Zeeman-esque Variations on a Boycean Theme: Integrating Models of Locational Structure and Spatial Interaction

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Congratulations David on 50 consecutive NARSC meetings!

1. Motivation

An objective that has motivated some of David Boyce's research in the last decade has been "integrating or combining models that are conventionally regarded as separate entities (Boyce, 2002)."

His 2002 chapter, "Combined Model of Interregional Commodity Flows on a Transportation Network," integrated input-output models representing each region of a system of regions with an interregional commodity flow and transportation network model.

The research reported in this chapter would be followed up by other papers, e.g.,

Ham, H., Kim, T.J., and Boyce, D. (2005) “Implementation and estsimation of a combined model of interregional multimodal commodity shipments and transportation network flows,” *Transportation Research B* 39, 65-79.

David’s work in this area, which has strongly influenced much of my own research over the last 7 or 8 years, may be viewed in the context of what Robert Bennett, Robert Haining, and Alan Wilson have termed the *integration of geographical models of locational structure and spatial interaction*.

A prime reason for integrating such models is that

"although spatial structure is in part a function of interaction flows within the system of which it is a part (so that changes in interaction patterns can *induce* changes in the spatial structure …), interaction flows are also dependent on structure." Bennett, Haining, and Wilson (1985, p. 630)

In their paper "Spatial structure, spatial interaction, and their integration: a review of alternative models," *Environment and Planning A*, 1985, **17**: 625-645, these authors suggest a framework for making sense of work on model integration and set out a research agenda for the future.

Because they are concerned with the mutual influence of locational structure and spatial interaction, Bennett, Haining, and Wilson (henceforth BHW) set about examining studies in the literature in the context of dynamic analysis.

They believe a suitable framework for doing so is provided by E.C. Zeeman's 1977 volume on *Catastrophe Theory.*

Zeeman views systems in terms of a vector of state variables, $\boldsymbol{x}$, and a vector of parameters, $\boldsymbol{u}$, and characterizes development in the study of systems as comprising six steps or stages.

1. The analysis of the surface of *equilibrium* states, including the investigation of any singularities.
2. The specification of *fast dynamics:* differential or difference equations for the ***x*** variables.
3. The specificaiton of *slow dynamics:* differential or difference equations for the ***u*** variables (or parameters).
4. The representation of any *feedback* between the fast and slow systems.
5. The study of the effect of noise or *fluctuations.*
6. The study of diffusion processes, which may involve taking space and time as ***u*** variables.

In my own research (with engineers and atmospheric scientists at Cornell University), I have been endeavoring to model the co-evolution of freight or commodity flows (*spatial interactions*) and the economic geography of production (*locational structures*) with an eye towards examining how increasing globalization (*an exogenous shock*) and changes in infrastructure systems (*the slow variables or parameters*) affect both commodity flows and economic geography and air quality.

Hence, I find BHW's framework in terms of Zeeman's characterization of progress in dynamic analysis useful for making sense of this research.

Outline of Talk

1. Motivation

2. Review of research objectives and questions of interest

3. Description of an evolutionary model of industrial structure, goods movement, and associated impacts

4. Discussion of model operationalization

5. Presentation of preliminary results

6. Assessment of research in terms of Zeeman's stages

2. Review of Research Objectives and Questions of Interest

The principal objective of this research is to develop modeling capability to investigate questions of interest to air quality planners. Questions of interest we address include:

1) How will emerging technologies and infrastructure changes (including transportation) and global climate and air pollution policies impact regional air quality by 2050?

2) How will urban and regional landscapes evolve in response to changes in production and distribution at regional and global scales? How will associated changes in land use affect emissions and air quality?

3) How will regional and national policy decisions affect the urban landscape and what are the implications for air quality under a future climate scenario?

4) What are the synergies between climate and air quality regulation? How can the results of these studies be best used to inform present and future policy decisions?

- The global economy has been an important factor in the determining emission trajectories.

- Perhaps the most significant change in the *global economy* over the past several decades has been the extent to which *globalization*—or the integration of economies at all scales—has proceeded.

- The spatial economy has increasingly come to be viewed as a *space of flows*. Moving along the links of networks are ever greater quantities of people, goods, material, money, and information. Settlements, in turn, appear as increasingly interdependent nodes through which these vast quantities pass.

- The acceleration of flows through space can be accounted for largely by technological advances in communications and transportation and the emergence of far-flung value chains, which are driven by economizing behavior and abetted by increasingly liberal trade agreements and industrial deregulation.

- These developments have enabled firms to exploit *economies of scale* and *scope* by fragmenting production processes and dispersing activities to least-cost locations (Jones and Kierzkowski, 2001).

•Consequently, the production of most goods worldwide now takes place in a distributed pattern over many locations in which semi-finished goods are shipped from one *specialized* establishment to another.

• *What* activities are carried out and *where* they agglomerate appear to be *path dependent*—initial advantages are reinforced due to scale effects (Venables, 2006).

• And with the increased use of just-in-time inventory management methods, all production has become more *transport intensive*.

• The obverse of this development is that most freight shipments are now between establishments operating in the same industry.

The volume of freight movement (in value terms) for all distances has been increasing at an annual rate, 6.6%, that is faster than GNP is increasing.

Distance Shipped (1) (Based on Great Circle Distance)	Value		
	2007 (million $)	2002 (million $)	Percent change
All distances	11,684,872	8,397,210	39.2
Less than 50 miles	3,851,545	2,503,895	53.8
50 to 99 miles	1,074,137	757,601	41.8
100 to 249 miles	1,777,031	1,329,245	33.7
250 to 499 miles	1,606,034	1,221,437	31.5
500 to 749 miles	1,019,498	844,880	20.7
750 to 999 miles	720,623	548,768	31.3
1,000 to 1,499 miles	730,366	501,419	45.7
1,500 to 1,999 miles	494,992	353,663	40.0
2,000 miles or more	410,646	336,302	22.1

Source: Bureau of Transportation Statistics

- As a consequence, the industrial cores of many regional economies have become *hollowed out* and regional economies world-wide have become increasingly interdependent through global supply chains (Munroe et al., 2007).

- A broad-based community of stakeholders is concerned about these developments, in large part because they lack a clear sense of how these interdependent developments are related and what they portend.

- Moreover, the design of effective policies to accommodate anticipated increases in freight movements and to promote public/private partnerships that can abate and mitigate deleterious externalities—including GHG emissions and other criteria pollutants—requires a better understanding of how cost and incentive structures affect the form and functioning of supply chains.

- While theoretical explanations of fragmentation at the firm and industry levels, public/private partnerships at urban and regional levels, and network externalities at the systems level are available, *we still lack theories and models that explicitly link decision-making of producers (or shippers) and carriers with impacts on nodes as well as links in transportation networks*.

- Donaghy (2010), Donaghy and Scheffren (2006), and Donaghy et al. (2006) have elaborated an empirically oriented framework that can characterize in large the evolution of goods movement, in which the state of affairs described above can arise.

- Development of this framework draws on contributions to the literatures on *fragmentation* (Jones and Kierzkowski, 2001), the '*new economic geography*' (Krugman and Venables, 1995), *dynamic networks* (Nagurney and Dong, 2002), and *commodity-flow modeling* (Wilson, 1970, Batten and Boyce, 1986, Friesz, Suo, and Bernstein, 1998, Friesz, Suo, and Westin, 1998, Boyce, 2002, and Ham et al., 2005).

- Akin to Friesz and Holguin-Veras (2005), the model characterizes a '*non-cooperative dynamic game*' between shippers and carriers but can also capture the effects of both economies of scale and scope.

- The model can be solved numerically by available dynamic variational inequality or other methods and will be adapted to accommodate the innovations in emissions inventory modeling introduced by Williams et al. (2008) and reflect changes in transportation technology (US DOT, 2003).

To be instructive about *future* developments, integrated models should be able to capture the stylized facts of *recent* developments in spatial flows and economic geography and reproduce, on the basis of economic reasoning:

• increased geographic concentration or clustering of sectoral activities,

• increased demand for intermediate inputs and intrasectoral trade, hence

• economies of scale and scope in production, and increased transport intensity of production,

• hence an increase in transport's share of emissions (non-point source) even as point source emissions decrease on a per-unit of production basis.

3. An Evolutionary Model of Industrial Structure, Goods Movement, and Associated Impacts

The framework from which we embark is that of a static commodity flow model.

Commodity flow models are used to forecast equilibrium flows of goods between locations (usually regions) and identify local production levels necessary to meet system demand levels. They are also used to identify transportation network bottlenecks and forecast the impacts on regional economies of changes in transport capacity e.g., link outages due to disasters.

Commodity flow models in *multi-period* programming settings are used to simulate the evolution of patterns of regional production and interregional trade for purposes of planning regional transportation infrastructure (highways, railroads, and port facilities).

3a. Notation

Nodes of the network through which goods are shipped are indexed by ***l*** and ***m**.*

Links joining such nodes are indexed by ***a*** and routes comprising contiguous links are indexed by ***r**.*

The length of some link *a* connecting two nodes is denoted by d_a .

If link *a* is part of route *r* connecting nodes *l* and *m*, an indicator variable δ^a_{lmr} assumes the value 1.0. It is 0 otherwise.

The length of a given route from some node *l* to another node *m,* D_{lmr}, is given by the sum of link distances along the route:

$$D_{lmr} \equiv \sum_a d_a \delta^a_{lmr} . \qquad (1)$$

Turning to quantities shipped through the network, we index sectors engaged in production in the spatial economy by ***i*** and ***j.***

Types of final demand will be indexed by ***k.***

Let X_l^i denote the total output (in dollars) of sector *i* produced at node *l*, x_{lm}^{ij} denote interindustry sales from sector *i* at location *l* to sector *j* at location *m*, and FD_{lm}^{ik} denote final demand of type *k* at location *m* for sector *i's* product at location *l*.

The physical flow of sector *i's* product from *l* to *m* along route *r* is h_{lmr}^i. This quantity is obtained by converting the value flow along route *r* from dollars to tons by means of the ratio of total annual interregional economic flow to total annual physical flow, q_x^i.

The total physical flow of all commodities shipped on a link *a* via all routes using the link is given by

$$f_a \equiv \sum_i \sum_{lmr} h_{lmr}^i \delta_{lmr}^x . \qquad (2)$$

3b. Fundamental Relations of the Model

Conditions that the network must satisfy at any point in time are as follows.

Material (or Commodity) Balance Constraint

$$X_l^i = \sum_m \sum_j x_{lm}^{ij} + \sum_m \sum_k FD_{lm}^{ij}, \forall i, \forall l \; ; \qquad (3)$$

Equation (3) ensures that shipments from industry *i* in location *l* do not exceed production by the industry in that location.

Conservation of Flows Constraint

$$\sum_r h_{lmr}^i = \sum_j x_{lm}^{ij} / q_x^i + \sum_k FD_{lm}^{ik} / q_x^i, \forall i, \forall l, \forall m \; ; \qquad (4)$$

Equation (4) reconciles physical and value flows.

Link Capacity Constraint

$$\sum_{i}\sum_{lmr} h^{i}_{lmr}\delta^{a}_{lmr} = f_a \leq k_a, \forall a; \quad (5)$$

Inequality (5) ensures that flows along links do not exceed capacities.

Non-Negativity and Feasibility Conditions

$$f_a \geq 0, \forall a;\ h^{i}_{lmr} \geq 0, \forall i, \forall l, \forall m, \forall r;\ x^{ij}_{lm} > 0, \forall i, \forall j, \forall l, \forall m. \quad (6)$$

And the conditions given in (6) ensure that the distribution of goods throughout the network is feasible.

Following Glover and Brzezinski (1989), we characterize the commodity-shipment-related emissions along a link and at a node as follows.

Let ϕ_a^s denote emissions per unit of physical flow per unit of distance over link *a* when *a* is not congested and let ϕ_l^s denote emissions per unit of physical flow at node *l* when *l* is not congested, both for pollutant *s*.

Let ψ_a and ψ_l be scaling coefficients and η_a and η_l emission-elasticities of congestion.

Then *commodity-shipment-related emissions along a link* of pollutant *s* can be expressed in terms of a link congestion function as

$$E_a^s = \phi_a^s f_a[1.0 + \psi_a (f_a / k_a)^{\eta_a}] d_a, \forall a, \forall s, \tag{7}$$

and *commodity-shipment-related emissions at a node* can be expressed as

$$E_l^s = \phi_l^s f_l[1.0 + \psi_l (f_l / k_l)^{\eta_l}] \tilde{d}_l, \forall l, \forall s, \tag{8}$$

in which $\tilde{d}_l$ is the average distance traveled by a shipment of industry *i* going to or through node *l when it is within the environs of node l*—e.g., a specified radius.

We characterize point-source industrial emissions of some pollutant *s,* aggregated over all industries *i* at location *l* as

$$E_l^{ps} = \sum_i emi_i^s \cdot X_l^i, \forall s, \forall l, \quad (9)$$

where emi_i^s is a *time-varying emissions intensity parameter*, after Tao et al. (2010).

3c. Critical Assumptions

In the sequel we shall assume that:

1. At each location *l* the behavior of all establishments engaged in production in a given industrial sector can be characterized by a *representative establishment*—hence we are allowing for the realistic possibility that firms may have multiple establishments located in different areas.

2. Firms operating the establishments act as *monopolistic competitors of the Chamberlinian sort*: they are input-price takers and set output prices by a mark-up over marginal cost.

For a firm with an establishment producing in sector *i* at location *l,* the mark-up π_l^i is given in terms of the price-elasticity of demand for X_l^i , σ_l^i, as $\pi_l^i = [\sigma_l^i / (\sigma_l^i - 1)]$.

Under the assumption of Chamberlinian monopolistic competition, the spatial markets in which firms compete are sufficiently competitive—barriers to entry are sufficiently low—so as to drive to zero profits earned (beyond normal returns to assets) by firms from production of commodities at all locations.

3. Each local representative establishment is assumed to produce its output according to a two-level C.E.S.—constant-elasticity-of-substitution—technology (Sato, 1967).

This fungible output can be used in production of other commodities or consumed in final demand (in the forms of household and government consumption, investment, and export).

At the first level, inputs of each industrial type procured locally and non-locally are aggregated into input bundles:

$$c_m^{ij} = \gamma_m^{ij} [\sum_l \theta_{lm}^{ij} (x_{lm}^{ij})^{-\varepsilon_m^{ij}}]^{-1/\varepsilon_m^{ij}}, \forall i, \forall j, \forall m. \quad (10)$$

In equation (10), c_m^{ij} is a bundle of inputs produced by representative establishments operating in industry *i* at various locations *l* used by the representative establishment in industry *j* in its production activities at location *m*. The parameters γ_m^{ij}, θ_{lm}^{ij}, and ε_m^{ij} have standard interpretations as *scale*, *factor-intensity* and *substitution* parameters. (See Ferguson, 1969.)

At the *second level* of the production function, total output by a representative establishment in a given industry in a given location is produced from the commodity bundle aggregates at the first level and labor and capital services, *Lm* and *Km* .

At the second level, we allow explicitly for the possibility of *increasing returns to scale* in production at the establishment, regardless of the number of varieties aggregated in the commodity bundles by employing a generalized C.E.S. function in which $\kappa_m^j \geq 1.0$ is the scale parameter. (See Henderson and Quandt, 1980.)

$$X_m^j = \beta_m^j [\sum_i \alpha_m^{ij} (c_m^{ij})^{-\rho_m^j} + \alpha_m^{Lj} (L_m^j)^{-\rho_m^j} + \alpha_m^{Kj} (K_m^j)^{\rho_m^j}]^{-\kappa_m^j / \rho_m^j}. \quad (11)$$

To make further progress with an explanation of economic behavior, we need to introduce prices as well as technology. Let p_l^j denote the f.o.b. (or mill) price of a unit of industry *j*'s output at location *l* and p_{lm}^j the delivered price of this output at *m*. Then, defining w_m^j and ucc_m^j as the wage rate and user cost of capital in industry *j* at location *m*, the mill price of this good under Chamberlinian monopolistic competition is given by

$$p_m^j = \pi_m^j \left[\sum_i \sum_l p_{lm}^i \cdot x_{lm}^{ij} + w_m^j \cdot L_m^j + ucc_m^j \cdot K_m^j \right] / X_m^j, \forall j, \forall m. \quad (12)$$

The *delivered price* at location *m* of a good *i* produced at location *l*, p^i_{lm}, includes the *unit cost of transport* by a carrier from location *l* to location *m*, ϑ^{ti}_{lm}, which is set by the carrier.

Collecting these various price components, the delivered price of a unit of good *i* at location *m* will be

$$p^i_{lm} = p^i_l + \vartheta^{ti}_{lm}, \forall l, \forall m, \forall i \qquad (13)$$

We now define several new variables for the *time rates of change* in installed capacity (net of depreciation), in interindustry and interregional commodity flows, in employment, and the f.o.b. goods price i.e., $I^j_m = \dot{K}^j_m$, $a^{xij}_{lm} = \dot{x}^{ij}_{lm}, a^{Lj}_m = \dot{L}^j_m$, and $a^{pj}_m = \dot{p}^j_m$.

The intertemporal optimization decision of a representative establishment in sector *j* at location *m* is to choose $I_m^j, a_{lm}^{xij}, a_m^{Lj}$ and a_m^{pj} so as to minimize the present value of costs of operation at and adjustment to equilibrium levels of capital, intermediate goods, and labor:

$$\int_{t_0}^{t_1} e^{-\lambda_m^{sj} t} \{ \sum_i \sum_l p_{lm}^i \cdot x_{lm}^{ij} + w_m^j L_m^j + ucc_m^j K_m^j + q_m^j I_m^j + \frac{\omega_m^{Kj}}{2} (I - \upsilon_m^{Kj} (K_m^j * - K_m^j))^2$$
$$+ \sum_i \sum_l \frac{\omega_{lm}^{xij}}{2} (a_{lm}^{xij} - \upsilon_{lm}^{xij} (x_{lm}^{ij} * - x_{lm}^{ij}))^2 + \frac{\omega_m^{Lj}}{2} (a_m^{Lj} - \upsilon_m^{Lj} (L_m^j * - L_m^j))^2 \qquad (14)$$
$$+ \frac{\omega_m^{pj}}{2} (a_m^{pj} - \upsilon_m^{pj} (p_m^j * - p_m^j))^2 \} dt,$$

subject to the following state equations and (3) – (6):

$$\dot{K}_m^j = I_m^j, \qquad (15)$$

$$\dot{x}_{lm}^{ij} = a_{lm}^{xij}, \forall i, \forall l \qquad (16)$$

$$\dot{L}_m^j = a_m^{Lj}, \qquad (17)$$

$$\dot{p}_m^j = a_m^{pj}. \qquad (18)$$

Partial-equilibrium levels to which state variables are adjusted are

Commodity Flows:

$$x_{lm}^{ij}* = \left[\frac{\theta_m^{ij}}{(\gamma_m^{ij})^{\varepsilon_m^{ij}}} \frac{\kappa_m^j}{\pi_m^j} \frac{\alpha_m^{ij}}{(\beta_m^j)^{\rho_m^j/\kappa_m^j}} \frac{p_m^j}{p_{lm}^i} \frac{(X_m^j)^{(\kappa_m^j+\rho_m^j)/\kappa_m^j}}{(c_m^{ij})^{(\rho_m^j+1)}} \right]^{1/(1+\varepsilon_m^{ij})} c_m^{ij},$$

Capital: $$K_m^j* = \left[\frac{\kappa_m^j}{\pi_m^j} \frac{\alpha_m^{Kj}}{(\beta_m^j)^{\rho_m^j/\kappa_m^j}} \frac{p_m^j}{\mathrm{ucc}_m^j} \right]^{1/(1+\rho_m^j)} (X_m^j)^{(\kappa_m^j+\rho_m^j)/(\kappa_m^j+\kappa_m^j\rho_m^j)}.$$

Labor: $$L_m^j* = \left[\frac{\kappa_m^j}{\pi_m^j} \frac{\alpha_m^{Lj}}{(\beta_m^j)^{\rho_m^j/\kappa_m^j}} \frac{p_m^j}{w_m^j} \right]^{1/(1+\rho_m^j)} (X_m^j)^{(\kappa_m^j+\rho_m^j)/(\kappa_m^j+\kappa_m^j\rho_m^j)},$$

Price: $$p_m^j* = \pi_m^j \left[\sum_i \sum_l p_{lm}^i \cdot x_{lm}^{ij} + w_m^j \cdot L_m^j + ucc_m^j \cdot K_m^j \right] / X_m^j$$

The intertemporal optimization decision of a *representative carrier* in location *i* is to choose a time-varying schedule of prices, ϑ_{lm}^{ti} , and time-varying flows of commodities along available routes r, h_{lmr}^{ij}, to maximize profits:

$$\int_{t_0}^{t_1} \mathrm{e}^{-\lambda_i^c t} \left\{ \sum_i \sum_m \vartheta_{lm}^{ti} \left(\sum_j x_{lm}^{ij} + \sum_k \mathrm{FD}_{lm}^{ik} \right) - \sum_i \sum_m \sum_r h_{lmr}^{i} D_{lmr} p_{lmr}^{ti} \right\} \mathrm{d}t$$

Subject to non-negativity conditions, material balance constraints, conservation of flow constraints and link and nodal capacity constraints.

4. Model Operationalization

Operationalization of the model entailed generating and procuring spatial time series data, estimating the model, and solving it.

Data required include:

- Commodity Flow Data
- Unit Transportation Cost Data By Mode
- Costs to Carriers
- Geographic Data

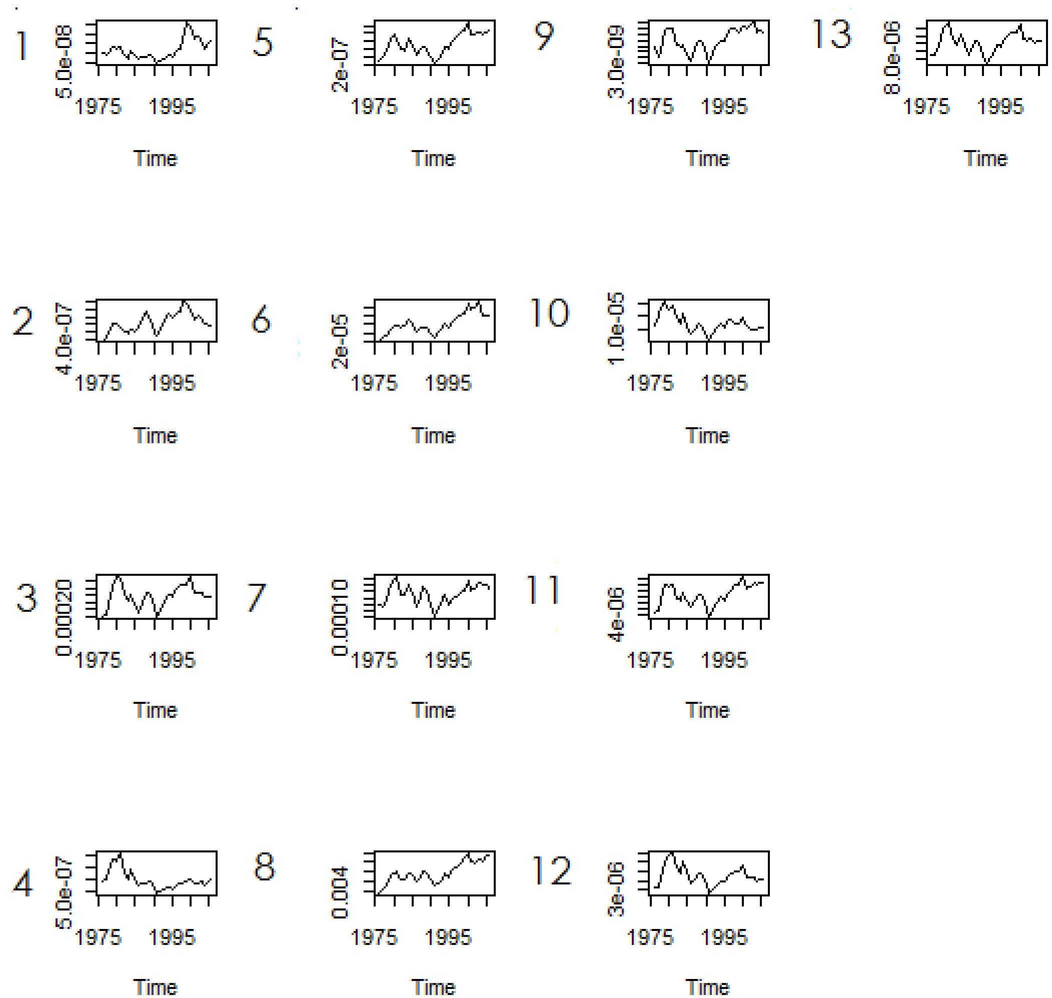
Annual time series on commodity flows were recovered for 1977 to 2007 from a regional econometric input-output model (REIM) for three regions—14 states and 13 industires—and the rest of the U.S by the following process (Donaghy and Chen, 2011):

- Jackson et al's (2006) approach to construct a commodity-by-commodity flow matrix was used to benchmark a REIM.
- Isarailevich et al's (1997) approach to derive annual multi-regional interindustry sales coefficients from an estimated REIM was then followed.
- The latter coefficients were then used to obtain spatial time-series data.

The sectoral scheme adopted was as follows:

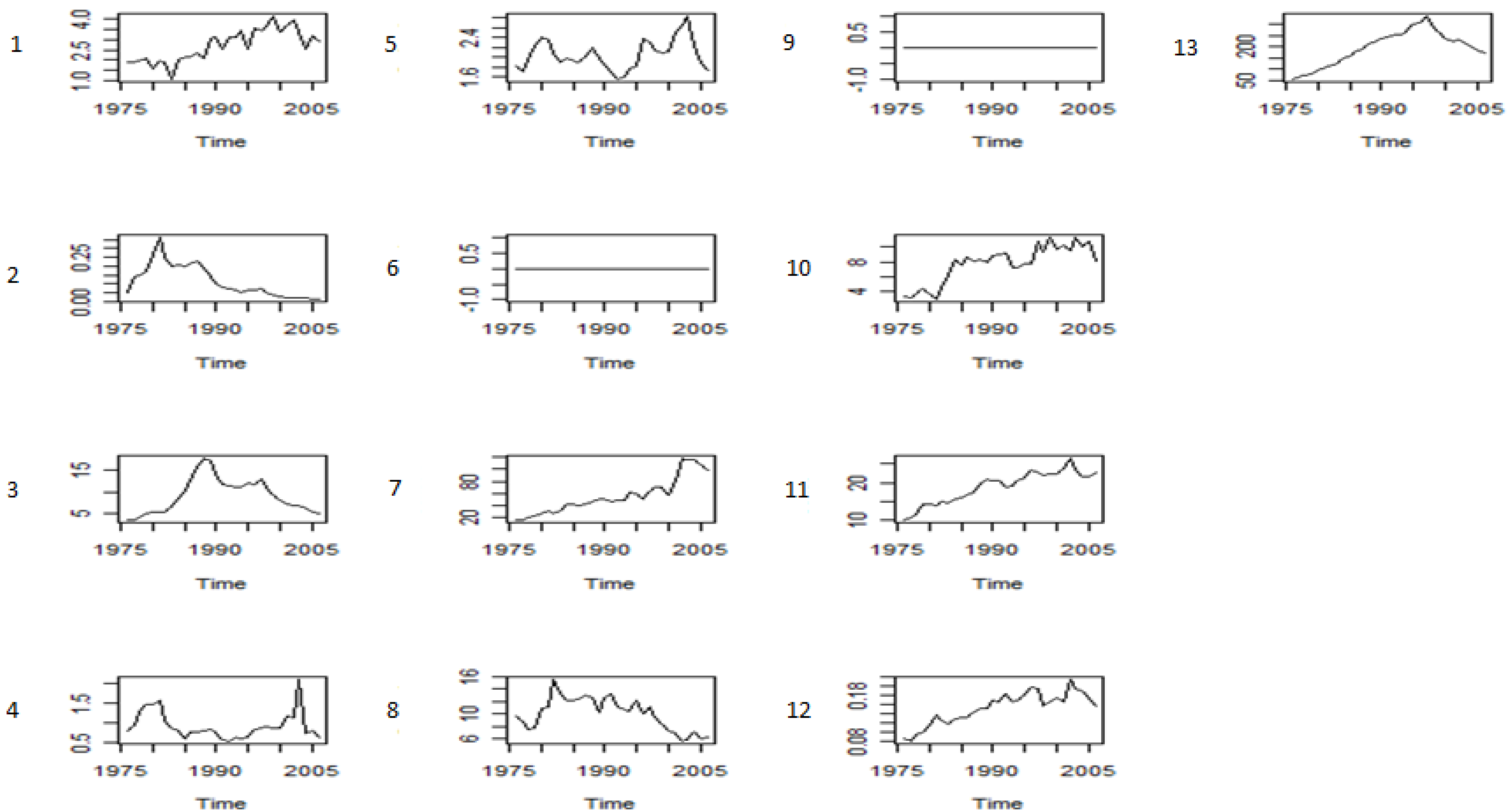
Sector	Description	NAICS Code
1	Agriculture, forestry, fishing, and hunting	11
2	Mining	21
3	Construction	23
4	Food product manufacturing	311
5	Chemical manufacturing	325
6	Primary metal manufacturing	331
7	Fabricated metal product manufacturing	332
8	Machinery manufacturing	333
9	Computer and electronic product manufacturing	334,335
10	Transportation Equipment	336
11	Other Non-durable Manufacturing	312-316,322-324,326
12	Other Durable Manufacturing	321,327,337,339
13	TCU, Service and Government Enterprises	42,44,45,48,49,51-56,61,62,71,72,81

Example of Time-varying Interindustry Sales Coefficients



Time profile for interregional inter-industry sales coefficients for sales from Machinery Manufacturing in Illinois to all industries in Indiana

Example of Time-varying Commodity Flows



Trade volumes for same-sector interstate trade from Illinois to Connecticut for 13 industries

Other data were obtained from the following sources:

Data on unit transportation cost by mode were available from the US Department of Transportation.

Cost-to-carrier data were available from the American Transportation Research Institute (ATRI) and Associate of American Railroads (AAR). We estimated by OLS the values of observations for missing years.

Geographical data: The industry center for each State/Industry is specified to county level through payroll and survey data. Transportation network information was obtained from the National Transportation Atlas Database (NTAD).

Model estimation

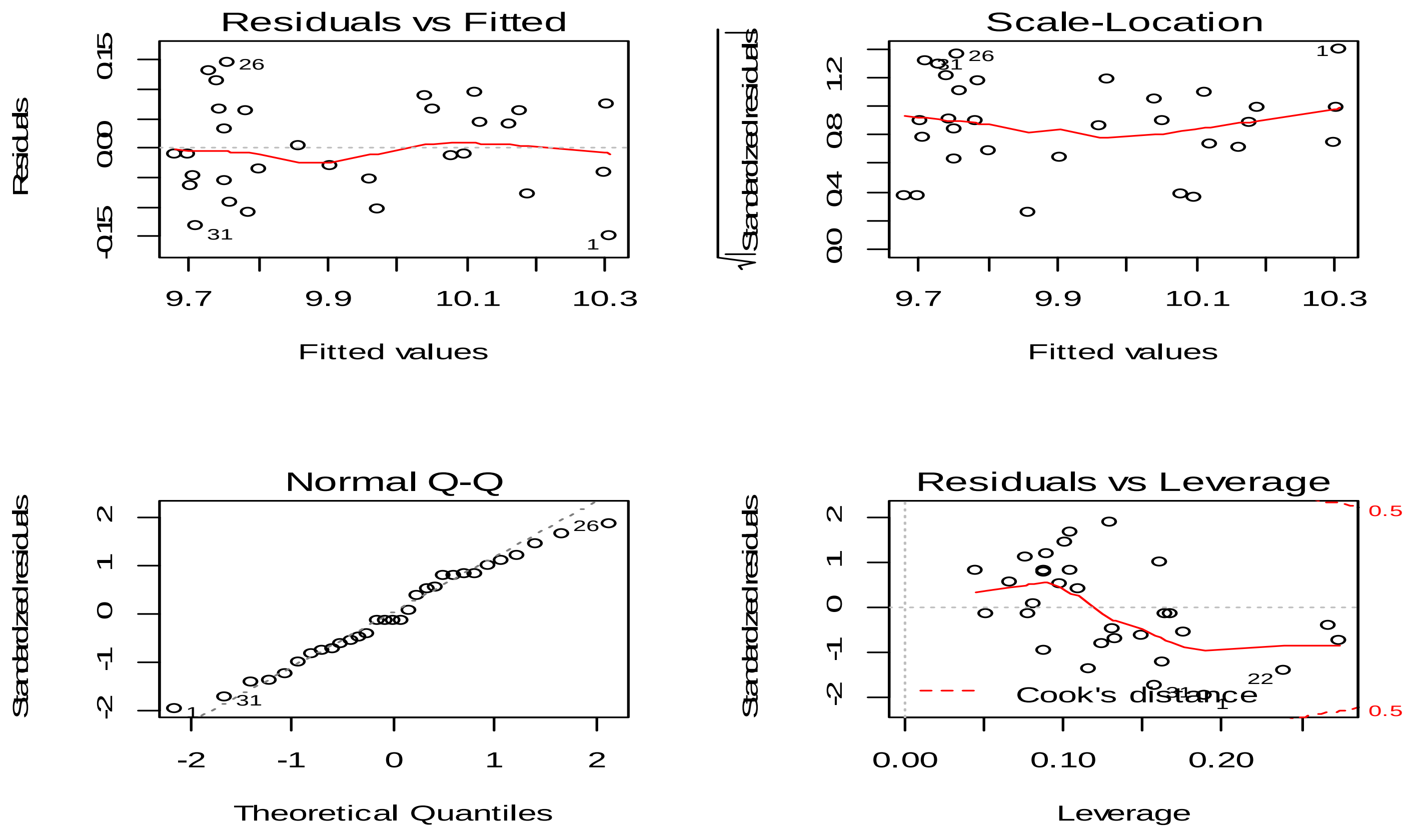
We took a divide-and-conquer approach (suggested by Robert Haining's work):

- parameters in input aggregator functions were estimated first by NLLS;
- parameters in partial equilibrium equations were estimated second by FIML;
- parameters in commodity-flow equations were estimated with previously estimated parameters constrained; and
- discretized disequilibrium adjustment equation parameters were estimated last.

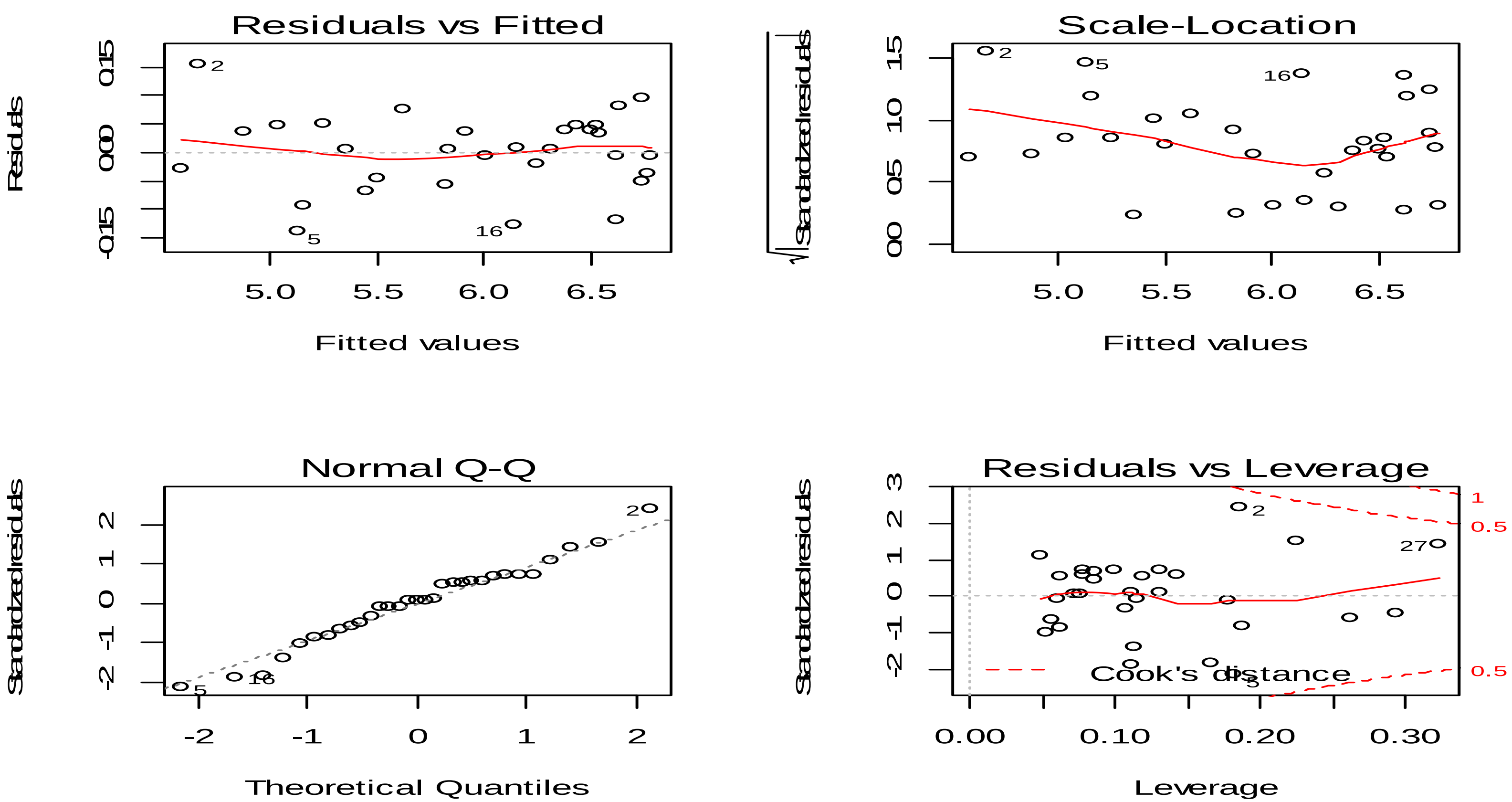
5. Preliminary results

The aggregator functions, partial-equilibrium conditions, and disequilibrium adjustment equations all fit the data acceptably well.

- No distinct patterns can be detected in plots of fitted values versus residuals (and square roots of residuals), indicating almost all available information in the data has been included in the model.
- The Q-Q plots indicate the residuals are distributed normally.
- Measures of Cook's distance indicated that there are no influential outliers.



Estimation Diagnosis for Partial Equilibrium Capital Equation for Transportation Industry in Rhode Island



Estimation Diagnosis for Partial Equilibrium Labor Equation for Transportation Industry in Illinois

Parameter \State	Illinois	Indiana	Michigan	Ohio	Wisconsin	Rest of U.S.
β_m^j	9.102 (4.467)	4.495* (3.951)	5.077* (4.678)	24.491 (8.410)	5.930* (6.861)	13.427 (3.165)
ρ_m^j	4.893 (2.305)	4.371* (3.839)	3.961* (2.391)	1.031* (1.267)	4.300* (2.464)	4.491 (4.102)
κ_m^j	1.672 (0.335)	1.071 (0.316)	1.347 (0.399)	2.275 (0.872)	1.626 (0.503)	1.016 (0.294)
α_m^{Lj}	0.307 (0.084)	1.207 (0.239)	0.513 (0.128)	1.391* (1.409)	1.753 (0.507)	0.964 (0.152)
α_m^{Kj}	0.978 (0.241)	0.828 (0.113)	1.032 (0.198)	1.016 (0.492)	0.803* (1.146)	0.989 (0.112)
α_m^{1j}	0.926* (1.289)	0.732 (0.365)	1.965 (0.674)	0.696 (0.184)	2.133 (0.706)	0.788 (0.356)
α_m^{2j}	1.577 (0.173)	1.038 (0.067)	1.094 (0.414)	0.613 (0.294)	0.942 (0.061)	1.172 (0.621)
α_m^{3j}	1.101 (0.454)	1.224 (0.125)	0.912 (0.283)	0.769* (0.512)	1.243 (0.115)	0.709* (0.420)
α_m^{4j}	1.119* (0.681)	0.769* (0.715)	0.873 (0.244)	1.029 (0.207)	1.641 (0.256)	0.853 (0.194)
α_m^{5j}	1.445 (0.632)	1.120 (0.586)	1.374 (0.197)	0.792 (0.361)	1.008 (0.491)	1.206 (0.501)
α_m^{6j}	1.199 (0.108)	1.008 (0.490)	1.056* (0.781)	1.634 (0.110)	0.919 (0.162)	1.573 (0.363)
α_m^{7j}	1.235 (0.593)	1.179 (0.138)	0.606 (0.192)	0.983 (0.485)	1.650 (0.519)	0.651 (0.174)
α_m^{8j}	1.091 (0.028)	1.032 (0.618)	1.649 (0.317)	1.094 (0.503)	0.843 (0.231)	1.216 (0.435)
α_m^{9j}	1.400 (0.466)	0.873 (0.272)	0.813 (0.147)	0.856 (0.392)	1.049 (0.513)	0.998 (0.207)
α_m^{10j}	1.236 (0.366)	1.221 (0.199)	1.461 (0.323)	1.562 (0.292)	0.615 (0.159)	0.751* (0.556)
α_m^{11j}	1.507 (0.365)	0.947 (0.320)	0.563* (0.381)	0.933 (0.379)	1.321 (0.618)	1.049 (0.325)
α_m^{12j}	0.651 (0.093)	1.009 (0.218)	0.814 (0.186)	1.181 (0.357)	1.175* (0.736)	0.828* (0.525)
α_m^{13j}	1.234 (0.538)	0.672 (0.137)	0.867 (0.371)	0.932 (0.470)	0.295 (0.116)	0.531 (0.170)

* Signifies an estimate not statistically discernible from zero at a conventional level of significance.

Table 5. Estimates of Technological Parameters and Standard Errors of their Estimates for Sector 8 in the Midwestern States

Solution of the full model

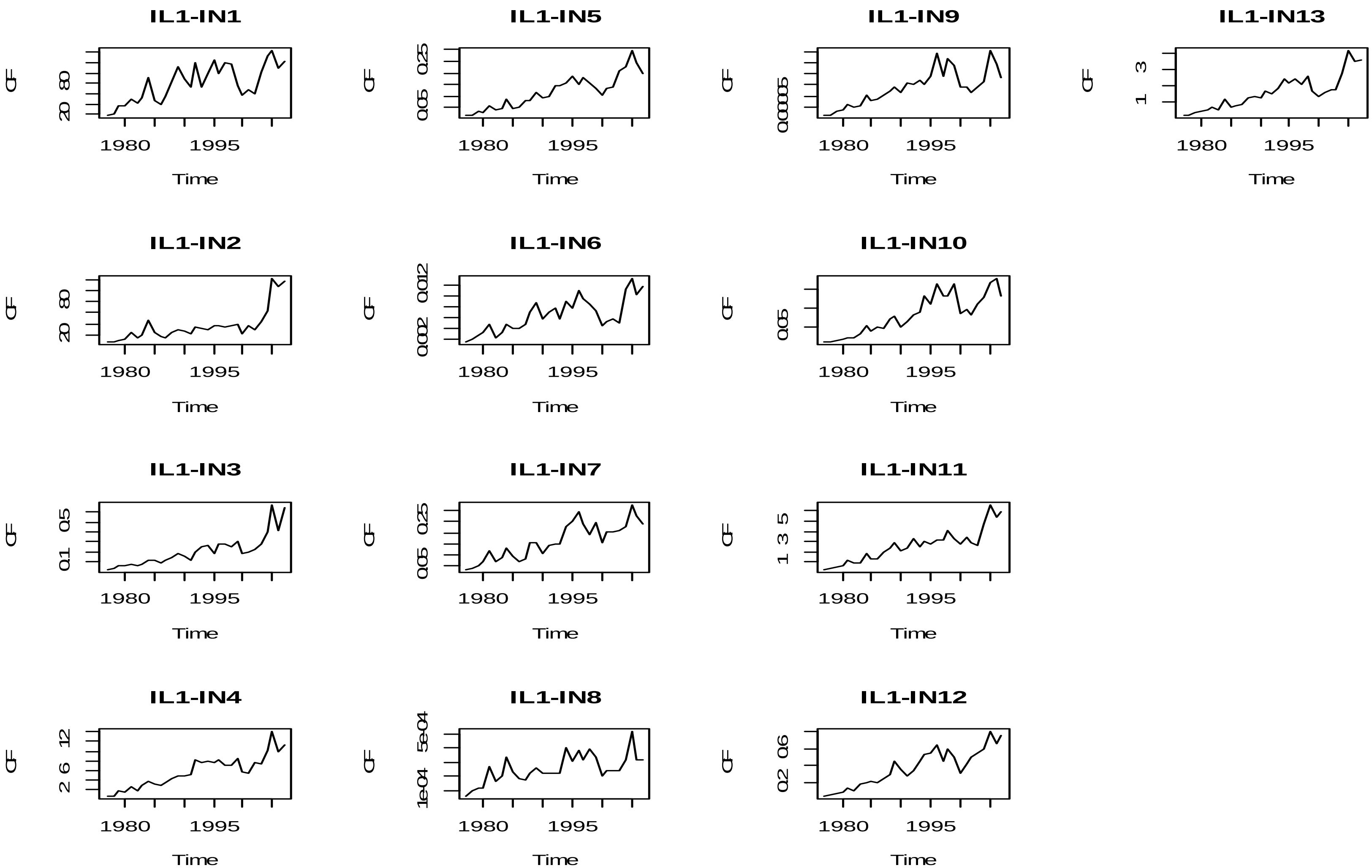
• Cost minimization for shippers feeds back annual increments in prices, capital, labor and freight movement;

• Profit maximization for carriers determines the charge of shipping and route of shipment for the next period.

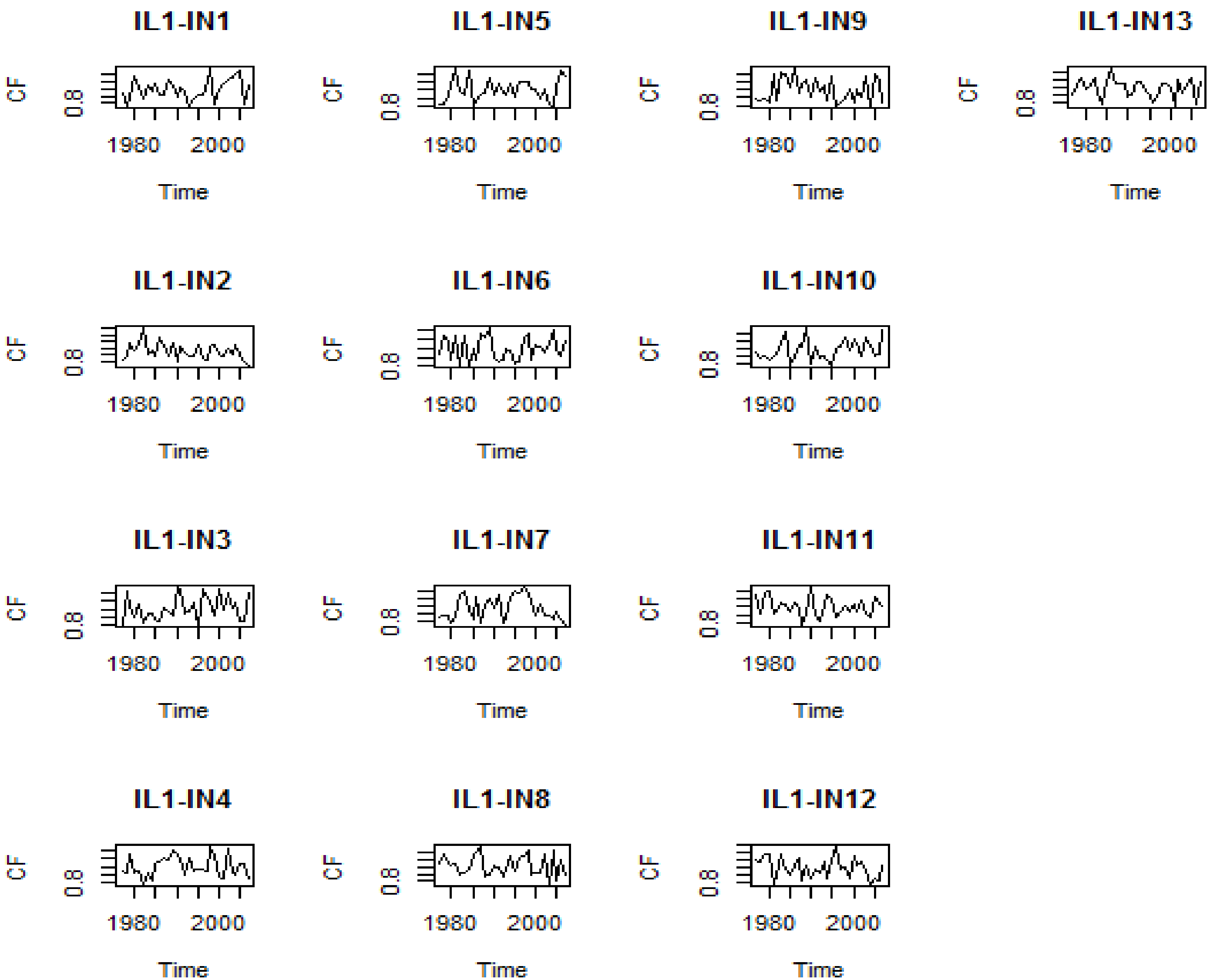
• For the Mid-west states and the rest of the U.S., the model was solved on an annual basis as a joint optimiz-ation problem in GAMS using the PATH solver. (See Rutherford, 1998) (The MCP solver can also be used for explicit variational inequality formulation.)

• The solution represents a non-cooperative Nash equilibrium between representative shippers and carriers.

Time-varying Commodity Flows of Agricultural Produce from Illinois to All Sectors in Indiana



In-sample Fit



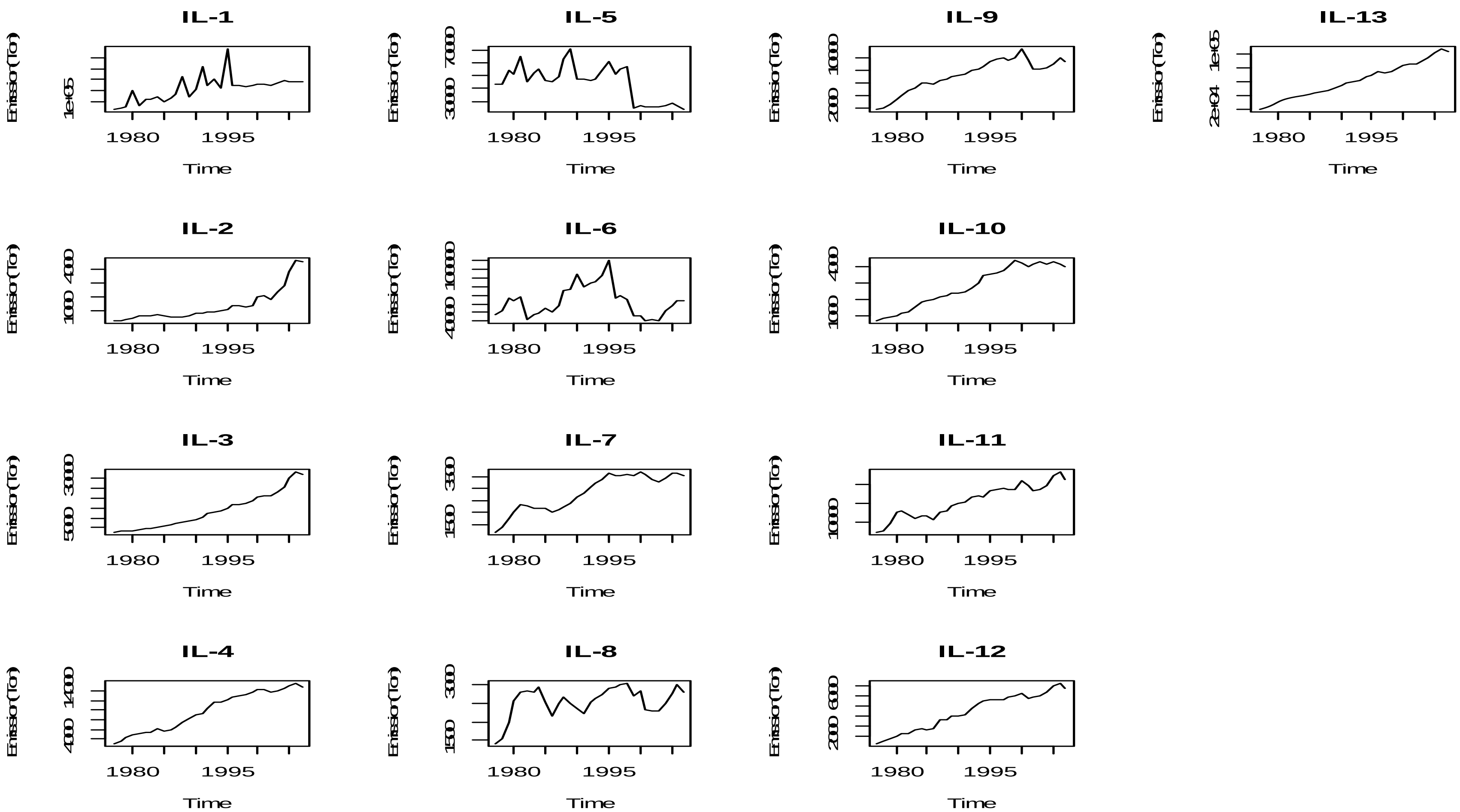
In-sample Percentage Root-Mean-Square Errors for Commodity-Flow Equations

Illinois	Indiana	Michigan	Ohio	Wisconsin	RUS
13.45%	10.15%	8.78%	15.09%	13.23%	22.76%

With respect to **emissions**, we found steady decline in emission intensity for most of the industries except for agricultural and the construction industry.

Generally speaking, total emissions will increase with increasing economy activity but will be reduced on a per-unit basis with advances in technology.

In-sample Model Solutions for CO Emissions in Illinois 1977-2007



6. Assessment in terms of Zeeman's stages

With respect to Zeeman's stages of development, urged upon us by BHW to assess progress in integration of models of locational structure and spatial interaction, we

1. Have characterized equilibrium states.
2. Have specified the fast dynamics in term of disequlibrium adjustment mechanisms—and captured stylized facts.
3. Have yet to specify some slow dynamics in the form of evolving infrastructure (but see Donaghy et al.,2005),
4. Have yet to represent feedback between fast and slow dynamics.
5. Have yet to study the effects of noise and fluctuations.
6. Have yet to study diffusion processes.

But … we *can* do 3-6 with the current model!

Thank you for your attention … and thanks David for your inspiration!