# Spatial Modeling in Technology Adoption Decisions: The Case of Shuttle Train Elevators

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This article empirically models a strategic game of technology adoption of shuttle train grain elevators with information on location of the firm and its competitors. A spatial econometric model illustrates the role of spatial interdependence of rivals' decisions as well as agronomic and competitive variables on discrete adoption decisions. The analysis assesses equilibria conditions that characterize technology adoption, in this case of shuttle train adoption, and the results provide an explanation of shuttle train adoption decisions in the grain handling industry in which spatial competition is critical.

*Key words*: concentrated likelihood function, shuttle trains, spatial correlation, technology adoption.



The adoption of shuttle train grain elevators is impacting the grain handling industry which has been considered mature for many years. Shuttle trains enhance rail efficiencies and provide incentives paid to shippers for more efficient origination, termination, and cycling of cars. Shuttle trains were introduced in the early-1990s and can be viewed as a technology change for which adoption is impacted by own and rival firm characteristics, spatial distribution of firms in the industry, and competition and agronomic characteristics. Data collected for this study indicate that 16% of the elevators were capable of shuttle train shipping (in 2001) at costs of about \$5–10 million each. Shuttle adoption thus requires substantial investment in technology by grain handlers. Few previous studies have addressed the impacts of shuttle trains, and none have addressed inter-firm rivalry in making adoption decisions.

Technology adoption has been the focus of an extensive literature. The literature on technology adoption in production agriculture has been rich, for example, Kislev and Peterson; Ruttan; Sunding and Zilberman, as well as applications to some highly specific technologies, for example, Griliches; Olmstead and Rhode. More recently, Barham et al. modeled characteristics that differentiate adopters of a genetically modified technology, while Case modeled a farmer's expected profit from adopting a new technology as a function of their own characteristics and the neighbor's expected profits. There have been fewer studies on technology adoption in industrial economics, e.g., Shavinina, in relation to studies of innovation and diffusion. In grain shipping there have been only a few studies that have analyzed technology adoption. Vachal et al. (1999) analyzed the financial variability of large grain loading facilities in the upper Midwest and Klindworth discussed the impacts of shuttle trains on grain marketing. Wilson and Wilson analyzed the efficiency gains associated with innovations in railroad grain shipping. Shuttle trains are another form of technology and adoption and are impacted by numerous competitive and agronomic variables.

The purpose of this article is to analyze the impact of firm characteristics, competitive factors, and spatial interdependencies on shuttle adoption decisions. Spatial interdependencies pose interesting economic and econometric issues. The economic issues are related to inter-firm rivalry on equilibrium decisions that characterize adoption. Inter-firm rivalry can be specified as a game and, depending on the payoff, may result in different equilibria. While the existence of multiple equilibria is widely understood, empirical tests of strategic games are scarce.

To link the strategic behavior to a discrete choice model of technological adoption, this article uses the locations among

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firms as variables. Modeling this link is innovative in the increasingly rich field of econometric modeling of spatial correlation. The spatial econometrics literature in recent years has increasingly incorporated the spatial interconnection across economic agents (Anselin; Irwin and Bockstael), which are important in agricultural industries since these are largely spatial (Anselin, Bongiovanni, and Lowenberg-DeBoer; Nelson; Nelson and Geoghegan). One of the econometric issues is specification of a model that allows firms' payoffs from shuttle adoption to be correlated with neighboring firms' decisions. In this case, a discrete choice model of technology adoption consists of a choice set impacted by inter-firm rivalry and potentially correlated across competitors. A spatial lagged dependent variable then needs to be incorporated in the dichotomous choice problem of adoption that depends on the distance to rivals that have adopted the technology.

Existing software used in spatial econometrics, e.g., Spacestat, which has been incorporated into an S-Plus module that works with Arc-View, do not include algorithms for spatial correlation models with a dichotomous dependent variable. We have developed an algorithm based on concentrating the likelihood function in terms of the spatial correlation coefficient to estimate the model. Factors that determine the probability of shuttle train adoption are then analyzed and parameters are estimated. We evaluate the equilibrium that explains inter-firm rivalry and spatial competition and estimate the marginal effects of elevator capacity, production density, production risk, and competition on the probability of adoption. Estimation using spatial correlation increases the statistical fit of the model, affects parameter estimates, and provides tests of strategic behavior that underlies microeconomic underpinnings that drives adoption and overinvestment. Without the adjustments for spatial correlation on the discrete dependent variables, the coefficient estimates are inconsistent.

The contribution of this study consists of spatial modeling and estimation of strategic and discrete technology adoption decisions of shuttle elevators in the grain handling industry. The model has important ramifications to many agricultural industries which are largely spatial and to which spatial rivalry is an important feature of competition. There have been few empirical studies on agricultural industries to which strategic behavior is modeled. The application to shuttle train adoption in the grain handling industries provides interesting perspectives on factors impacting adoption decisions.

## Shuttle Train Technology

The U.S. grain elevator industry has been experiencing a continued pace of consolidation into a smaller number of high capacity train-loading facilities (Vachal, Bitzan, and Baldwin). This change is in part a response to programs initiated by rail carriers. Most U.S. and Canadian railroads have been developing and offering more sophisticated mechanisms for shipping grain. One of these is what is commonly referred to as shuttle trains which can be envisioned as a new logistical technology for grain shipping. This is a continuation of changes that evolved from single-car shipments prior to the early-1980s, to the varying size of unit trains ranging from 25 or 26 cars to 50 or 52 cars during much of the period from the mid-1980s to the mid-1990s. Each of these required shipping in larger units, but the technical requirements for shuttle trains generally required construction of new plants. A shuttle train involves shipping 100 (or more) cars from a single origin loaded in fifteen hours, to a single destination and unloaded in fifteen hours, and operating the train as a continuous cycle with a number of successive movements.

Use of shuttle trains was experimented with by some carriers in the early-1990s on selected routes and commodities. Adoption rates vary substantially. As examples, in Minnesota, 19% of the elevators have shuttle capabilities. In contrast, in Montana, a number of shuttle stations comprise just 5% of the elevators.

A shuttle train is a form of technological change in grain logistics, as distinguished from traditional movements. For railroads, shuttle trains involve keeping the grain cars, locomotives, and crew together through the entire movement. This differs from other regimes whereby trains with 26 and 52 cars from multiple origins are assembled at a rail yard, connected to a single train, and routed to another rail yard where they are "constructively placed" and then separated to go to their alternative receiver plants. By moving the larger shuttle trains as a continuous movement from origin to destination, and then continuing to the next origin as a single unit, this increases the number of car cycles and reduces costs substantially. Carriers' motives for offering these alternatives are to improve efficiencies in equipment utilization, but to do so requires investment by the shipper in new plants and/or other investments to upgrade capital. Shuttle trains are two to three times more productive than those in conventional service, and this efficiency results in improvements in equipment utilization and availability. Adoption has the effect of increasing rail capacity and efficiency and improves logistics, dramatically resulting in reduced costs. Grain car cycle time in some regions and carriers has increased from in the area of fourteen to eighteen trips per year to thirty trips per year, and some carriers have indicated that it has reduced their costs by up to 30%.

Conforming to shuttle movements for handling firms requires investment in different loading technology, track space to hold 100+ cars at a time, as well as plant configuration with respect to receiving, storage, and outbound capabilities. For shuttle movements, there are three important features. First, handlers contract with railroads to ship a shuttle train over a specific period, in successive trips cycling continuously between origins and destinations. The shipper commits to loading and shipping multiple 100 (or more) car trainloads of corn, wheat, soybeans, milo, etc., over a six- to nine-month period on the railroad in exchange for a lower rate and a service guarantee. Second, shuttles are subject to narrow scheduled windows for car placement and penalties are paid by the railroad if that window is not met. Trains typically have fifteen-hour loading requirements for the shipper and are subject to penalties if it is not released within fifteen hours. Thus, use of shuttles requires a change in merchandising practices involving coordination of the entire set of successive movements. Third, the shuttle train contract provides incentive allowances and discounted rates (or rate spreads relative to the rate for a 54-car movement) for shuttle train shippers if they meet requirements of the shuttle contract. The incentives can range in the area of upwards to $500/car, but are highly dependent on meeting the requirements established by the carrier. By utilizing a plant for shuttle movements, handlers can increase annual output, lower their marginal costs, and benefit from the rail rate incentive. However, there are investment costs and risks that affect the likelihood of receiving incentive payments, including timing of farmer deliveries, export shipments and transit times, storage constraints, etc.

For railroads, shuttle trains involve operational changes that improve efficiencies. For handlers, shuttle trains involve a technology change due to the need to invest in the infrastructure and technology to accrue their savings. There are several competitive impacts related to adoption of shuttle train operations (Klindworth). These include real savings accruing those shippers that adopt shuttle train operations and qualify for the multitrip discounts. In the current regime these incentives amount to 9c/b or more, depending on meeting the technical requirements of the shipment. Some of these cost savings are reflected in the form of increased bids to growers (bids are generally derived as a terminal market grain price, less handling margins, and shipping costs) to attract grain to meet shuttle obligations. The competitiveness of surrounding shippers diminishes due to the lower shipping cost of the shuttle rival, and due to the inability co-load with other elevators. Finally, gathering areas of firms which become shuttle train loaders' increase and farmers truck their grain longer distances in quest of higher grain prices. The typical draw area for a shuttle train increases to about 25–30 miles, dependent on local competition and truck delivery costs and in some cases the advantage would enable corn to be delivered from as far as 50 miles away.

## Strategic Interaction and Shuttle Adoption Decisions

We build on earlier specifications by Case, and subsequently by Dubin, that model technology adoption using cross-sectional spatial observations. Dubin shows that a firm's unobserved utility (expected profit) from adopting an innovation is a function of its own characteristics, plus its distance from other adopters. Each variable represents the influence firm $j$ has on firm $i$. The model was estimated by simulating spatially autocorrelated data using a two-step process. In the first stage, he simulated standard logit observations. In the second stage, he allowed non-adopters to be influenced by their proximity to the stage one adopters through the influence function.

These studies show that greater expected payoffs and lower investment costs result in greater adoption. The intensity of competition impacts expected post-adoption profits. Other variables include own and rival firms' characteristics including size and the distance among them. The expected profit from adoption depends on rivals' decisions and diminishes with distance. The influence of rivals' adoption decisions can be evaluated from the econometric results, in this case on distance. If they are significant, there is spatial interaction and vice versa.

We illustrate the sources of incentives to adopt shuttle technology and uncertainties by first assuming a grain handling firm that is not confronting competitors. The expected payoff without a shuttle is defined as

$$\pi_N = (M \cdot Q_H) - C(Q_H)$$

where $\pi_N$ is the expected payoff, for example, annual, under non-adoption; $M$ and $Q_H$ are gross-margin and volume shipped, respectively; and C is cost that is a function of $Q_H$. A comparable payoff for shuttle adoption, either a new plant or an expansion, is

$$\begin{aligned}\pi_A = &(M \cdot Q_H + \Delta M + \Delta Q_H)\\ &- (C(Q_H + \Delta \cdot Q_H) + K)\end{aligned}$$

where $\Delta M$ and $\Delta Q_H$ are the change in margin and volume as a result of adopting the shuttle, and $K = K_O - K_{RR}$ is the net annualized capital cost associated with the shuttle investment where $K_O$ is the own firm's capital and $K_{RR}$ is the railroad's contribution. As a result of adopting a shuttle, the elevator operates at a lower marginal cost which is a function of new technology and greater volume, as suggested by Klindworth, and as such can expand its volume by attracting further distant grain.

Ignoring the impact of competition, the shuttle technology will be adopted by the shipper if $\pi_A - \pi_N > 0$. Distance among competitors, however, plays a role in formulating expectations about post-adoption payoffs. Both $\Delta M$ and $\Delta Q_H$ depend on inter-firm rivalry that hinges upon distance from competitors. In addition, $\Delta Q_H$ and $Q_S$ depend on agronomic variables including production density, variability, and homogeneity of production which captures the impact of growing many different crops in a region.

The impact of rivalry on adoption decisions can be interpreted in a two-firm game. We define their conditional expected payoffs by denoting competitor $i, j = 1, 2$ and $i \neq j$:

$$\begin{aligned}\pi_{jAA} &= \pi_{jA} \mid A_i = [(M \cdot Q_{jH} + \Delta M \cdot \Delta Q_{jH})\\ &\qquad - (C(Q_{jH} + \Delta \cdot Q_{jH}) + K_j)] \mid A_i\\ \pi_{jAN} &= \pi_{jA} \mid N_i = [(M \cdot Q_{jH} + \Delta M \cdot \Delta Q_{jH})\\ &\qquad - (C(Q_{jH} + \Delta \cdot Q_{jH}) + K_j)] \mid N_i\\ \pi_{jNA} &= \pi_{jN} \mid A_i = [(M \cdot Q_{jH}) - C(Q_{jH})] \mid A_i\\ \pi_{jNN} &= \pi_{jN} \mid N_i = [(M \cdot Q_{jH}) - C(Q_{jH})] \mid N_i\end{aligned}$$

where $A_i$ and $N_i$ indicate, respectively, adoption and non-adoption by firm $i$. In this case, $\Delta M$, $\Delta Q_{jH}$, and $Q_{jS}$ have conditional values on whether the rival adopts and distance from the rival. These can be illustrated in the form of a two-firm technology adoption game as shown below:

| Player 1's Strategies | Player 2's Strategies: No Adoption | Player 2's Strategies: Adopt |
|---|---|---|
| No Adoption | $\pi_{1NN}, \pi_{2NN}$ | $\pi_{1NA}, \pi_{2NA}$ |
| Adopt | $\pi_{1AN}, \pi_{2AN}$ | $\pi_{1AA}, \pi_{2AA}$ |

Note: Payoffs are defined as $\pi_{1NN}$, $\pi_{2AA}$ where subscripts 1 and 2 refer to firms 1 and 2, respectively. $N$ and $A$ identify No-adoption and Adoption strategies, respectively (e.g., $\pi_{1NA}$ indicates the payoff when firm 1 does not adopt and firm 2 adopts; and $\pi_{1AN}$ indicates the payoff when firm 1 adopts and firm 2 does not).

The game captures the long-run inter-firm relationships that define alternative Nash Equilibrium (NE) of shuttle adoption.

The game allows several possible choices: both firms adopt, neither adopts, and only one firm adopts. The amount of grain shipped from a region is fixed and, therefore, would be a zero-sum game. Each player's dominant strategy would be that which $\max\{\pi_{jA}, \pi_{jN}\}$ conditional on competitors' choices and only some strategies are NE.

Values of the payoffs can be used to explain adoption decisions. We envision several alternative NE's building on the classic normal form games (Watson, p. 84). The decision could be either *Pareto Coordination* or *Chicken*. In the former, each player receives a positive payoff if they select identical strategies and if players prefer greater payoffs. In this case, coordination results in a Pareto improvement and the NE can occur with either Adopt/Adopt or No Adopt/No Adopt. In chicken, sometimes referred to as *Hawk-Dove*, the NE is for the players to choose different strategies. Under chicken, a firm would not adopt if the competitor adopts and the likely outcome would be for a reduced volume and reduced margins for the non-adopter.

The incentive to adopt increases when competitors adopt under coordination; while under chicken, adoption by the competitor reduces the chances for the competitor to adopt, that is, pre-empts the rival's adoption. The increase in handling capacity would be less under chicken than coordination since under the latter there is a spatial multiplier effect in adoption, that is, adoption by one creates incentives for competitors to also adopt. The equilibrium depends on the values of the payoffs which stem from the firm's technology that depends on plant characteristics, the spatial distribution of competition, risk, and agronomic characteristics of the region. In addition, given that these values are unknown (or known subject to errors), mixed equilibria are likely.

### *The* n-*Player Game*

The two-player game allows a normal-form representation of plausible underlying strategic behavior explaining technological adoption. With more than two players, the intuition of chicken and coordination remains. Under a strategic game where coordination prevails, the incentive to adopt increases if the kth neighbor adopts and, conversely, under chicken, the incentive to adopt decreases if the kth neighbor adopts.

Multiple players are introduced in the empirical analysis by constructing a composite index of firms' adoption decisions. The game compares the incentive to adopt to this index of competitors' adoption decisions (given that there are multiple form choices). In the $n$-player game, the difference of payoffs from adoption or not adoption for firm j conditional on adoption by neighboring firms is

$$[\pi_{jA} - \pi_{jN} \mid IA_j] = F(E_j, IA_j)$$

where $E_j$ is the characteristics of the firm and its production environment, and $IA_j$ is the index of adoption by competitors to firm $j$ (defined below).

If

$$\text{(1a)} \quad \partial(\pi_{jA} - \pi_{jN})/\partial IA_j > 0$$

then the incentive to adopt increases when competitors adopt, and diminishes if competitors do not adopt, which corresponds to the coordination strategic game. Alternatively, under chicken, the incentive of the firm to adopt decreases when competitors adopt the technology and vice versa. In this case,

$$\text{(1b)} \quad \partial(\pi_{jA} - \pi_{jN})/\partial IA_j < 0.$$

To model the index of adoption, we allow the effects of competitors' adoption rates to depend on the distance between firm $j$ and its competitors (as in Dubin). A flexible form for the composite index of adoption that accounts for distance is represented as

$$\text{(2)} \quad IA_j = \sum_{j \neq k} \text{Shuttle}_k \cdot \exp(-D_{jk}/\gamma_1)$$

where $\text{Shuttle}_k = 1$ if firm $k$ adopts and 0 otherwise, and the parameter $\gamma_1$ scales the degree of concavities in a transportation cost function with respect to the distance between rivals $j$ and $k$, $D_{jk}$. A special case occurs when $\gamma_1 \to \infty$ which implies that only the total number of rivals that adopt is relevant and not the distance among elevators. Distance is included in the specification through its interaction with rivals' adoption decisions, and it generates variability in the index across observations that allows identification of the adoption game.

From (1) and (2), the composite derivative of distance on the index of adoption and the effect of the index of adoption on payoffs is

$$\begin{aligned} \text{(3)} \quad & \partial(\pi_{jA} - \pi_{jN})/\partial D_{jk} \\ & \quad = (\pi_{jA} - \pi_{jN})/\partial IA_j \\ & \qquad \cdot \text{Shuttle}_k \cdot (-1/\gamma_1) \cdot \exp(-D_{jk}/\gamma_1) \end{aligned}$$

where an increase in the distance to technology adopters decreases the index of competitors' adoption (when $\gamma_1 > 0$) and, thus, lowers the incentive to adopt under (1a). As a result, the equilibrium of the adoption strategy game, for example, coordination or chicken, can be identified through the effect of distance among competitors.

Other factors, for example, characteristics of the firm, that explain payoffs from shuttle adoption can then be separated from the effect of inter-firm rivalry on adoption decisions. In particular, the partial effect of neighbors' adoption identifies the prevailing strategic game (chicken or coordination) in technological adoption by firm $j$. Identification of the underlying strategy (chicken or coordination) provides insight into the micro-economic conditions that result in excess overinvestment, which is typically chronic in the handling sector and other industries involving large fixed, relative to marginal costs (Johnson and Pasour). Under coordination, if both rivals adopt, excess capacity may evolve since competitors match neighbors' technology upgrades.

## Specification and Estimation: A Spatial Logistic Model of Technological Adoption

The econometric issues in modeling technological adoption include the qualitative effect of inter-firm competition and how location impacts rivalry in a discrete choice framework. We develop a spatial logistic model to evaluate factors that impact adoption decisions and, in particular, the reaction function to competitors' adoption decisions. The model is specified so that factors that explain payoffs from adoption are separated from the partial effect of neighbors' decision to adopt on the firm's own decision. Depending on this partial effect, the strategy (chicken or coordination) that prevails on the adoption decision is identified.

The payoff of a firm's decision to adopt depends on its own characteristics and those of its rivals, in addition to their geographic relationship with rivals, and agronomic characteristics. Ultimately, the firm's decision is based on these variables, but its expected payoff from adoption is not observed. However, we do observe the result of its decision to adopt or not, $A_j = 1$ or $A_j = 0$, which can be used to formulate a spatial logistic model.

A discrete model of shuttle adoption decisions for firm $j$ is defined in terms of a set of competitive and agronomic variables. Competitive variables include elevator capacity $C_j$; neighbors' characteristics $C_{2j}$, that is, capacity of competing elevators to $j$ weighted by distance; technological adoption by competitors $IA_j$; and competition density $N_j$, measured by the number of elevators within a 20-mile radius of plant $j$. Agronomic variables include production density in elevator j's county measured as total grain production divided by area in the county, $Y_j$; and adoption may also depend on production risk, the variability of production measured by the standard deviation of the elevator's county production density, $sd_j$. The Herfindahl index, $H_j$, was used as a measure of crop diversification. A value of 1 means only one crop is produced, and as more crops are grown, the value diminishes. Increased homogeneity increases the expected value of $Q_{is}$ because shuttle movements require shipments from a single origin to a single destination plant. These are generally more compatible for regions that produce fewer different grains in part because the density of production of each would then be greater and for destination elevators receiving a single grain in a given train.

In addition to the firm and competitor characteristics, other unobservable factors affect technology adoption and, therefore, the probability of adoption can be specified as

$$\text{Prob}(A_j = 1) = F(I_j)$$

where

$$I_j = \boldsymbol{\beta}\mathbf{X}_j = \alpha + \beta_1 C_j + \beta_2 C_{2j} + \beta_3 IA_j + \beta_4 H_j + \beta_5 Y_j + \beta_6 N_j + \beta_7 sd_j \tag{4}$$

for $\mathbf{X}_j = (1, C_j, C_{2j}, IA_j, H_j, Y_j, N_j, sd_j)$

and if $F(\bullet)$ is a logistic distribution, then

$$\text{Prob}(A_j = 1) = \frac{\exp(I_j)}{1 + \exp(I_j)}.$$

### *Spatial Lagged Dependent Variable in a Logistic Model*

Adoption by competitors in (4) is captured with a spatial dichotomous lagged dependent variable that models spatial correlation in the choice set. The spatial dichotomous lagged dependent variable is the decision of elevators to adopt or not adopt. The coefficient for the spatial lagged dependent variable (Shuttle$_k$) varies with distance between observations: $\beta_3 \exp(-D_{jk}/\gamma_1)$ where the parameter $\gamma_1$ in the spatial lag for adoption scales the degree of concavities in a transportation cost function with respect to distance. The coefficient is expected to be larger when two elevators are more closely located to each other, and the factor $\exp(-D_{jk}/\gamma_1)$ incorporates the existence of uneven frequencies in the spatial framework (see Dubin; McMillan). Similarly, the coefficient of the spatial lagged explanatory variable (capacity elevator $k$) varies with distance between observations: $\beta_2\exp(-D_{jk}/\gamma_2)$ where the parameter $\gamma_2$ in the spatial lags for competition scales for uneven frequencies in the data.

The spatial logistic model of shuttle adoption in (4) is specified as

$$(5)\qquad I_j = \beta \mathbf{X}_j = \alpha + \beta_1 C_j + \sum_{j \neq k} \beta_{2k} C_k + \sum_{j \neq k} \beta_{3k} \text{Shuttle}_k + \beta_4 H_j + \beta_5 Y_j + \beta_6 N_j + \beta_7 sd_j$$

where $\beta_{2j} = \beta_2[\exp(-D_{jk}/\gamma_2)]$ and $\beta_{3j} = \beta_3[\exp(-D_{jk}/\gamma_1)]$. From (3)–(5), the marginal effect of distance on the probability of adoption is

$$\begin{aligned} &\partial \text{Prob}(\text{Shuttle adoption}_j)/\partial D_{jk} \\ &= \Lambda_j[1 - \Lambda_j][\text{Shuttle}_k \times \exp(-D_{jk}/\gamma_1) \times (-\beta_3/\gamma_1)] \\ &\quad + \Lambda_j[1 - \Lambda_j][C_k \times \exp(-D_{jk}/\gamma_2) \times (-\beta_2/\gamma_2)] \end{aligned}$$

where $\Lambda_j = \frac{\exp(I_j)}{1 + \exp(I_j)}$; and the component of the marginal effect that interacts with the competitor decision to adopt a shuttle is

$$\begin{aligned} &[\partial \text{Prob}(\text{Shuttle adoption}_j)/IA_k][\partial IA_{jk}/\partial D_{jk}] \\ &= \Lambda_j[1 - \Lambda_j][\mathit{Shuttle}_k \times \exp(-D_{jk}/\gamma_1) \times (-\beta_3/\gamma_1)] \end{aligned}$$

where this marginal effect captures the change on the probability of adoption when the distance to the nearest competitor increases by one unit.

The sign and size of $\beta_3$ in (5) are determined by industry interdependency. Under atomistic competition, firms' choices are independent of competitors' choices and $\beta_3$ would be nonsignificant (nil). With spatial interdependence, payoffs from adoption depend on neighbors' choices. In this case, the sign of $\beta_3$ determines whether Pareto coordination or chicken explains adoption decisions, when factoring out other characteristics of the firm. If $\beta_3 > 0$, then an increase in the distance between elevators decreases the probability of adoption if the other has adopted. This would correspond to Pareto Coordination. The alternative solution where $\beta_3 < 0$ would be consistent with chicken. The coefficient $\gamma_1$ shows how this effect varies with distance.

### *Estimation Procedures*

Existing spatial econometric software do not allow for estimation of models with dichotomous dependent variables with spatial correlation in (5). Thus, for estimation, an algorithm was created from concentrating the likelihood function with respect to the spatial correlation coefficients ($\gamma_1$, $\gamma_2$). Concentration of the likelihood makes logit estimation with nonlinear spatial correlation tractable. In particular, the estimator of (4) with the index function in (5) can be obtained by solving the optimization:

$$(6)\qquad \max_{\gamma_1, \gamma_2} \ \ln L(\gamma_1, \gamma_2) \quad \text{s.t.} \quad \Sigma_i (A_i - \Lambda_i)\mathbf{X}_i(\gamma_1, \gamma_2) = \mathbf{0}$$

where

$$\ln L(\gamma_1, \gamma_2) = \Sigma_i A_i \ln\{\Lambda_i\} + \Sigma_i (1 - A_i) \ln\{1 - \Lambda_i\}$$

$$\Lambda_j = \frac{\exp(I_j)}{1 + \exp(I_j)}$$

and

$$\mathbf{X}_j(\gamma_1, \gamma_2) = \left(1, C_j, \sum_{j \neq k} \exp(-D_{jk}/\gamma_2) C_k, \sum_{j \neq k} \exp(-D_{jk}/\gamma_1) \mathit{Shuttle}_k, H_j, Y_j, N_j, sd_j\right).$$

The algorithm to maximize the concentrated likelihood solves the constrained optimization problem in (6) in terms of $\gamma_1$ and $\gamma_2$, and it is implemented in GAUSS through a simple grid search.

### *Data Sources*

Elevators and shuttle loading stations on the three largest grain hauling railroads (Burlington Northern-Santa Fe, Union Pacific, and Canadian Pacific Railway) were used in this study. Databases on elevator and shuttle locations were obtained directly from these carriers. These databases contain the information about elevators' names, locations, zip codes, mailing addresses, storage capacities, and track capacities. Other sources included the *Membership Directory* distributed by the Grain and Feed Associations of the nine states: North Dakota, South Dakota, Montana, Minnesota, Colorado, Kansas, Nebraska, Oklahoma, and Texas. More than 2,400 elevators comprised this population. Due to missing data for some elevators, some were deleted resulting in 2,309

**Table 1. Descriptive Statistics**

| Variable | Mean | Standard Deviation |
|---|---|---|
| Adoption ($A_j$) | 0.16 | 0.37 |
| Capacity ($C_j$) | 1.34 | 2.55 |
| Competition density ($N_j$) | 8.71 | 6.20 |
| Production density ($Y_j$) | 20.11 | 14.46 |
| Standard deviation ($sd_j$) | 3.26 | 1.95 |
| Herfindahl index($H_j$) | 0.46 | 0.50 |

Note: Capacity is measured in million tons.

useable observations which were used for estimation. Every elevator's location is defined as a zip code to conform to the spatial measurements.

Agricultural data were obtained from the U.S. Department of Agriculture (USDA), National Agricultural Statistics Service (NASS), which gives all geographic data for the years 1996–2000. All geographic data are used on the county basis to match other data. Agricultural data included crop production and the distribution of the primary crops of wheat, soybeans, corn, barley, sorghum, and sunflower seeds. Table 1 reports the mean and standard deviation of the variables used in the analysis. Production density is calculated as a five year average, and grain handler production risk is the standard deviation of the mean estimate for production density.

## Specification Tests and Results

The economic interpretation of the spatial lagged dependent variables in modeling technological adoption is important. This section evaluates the effect of this variable. The model is estimated with and without the index of adoption, and four different specifications are estimated for purposes of evaluating shuttle adoption decisions and model specification. These include: Model 1, the unrestricted nonlinear logit model in (5); Model 2, the restricted nonlinear logit model in (5) without the lagged dependent spatial variable (i.e., $\beta_3 = 0$); Model 3, the logit model without spatial elements of competition (i.e., $\beta_2 = \beta_3 = \beta_6 = 0$); and Model 4, the logit model estimated using only adoption and characteristics of the closest neighbor, for example, $IA_j = \beta_3[\exp(-D_{jk}/\gamma_1)]\text{Shuttle}_k$, where firm $k$ is the closest competitor to firm $j$.

Results and convergence of the algorithm in (6) were used to estimate the unrestricted nonlinear logit model in (5) and are shown in table 2. These results show that the likelihood function is maximized at $\gamma_1, \gamma_2) = (1.9, 1.4)$, and the likelihood function increases by 36% with a significance level of 0.9999 relative to the model with no spatial lagged dependent variable. These scale parameters capture the degree in which transfer costs affect inter-firm rivalry.

The parameter estimates and marginal effects for Models 1 through 4 are shown in tables 3 and 4, respectively. The value of the likelihood function increases substantially when going from a model excluding competition, that is, Model 3, and Model 2, the $n$-Player logistic model with no index of adoption, to Model 1, the $n$-Player logistic model with the index of adoption. The index of adoption is the most important variable in explaining technological adoption. This indicates that adoption is not only determined directly by the firms' own characteristics, but also to a great extent on the spatial distribution of competition and their decisions with respect to adoption.

**Table 2. Estimated Log-Likelihood Function for Values of the Distance Scale Parameter**

| $\gamma_1$ | $\gamma_2 = \mathbf{2}$ | $\gamma_1$ | $\gamma_2 = \mathbf{1.4}$ | $\gamma_1$ | $\gamma_2 = \mathbf{1}$ | $\gamma_1$ | $\gamma_2 = \mathbf{0.5}$ |
|---|---|---|---|---|---|---|---|
| 10 | −391.6 | 10 | −384.2 | 10 | −391.8 | 10 | −402.9 |
| 8 | −386.7 | 8 | −376.2 | 8 | −386.4 | 8 | −399.6 |
| 5 | −381.6 | 5 | −367.3 | 5 | −380.7 | 7 | −396.7 |
| 4 | −378.2 | 4 | −364.7 | 4 | −378.8 | 6 | −391.8 |
| 3 | −371.9 | 3 | −361.8 | 3 | −376.3 | 5 | −389.4 |
| 2.2 | −368.0 | 2 | −359.2 | 2 | −373.4 | 4 | −386.6 |
| **2.1** | **−367.3** | **1.9** | **−359.0** | 1.6 | −373.0 | 3 | −382.8 |
| 2 | −368.5 | 1.8 | −359.0 | 1.5 | **−373.2** | 2 | −377.3 |
| 1.9 | −369.2 | 1.7 | −359.0 | 1.4 | −373.6 | 1 | **−375.8** |
| 1.8 | −372.1 | 1.5 | −359.6 | 1 | −380.2 | 0.9 | −378.2 |
| 1 | −395.1 | 1 | −368.2 | 0.5 | −435.8 | 0.5 | −418.9 |

Note: The likelihood function was maximized at $(\gamma_1, \gamma_2) \neq (1.9, 1.4)$. The grid search was evaluated in increments of 0.1 for refining the search.

**Table 3. Estimated Logistic Models**

| Variable/ Coefficient | *n*-Player Logistic Model 1 | | *n*-Player Logistic Model with No Index of Adoption Model 2 | | No-Competition Model 3 | | Two-player Logistic Model 4 | |
|---|---|---|---|---|---|---|---|---|
| | Est | *t*-Value | Est | *t*-Value | Est | *t*-Value | Est | *t*-Value |
| $\alpha$ | −3.69 | −12.70 | −3.35 | −14.04 | −3.20 | −13.89 | −3.34 | −13.81 |
| $C_j/\beta_1$ | 0.34 | 6.65 | 0.27 | 6.77 | 0.18 | 7.65 | 0.20 | 6.67 |
| $C_{2j}/\beta_2$ | −0.19 | −5.92 | −0.06 | −2.86 | na | na | −0.05 | −2.25 |
| $IA_j/\beta_3$ | 3.22 | 15.65 | na | na | na | na | 1.86 | 9.76 |
| $H_j/\beta_4$ | 0.15 | 0.66 | 0.51 | 2.82 | 0.45 | 2.61 | 0.37 | 2.04 |
| $Y_j/\beta_5$ | 0.02 | 2.15 | 0.03 | 4.14 | 0.03 | 4.67 | 0.03 | 3.64 |
| $N_j/\beta_6$ | −0.10 | −4.12 | 0 | 0.16 | na | na | −0.03 | −1.99 |
| $sd_j/\beta_7$ | −0.03 | −0.45 | −0.11 | −2.86 | −0.13 | −2.11 | −0.10 | −1.68 |
| Value log-likelihood function | −359 | | −569 | | −575 | | −531 | |

Inclusion of the index of adoption in (5) affects the estimates and increases the statistical fit of the model. Information that contributes most in explaining adoption is the spatial lagged dependent variable, while exclusion of spatial components is manifested in larger estimates for the risk components ($sd_j$) and an underestimation of the effect of own capacity $C_j$ in adoption decisions. Without the spatial lagged dependent variable, the model underestimates the effects of neighbor characteristics and overstates the effect of risk on adoption decisions. Further, there are statistical gains from including *n*-players relative to assuming a two-player game [we thank an anonymous reviewer for this suggestion]. Respecifying competition to include the effect of all competitors (Model 1) as opposed to only the closest rival (Model 4) has a substantial increase in the model fitness. The effect of production density on adoption is robust to the number of players, but the effect of risk, capacity, and density of competition is sensitive to the inclusion of *n*-players. Production risk does not significantly impact adoption, while the density of competition is statistically significant. These effects differ from the two-player logistic model.

Model 1 is the best model for interpreting adoption decisions. Four groups of factors impact adoption including agronomic characteristics, own and rival firm characteristics, industry competition and spatial distribution of competition. Each is discussed using the marginal effects first and then we interpret the equilibria suggested from these results.

Each of the agronomic variables impacts the realizations of $Q_H$ and $Q_S$. These results confirm that there is a greater probability of adopting shuttles in more dense production regions. More dense production increases the potential impact on $Q_H$ and $Q_S$. Production risk and diversity, though intuitively appealing, are

**Table 4. Estimated Marginal Effects**

| Variable/ Coefficient | *n*-Player Logistic Model Model 1 | *n*-Player Logistic with No Index of Adoption Model 2 | No-Competition Model 3 | Two-Player Logistic Model 4 |
|---|---|---|---|---|
| $C_j/\beta_1$ | 0.0143 | 0.0176 | 0.0116 | 0.0122 |
| $C_{2j}/\beta_2$ | −0.0079 | −0.0042 | na | −0.0033 |
| $IA_j/\beta_3$ | 0.1315 | na | na | 0.1145 |
| $H_j/\beta_4$ | 0.0061 | 0.033 | 0.0296 | 0.0230 |
| $Y_j/\beta_5$ | 0.0008 | 0.002 | 0.0023 | 0.0017 |
| $N_j/\beta_6$ | −0.0042 | 0.0002 | na | −0.0021 |
| $sd_j/\beta_7$ | −0.0012 | −0.0074 | −0.0083 | −0.0061 |

Note: Estimates were derived using mean values of independent variables.

not statistically significant. Thus, even though some industry representatives suggest that diverse and/or risky production detracts from shuttle adoption, these results suggest that it is simply production density that induces adoption.

Both own firm and rival capacity have a significant impact on adoption decisions, and the signs are as expected. Larger firms have a greater likelihood of adopting than smaller ones, and larger rivals have a greater impact on pre-empting adoption. Values of marginal effects indicate the own firm capacity has a greater impact. Rivals' capacity has a negative impact meaning the larger a rival's capacity, the less likely an elevator will adopt. If the rival's capacity is small, an increase in capacity has a greater effect on an elevator's shuttle adoption decision than if the rival is a large competitor.

The intensity of competition is reflected in *N*. As *N* increases, the probability of adoption decreases. Therefore, intense competition (high *N* in a given region) and/or a large competitor reduces the likelihood of adoption and vice versa. The spatial composition of competitors, as defined in IA, impacts adoption decisions. An increase in the index, reflective of adoption by competitors increases the probability of adoption, but its impact diminishes with increased distance from rivals (see table 5).

The adoption game may have several equilibria. While we do not observe values of the payoff matrix, we do observe decisions resulting from that structural game. The equilibrium results suggest a Pareto Coordination solution prevails, since $\beta_3 > 0$, meaning that the firm's incentive to adopt increases if its rivals choose adopt. Indeed, the effect of inter-firm rivalry on the NE is that the probability of adoption increases if the competitor adopts. Taken together, the results provide a logical explanation as to why there is more intense adoption in some regions and why competitive conditions induce a greater rate of adoption than otherwise.

**Table 5. Marginal Effect of Distance to Rival Firm That Adopts on Adoption Probability**

| Distance (miles) | Marginal Effect |
|---|---|
| 1 | −0.04734 |
| 2 | −0.0243 |
| 3 | −0.01248 |
| 4 | −0.00641 |
| 5 | −0.00329 |
| 6 | −0.00169 |
| 7 | −0.00087 |
| 8 | −0.00045 |
| 9 | −0.00023 |
| 10 | −0.00012 |
| 15 | −0.000004 |
| 20 | 0 |

## Summary and Conclusions

A recent example of technology adoption occurring in the grain handling industry is that of shuttle trains and elevators. Since their inception, there has been widespread adoption of these shipping technologies throughout the United States and Canada. This article empirically modeled the strategic game of shuttle adoption by grain elevators aiming at expanding their geographical market share, while reducing grain handling costs.

A spatial econometric model was developed and estimated to describe the impact of competition on adoption of this technology, in addition to agronomic variables. Conditional analysis is used and results indicate that the single most important variable explaining adoption is whether a firm's rival adopts. The strategic behavior inferred in the empirical results suggests that adoption is principally driven by competitors' decisions. If a rival adopts, it induces adoption by other rivals, but this impact is highly dependent upon distance.

Other important variables include own and rival firm characteristics and agronomic variables. Large firms have a greater tendency to adopt than small and the size of the rival has a negative impact on adoption decisions. There is a greater tendency for adoption in regions with high production density and less dense competition. These variables impact the rate at which firms are capable of exploiting the efficiency gains associated with this shipping technology, and are reflected in their adoption decisions.

While the focus of this analysis was on firm level adoption decisions, a number of policy implications can be suggested and imply areas of future research. First, shuttle trains result in cost savings and the distribution of these among railroads, shippers, and farmers remains an important question. From these results however, it is clear the cost savings are adequate to provide some positive savings to each. Second, the spatial multiplier in technology change clearly suggests an accelerated evolution of a longer-term trend toward fewer origins, and ultimately destinations. Lastly, though this technology to date has been largely focused on grain origins and export elevators, future initiatives will no doubt be to introduce like technologies for domestic processing locations.

There are many agricultural industrial problems in which spatial econometrics can be used to better understand inter-firm rivalry and competition. While the use of spatial econometrics has escalated in recent years, its use and economic interpretation in different applications remain novel. Most of these use models with continuous dependent variables. There have been far fewer with discrete dependent variables and spatial autocorrelation. As illustrated in these results, adjusting for these impacts increases the statistical fit, affects parameter estimates, and provides an interpretation of strategic behavior. Future work can further explore the micro-foundations of inter-firm rivalry on investment and adoption decisions tested in this article in other industries.

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