Estimating Dynamic Games of Complete Information with an Application to the Generic Pharmaceutical Industry

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Research Objectives

- Develop a method to estimate a dynamic game of complete information with unobservable heterogeneity among agents.
- Is there a dynamic spillover effect of current experience (entry) on future performance (costs and entry)?
- Alternatively put, might a firm enter even if current opportunity was loss generating as long as entry improves future opportunities (PDV of sum of payoffs)?
- Apply method to a model of entry in the generic pharmaceutical industry:
  - Evaluate the effects of current entry on future costs and entry.
  - Evaluate the effects of costs on entry.
Related Literature (Not Exhaustive!)

Games of Complete Information:

- Bresnahan and Reiss (1991)
- Berry (1992)
- Scott Morton (1999)
- Ching (2004, 2008)
- Ciliberto and Tamer (2006)
- Bajari, Hong and Ryan (2007)

Games of Incomplete Information:

- Berry, Pakes, and Ostrovsky (2003)
- Bajari, Benkard and Levin (2007)
- Pesendorfer and Schmidt-Dengler (2007)
Institutional Background (based on Scott Morton (1999))

- Preparation of ANDA can take a long time and is costly.
- FDA does not reveal when and from whom it receives applications.
- 1989 "generic scandal."
Overview

- There are $i = 1, \ldots, I$, firms.
- Firms maximize PDV of profits over $t = 1, \ldots, \infty$.
- Each period $t$ a market opens and firms make entry decisions:
  - If enter $A_{i,t} = 1$, else $A_{i,t} = 0$.
- Number of firms in the market at time $t$, is $N_t = \sum_{i=1}^{I} A_{i,t}$.
- Profits for firm $i$ at time $t$ are $\Pi_{i,t} = R_t / N_t - C_{i,t}$.
- Revenue ($R_t$) at time $t$ is exogenously determined and shared equally.
Overview

▶ Cost are endogenous to past entry decisions (source of dynamics):
  ▶ \( c_{i,t} = \mu_c + \rho_c (c_{i,t-1} - \mu_c) - \kappa_c A_{i,t-1} \).

▶ Firms move simultaneously.

▶ Equilibrium selection: pick first equilibrium after ranking firms in ascending order of costs.
  ▶ In Scott Morton (1989):
    ▶ Identical marginal costs, observable heterogeneity in fixed costs.
    ▶ Complete and symmetric information, firms know each other’s costs and revenue.
    ▶ Simultaneous move static game.
Choice Specific Value Function

\[ V_i(A_{i,t}, A_{-i,t}, C_{i,t}, C_{-i,t}, R_t) = A_{i,t} \left( \frac{R_t^\gamma}{N_t} - C_{it} \right) + \beta \mathbb{E} \left[ V_i(A_{it+1}^E, A_{-it+1}^E, C_{it+1}, C_{-it+1}, R_{t+1}) \mid A_{it}, A_{-it}, C_{it}, C_{-it}, R_t \right] \]
Pure Strategy Markov Perfect Equilibrium

Equilibrium Condition:

\[ V_i(A_{i,t}, A_{-i,t}, C_{i,t}, C_{-i,t}, R_t) \geq V_i(A_{i,t}, A_{-i,t}, C_{i,t}, C_{-i,t}, R_t) \quad \forall \ i, t \]

where

\[
V_i(A_{it}^E, A_{-it}^E, C_{it}, C_{-it}, R_t) = A_{it}^E \left( \frac{R_t^\gamma}{N_t^E} - C_{it} \right) + \\
\beta \mathcal{E} \left[ V_i(A_{it+1}^E, A_{-it+1}^E, C_{it+1}, C_{-it+1}, R_{t+1}) \mid A_{it}^E, A_{-it}^E, C_{it}, C_{-it}, R_t \right],
\]

and number of firms in equilibrium:

\[ A_{i,t}^E, A_{-i,t}^E, \Rightarrow N_t^E \]
Ex Ante Value Function

Since a game of complete information:

\[ V_i(C_{i,t}, C_{-i,t}, R_t) = V_i(A_{i,t}^E, A_{-i,t}^E, C_{i,t}, C_{-i,t}, R_t). \]

\[ V_i(C_{i,t}, C_{-i,t}, R_t) = A_{i,t} \left( R_t^\gamma / N_t - C_{it} \right) + \]

\[ \beta \mathbb{E} \left[ V_i(C_{it+1}, C_{-it+1}, R_{t+1}) | A_{it}^E, A_{-it}^E, C_{it}, C_{-it}, R_t \right] \]
Model Solution

- Main computational burden is finding a fixed point for $V_i(C_{i,t}, C_{-i,t}, R_t)$.

- The value function for all players is:

  $$V(C_t, R_t) = \left( V_1(C_{1t}, C_{-1t}, R_t), \ldots, V_l(C_{lt}, C_{-lt}, R_t) \right)$$

- The value function is approximated by a local linear function (e.g., Keane & Wolpin 1997).

- The integral is computed by Gauss-Hermite quadrature.
Model Solution

- Approximate the value function $V$ at time $t + 1$ using a piecewise linear approximation.
  - Map $s$, the log of the state variable $S = (C_1, \ldots, C_i, R)$, to a coarse grid. Grid points determine both the centroid of the linear approximator and which linear approximator is to be used at $s$.
  - For a three player game, at each centroid $V = b + Bs$, where $V$ is $3 \times 1$, $b$ is $3 \times 1$, $B$ is $3 \times 4$, and $s$ is $4 \times 1$.

- Approximator is determined for each centroid by solving the game at a point cloud of state variables around the centroid, computing the coefficients $b$ and $B$ by regression, and iterating until $b$ and $B$ stabilize.
  - Typically 6 centroids and 20 iterations are required.
Revenues and Costs

Notation: let $x_t = \log X_t$.

Revenue:

$$r_t = \mu_r + \sigma_r \epsilon_{0,t}$$

Cost has two components: (i) $C_{u,i,t}$, known by all firms but not us, & (ii) $C_{k,i,t}$, known to everyone.

$$c_{i,t} = c_{u,i,t} + c_{k,i,t}$$

$$c_{u,i,t} = \mu_c + \rho_c (c_{u,i,t-1} - \mu_c) + \sigma_c \epsilon_{it}$$

$$c_{k,i,t} = \rho_c c_{k,i,t-1} - \kappa_c A_{i,t-1}$$
Sequential Importance Sampling: Set Up

- Observable states: \( y_t = (A_{1t}, \ldots, A_{lt}, c_{k,1,t}, \ldots, c_{k,l,t}, r_t) \).
- Unobservable states: \( x_t = (c_{u,1,t}, \ldots, c_{u,l,t}) \)
- Firm entry decision density:
  \[
  p(A_t| r_t, x_t, y_{t-1}, \theta) = \prod_{i=1}^{l_i} \left( p_a I(A_{it}=A^c_{it}) (1 - p_a) I(A_{it} \neq A^c_{it}) \right)
  \]
- Measure of goodness of fit: \( p_a \)
- Parameters: \( \theta = (\mu_c, \rho_c, \sigma_c, \kappa_c, \mu_r, \sigma_r, \beta, p_a) \)
- To compute likelihood draw each random element from (log) Normal distribution with mean zero and specified standard deviation.
Sequential Importance Sampling: Set Up II

- Transition density for unobservable states:

\[ p(x_t|x_{t-1}, \theta) = n \left( x_t \mid \mu_c + \rho_c (x_{t-1} - \mu_c), \sigma^2_c \right). \]  

(5)

- Initial density:

\[ p(x_0|\theta) = n \left( x_0 \mid \mu_c, \sigma^2_c / \sqrt{1 - \rho^2_c} \right). \]  

(6)

- Transition density for observable states:

\[ p(y_t|y_{t-1}, x_t, \theta) = p(A_t|r_t, y_{t-1}, x_t, \theta) p(r_t|y_{t-1}, x_t, \theta) \]  

(7)

\[ = p(A_t|r_t, y_{t-1}, x_t, \theta) n(r_t \mid \mu_r, \sigma^2_r) \]

- Likelihood for revenue over the pre-scandal period

\[ P(Y_{pre} \mid \theta) = \prod n(r_t \mid \mu_r, \sigma^2_r) \]
Priors (Dogmatic)

- $\beta = 0.96875$
  - Corresponds to 20% annualized, ave data freq is 1.5 mos.
  - Discount rate is poorly identified
  - 20% for the drug industry is well documented

- $\gamma_r = 0.9375$
  - $R - R^{\gamma_r}$ is the revenue conceded ex ante to marginal firms
  - $\gamma_r$ is poorly identified
  - A regression of entrants on revenue over the entire sample brackets $\gamma_r$ between 0.908 and 1.0

- $p_a = 0.9375$
  - Imposed for convenience
  - $p_a$ affects the particle survival rate
  - Nothing else is affected for $p_a > 0.7$
Priors (Uninformative)

- Unobservable cost dynamics
  - $-\infty < \mu_c < \infty$
  - $-1 \leq \rho_c \leq 1$
  - $0 < \sigma_c$

- Experience effect
  - $0 < \kappa_c$

- Revenue
  - $-\infty < \mu_r < \infty$
  - $0 < \sigma_r$
Sequential Importance Sampling: Implementation I

For $t = 0$

- Start $N$ particles by drawing $x_{0}^{(i)}$ for $i = 1, \ldots, N$ from the initial density (6).
- Compute

$$p(y_{0}|\theta) = \int p(y_{0}|y_{-1}, x_{0}, \theta) p(y_{-1}, x_{0}|\theta) \, dx_{0}$$

$$= \frac{1}{N} \sum_{i=1}^{N} p(y_{0}|y_{-1}, x_{0}^{(i)}, \theta).$$
For $t = 1, \ldots, n$

- For each particle draw $\tilde{x}_t^{(i)}$ from the transition density (5) and set

$$\tilde{x}_{0:t}^{(i)} = (x_{0:t-1}^{(i)}, \tilde{x}_t^{(i)}).$$

- For each particle compute the particle weights $\tilde{w}_t^{(i)}$ using the observation density (7); i.e.

$$\tilde{w}_t^{(i)} = p(y_t | y_{t-1}, \tilde{x}_t^{(i)}, \theta)$$

- This involves solving the game and is computationally very costly.
- We use a piecewise linear approximation to the value function in our computations.
Sequential Importance Sampling: Implementation III

▶ For $t = 1, \ldots, n$
  ▶ Normalize the weights so that they sum to one.
  ▶ For $i = 1, \ldots, N$ sample with replacement the particles $x_{0:t}^{(i)}$ from the set \{$\tilde{x}_{0:t}^{(i)}$\} according to the weights (particles with unequal weights are denoted by \{$\tilde{x}_{0:t}^{(i)}$\}; after resampling the weights are equal and the particles are denoted by \{$x_{0:t}^{(i)}$\}).
  ▶ Compute

$$p(y_t|y_{1:t-1}, \theta) = \int p(y_t|y_{t-1}, x_t, \theta) p(y_{t-1}, x_t|y_{1:t-1}, \theta) \, dx_t$$

$$= \frac{1}{N} \sum_{i=1}^{N} p(y_t|y_{t-1}, x_t^{(i)}, \theta)$$
Done. The likelihood is:

$$p(y_{1:t} | \theta) = p(y_0, \theta) \prod_{t=1}^{n} p(y_t | y_{1:t-1}, \theta).$$

Compute Posterior using MCMC (Metropolis-Hastings within Gibbs).
Data: Scott Morton (1999)

- All ANDA approvals between 1984 and 1994.
- Data on 1,233 ANDAs, and 363 markets (entry opportunities).
- Data on:
  - Submission date, approval date, applicant name.
  - Characteristics of drug: ingredient, concentration, route, form.
  - Characteristics of drug markets: drug therapeutic class, patent expiration date, brand name drug, revenue of brand name drug the year before expiration, revenue from hospitals.
  - Characteristics of firms: stock of all drugs approved before 1984 for firms, measures of entry cost, parent or subsidiary firm, whether firm indicted in scandal.
Data: Estimation Sample

- Focus on markets for orally ingested generics in the form of pills.
- Dominant firms Mylan, Novopharm, Lemmon, Geneva, and a “composite” firm, i.e., “Other.”
- Estimation sample period is 1990-94 (40 markets).
- Data from 1984 to 1989 used to prime the recursion:
  \[ c_{k,i,t} = \rho_c c_{k,i,t-1} - \kappa_c A_{i,t-1} \]
- Data used in estimation: total market revenues and entry decisions of firms.
### Table 1. Data

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Mean

| 0.45 | 0.28 | 0.25 | 0.25 | 3.3 | 126901 |

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<td>$\gamma$</td>
<td>0.9375</td>
<td>0.9375</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.96875</td>
<td>0.96875</td>
</tr>
<tr>
<td>$p_a$</td>
<td>0.9375</td>
<td>0.9375</td>
</tr>
<tr>
<td>CER firm 1</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td>CER firm 2</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>CER firm 3</td>
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<td>0.11</td>
</tr>
<tr>
<td>CER firm 4</td>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td>CER all firms</td>
<td>0.09</td>
<td>0.11</td>
</tr>
<tr>
<td>MCMC Reps</td>
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<td>1400000</td>
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</table>

Shown is the mode of the multivariate posterior distribution not the modes of the marginal posterior distributions. Standard deviations are shown in parentheses. CER is the classification error rate when the parameters are set to the posterior mode. The CER is the the proportion of the cases where $A_{it} \neq A_{i,t,j}^{c}$ computed both by firm and overall.
Figure 1. Marginal Posterior Distributions, Three Firm Model.
Figure 2. Marginal Posterior Distributions, Four Firm Model.
Results

Figure 3. Cost, Revenue, and Entry Decisions.

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Figure 4. Cost and Entry Decisions of the Dominant Firms.
Figure 5. Actual and Predicted Entry Decisions. Plotted as circles are the entry decisions of the three dominant firms in the three firm model. The crosses are the average predictions of the three firm model computed by averaging game solutions at Step 2e of the importance sampler at the maximum likelihood estimate.
Conclusion and Future Work

- Solve and estimate a dynamic model of complete information using sequential importance sampling.
- Stylized model fits data reasonably well ($p_a = 0.09, 0.11$).
- Costs affect entry decisions.
- Dynamic spillovers of experience, i.e., entry decisions affect future costs.
- Current methods work for a discrete choice set, e.g., entry/exit, technology adoption/upgrade, introduction/discontinuation of products, relocation of stores/firms/factories etc.
- Extend to allow for mixed discrete-continuous choices, e.g., introduction of new product/brand and advertising decision.
- Examine applicability to dynamic games of incomplete information.