An Agent-Based Gaming Approach to Simulating the Evolution of Commodity Flows

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Objectives and motivation

Freight forecasting in the United States has historically relied upon commodity-flow data, either purchased from commercial vendors or, more recently, made publicly available through the Federal Highway Administration’s (FHWA) Freight Analysis Framework (FAF) program. For forecasting future freight flows, these sources provide static portrayals of existing trends. To forecast freight flows based on alternative assumptions—the impacts of infrastructure investments, operating policies and regulations, competition between regions, global trade patterns and macroeconomic shifts—requires a more flexible approach.

Buyers and sellers (receivers and shippers) represent the endpoints of supply chains. While carriers and distributors play critical intermediate roles, the flows between buyers and sellers largely determine origin-destination patterns of freight movements.

Their roles are larger than this, however, as these microeconomic decisions to trade with a particular business partner aggregate to comprise regional and even global economies. In this research we describe a scenario modeling tool developed by the Chicago Metropolitan Agency for Planning (CMAP) for forecasting future freight flows under different sets of investment, policy and macroeconomic assumptions; to perform focused analysis on specific industries; and to answer questions as to how these factors might affect the freight-dependent business community.

General description

The central component of this system is an agent-based model of the relationships between buyers and sellers of commodities that generate freight movements, provisionally called the procurement market game (PMG). PMG produces emergent market behavior that results from starting conditions, which include game-theoretic payoff values, assumed decision-maker utility expressions, production demands and constraints, and transport-logistics costs represented by buying and selling agents. Agents follow relatively simple sets of rules in interacting with other agents. By modifying agent decision rules, payoffs and starting conditions, it is possible to test a wide variety of potential markets and assumptions. Through iterative play, agents learn about other agents and their position in the market and seek trading relationships that lead to higher payoffs.

The modeling approach used in PMG is inspired by the theory of buyer-seller networks proposed by Kranton et al (2001) and incorporates concepts for agent interactions from other sources. It is similar to a principal-agent screening game of moral hazards with post-contractual hidden information (e.g. Stiglitz and Weiss, 1990; Rasmussen, 2006), but is considerably more complex because it involves multiple principals and agents, buyers and sellers, and is a repeated game with feedback and belief updating. To our knowledge, this is the first attempt to apply an agent-based gaming approach to model the evolution of relationships between shippers and receivers for public sector freight forecasting.

A number of researchers in freight modeling have advanced other game-theoretic approaches, most notably to capture the symbiotic relationships between shippers and carriers in supply-chain formation (e.g., Harker (1983) and Harker and Friesz (1986). These model formulations solve for variations on Cournot-Nash equilibrium solutions to predict network flows under profit maximization and assumptions of perfect competition, resulting in a generalized spatial price equilibrium model (GSPEM). An early version of Friesz’s work contributed to the Freight Network Equilibrium Model (FNEM) developed by George Mason University under funding from the U.S. Department of Energy and the U.S. Central Intelligence Agency to model global freight traffic. Subsequent research by Friesz and Holguin Veras (2005) provided theory for dynamic extensions to the GSPEM framework. More recently, Holguin Veras et al (2007) modeled games between carriers and receivers to study cooperation on the issue of off-hour deliveries, developing a mathematical programming solution. Meanwhile, incorporating macroeconomic drivers into these mathematical programming formulations, using computable general equilibrium models of the national economy, have proved to be mathematically challenging, and validation has been elusive (Friesz and Kwon, 2007).

Recognizing the limitations of mathematical programming approaches, researchers have begun to develop freight/commercial activity-based micro-simulation models that can better capture decision-maker behavior and avoid unrealistic assumptions on market competition and perfect information. Recent examples include the work of Leitdke (2009), Samimi et al (2010), Baindur and Viegas (2011), and Cavalcante and Roorda (2013).

PMG has been implemented as an extension to CMAP’s mesoscale freight forecasting model and therein fulfills a role in establishing the origins and destinations of freight flows, not just for the Chicago region but globally. The mesoscale freight model simulates firms/establishments throughout the U.S. by six-digit NAICS commodity codes and creates agents representing imports and exports of these same commodity codes that are equivalent to the supply and demand from foreign countries. Using U.S. BEA input-output tables, the model creates pools of commodity producing firms that need to procure specific input commodities and quantities needed to fulfill their production quotas. Buyer agents for each commodity-seeking
firm are entered into a procurement market along with pools of selling agents representing all of the firms that produce the commodity. This is done for more than 200 commodity markets, with PMG called as a kernel.

The desire to calculate expected utilities and revenues as a function of realistic input variables led to the development of payoff values formulated as weighting factors. The input variables—quantities of commodities to be purchased, seller capacities to fill orders, prospective shipping times and unit costs—are evaluated by buying agents, and the expected revenues for these transactions are evaluated by selling agents. These weighting factors upgrade or downgrade the nominal value of the trades and are used to update agent beliefs about other agents with whom they have traded in the past.

PMG is a Bayesian game in the sense that players do not know the other player’s type and preferences. Specifically, buyers do not know amounts of other contract offers an individual seller might have. If the seller has many competing contracts, it might not be able to fulfill the buyer’s order after accepting the contract. Similarly, sellers do not know how many or the value of other contracts that the buyer may have offered to other sellers. A buyer may offer to procure a larger or smaller amount from the same seller in different iterations, depending on where that seller ranks in the buyer’s evolving esteem. Since a player does not know how it rates in the mind of the other agent, the incentive to cooperate or defect is based on expected values from past encounters. Through iterative game play, agents form attachments to particular trading partners, leading to stable alliances over a sufficient number of rounds.

**Results and Conclusions**

PMG can be configured with different sets of payoff weights and other sets of assumptions regarding the information available to agents about other agents and assumptions about underlying agent motivation, which leads to different types of games being played, some of which may be more appropriate than others for a particular market. Agents may place a greater value on commodity cost or shipping time and supplier responsiveness, depending on the whether the commodity is considered to be innovative or functional (value-to-weight ratio). Initial payoff values can be configured to encourage experimentation or inertia. Through experimentation on miniature pools of buying and selling agents, it is possible to show how different sets of input assumptions lead to quicker or more stable convergence in trading partner alliances. While the scenario modeling tool is sufficiently general and flexible to model many different types of commodity markets, further research would be needed to develop sets of starting parameters that accurately represent a particular market.

Using realistic-size market data, it is also possible to show how different assumptions lead to changes in shipment distance distributions, modes, and spatial flow patterns. In most commodity markets, buying agents will far outnumber selling agents, which can lead to lengthy run times, even if total supply is assured to exceed total demand, simply because individual sellers are capacity constrained and seek to secure the largest contracts. The next major steps in testing the model are to compare its predicted flow patterns for individual commodity markets to the FAF data, and to apply the full model system, including the entire global economy, to a realistic policy scenario, such as the evaluation of Chicago’s multi-billion dollar investment to improve regional rail freight throughput.

**References**


**Keywords:** agent based; game theory; commodity flows