, 2$, transacting with retailer j; $j = 1, 2$
$c_{jk}(q_{jk}) = M_{2jk} \times q_{jk}$	Transaction costs faced by retailer j; $j = 1, 2$, transacting with demand market k; $k = 1, 2$
$\hat{c}_{jk} = M_{3jk}$	Unit transaction costs faced by demand market k; $k = 1, 2$, transacting with retailer j; $j = 1, 2$
$r_{ij1}(q_{ij1}) = G_{1ij} \times q_{ij1}^2$	Risk faced by manufacturer i; $i = 1, 2$, transacting with retailer j; $j = 1, 2$,
$r_{jk}(q_{jk}) = G_{2jk} \times q_{jk}^2$	Risk faced by retailer j; $j = 1, 2$, transacting with demand market k; $k = 1, 2$

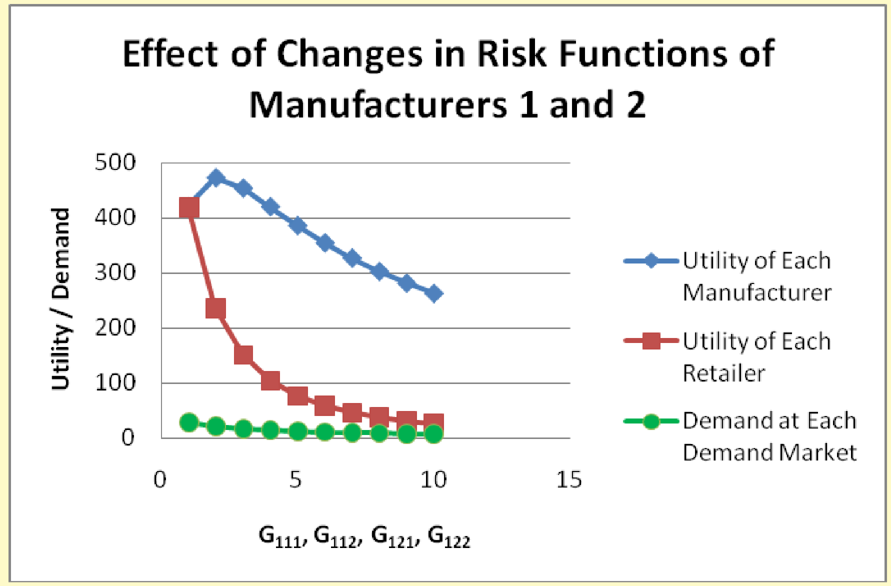
Numerical Examples and Sensitivity Analysis



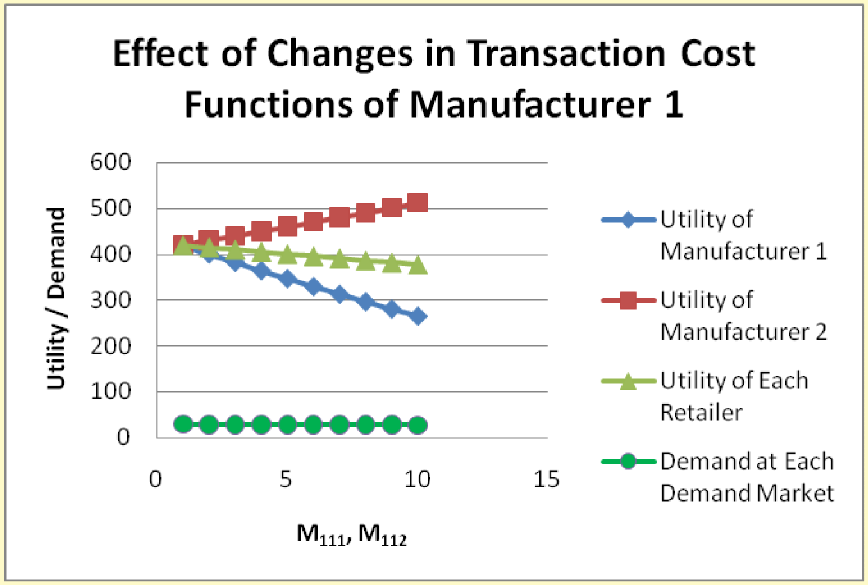
Supply Chain Network

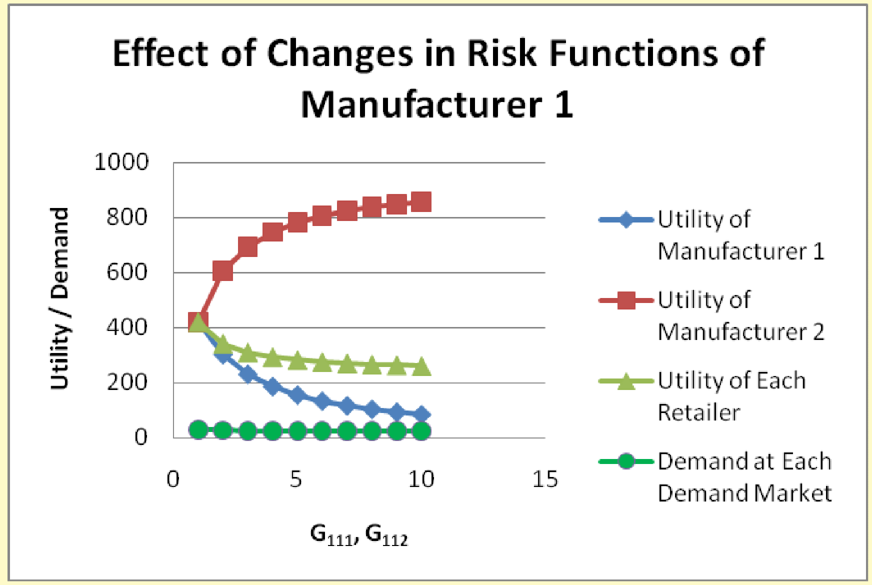
Numerical Examples and Sensitivity Analysis



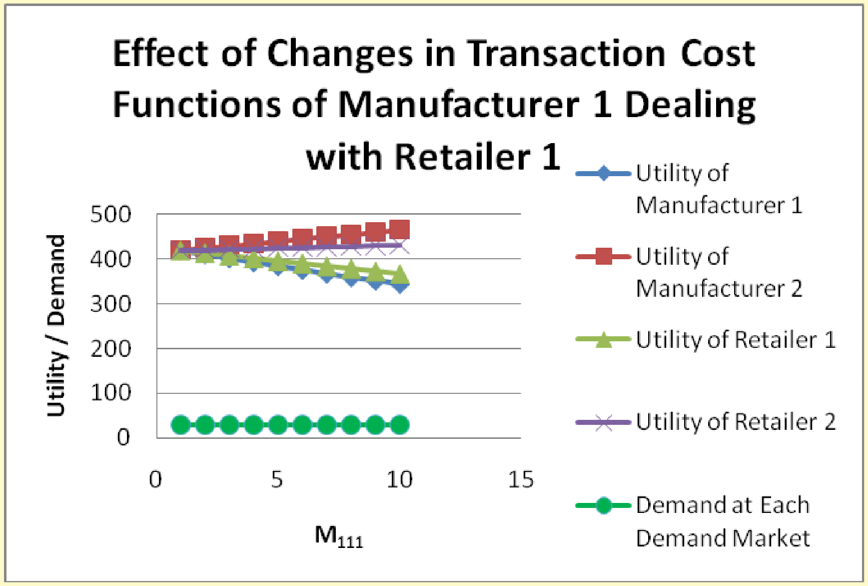


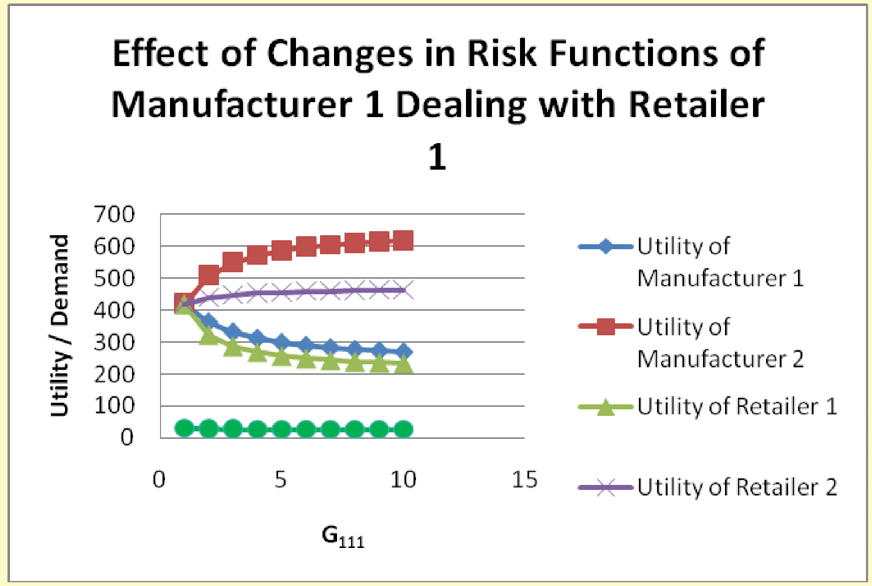
Numerical Examples and Sensitivity Analysis



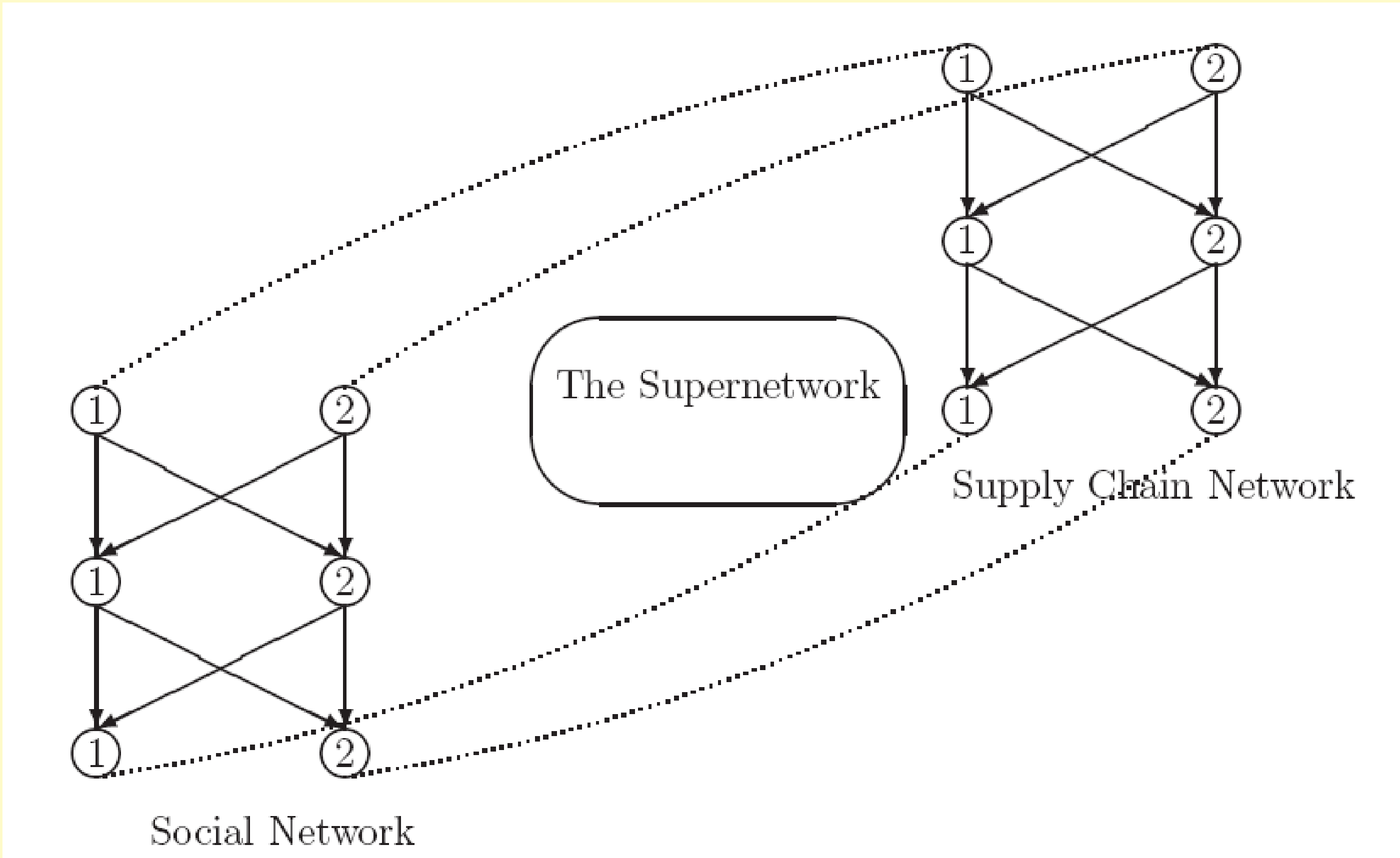


Numerical Examples and Sensitivity Analysis





Numerical Examples and Sensitivity Analysis

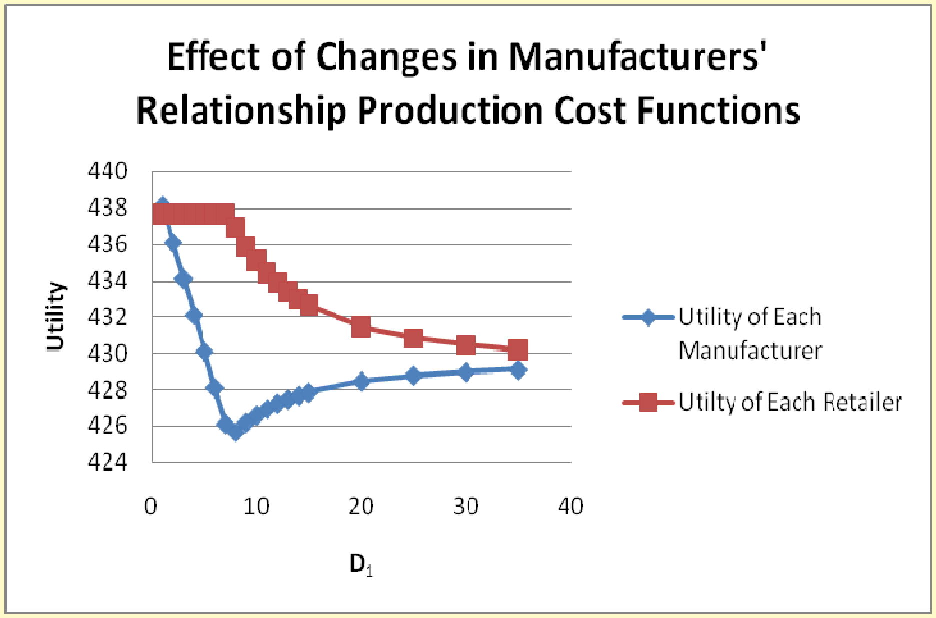


Numerical Examples and Sensitivity Analysis

Table 3.9. Relationship Value Functions and Relationship Production Cost Functions

Notation	**Definition**
$v_{ij1}(h_{ij1}) = C_1 \times h_{ij1}$	Example 3.2: Relationship value function associated with manufacturer i; $i = 1, 2$, and retailer j; $j = 1, 2$
$v_{jk}(h_{jk}) = C_2 \times h_{jk}$	Example 3.2: Relationship value function associated with retailer j; $j = 1, 2$, and demand market k; $k = 1, 2$
$v_{ij1}(h_{ij1}, q_{ij1}) = E_1 \times h_{ij1} \times q_{ij1}$	Example 3.3: Relationship value function associated with manufacturer i; $i = 1, 2$, and retailer j; $j = 1, 2$
$v_{jk}(h_{jk}, q_{jk}) = E_2 \times h_{jk} \times q_{jk}$	Example 3.3: Relationship value function associated with retailer j; $j = 1, 2$, and demand market k; $k = 1, 2$
$b_{ij1}(h_{ij1}) = D_1 \times (h_{ij1})^2$	Relationship production cost function associated with manufacturer i; $i = 1, 2$, and retailer j; $j = 1, 2$
$b_{jk}(h_{jk}) = D_2 \times (h_{jk})^2$	Relationship production cost function associated with retailer j; $j = 1, 2$, and demand market k; $k = 1, 2$

Numerical Examples and Sensitivity Analysis



Supernetwork 2

"The Evolution and Emergence of Integrated Social and Financial Networks with Electronic Transactions: A Dynamic Supernetwork Theory for the Modeling, Analysis, and Computation of Financial Flows and Relationship Levels"

Anna Nagurney, Tina Wakolbinger, and Li Zhao (2006), *Computational Economics* 27, 353-393.

Research Motivation

- Increasing importance of electronic financial transactions
  - Claessens, Glaessner, and Klingebiel (2000)
- Realization of strong importance of personal relationships in financial transactions
  - Micro-financing
    - Anthony (1997), Ghatak (2002)
  - Lending
    - Sharpe (1990), Petersen and Rajan (1994, 1995), Berger and Udell (1995), Uzzi (1997, 1999), DiMaggio and Louch (1998), Arrow (1998), Burt (2000), Boot and Thakor (2000)

Relationships in Financial Transactions

- Make firms more likely to get loans and to receive lower interest rates on loans (cf. Uzzi (1999))
- Can protect investors in partly fraudulent businesses (cf. Baker and Faulkner (2004))

Supernetwork 2

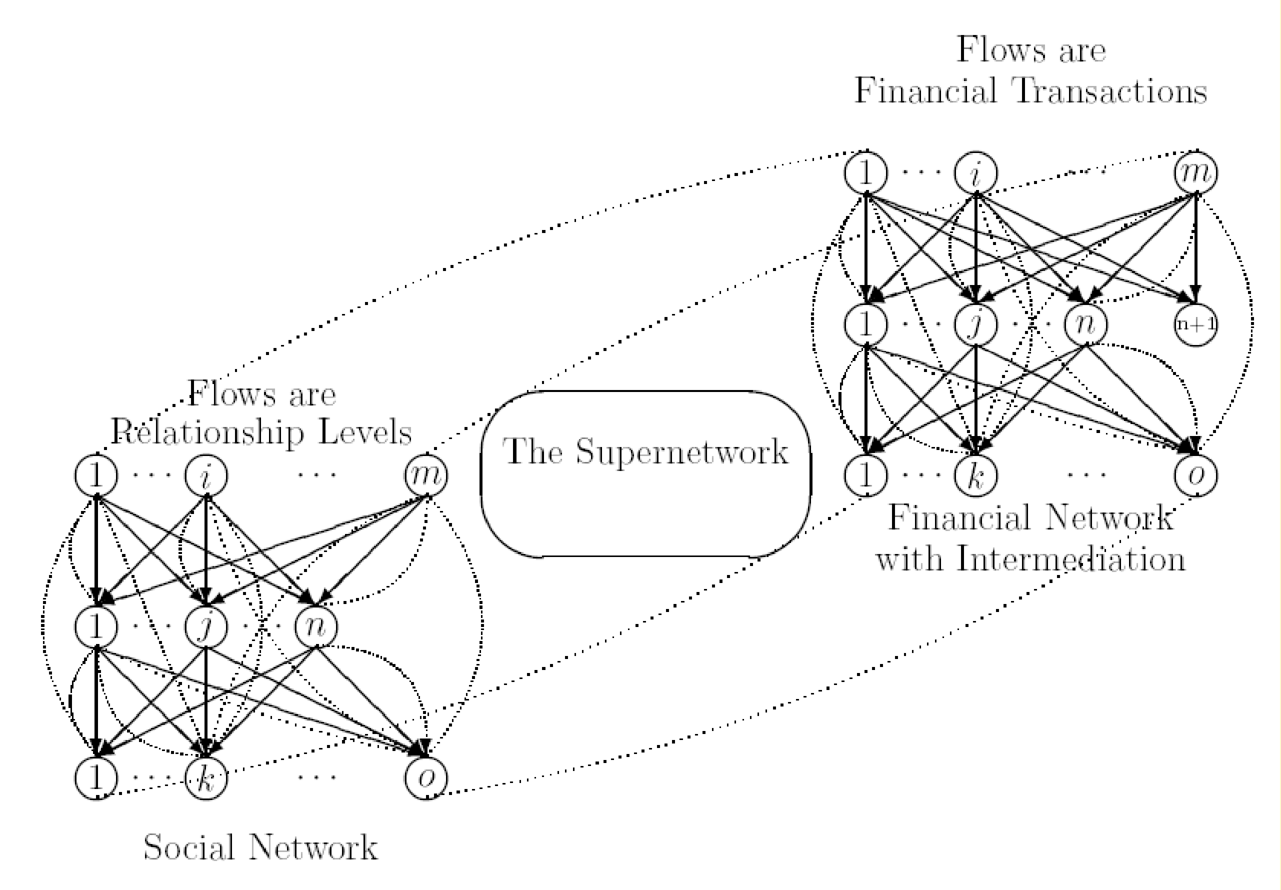
- Models the interaction between financial and social networks
- Captures interactions among individual sectors
- Includes electronic transactions
- Allows for non-investment
- Incorporates transaction costs and risk
- Shows the dynamic evolution of:
  - Financial flows and associated prices on the financial network with intermediation
  - Relationship levels on the social network

Behavior of Decision-Makers

- Source agents and intermediaries
  - Maximize net revenue
  - Minimize risk
  - Maximize relationship value
  - Individual weights assigned to the different criteria

- Risk-return analysis
  - Markowitz (1952, 1959)

Supernetwork Structure



Supernetwork 3

"Financial Engineering of the Integration of Global Supply Chain Networks and Social Networks with Risk Management"

Jose M. Cruz, Anna Nagurney, and Tina Wakolbinger (2006), *Naval Research Logistics* 53, 674-696.

Supernetwork 3

- Extends the supernetwork consisting of a supply chain and a social network to the international domain
  - Introduction of multiple countries and currencies
- Includes more general risk and relationship value functions

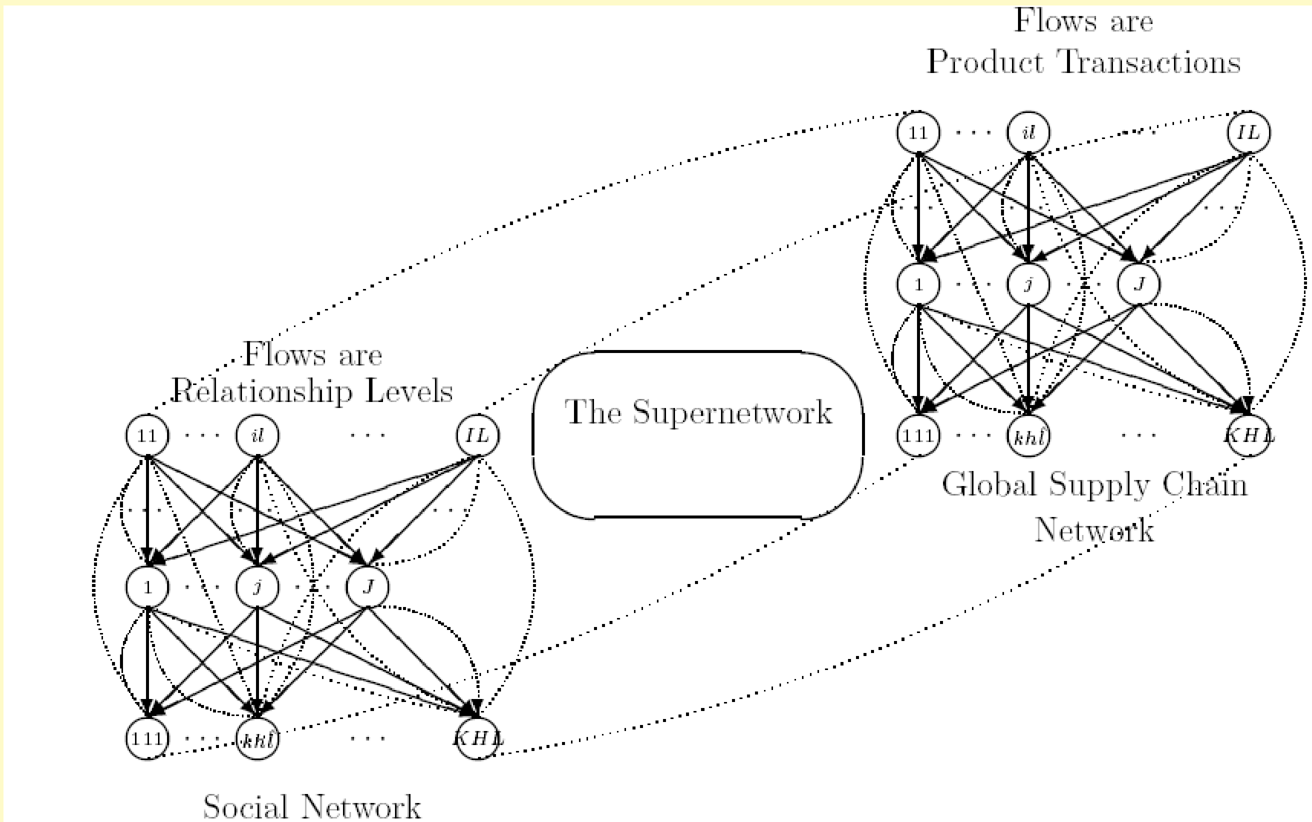
Motivation

- Global transactions are increasingly exposed to new risks and uncertainties
- Global marketplaces are increasingly competitive
- Relationships are a critical business asset in international transactions (cf. Castells (2000))
- Increasing interest in conceptualizing and measuring value in business-to-business relationships (cf. Hogan (2001))

Assumptions

- L countries
- Retailers are not country specific
- H different currencies
- Exchange rates are fixed
- All transaction costs are measured in a base currency
- The demand for the product in a country can be associated with a particular currency

Network Structure



Supernetwork 4

"The Co-Evolution and Emergence of Integrated International Financial Networks and Social Networks: Theory, Analysis, and Computations"

Anna Nagurney, Jose M. Cruz, and Tina Wakolbinger (2004), invited chapter for **Globalization and Regional Economic Modeling**, edited by R. Cooper, K. P. Donaghy, G. J. D. Hewings, Springer.

Contributions

First international network model to include

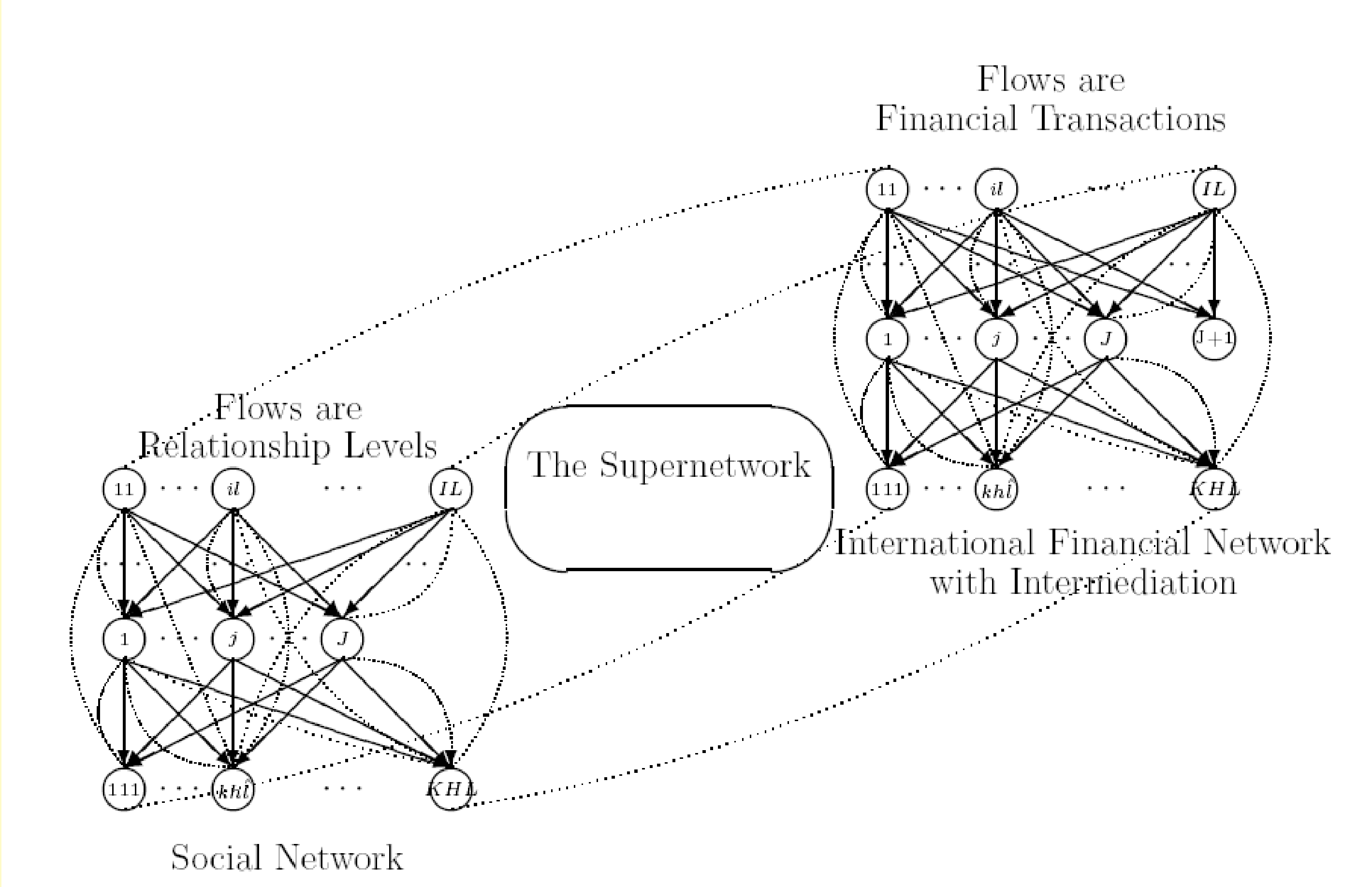
- Multicriteria decision-makers
  - Net revenue maximization
  - Risk minimization
  - Relationship value maximization
- Electronic transactions
- Dynamic adjustment processes

The model can handle as many

- Countries, currencies
- Source agents, intermediaries, demand markets

as needed

Supernetwork Structure



Novelty of the Research

- Economic flows and social network structure are interrelated
- Supernetworks show the dynamic co-evolution of economic flows and social network structure
- Relationships have different strength
- Networks of relationships have a measurable economic value

Future Research

- Empirical and theoretical exploration of
  - Role of asymmetric information and reputation in electronic marketplaces and supply chains
- Further development of theoretical models with emphasis on
  - Multi-period models
  - Dynamics
  - Uncertainty

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Thank you!

Eugene M. Isenberg School of Management

Virtual Center for Supernetworks