Replication Notes for "The Costs of Environmental Regulation in a Concentrated Industry"

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1 Introduction

This report summarizes the theoretical model and the empirical strategy used in Stephen P. Ryan (2012), "The Costs of Environmental Regulation in a Concentrated Industry,". Then, the report proceeds to replicate Tables 6 - 9 that are found in the paper, which eventually estimate and compare various dynamic cost parameters in the U.S. Portland cement industry before and after the 1990 Clean Air Act Amendments.

2 Theoretical Model

The paper develops a dynamic model of oligopoly to examine how environmental regulation (through the 1990 Amendments to the Clean Air Act) affects the market structure, firm behavior, and welfare in the Portland cement industry. The key ingredients are as follows.

2.1 Market Structure

- **Regional markets**: The U.S. Portland cement industry is divided into spatially distinct local markets, due to very high transportation costs. Each market consists of a small number of firms producing a homogeneous good.
- **State Space**: Let $s_t = (s_{1t}, s_{2t}, \ldots, s_{Nt})$ be the vector of firms' capacities in period t. The total number of potential firms is N, including both active firms (with positive capacity) and potential entrants (with zero capacity).

2.2 Per-Period Payoffs

- **Demand:** Each market m faces a (log) demand function

$$\ln Q_m = \alpha_{0m} + \alpha_1 \ln P_m + \epsilon_m,$$

with an elasticity of demand α_1 and a market intercept α_{0m} (which can vary across markets). Here, Q_m is total demand in market m, P_m is the (endogenous) market price, and ϵ_m is a demand shock.

- **Production (quantity) game:** In each period, active firms engage in a capacity-constrained Cournot game. If firm i has capacity s_i, its cost function is

$$C_i(q_i) \;=\; \delta_0 + \delta_1 \, q_i \;+\; \delta_2 \, \mathbf{1}(q_i > \nu s_i) \left(q_i - \nu s_i\right)^2,$$

where $\nu \in (0,1)$ is a threshold capacity utilization rate. Once total production in a market is determined, we back out the market price from the demand curve.

- **Fixed costs and investment costs:** Let x_i denote firm i's capacity change (which can be positive, negative, or zero). The cost of adjusting capacity is given by

$$\Gamma(x_i;\, \gamma_i) \;=\; 1(x_i > 0) \left(\gamma_{1i} + \gamma_2 x_i + \gamma_3 x_i^2\right) \;+\; 1(x_i < 0) \left(\gamma_{4i} + \gamma_5 x_i + \gamma_6 x_i^2\right),$$

where γ_{1i}, γ_{4i} are random *fixed* costs of (positive/negative) capacity adjustment, and $\gamma_2, \gamma_3, \gamma_5, \gamma_6$ are parameters to be estimated.

- **Entry and exit costs:** Potential entrants pay a sunk cost κ_i upon entry, while exiting incumbents receive a scrap value ϕ_i, which may be positive or negative. Both κ_i and ϕ_i are random (with known families of distributions). A firm that remains active in period t earns operating profits from the Cournot game, minus any capacity-adjustment costs.

2.3 Industry Dynamics: Markov Perfect Equilibrium

Time is discrete, $t = 0, 1, 2, \ldots$, and firms discount future profits at rate $\beta \in (0, 1)$. Within each period:

1. Incumbents decide whether to exit (and receive ϕ_i).

2. Potential entrants and continuing incumbents receive private draws of their adjustment costs and decide how much to invest/disinvest (x_i). New entrants also pay κ_i.

3. Firms engage in a Cournot quantity competition in the product market.

4. The state s_{t+1} is realized (capacity changes come online at $t+1$).

A *Markov Perfect Nash Equilibrium* (MPNE) requires each firm's strategy to be a best response given the strategies of competitors and the current industry state (s_t).

3 Empirical Strategy

To estimate the model parameters and conduct counterfactuals, the paper implements a two-step approach following Bajari et al. [2007] (BBL).

3.1 Step One: Reduced-Form Estimation of Profits and Policies

1. **Demand Curve:**

$$\ln Q_{jt} \;=\; \alpha_0 \;+\; \alpha_1 \ln P_{jt} \;+\; \alpha_{2j} \;+\; \alpha_3' X_{jt} \;+\; \epsilon_{jt}.$$

   Instruments such as fuel prices (coal, gas, electricity) and labor wages help address endogeneity of price. This recovers the market demand curve.

2. **Production Costs:** Given the demand curve, the model solves a capacity-constrained Cournot game to match predicted outputs q_i to data. This identifies δ_1, δ_2, and ν.

3. **Policy Functions for Entry, Exit, and Investment:**

   - **(S,s)–type capacity investment rule:** The paper models firms' capacity adjustments as an *(S,s) investment rule.* For those that do adjust:

$$\ln s_{it}^* \;=\; \text{(spline terms in own capacity and rivals' capacity)},$$

     and the width of the "bands" $[\underline{s}_{it}, \overline{s}_{it}]$ is also estimated in a similar manner.

   - **Entry Probability:** (Probit)

$$\Pr(\chi_i = 1 \,|\, s_i = 0) \;=\; \Phi\Big(\psi_1 + \psi_2 \sum_{j \neq i} s_j + \psi_3 1(\text{post-1990})\Big).$$

   - **Exit Probability:** (Probit)

$$\Pr(\chi_i = 0 \,|\, s_i > 0) \;=\; \Phi\Big(\psi_4 + \psi_5 s_i + \psi_6 \sum_{j \neq i} s_j + \psi_7 1(\text{post-1990})\Big).$$

These reduced-form policy functions are flexible approximations of the true (optimal) strategies in the MPNE.

3.2 Step Two: Structural Recovery of Dynamic Parameters

The paper then imposes optimality (Markov perfect equilibrium) on these recovered policy functions to identify the *structural* parameters:

- Distribution parameters of the fixed adjustment costs, $(\mu_\gamma^+, \sigma_\gamma^+)$ and $(\mu_\gamma^-, \sigma_\gamma^-)$ for investment and divestment, respectively.
- Distribution parameters of scrap values ϕ_i.
- Distribution parameters of sunk entry costs κ_i.

Key Idea. A firm's *ex-ante* value of state s can be written (due to linearity in parameters) as

$$V_i(s;\theta) \;=\; W_i(s) \cdot [\,1,\; \theta\,]',$$

where $W_i(s)$ is obtained by simulating forward using the observed policy functions, and θ is a vector of unknown cost parameters (entry, exit, adjustment). In equilibrium, no firm can profitably deviate from its observed policy. A two-step or "BBL" estimator selects θ to minimize the profitability of hypothetical deviations, thus ensuring that observed policies are indeed optimal.

Fixed-Cost Distributions

In order to map the estimated policy functions (probabilities of choosing a certain investment/divestment) back to the underlying distribution of random cost draws, the paper relies on the fact that (for instance)

$$\Pr(\text{invest at } s) \;=\; \Pr\bigl(\gamma_{1i} \;+\; \gamma_2 x^* + \cdots \;\leq\; V_i(s) - V_i^0(s)\bigr),$$

where $V_i(s)$ is the future value from investing, and $V_i^0(s)$ is the future value of not investing. This leads to closed-form or numerical inversion (depending on parametric assumptions) of the distribution of $\gamma_{1i}, \ldots$ from the observed policy probabilities.

Sunk Entry Costs

Finally, once the investment cost distribution is known, the paper infers the sunk entry cost distribution from the observed entry probabilities. For example, if $\Pr(\text{entry} \mid s)$ is known from the data, and

$$EV^e(s) \;=\; \max_{x\geq 0}\Big\{-\gamma_1 x - \gamma_2 x^2 - \kappa + \beta\,\mathbb{E}[V_i]\Big\},$$

then one can invert

$$\Pr(\kappa + \gamma_1 \leq EV^e(s)) \;=\; \Phi\Big(EV^e(s);\, \mu_\kappa + \mu_\gamma,\, \sigma_\kappa^2 + \sigma_\gamma^2\Big)$$

to estimate $(\mu_\kappa, \sigma_\kappa)$, the mean and variance of the sunk entry costs.

4 Replication

This replication focused on obtaining the policy functions and finding the market parameters. In other words, the application starts from the *Policy Functions* part of the Step One of the Empirical Strategy. It deemed the previous Demand and Production Cost estimations as given. This is both due to interest of time and also because this is the part which constitutes the computational bulk of the paper. Since the main aggregate dataset was not available at the time, I have generated simulated data echoing the moments presented in the earlier tables of the paper and did the estimation based on that data. Hence, any discrepancy across my results and the original paper may potentially be due to this or a result of the computational shortcuts I take hereafter. The most notable of these shortcuts include lower number of alternative policies factored in during the estimation of Table 9, considering a smaller subsample of states during the estimation of Table 9, and not using the subsampling method for finding the standard errors of the estimates of Table 9. As doing otherwise greatly increases the runtime of the code that already takes a certain amount of time. One more difference is that I allowed for investment policies to change after the new regulation. Below I report the Tables generated in this exercise. Also, I included extra information for the preferred empirical specification of the paper, which is specification I.

5 Discussion

Tables 6-7 show the investment policy function estimations:

- Table 6 (Band equation) estimates how far capacity must deviate before firms adjusts.
- Table 7 (Target equation) estimates what capacity level firms adjust to when they do make changes.

Table 6.1: Pre-1990 Investment Policy Function Results(Adjustment Band Size)

	Specification			
	I	II	III	IV
Sum Competitors Capacity B-spline 1	-6.66 (31.20)	-5.35 (27.64)	-2.89 (28.07)	5.83 (12.81)
Sum Competitors Capacity B-spline 2	5.22 (6.52)	2.04 (5.99)	6.60 (6.44)	2.98 (3.80)
Sum Competitors Capacity B-spline 3	1.93 (2.42)	3.46 (2.53)	3.05 (2.70)	3.37 (3.58)
Sum Competitors Capacity B-spline 4	3.21 (1.90)	1.25 (1.85)	5.26 (1.63)	6.00 (1.42)
Sum Competitors Capacity B-spline 5	2.99 (1.38)	0.93 (1.39)	3.48 (1.62)	4.52 (1.15)
Sum Competitors Capacity B-spline 6	5.01 (1.10)	4.49 (1.09)	6.13 (0.81)	6.02 (0.46)
Own Capacity B-spline 1	4.84 (29.92)	3.89 (26.59)	-14.60 (24.60)	-20.42 (8.25)
Own Capacity B-spline 2	-0.51 (6.60)	2.09 (6.00)	3.13 (4.88)	3.40 (1.48)
Own Capacity B-spline 3	1.60 (2.52)	1.40 (2.25)	-1.58 (2.47)	-2.66 (0.96)
Own Capacity B-spline 4	1.87 (1.60)	1.12 (1.46)	0.34 (1.49)	0.87 (0.53)
Own Capacity B-spline 5	3.19 (1.37)	2.32 (1.27)	-0.18 (1.83)	-1.33 (0.66)
Population B-Spline 1		33.62 (32.98)		
Population B-Spline 2		-8.58 (8.21)		
Population B-Spline 3		6.50 (3.01)		
Population B-Spline 4		0.93 (1.52)		
Population B-Spline 5		3.30 (1.37)		
Capacity is Per-Capita	No	No	Yes	Yes
Region Fixed Effects	No	No	No	Yes
Adjusted R^2	0.7287			
Band σ^2	5.17			
Number of observations	73			

Table 6.2: Post-1990 Investment Policy Function Results(Adjustment Band Size)

	Specification			
	I	II	III	IV
Sum Competitors Capacity B-spline 1	32.41 (34.07)	24.40 (34.73)	5.93 (34.71)	17.08 (117.05)
Sum Competitors Capacity B-spline 2	-7.77 (9.38)	-6.44 (9.54)	1.26 (9.41)	12.82 (20.07)
Sum Competitors Capacity B-spline 3	4.58 (2.85)	3.07 (3.17)	3.13 (3.04)	5.88 (4.59)
Sum Competitors Capacity B-spline 4	4.82 (1.53)	4.79 (1.60)	4.83 (1.62)	7.12 (1.87)
Sum Competitors Capacity B-spline 5	1.62 (1.30)	0.08 (1.56)	1.95 (1.18)	4.64 (1.95)
Sum Competitors Capacity B-spline 6	5.98 (1.01)	5.70 (1.08)	8.34 (1.77)	8.02 (1.44)
Own Capacity B-spline 1	10.61 (20.12)	7.49 (20.54)	4.98 (25.49)	1.72 (19.42)
Own Capacity B-spline 2	-2.39 (4.72)	-1.11 (4.89)	-1.45 (5.42)	0.56 (3.59)
Own Capacity B-spline 3	4.31 (2.64)	3.36 (2.73)	1.74 (2.56)	1.21 (2.26)
Own Capacity B-spline 4	1.09 (1.30)	1.36 (1.37)	0.87 (1.77)	0.08 (1.73)
Own Capacity B-spline 5	2.92 (1.34)	2.52 (1.41)	1.90 (1.31)	1.24 (1.11)
Population B-Spline 1		29.28 (54.36)		
Population B-Spline 2		-7.61 (13.29)		
Population B-Spline 3		4.74 (3.11)		
Population B-Spline 4		-0.10 (1.10)		
Population B-Spline 5		2.02 (1.74)		
Capacity is Per-Capita	No	No	Yes	Yes
Region Fixed Effects	No	No	No	Yes
Adjusted R^2	0.7909			
Band σ^2	3.95			
Number of observations	69			

Table 7.1: Pre-1990 Investment Policy Function Results(Target Level)

	Specification			
	I	II	III	IV
Sum Competitors Capacity B-spline 1	-3.15 (46.11)	-0.77 (40.36)	0.32 (40.44)	5.14 (13.02)
Sum Competitors Capacity B-spline 2	5.61 (9.63)	0.47 (8.74)	7.38 (9.27)	9.04 (3.87)
Sum Competitors Capacity B-spline 3	4.01 (3.58)	6.99 (3.70)	5.29 (3.88)	6.67 (3.64)
Sum Competitors Capacity B-spline 4	4.81 (2.80)	1.61 (2.70)	7.22 (2.34)	9.06 (1.44)
Sum Competitors Capacity B-spline 5	4.78 (2.03)	1.68 (2.03)	4.54 (2.33)	6.51 (1.17)
Sum Competitors Capacity B-spline 6	7.78 (1.63)	7.00 (1.60)	9.39 (1.16)	8.84 (0.47)
Own Capacity B-spline 1	23.41 (44.22)	21.56 (38.83)	-5.15 (35.44)	-4.81 (8.39)
Own Capacity B-spline 2	-5.53 (9.76)	-1.38 (8.77)	-0.09 (7.03)	-0.33 (1.50)
Own Capacity B-spline 3	3.28 (3.73)	2.89 (3.29)	-0.33 (3.56)	-0.09 (0.97)
Own Capacity B-spline 4	2.33 (2.36)	1.28 (2.14)	-0.19 (2.15)	0.31 (0.54)
Own Capacity B-spline 5	4.36 (2.03)	3.03 (1.85)	1.45 (2.63)	0.81 (0.67)
Population B-Spline 1		63.98 (48.17)		
Population B-Spline 2		-16.71 (11.99)		
Population B-Spline 3		10.25 (4.40)		
Population B-Spline 4		1.44 (2.22)		
Population B-Spline 5		4.88 (2.00)		
Capacity is Per-Capita	No	No	Yes	Yes
Region Fixed Effects	No	No	No	Yes
Adjusted R^2	0.7332			
σ^2	11.30			
Number of observations	73			

Table 7.2: Pre-1990 Investment Policy Function Results(Target Level)

	Specification			
	I	II	III	IV
Sum Competitors Capacity B-spline 1	39.73 (51.31)	24.52 (51.75)	-0.93 (53.14)	-4.70 (167.91)
Sum Competitors Capacity B-spline 2	-8.22 (14.12)	-5.49 (14.21)	5.99 (14.41)	8.57 (28.79)
Sum Competitors Capacity B-spline 3	7.01 (4.29)	4.24 (4.72)	3.52 (4.66)	9.60 (6.58)
Sum Competitors Capacity B-spline 4	6.69 (2.30)	6.69 (2.38)	7.53 (2.47)	9.76 (2.68)
Sum Competitors Capacity B-spline 5	3.11 (1.96)	0.44 (2.32)	3.11 (1.80)	6.94 (2.80)
Sum Competitors Capacity B-spline 6	8.85 (1.52)	8.34 (1.61)	12.03 (2.71)	11.81 (2.06)
Own Capacity B-spline 1	5.84 (30.31)	0.15 (30.60)	11.99 (39.03)	9.59 (27.85)
Own Capacity B-spline 2	-3.36 (7.10)	-0.98 (7.28)	-4.78 (8.30)	-2.62 (5.15)
Own Capacity B-spline 3	5.55 (3.98)	3.86 (4.07)	2.95 (3.91)	2.39 (3.25)
Own Capacity B-spline 4	1.85 (1.96)	2.28 (2.04)	0.71 (2.71)	-1.11 (2.49)
Own Capacity B-spline 5	4.16 (2.02)	3.27 (2.10)	3.13 (2.00)	2.41 (1.59)
Population B-Spline 1		59.66 (81.00)		
Population B-Spline 2		-13.94 (19.81)		
Population B-Spline 3		7.05 (4.64)		
Population B-Spline 4		0.26 (1.64)		
Population B-Spline 5		3.21 (2.59)		
Capacity is Per-Capita	No	No	Yes	Yes
Region Fixed Effects	No	No	No	Yes
Adjusted R^2	0.7845			
σ^2	8.96			
Number of observations		69		

Table 8: Entry and Exit Policy Function Results

	Specification			
	I	II	III	IV
Exit Policy - Pre 1990				
Own Capacity	-0.0182 (0.1629)	0.0091 (0.1637)	0.0095 (0.0832)	
Competitors Capacity	-0.0082 (0.0529)	-0.0245 (0.0536)	-0.0126 (0.0296)	
Constant	-1.2435 (0.1928)	-1.4301 (0.2175)	-1.2469 (0.0655)	
Exit Policy - Post 1990				
Own Capacity	0.0019 (0.1559)	0.0176 (0.1563)	0.0087 (0.0949)	
Competitors Capacity	-0.0024 (0.0539)	-0.0171 (0.0547)	-0.0120 (0.0339)	
Constant	-1.2153 (0.1977)	-1.3670 (0.2192)	-1.1919 (0.0677)	
Entry Policy - Pre 1990				
Competitors Capacity	-0.0151 (0.0525)	-0.0151 (0.0525)	0.0078 (0.0111)	
Constant	-1.2381 (0.1588)	-1.2381 (0.1588)	-1.3109 (0.0648)	
Entry Policy - Post 1990				
Competitors Capacity	0.0007 (0.0537)	0.0007 (0.0537)	0.0095 (0.0137)	
Constant	-1.2226 (0.1632)	-1.2226 (0.1632)	-1.2512 (0.0672)	
Pre 1990				
Log Likelihood (Exit)	-393.33			
Log Likelihood (Entry)	-393.31			
Prob > χ^2 (Entry)	0.0000			
Post 1990				
Log Likelihood (Exit)	-379.88			
Log Likelihood (Entry)	-379.88			
Prob > χ^2 (Entry)	0.0000			

Table 9: Dynamic Parameters

Parameter	Before 1990 Estimate	After 1990 Estimate	Difference Estimate
Investment Cost	320	263	-58
Investment Cost Squared	0	0	0
Divestment Cost	-64	-283	-218
Divestment Cost Squared	3151	5923	2771
Investment Fixed Costs Mean	722	1120	398
Investment Fixed Costs Std Dev	136	222	86
Divestment Fixed Costs Mean	304576	249164	-55413
Divestment Fixed Costs Std Dev	157466	178828	21362
Scrap Values Mean	-65521	-53503	12018
Scrap Values Std Dev	97073	79800	-17272
Entry Costs Mean	183152	321200	138047
Entry Costs Std Dev	79307	80144	837

These tables captue an (S,s)-type investment rule, where the firms only adjust capacity when it deviates significantly from their target level. Table 8 shows the entry and exit policy function estimates. Table 9 compares the structural parameters before and after the 1990 Clean Air Act Amendments. These parameters are the main focus of the empirical strategy. Looking at the replicated results compared to Ryan (2012), the following patterns are successfully captured are

1. The entry cost mean increased substantially after 1990 (from 183K to 321K in the replication, similar to Ryan's increase from 183K to 223K).
2. Investment fixed costs mean increased post-1990 in both cases.
3. Similar magnitudes for scrap values and divestment costs.

Key points where the replication differs is:

1. The replicated investment costs are slightly higher pre-1990 (320 vs 230)
2. The replicated divestment cost squared shows a much higher increase post-1990.
3. The replicated entry cost increase is more dramatic (138K difference vs 41K in Ryan).

Overall, despite being off for investment adjustment cost and divestment adjustment cost, it seems that this replication ended up successfully replicating the primary finding of this paper: that is the fixed entry costs are much higher after the new act, leading to a further intensified concentration in the market. This increased concentration further helps explain subsequent changes in industry market structure, reduced entry, higher prices, and ultimately non-trivial welfare effects on both consumers and incumbents. The failure of this replication in capturing the adjustment policies are likely to have stemmed from the simulated capacity adjustment data not reflecting the original data that well.

References

Bajari, P., C. L. Benkard, and J. Levin (2007). "Estimating Dynamic Models of Imperfect Competition." *Econometrica* 75(5): 1331–1370.

Ryan, S. P. (2012). "The Costs of Environmental Regulation in a Concentrated Industry." *Econometrica*, 80(3): 1019–1061.