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Paper Title & Number

An Agent-Based Computational Economics Approach to Forecasting Freight Flows for the Chicago Region [ITM # 46]

Abstract

A bi-lateral trading game is developed as the core component of the supplier selection mechanism of the Chicao meso-scale freight model. In the procurement market game (PMG), agents representing producers of an output commodity ("buyers") are instantiated with a quantity of an input commodity to purchase and a set of preference weights that allow them to tradeoff unit costs, service time, and potentially other attributes when considering the utility of a potential trading partner. Buyers are also endowed with "attitudes" towards risk, such as the maximum proportion of units to be purchased from any one source. Agents representing suppliers of the commodity to be traded ("sellers") are instantiated with an annual production capacity and unit costs. The primary objective of sellers is to capture as much revenue as possible from buyers, up to their capacity limit. Because both buyers and sellers are situated geographically, transportation and logistics costs and shipping times are a function of network shipping and receiving locations and the service characteristics of available freight modes.

Statement of Financial Interest

The research presented here has been funded through a contract with the Chicago Metropolitan Agency for Planning (CMAP) and the working model is intended as a deliverable under that contract. The authors have no additional direct financial interest in this research to the extent that it does not present proprietary methods, software, or information to be offered for sale; however, the authors do have an indirect financial interest in the success of this research in so far as it promotes similar consulting engagements.

Statement of Innovation

This research is an innovative application of game theory to model the evolution of freight supply chain relationships, focusing on buyer-supplier relationships in a procurement market context with multiple choice attribute dimensions. To our knowledge, this is the first such application of a game theoretic approach to modeling the supplier selection mechanism for public-sector freight transportation planning purposes. Importantly, the agent-based approached used here differs from other micro-simulation approaches in that buying and selling agents learn about each other. Through repeated games, agents form preferences for specific trading partners based on past interactions and may adjust their tolerances for risk based on market constraints. From a practical perspective, this research represents a departure from the existing methods of forecasting freight flows, which are based on an assumed continuation of existing commodity-flow relationships.

An Agent-Based Computational Economics Approach to Forecasting Freight Flows for the Chicago Region

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An Agent-Based Computational Economics Approach to Forecasting Freight Flows for the Chicago Region

Objectives, motivations and innovation

Transportation planners in the U.S. have benefitted greatly by the development of the Freight Analysis Framework (FAF) set of data products, which have enabled analysis of not only recent (2007) but also future freight flows by commodity type across a zone systems that permits a useful level of spatial resolution between and within metropolitan regions. The most recent available version, FAF[3] provides forecasts of future freight flows forecasts for the year 2040, based on a continuation of current trends, which is one possible depiction of the future.

For policy and planning sensitivity analysis, however, it is desirable to vary forecasts to reflect potential changes in macroeconomic conditions (e.g., tariffs, labor costs and oil prices), technological shifts in logistics and supply chain practices (e.g., near-sourcing, out-sourcing), and regional infrastructures (e.g., port expansions, regional rail congestion relief projects). The Chicago Metropolitan Agency for Planning (CMAP) has recently developed the first generation of a regional freight forecasting model that features two levels of resolution: "mesoscale" resolution, connecting Chicago to the rest of the nation and the world; and "microscale" resolution, a tour-based simulation model of freight movements within the region. To this already comprehensive set of tools, CMAP is now developing an extension to the mesoscale model to forecast future freight flows (FFF).

The agent-based FFF modeling tool was developed to allow high-level scenario modeling of different assumptions regarding the formation of business supply chains in a global economy. It is designed to provide a mechanism for modeling theoretically plausible shifts in the magnitude and direction of flows and modal usage in response to both regional and extra-regional stimuli. Its value is not to produce more accurate point forecasts per se, but rather to focus policy discussions. Given a set of plausible alternative future outcomes, the agent-based FFF model can predict under which sets of circumstances (scenario assumptions) various outcomes are likely to occur. Moreover, it may predict emergent patterns of responses that the analyst did not expect, but might find worthy of consideration.

The FFF tool was designed to answer questions such as the following:

- How would a planned large intermodal facility in the middle of Iowa affect freight flows through Chicago? To what extent would it divert business from the Chicago region's highly congested trans-shipment centers? Would this diversion actually provide compensating congestion relief?
- Would the completion of Chicago's CREATE program, a multi-billion dollar program to improve rail infrastructure to ease congestion and minimize impacts on non-rail traffic stimulate additional freight flows within the region? How do assumptions about future fuel prices affect the relative size of these impacts?

- Would the anticipated expansion of Port of Prince Rupert, BC funnel more cross-continental freight flows through Chicago? To what extent might it be offset by planned expansions to the capacity of the Panama Canal, which may divert shipments from Asia by allowing larger ships to travel directly to the U.S. East Coast?
- What if there is a sea change in the volume of international trade with China due to rising wages in that country? Will U.S. firms begin purchasing more commodities from domestic sources and, if so, how will this affect freight flows through Chicago?

The agent-based FFF belongs to a general class of agent-based computational economic models in which agents interact according to a relatively limited set of alternative actions, but over many such encounters learn about each other and develop preferences for other agents. In the aggregate, behavioral patterns emerge, and the game designer can influence those emergent patterns by varying starting assumptions.

Agent-based computational economics (ACE) (Tesfatsion and Judd, 2006) is an emerging, alternative approach to classical economic theory that is often applied to the study of market behavior. ACE methods utilize computer simulations of individual market actors, or agents, who follow relatively simple sets of rules in interacting with other agents. Through careful construction, it is possible to specify a set of agents endowed with decision rules, outcome payoffs and starting conditions, such that the simulated interactions played out over time will result in outcomes that resemble actual market behavior. By modifying agent decision rules, payoffs and starting conditions, it is possible to test a wide variety of potential markets and assumptions. Some of the more commonly studied applications of ACE include the formation of trading networks and sourcing decisions.

Game theoretic principles are widely used in the global supply chain and logistics profession to develop more efficient practices, particularly for sourcing decisions and supply chain coordination. For example, with the rise of internet-based commerce, electronic procurement systems have emerged as a preferred means for producers of commodities to solicit bids and select suppliers for various input commodities and services (Chandrashekar et al 2007). A chief reason for the popularity of “e-procurement” systems is the ability to automatically control market outcomes through auction mechanism design, which amounts to reverse engineering a market process by specifying a set of rules, payoffs and initial conditions that will result in a preferred market outcome. Researchers in the field of algorithmic game theory have combined mechanism design with computer science to develop sophisticated algorithms to provide computationally efficient implementation solutions that can handle a wide variety of complex market situations in an automated fashion (Nissan et al 2007).

One example of a desirable outcome of a procurement situation, from the perspective of the buyer, is for suppliers to bid “truthfully” with respect to their actual costs, i.e., to avoid strategic lying. Vickery (1961) proposed an early solution to this problem, the second-price sealed-bid auction in which the winning provider/seller was the submitter of the lowest bid (in the case of procurement). In a “Vickery auction,” the price paid to the winner is that of the second-lowest bid; thus, there is no incentive to bid higher than cost. Auction mechanisms vary in complexity and computational tractability, depending on starting conditions, such as whether there are multiple buyers as well as sellers (called a "double auction"), or whether there is a single commodity up for bid or a multi-commodity bundle.

Methodology

In the CMAP freight modeling system, firms are represented as commodity-producing agents, defined by firm size, North American Industrial Classification (NAICS) code, and by the 43 categories used by the Standard Classification of Transported Goods (SCTG) and Freight Analysis Framework (FAF3). Firms are simulated based on data from County Business Patterns, and Bureau of Economic Analysis's (BEA) Input-Output (IO) Accounts and are located either in traffic analysis zones within the Chicago region, or in "FAF zones" representing other regions of the U.S. and foreign countries.

The FFF element utilizes the relationships found in the IO data as the basis for supply-chain network formation. For each output commodity produced by a firm, the IO "Use" tables provide a "recipe" for the producer value of input commodities. To forecast future freight flows, the modeling system allocates total commodity production to producer agents, based on firm size and NAICS code. The simulation also includes firms that consume transportable commodities, but do not necessarily produce them, such as wholesalers, retailers and service industries. Wholesalers are a special case because they purchase commodities for resale, providing economies of scale in storage and shorter lead times to their customers, and represent an alternative to direct purchases from manufacturers. Currently, the simulation does not include households as recipients of freight deliveries, as these are intended to be covered by a separate, future commercial services model that will likely operate at the tour level. For each input commodity specified by the IO tables, the purchasing firm chooses one or more suppliers from a pool of agents in the simulation who produce that commodity. The supplier pool may include intra-firm establishments, other regional suppliers, and supplier agents from other U.S. states and other countries. Costs of production vary by each potential supplier's attributes, taking into account regional differences in both transport and non-transport costs. Transport costs are derived from multi-modal network path values, considering truck, rail, water and air modes.

An ACE approach is used to select suppliers for each commodity to be sourced under a variety of commodity markets and firm typology assumptions. Important considerations are the ability to represent variation in vertical integration practices, propensities to out-source to foreign countries and so-called near-sourcing. Thus, the utility of choosing a supplier as the source for a particular commodity depends on the commodity itself (e.g., bulk versus specialty goods), resulting in varying decision weights assigned to cost vis-à-vis quality considerations, such as timeliness of delivery and the need to maintain quality control over the product. To facilitate scenario testing, the model design calls for the ability to vary assumptions regarding:

- total levels of production;
- technical coefficients of production found in the IO tables;

- transport and non-transport unit costs, including foreign trade tariffs and wage levels; and
- network infrastructure changes, such as port capacity expansions, intermodal terminal capacities, and similar infrastructure changes.

The approach to matching producers with suppliers is provisionally called a "procurement market game." It is loosely based on a more general "trade network game" originally developed by McFadzean *et al* (2001) to illustrate general principals of evolutionary game theory and ACE. Our approach is intended to be sufficiently general and flexible such that it can be applied to all of the commodity markets that need to be modeled to support the forecast of future freight flows without modifying the basic structure of the game. A general, flexible framework avoids the complicated, time-intensive and potentially error-prone task of studying and trying to represent what actually goes on in numerous different commodity markets. Instead, commodity markets would be differentiated from each other by the inputs to the game—the number and attributes of agents assumed to be competing in the market, their preferences and cost structures.

In the procurement market game (PMG), agents representing producers of an output commodity ("buyers") are instantiated with a quantity of an input commodity to purchase and a set of preference weights that allow them to tradeoff unit costs, service time, and potentially other attributes when considering the utility of a potential trading partner. Buyers are also endowed with "attitudes" towards risk, such as the maximum proportion of units to be purchased from any one source. Agents representing suppliers of the commodity to be traded ("sellers") are instantiated with an annual production capacity and unit costs. The primary objective of sellers is to capture as much revenue as possible from buyers, up to their capacity limit. Because both buyers and sellers are situated geographically, transportation and logistics costs and shipping times are a function of network shipping and receiving locations and the service characteristics of available freight modes.

PMG is a repeated game, played for a specified number of iterations. The analyst specifies a payoff matrix, which represents how agents value their trading experiences with other agents, and parameters indicating how this information is used to calculate expected payoffs of subsequent rounds. During a given iteration, buyers evaluate the bundles of cost and services offered by each seller in the market, deriving an expected utility for a procurement contract. The buyer will offer a contract to a seller if the expected utility of contracting with that seller exceeds the expected utility for alternate sellers, or if higher-rated sellers cannot fulfill the buyer's order quota or reject the buyer's offer all together. A seller may reject a buyer's contract offer if the seller does not have the capacity to fulfill it, ranking other buyers ahead of it based on their order size or utility.

A payoff matrix represents a set of values that each agent receives, depending on whether they unilaterally decide to "cooperate" or "defect." In the parlance of the PMG, these terms are re-cast to mean "favored trading partner" or "not favored." Payoff weights are scalars that are applied to the nominal utility of a potential buyer or seller's offer, with a high positive payoff weight symbolizing a cooperative outcome, and lower positive payoff weights given to a noncooperative outcome. Sellers who cannot fulfill a buyer's order requirements are also downgraded commensurately. All agents start off with an initial expected utility that is slightly more positive in order to encourage trading. Through successive rounds of trades, however, agents accumulate a memory of past trade encounters with the same agents and adjust their expectations accordingly. To satisfy procurement needs, there may be some markets where a buying agent must contract with a seller that would not be a preferred provider due to scarce aggregate supplier capacity, or the desire to minimize risk by purchasing goods from multiple sources. Likewise, depending on the commodity, there may be some markets where competition for customers forces sellers to provide commodities to buyers who would not be their preferred choice, either.

The final round of the game indicates which agents established trading relationships and the quantities of commodities bought and sold. In most markets, buyers will far outnumber sellers; however, buyers will likely purchase commodities from multiple sellers, either for reasons of risk-minimization or limited individual seller capacity.

For each of more than 300 NAICS commodity types, a PMG will be played to determine buyer and supplier relationships for the commodity. The buyer pool will consists of all firms that use the particular commodity as a production input, and an annual purchasing amount will be determined by multiplying the direct requirements percentage of this input commodity by the firm's total output level for their primary output commodity. The supplier (seller) pool consists of all firms that are primary producers of the particular commodity, and the amount that they are able to supply (capacity) will be determined by their total output level for that commodity. Firms are represented by buying and selling agents who possess attributes representing typologies assigned to each agent. For buyers, typologies derived from the supply-chain and logistics literature are used to assign preference weights for various sourcing bundle attributes, such as:

- Total unit cost
- Expected delivery time (travel time)
- Expected shipment frequency or size
- Geographic proximity

Buyers are also assigned risk profiles that represent a maximum amount that they are willing to purchase from any single seller, which can be tied to seller attributes. For example, to minimize the risks associated with natural disasters or labor strikes, many global firms are diversifying not only their supplier base but also their shipping channels.

Selling agents are defined by offering a particular bundle of these same attributes and will be capacity constrained, meaning that they will only be able to supply an amount of a commodity equal to their production output. Unit costs reflect both non-transport costs and transport-costs. Transport and logistics costs are derived from the multi-modal skim tables, based on the geographic locations (FAF zones) of each buying and selling agent. Each selling agent is represented by a single representative transport mode path, e.g., truck, rail-truck, water-truck, or air-truck. For any potential buyer-seller pair, this mode-path combination will also determine the expected delivery time and expected shipment size, based on modal capacity. In this way, the choice of a supplier subsumes the choices of distribution channels.

Major Results

We coded the core PMG program and tested it using a various configurations of test inputs, using a small set of agents and hypothetical cost and level of service scenarios aimed at stress testing it. For example:

- What happens when there is a dominant buyer or seller agent in the market?
- What happens when there is insufficient supplier capacity to serve all buyers?
- How do different assumed payoff matrix values (game types) affect the buyer-supplier relationships that form?
- What are the effects of different assumptions regarding the amount of information that buyers and sellers have about the market and competition?
- How do various assumptions on buyers' risk minimization strategies interact with seller capacities in a constrained market?

We then integrated the PMG program with the rest of the meso-scale model and to create the FFF, creating all of the synthetic firms/establishments needed for the full forecasting simulation and using realistic cost and level of service data. The next step is to test various commodity markets and fine tune the model through comparisons with FAF[3] baseline and future freight flows. For this conference, we will demonstrate how the FFF works for one commodity sourcing market and present summaries of outcomes to demonstrate its behavior. Future plans include sensitivity tests designed to answer the type of scenario questions posed at the beginning of this paper.

Implications for the practice of freight modeling

For policy and planning sensitivity analysis, the next generation of innovative models will need to create commodity flow distributions endogenously, rather than relying upon static, exogenous inputs from FAF or other commodity flow data. Importantly, desired policy sensitivity requires demand patterns to be responsive to macroeconomic price signals, technological changes, and large-scale infrastructure investments that affect the magnitude and direction of future freight flows. While it is acknowledged that emerging drivers of future freight flows are difficult to predict with certainty, they can and will be discussed. An agent-based computational economics approach to modeling supply-chain sourcing decisions, such as the subject of this research, enables the analyst to assert assumptions about alternative future conditions and to observe and evaluate the emergent behavior and its aggregate outcomes.

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