Testing Profit Maximization in the U.S. Cement Industry*

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Abstract

Motivated by a commonly held intuition that the cement industry is not competitive, we perform a revealed preference test to examine whether the United States cement industry could have been profit maximizing from 1993-1998. Rather than looking at technical efficiency, we create and examine a measure of necessary competitive price taking profit loss of the cement industry using information on aggregate output and aggregate inputs. One contribution of this paper is to compile a comprehensive dataset of United States cement producers, cement production, cement inputs data, and input/output prices. In particular, we combine data found in the U.S. Mines Geological Yearbooks, the Portland Cement Association, the American Energy Review, and the St. Louis Federal Reserve. Assuming technology is static, non-negative profits for firms, and a priori knowledge of inputs/outputs, we find the U.S. cement industry had a necessary competitive price taking profit

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loss of 755.1 million 1996 dollars.

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1 Introduction

The purpose of this paper is to formally confirm the commonly held intuition that the cement industry is not competitive. We develop a novel revealed preference methodology to do so. For example, Ryan (2012) and Miller et al. (2017) claim that the cement industry is concentrated.

While revealed preference tests of profit maximization have existed since Afriat (1972), there have been few applications in practice. The reason for this is that acquiring information on firm level inputs/outputs and prices is often difficult.[1] In contrast, aggregate inputs and input prices for an industry within a year are often easier to access from government agencies.[2] Using aggregate data, these applications often check whether the weak axiom of profit maximization is satisfied and compute measures of technological efficiency. However, these applications often do not account for which firms are present in the industry. Moreover, when firm level data are not observed, estimates of technological efficiency are difficult to interpret since individual firms may have different production technologies. This paper applies recent nonparametric methods of Chambers and Rehbeck (2021) to examine whether the U.S. cement industry could be profit maximizing from 1993-1998 using data from Ryan (2012) as well as newly gathered data on prices and quantities of physical inputs to cement such as limestone, marl, labor hours, and energy.

As mentioned previously, measures of technological efficiency are difficult to interpret when firm production is unobserved. Thus, we develop a notion of *necessary competitive price taking profit loss* to quantify the size of violations of profit maximization within the market. This measure can roughly be described as the amount of profit that was necessarily lost by firms without making any assumptions on individual firm technologies. We consider two measures: One for the market as a whole and one for firms. The measure for the market as a whole computes the minimum additional profit that could

[1]There are some exceptions. For example, Chavas and Aliber (1993) is able to collect detailed input/output data of farmers in Wisconsin.

[2]For example, Hailu and Veeman (2001) is able to collect detailed information of aggregate inputs/outputs and prices for the Canadian paper and pulp industry.

have been earned by using alternative revealed feasible production processes. The measure for firms gives the smallest weighted profit each firm could have earned by using alternative revealed production processes. In both cases, the necessary competitive price taking profit loss is essentially the money that firms leave on the table by choosing production plans that do not profit maximize. These measures may also be easier to describe to those outside of the industry being tested since the measures are in dollars rather than percentage of lost production.

We examine profit maximization of the United States cement industry using aggregate data on the United States cement producers, cement production, cement inputs data, and input/output prices. We gather data from the U.S. Mines Geological Yearbooks, the Portland Cement Association, the American Energy Review, and the St. Louis Federal Reserve from 1993-1998 for our main test. In particular, this dataset enriches aggregate data relative to work of Ryan (2012) which uses a dynamic parametric model to analyze the effect of environmental policies on the cement industry. Details on data collection methods are collected in Appendix B.

Assuming static production technologies, non-negative profits, and known inputs/outputs, we find that the U.S. cement industry is not profit maximizing. For this case, we find from 1993-1998 that the market necessary competitive price taking profit loss is $755.1 million.[3] Surprisingly, we find that if we allow firm production sets to weakly increase over time and do not require non-negative profits, then the data *can* be rationalized by profit maximization. However, for the years 1993-1998 we observe little technological change of cement kilns and we expect firms would shut down if they did not make positive profit so these assumptions do not match the data. We discuss this further in Section 4.2.

The classical work on this notion is due to Afriat (1972) and Hanoch and Rothschild (1972), with an exposition by Varian (1984). Other works include Diewert and Parkan (1983) and The primitive in these works consists of a collection of production decisions *for a single firm*, together with prices: these are

[3]Within the paper, we use 1996 dollars for comparison to the work of Ryan (2012).

the observations. Afriat (1972) characterizes profit-maximizing firm behavior via an axiom called the *weak axiom of profit maximization*, which states that for any given observed price/production pair, the firm would garner weakly less profits by switching production to any other observed production level. Our contribution is to study aggregated market-level production data, where the novelty is that we know which firms are present in a given observation. Were these firms to stay the same across observations, the fact that profit-maximization behavior aggregates across firms would mean the weak axiom of profit maximization would again be necessary and sufficient as a test of profit maximization. The change in firms from observation to observation provides a novel source of variation for our problem.

The remainder of the paper proceeds as follows. Section 2 defines the model of market profit maximization and describes the test. Section 3 defines a measure of necessary competitive price taking profit loss that measures in dollars how large errors of profit maximization would be for *any* production set. Section 4 outlines the illustrative empirical analysis on the cement industry and provides the results. Section 5 contains our final remarks. All proofs are in Appendix A.

2 Model

We consider a model of profit maximization with market level data. There is a finite set of commodities, denoted by $k \in \{1, \ldots, K\}$. There is also a finite set of *potential firms*, indexed by F. A *market supply observation* is a triple consisting of $\langle P, \pi, y \rangle$, where $P \subseteq F$ and $P \neq \varnothing$ comprises the participants in the market, $\pi \in \Re^K_+$ lists the *market prices*, and $y \in \Re^K$ gives the *net outputs* in the market. We will sometimes refer to y as the *market supply.* A *market supply dataset* is a finite collection of market supply observations, $\{\langle P^j, \pi^j, y^j \rangle\}_{j=1}^J$. Often, we occasionally interpret the indices of J temporally, so that $l < j$ means that observation l was taken prior to observation j.

In this paper, we examine whether a market supply dataset could have been generated by price taking profit maximizing firms. For a market supply dataset and a firm $f \in F$, we define the set of observations in which firm f is a participant as $\mathcal{O}^f = \{j : f \in P^j\}$. This object is important since a firm will only have a chance to violate profit maximization when it participates in the market.

Definition 1. *We say a market supply data set is* profit rationalizable *if for every $f \in F$, there is a production set $Y_f \subseteq \Re^k$ such that firm f is profit maximizing for each $j \in \mathcal{O}^f$, so there is $y_f^j \in Y_f$ where*

$$\pi^j \cdot y_f^j \in \arg\max_{y \in Y_f} \pi^j \cdot y$$

and the sum of net outputs across all firms equals the market supply so for all $j \in \{1, \ldots, J\}$

$$\sum_{f \in P^j} y_f^j = y^j.$$

The production set is fully nonparametric and encodes what the firm can produce with a given set of net outputs. We can think of this as being generated by various production processes at the firm.[4] The condition for the benchmark model of profit rationalizability requires that there is no way to shift industry production within firms across observations in a way that increases profits. In particular, the statement of the result gives a condition on transition matrices over the periods each firm participates. A *transition matrix* is a nonnegative matrix whose rows sum to 1; for example, $\Lambda \in \Re_+^{n \times n}$ is a transition matrix if for all i, $\sum_l \Lambda_{i,l} = 1$. The result on transition matrices follows by renormalizing Lagrange multipliers from a linear programming duality as shown in Chambers and Rehbeck (2021). Below is the formal statement of the main result. We present below the test for aggregate profit maximization from Chambers and Rehbeck (2021) absent any structural hypothesis on the production sets.

Theorem 1. *For any market supply dataset $\{(P^j, \pi^j, y^j)\}_{j=1}^J$, the following are equivalent:*

[4] We note that Definition 1 does not assume that firms leave the market when they make zero profit.

1. *The market supply dataset is profit rationalizable.*

2. *For every $j \in J$ and firm $f \in P^j$, there exist net outputs for the fth firm given by $y_f^j \in \Re^K$ such that*

   (a) *For all $j \in J$, $\sum_{f \in P^j} y_f^j = y^j$*

   (b) *For all $f \in F$ and all $j, l \in \mathcal{O}^f$, $\pi^j \cdot y_f^l \leq \pi^j \cdot y_f^j$.*

3. *For every set $\{\mu^j\}_{j=1}^J$ with $\mu^j \in \Re^K$ and every set of transition matrices $\{\Lambda(f)\}_{f \in F}$ with $\Lambda(f) \in \Re_+^{\mathcal{O}^f \times \mathcal{O}^f}$, if for every $j \in J$ and every $f \in P^j$,*

$$\sum_{l \in \mathcal{O}^f} \Lambda(f)_{l,j} \pi^l = \pi^j + \mu^j, \tag{1}$$

   then

$$\sum_{j=1}^{J} \mu^j \cdot y^j \leq 0.$$

The important thing to note is that the second condition gives a linear program to check the profit maximizing conditions. The third condition is based on a duality result which will help us later interpret the measure of necessary competitive price taking profit loss. Next, we describe how to alter this test when there are additional assumptions on the production sets.

2.1 Structure on Production Sets

There are several restrictions on production sets that are of interest to test. We present these cases below. For the vector $x \in \Re^K$ and a set $S \subseteq \{1, \ldots, K\}$, we use the notation $x|_S$ to be all entries of x for dimensions in the set S. We focus on when inputs and output constraints are ex-ante known and when production sets are increasing. An increasing production set means that the technology of producing cement is weakly increasing with respect to time.

- *Input/Output constraints:* We ask that for all $f \in F$ that $k \in IN \subseteq \{1, \ldots, K\}$ are inputs so $(y_f^k)|_{IN} \leq 0$ and $k \in OUT \subseteq \{1, \ldots, K\}$ are outputs so $(y_f^k)|_{OUT} \geq 0$.

- *Nonnegative profits:* We ask that for all $f \in F$, all $j \in \mathcal{O}^f$, that $\pi^j \cdot y_f^j \geq 0$.

- *Increasing Production Sets:* We ask that for all f and $l < j$ that production sets satisfy $Y_f^l \subseteq Y_f^j$.

We discuss how these conditions can be imposed by altering the linear program in Theorem 1. First, the input/output constraints simply need to be added to the linear program in Theorem 1. Similarly, the non-negative profits constraint can be added to the linear program. The increasing production sets require altering the constraint in Theorem 1.2.b to: For all $f \in F$ and all $j, l \in \mathcal{O}^f$ with $l < j$, $\pi^j \cdot y_f^l \leq \pi^j \cdot y_f^j$. All of these are linear and are easy to implement.

3 Necessary competitive price taking profit loss

Before performing the empirical analysis, we develop the notion of an approximate profit maximizing firm and show how to use this to find measures of *necessary competitive price taking profit loss* for the market and firms. We define *necessary competitive price taking profit loss* to be the smallest amount of profit lost from imperfect optimization for price taking profit maximizing firms. This gives a measure of how far the market is from profit maximization in a similar spirit to efficiency indexes developed by Debreu et al. (1974), Farrell (1957), Afriat (1967), Charnes et al. (1978), Varian (1990), and Färe and Grosskopf (1995).

Our focus on the minimal amount of necessary competitive price taking profit loss is primarily for convenience, since it can be checked by linear programming and is easy to interpret. For example, any welfare measure that incorporates firm profits and assumes profit maximization will necessarily have errors that are at least as large as the necessary competitive price taking profit loss in the market.

Before defining an *approximate profit maximizer*, recall that a firm $f \in F$ with production set Y_f is profit maximizing at observation $j \in \mathcal{O}^f$ when there is a $y_f^j \in Y_f$ such that

$$\pi^j \cdot y \leq \pi^j \cdot y_f^j$$

for all $y \in Y_f$. An *approximate profit maximizer* is similar to a profit maximizer, except we allow the firm to make profit maximization errors. Formally, the firm $f \in F$ with production set Y_f at observation $j \in \mathcal{O}^f$ is approximately profit maximizing at level $\varepsilon_f^j \in \Re_+$ when

$$\pi^j \cdot y \leq \pi^j \cdot y_f^j + \varepsilon_f^j$$

for all $y \in Y^f$. In other words, the firm potentially loses ε_f^j dollars by not maximizing. This notion is related to other concepts studying approximate maximizers in revealed preference theory (Dziewulski, 2018; Allen and Rehbeck, 2019), but we consider these ideas in the case of profit maximization. The approximation error is both observation and firm specific.

We now use the approximation errors when firms profit maximize to define a notion of *neccessary profit loss* (NPL). We consider NPL measures that depend on the whole market and those that depend on individual firms. The *market level necessary competitive price taking profit loss* (m-NPL) will be the total amount of profit that is necessarily lost by all firms. The *firm level necessary competitive price taking profit loss* (f-NPL) is defined to be the smallest worst case (across firms) profit loss of a firm in the market. These measures address how far the market and firms are respectively from the conditions of profit maximization. We now give formal definitions of the m-NPL and f-NPL.

Definition 2. *The market necessary competitive price taking profit loss (m-NPL) of a market supply dataset* $\{\langle P^j, \pi^j, y^j \rangle\}_{j=1}^J$ *is defined as*

$$\min_{y_f^j \in \Re^K, \varepsilon_f^j \in \Re_+} \sum_{f \in F} \sum_{j \in \mathcal{O}^f} \varepsilon_f^j$$
$$s.t.\ \pi^j \cdot y_f^l \leq \pi^j \cdot y_f^j + \varepsilon_f^j \quad \forall f \in F \ and \ \forall j, l \in \mathcal{O}^f$$
$$\sum_{f \in P^j} y_f^j = y^j \quad \forall j \in J$$

Definition 3. *The firm necessary competitive price taking profit loss (f-NPL) of a market supply dataset* $\{\langle P^j, \pi^j, y^j \rangle\}_{j=1}^J$ *is defined as*

$$\min_{y_f^j \in \Re^K, \varepsilon_f^j \in \Re_+} \max_{f \in F} \left\{ \sum_{j \in \mathcal{O}^f} \varepsilon_f^j \right\}$$

$$s.t.\ \pi^j \cdot y_f^l \leq \pi^j \cdot y_f^j + \varepsilon_f^j \quad \forall f \in F \ and\, \forall j, l \in \mathcal{O}^f$$

$$\sum_{f \in P^j} y_f^j = y^j \quad \forall j \in J$$

The m-NPL and f-NPL are both zero when firms are profit maximizing and non-zero otherwise. One interpretation of these numbers is that the m-NPL gives a lower bound on errors for profit maximizing errors with market data. Importantly, these errors could affect welfare measures that include firm profits. Similarly the f-NPL provides a bound on errors in profit maximization for all firms. One can impose nonnegative profit maximization, increasing production sets, and firm constraints when checking for either NPL by varying the constraints as discussed in Section 2.1.

Before proceeding, we give dual formulations of both the m-NPL and the f-NPL. In particular, the dual formulation of the m-NPL affords a meaningful use of the variables in Theorem 1.

Theorem 2. *The m-NPL is given by:*

$$\max_{\mu^j \in \Re^K} \sum_{j=1}^J \mu^j \cdot y^j$$

subject to

$$\sum_{l \in \mathcal{O}^f} \Lambda(f)_{l,j} \pi^l = \pi^j + \mu^j, \quad \forall j \in J \ and\ \ \forall f \in P^j$$

where each $\Lambda(f) \in \Re^{\mathcal{O}^f \times \mathcal{O}^f}$ *is a transition matrix.*

In terms of interpretation, the m-NPL is the largest profit a firm could make by re-optimizing production using production processes that are observed to be feasible. Mathematically, the variables $\Lambda(f)$ and μ^j are dual variables (Lagrange multipliers) where the $\Lambda(f)$ can be made transition matrices through a renormalization. At optimal solutions to the original m-NPL problem (say y^*, ε^*), or to the dual problem (say $\Lambda^*(f)$, μ^*), the standard complementary slackness conditions hold, so that for $f \in F$ and $j, l \in \mathcal{O}^f$ with $j \neq l$, $\Lambda(f)_{j,l} > 0$ only in the case the constraint binds; that is when the optimal y^* and ε^* has

$$\pi^j \cdot y_f^{j*} + \varepsilon_f^{j*} = \pi^j \cdot y_f^{l*}.$$

Further, $\Lambda(f)_{j,l}$ specifies the rate at which the m-NPL would decrease were we to allow a small violation of this particular profit maximization constraint. Thus, if $\Lambda(f)_{j,l} > 0$ and it were possible to increase production of outputs holding other inputs fixed, then the m-NPL would decrease. Likewise, the variable μ_k^j specifies the rate at which the m-NPL would decrease were we to decrease y_k^j. In particular, if $\mu_k^j < 0$, this means that decreasing y_k^j would actually *increase* the m-NPL, so that increasing y_k^j would decrease the m-NPL. Intuitively, this suggests the firm could decrease their use of good k as an input for period j to move closer to profit maximizing behavior.

The next theorem gives the dual characterization of the f-NPL. Here, the notation $\beta \in \Delta(F)$ is a member of $\Re_+^F$ whose coordinates sum to one (so, a probability on F). In particular, this gives the lowest weighted average of profit that could have been earned by re-optimizing to feasible production processes.

Theorem 3. *The f-NPL is given by*

$$\max_{\mu^j \in \Re^K} \sum_{j=1}^{J} \mu^j \cdot y^j$$

subject to

$$\beta_f \sum_{l \in \mathcal{O}^f} \Lambda(f)_{l,j} \pi^l = \beta_f \pi^j + \mu^j, \quad \forall j \in J \textit{ and } \forall f \in P^j$$

where each $\Lambda(f) \in \Re^{\mathcal{O}^f \times \mathcal{O}^f}$ *is a transition matrix and* $\beta \in \Delta(F)$.

4 Empirical Analysis

We use the tests developed in Section 2 and the necessary competitive price taking profit loss measures in Section 3 to examine whether the cement industry in the United States between 1993 to 1998 is profit maximizing.[5] The cement industry is well known to be a concentrated industry and prices can vary depending on the region. For these reasons, one would not expect market level data to satisfy profit maximization.[6] Thus, this application informs whether the nonparametric test of market profit maximization outlined here can discriminate failures of profit maximization in practice.

Empirically, we find that the US cement industry from 1993-1998 is not profit maximizing for any production set when assuming firms earn non-negative profits. This shows the conditions are strong enough to refute profit maximization within an industry where violations are thought to occur. The rest of this section overviews the United States cement industry and provides details on the size of violations from profit maximization using the necessary competitive price taking profit loss measures introduced in Section 3.

4.1 United States Cement Industry Overview

At a high level, the cement manufacturing process uses inputs of raw materials, energy, and labor to product cement as an output. We include information from all of these inputs in the main analysis. We treat cement as a homogeneous good as it has strict standards of production.[7] As a percentage of total mass, the main raw material of cement is limestone (approximately 84%) while other materials make up the rest of the physical inputs.[8]

[5]Additionally we have data from 1980-1998. For data quality reasons, we focus on the time period from 1993-1998. Results for the full set of data are in Appendix C.

[6]For example, the largest four firms accounted for 32.5% of production in 1997 (Ryan, 2012). That prices vary by state can be seen looking at the cement entry of the United States Geological Survey Minerals Yearbook.

[7]For the study, we examine sales of all cement which includes both Portland and masonry cement. Both Portland and masonry cement have strict standards of production by ASTM International (International, 2018a,b).

[8]The percentage of total mass of limestone in the production of cement is derived from Table 3 in Van Oss and Padovani (2002). The interested reader can find additional details

In addition to the cement industry being a good candidate to refute profit maximization, it is also of economic importance. The cement industry accounted for 1.3% of all U.S. anthropogenic carbon dioxide emissions in 2000 (Van Oss and Padovani, 2003). This fact has lead to the cement industry receiving attention when studying environmental policy (See Ryan (2012) and Fowlie et al. (2016)). This literature studies responses of cement production to changes in environmental policy using regional data since the market is concentrated and there is variation in prices across regions. To gain traction on these problems, the economic models often impose functional form restrictions on the production set for each firm.[9] This paper complements the existing literature by showing that even without specifying structure on the production set of each firm, industry wide cement production is not profit maximizing.

We now discuss the data used to conduct the empirical analysis. We include information on cement output, raw material inputs, energy inputs, and labor inputs. The complete list of goods we include in the analysis is summarized in Table 1. We examine the cement industry using yearly aggregate data for the cement industry. The data on the amounts of inputs and outputs are readily available from the U.S. Mines Geological Yearbook and the Portland Cement Association. The U.S. Mines Geological Yearbook also contains information on the prices of cement and raw materials. The average yearly price of energy inputs was collected from the American Energy Review. We use average yearly manufacturing wages from the St. Louis Federal Reserve as the price of labor inputs. Lastly, we gathered information on the firms that participate in the cement industry from the Portland Cement Association. Additional details on data collection are in Appendix B.

on the cement industry in Van Oss and Padovani (2002).

[9]The restrictions of Ryan (2012) and Fowlie et al. (2016) are on the cost function which effectively limits the production set of each firm.

Final Product	Raw Materials	Energy	Labor
Cement	Limestone	Coal	Hours Worked
	Marl	Oil	
	Clay/Shale	Natural Gas	
	Sand	Electricity	
	Iron Ore		
	Gypsum		

Table 1: Goods Included in Model

One important feature of market level data is that firms may enter/exit the industry while their production is unobserved. We provide some descriptive details on firm entry between 1993-1998. For this time period, there are 118 different firms that participated in the cement industry. We display in Table 2 the number of firms that participate in the cement industry each year and how many entered/exited the industry relative to the previous year. There is a large number of firms (118) relative to the number of time periods (6).

There is some entry/exit in the industry during this time period, but not much. Of the three firms who entered, two of them only operated grinding facilities. Similarly, two of the three firms who exited only operated grinding facilities. Since kilns are responsible for creating clinker which is the precursor to cement, these can be considered as relatively small firms. For the remaining firm who entered in 1994, we note it has one kiln (below the median of 2 in 1994), below median clinker capacity, and below median grinding facilities. For the remaining firm who exited in 1994, we note that it has one kiln (below median of 2 in 1993), above median clinker capacity, and below median grinding facilities.

Year	1993	1994	1995	1996	1997	1998
Number of Firms	115	115	117	115	115	115
Entering Firms	-	1	2	0	0	0
Exiting Firms	-	1	0	2	0	0

Table 2: Firm Participation from 1993-1998

4.2 Results

We examine a variety of different structural conditions when checking whether the data are described by price taking profit maximization in Table 3 and Table 4. Within these tables, the two rows denote whether we impose a static technology or an increasing technology. In contrast, the columns denote whether there are no restrictions on inputs/outputs, restrictions on input/output, or restrictions on input/outputs and non-negative profits. Within each entry of the tables, we present either market or firm level necessary competitive price taking profit loss.

We examine both when there is a static production set and when the production set increases. We examine each of these conditions with the restrictions of non-negative profits and restricting goods to be inputs/outputs. In particular cement is restricted to be an output while the other goods are assumed inputs. The results on the m-NPL are presented in Table 3. We note that the weakest test of this model with increasing production sets is able to profit rationalize the model without restricting profits to be non-negative. However, the restriction of allowing *all* firms to have weakly increasing production sets every period is likely too weak and does not match the structure of the cement industry. For example, the main technology used in the production of cement are large kilns to produce heat that facilitates the chemical reactions used to produce cement. During the time period from 1993-1998, only six kilns were updated. Thus, we believe the static technology better represents the information we have on the production sets.

	Unrestricted	Input/Output	Input/Output and Non-negative Profits
Static	348.0	348.0	755.1
Increasing	0	0	109.0

Table 3: m-NPL in millions of 1996 dollars

For models that assume static production sets, the m-NPL is $755.1 million when one has restrictions on inputs/outputs and non-negative profit maximization. Recall that m-NPL is a summation of all profit losses for all firms across all time periods. Therefore, \$755.1 million is the amount of profit that is needed to rationalize the market data from 1993-1998 while imposing competitive price taking profit maximizing firms when the inputs and outputs are known and firms make non-negative profit. One interesting feature of the test is that the constraints on which goods are inputs and outputs does not affect the analysis. For some comparison on the magnitude of the m-NPL, the dynamic structural work of Ryan (2012) finds welfare errors of \$300 million when comparing the results to a static structural model that incorporates regional pricing and competition. These values are not directly comparable since Ryan (2012) uses a structural model while the analysis here is non-parametric. However, the magnitude of error from assuming profit maximization of the industry is more than twice the size of the errors from dynamic versus static considerations. Since most welfare calculations include industry profit, this could have large effects on welfare comparisons when one assumes profit maximization at the aggregate when there is regional price variation and competition.

Next, we examine the f-NPL in Table 4. The f-NPL is substantially smaller than the m-NPL, which is expected as it is a measure for a single firm. Also, we note that the m-NPL is not far from the number of firms times the f-NPL.[10] This suggests that the best way to distribute profit maximizing errors is to give about the same amount of error to each firm. The error in profit maximization to a firm is \$6.566 million for static firm production sets, restrictions on inputs/outputs, and non-negative profit maximization.

	Unrestricted	Input/Output	Input/Output and Non-negative Profits
Static	3.026	3.026	6.566
Increasing	0	0	0.948

Table 4: f-NPL in millions of 1996 dollars

[10]To see this, note $118 \cdot 6.566 = 774.788$.

5 Conclusion

In this paper, we construct a test of market profit maximization when a researcher has knowledge of market supply, market prices, and firm participation. Roughly, the test examines whether firms could improve profits by re-optimizing using known production processes. We extend the test to examine restrictions on the production sets, non-negative profit maximization, and weakly increasing production sets. We then develop notions of approximate profit maximizer and necessary competitive price taking profit loss to measure how far the market and firms are from profit maximization in terms of optimization error. We these results to show that the U.S. Cement industry is not profit maximizing when assuming non-negative profits and that the necessary competitive price taking profit loss for the market is $755.1 million dollars for the conditions that most closely match the market (static firm production sets, input/output constraints, and non-negative profits).

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Appendix A Proofs

Proof of Theorem 2. We apply Theorem 3.1 of Gale (1989). We seek, for all $j \in \{1, \ldots, J\}$, all $f \in P^j$, and all $k \in \{1, \ldots, K\}$, ε_f^j and $y_{f,k}^j$ such that

1. For each $j \in J$ and $f \in P^j$, $\varepsilon_f^j \geq 0$
2. For each $f \in F$ and binary $\{j, l\} \subseteq \mathcal{O}^f$, $\pi^j \cdot y_f^j + \varepsilon_f^j - \pi^j \cdot y_l^f \geq 0$
3. For each $j \in J$, $f \in P^j$, and $k \in \{1, \ldots, K\}$, $\sum_{f \in P^j} y_{f,k}^j = y_k^j$

to maximize $\sum_{f \in F} \sum_{j \in \mathcal{O}^f} \varepsilon_f^j$.

Applying Theorem 3.1 of Gale (1989), we obtain, for each $\varepsilon_f^j \geq 0$ constraint, a multiplier $\alpha_f^j \geq 0$, for each constraint of type 2 (an ordered pair j, l with $j \neq l$), a multiplier $\Lambda(f)_{j,l} \geq 0$, and for constraints of type 3, a multiplier $\mu_k^j \in \Re$.

Our goal is then to maximize $\sum_{j \in J} \mu^j \cdot y^j$ subject to for all $j \in J$ and $f \in P^j$, $\sum_l \Lambda(f)_{j,l}\pi^j + \mu^j = \sum_{l \in \mathcal{O}^f, l \neq j} \Lambda(f)_{l,j}\pi^l$ and $\alpha_f^j + \sum_{l \in \mathcal{O}^f, l \neq j} \Lambda(f)_{j,l} \leq 1$, or removing the α_f^j constraint, $\sum_{l \in \mathcal{O}^f, l \neq j} \Lambda(f)_{j,l} \leq 1$. By creating a term $\Lambda(f)_{j,j}$ for each $j \in J$ and $f \in P^j$, we see we obtain exactly the optimization problem in Theorem 2.

$\square$

Proof of Theorem 3. We remark that the proof relies on the same technique as in the proof of Theorem 2. First, the original problem can be reformulated as the linear program

$$\min \quad \varepsilon$$

subject to:

1. For all $f \in F$ and $j \in \mathcal{O}^f$, $\varepsilon_f^j \geq 0$.
2. For all $f \in F$ and $j, l \in \mathcal{O}^f$, $\pi^j \cdot y_f^j + \varepsilon_f^j \geq \pi^j \cdot y_f^l$.
3. For all $j \in J$, $\sum_{f \in P^j} y_f^j = y^j$.

4. For all $f \in F$, $\varepsilon - \sum_{j \in \mathcal{O}^f} \varepsilon_f^j \geq 0$.

Applying Theorem 3.1 of Gale (1989), for each constraint of type 1 above, we obtain for all firms f and for all $j \in \mathcal{O}^f$ a multiplier $\alpha_f^j \geq 0$. For each constraint of type 2, we obtain for all firms and ordered pairs (j, l) with $j \neq l$ the multipliers $\Lambda(f)_{j,l} \geq 0$. For constraints of type 3, we obtain for each period j and all goods k a multiplier $\mu_k^j \in \Re$. Finally, for constraints of type 4, we obtain for each firms a multiplier of $\beta_f \geq 0$.

Our goal is to maximize $\sum_{j \in J} \mu^j \cdot y^j$ subject to for all $j \in J$ and $f \in P^j$, $\sum_l \Lambda(f)_{j,l} \pi^j + \mu^j = \sum_{l \in \mathcal{O}^f, l \neq j} \Lambda(f)_{l,j} \pi^l$ and $\alpha_f^j - \beta_f + \sum_{l \in \mathcal{O}^f, l \neq j} \Lambda(f)_{j,l} \leq 0$, and $\sum_{f=1}^F \beta_f \leq 1$. Note that at least one $\beta_f > 0$. To see this, suppose all β_f are zero so by complementary slackness, it would follow for each $f \in F$ that $\varepsilon - \sum_{j \in \mathcal{O}^f} \varepsilon_f^j > 0$. In this case though, ε would not be at a minimum. Since at least one $\beta_f > 0$ we can assume the inequality is equal since we can divide by $\sum_{f=1}^F \beta_f$ without changing the solution so that $\beta \in \Delta(F)$. Similarly, we can remove the α_f^j term to get that $\sum_{l \in \mathcal{O}^f, l \neq j} \Lambda(f)_{j,l} \leq \beta_f$. We can now create a term $\Lambda(f)_{j,j}$ for each $j \in J$ and $f \in P^j$. We now see that the conditions from Theorem 3 match those for the dual problem. $\square$

Appendix B Data Collection Methods

To perform the analysis in the main text, we use data from a variety of sources. In particular, data from 1980-1998 was collected from: the United States Geological Survey (USGS) Minerals Yearbook, the American Energy Review, the Portland Cement Association (PCA), the United States Bureau of Labor Statistics (US BLS), and the St. Louis Federal Reserve. In the following paragraphs, we describe what data was used from each source and how the data was processed for use in the test of profit maximization of aggregate cement production.

Much of the data was collected from the United States Geological Survey (USGS) Minerals Yearbooks published between 1980-1998. Most entries for a given material (e.g. cement) in the USGS Mineral Yearbook have information on various industry and regional level statistics for the current year and several previous years. There are often inconsistencies with the data if one looks across different years since the Mineral Yearbook is often published before firms in the industry have responded to the surveys issued by the USGS.[11] For this reason, when we use information from the USGS Minerals Yearbook we take the information from the latest year it appears in a yearbook entry.

The data on industry wide production of cement was gathered from the USGS Minerals Yearbook entry on cement. The entry on cement contains data on output, price, raw materials inputs, and energy inputs. For example, the information on production and unit value of cement for 1995 were collected from Table 1 in the USGS cement entry from 1999. We treat the unit value as the average price of cement in the United States for a given year in the main analysis.

The data on raw material input quantities for cement was also collected from the USGS Mineral Yearbook entry on cement. For example, the information on input quantity in 1998 was collected from Table 6 in the 1999 yearbook entry on cement. The data categories are not always consistent across years so we discuss how inputs are grouped into those mentioned in Table 1 in the main text. When inputs are split between clinker and cement production, we add these entries to produce the total quantity inputs for a given year. For some consistency, we note that the inputs of sand and gypsum for cement production match from their respective USGS yearbook entries match the associated amounts in the yearbook entry on cement. We differ from the yearbook entry since we treat all cement rock as marl and all ferrous material as iron ore. We make this distinction to match the data from the cement yearbook entry to the associated prices we use for the different materials from other USGS yearbook entries. We also include coral into the category "limestone" for analysis since later entries in the yearbook do not make a distinction between coral and limestone. Similarly, we treat clay and shale as the same good since the price information is on the price of common clay and shale so these inputs cannot be separated.

[11] We are grateful for Henrick vanOss for pointing out this detail in a personal correspondence.

The cement entry in the USGS mineral yearbook also contains the information on the quantity of different energy inputs. For example, we collect data on fuel usage for 1998 from Table 7 in the cement yearbook entry from 1999. Quantities for oil and natural gas are recorded directly from the table. The quantity of "coal" used in the analysis is the sum of coal, coke, and petroleum coke. We aggregate these quantities together since earlier data does not always make these distinctions. Therefore, we have comparable amounts of "coal" across different time periods. Also, we make the assumption that all coal is bituminous to match the amount of coal to a single price from the American Energy Review. This seems a reasonable first approximation since looking at previous yearbook entries, we see that virtually all coal used is bituminous (e.g. over 94% in 1995). We note that in 1991 there is no record of energy usage in the cement industry. This is the only missing data of all materials from 1980-1998. Therefore, the the largest dataset we use to examine profit maximization includes data from 1980-1990 and 1992-1998.

The final piece of information we gather from the cement entry of the USGS yearbook is electricity usage. For example, electricity usage for 1998 was collected from Table 8 of the cement yearbook entry in 1999. We treat the electricity category as the sum of all purchased energy by cement plants in a given year. For example, the electricity usage is the sum of purchased energy from all plants plus the energy purchased for plants that grind materials in 1998.

So far, we have accounted for all quantity amounts with the exception of labor. We measure labor as total hours worked which is derived using the information on the amount of cement produced with information from the Portland Cement Association (PCA). In particular, PCA records the average number of labor hours needed to produce a thousand metric tons of cement. Total labor hours for a given year is generated by multiplying the quantity of cement produced by the labor hours per metric ton from PCA.

The above paragraphs documents how we obtained data on the quantities produced from various data sources. However, we have not mentioned the unit of measurement for each input/output. From 1980-1999, the USGS changed the units that inputs/outputs were measured in from English/U.S. engineering units to metric units. For the analysis, we measure all inputs/outputs in metric units when possible. Therefore, we often had to apply a conversion factor to these measurements for different years. All the information on the change of units and measurement units used in different time periods are recorded in Table 5. There are four main types of unit changes those for mass (cement, limestone, marl, clay/shale, sand, iron ore, gypsum, and coal), liquid volume (oil), and gaseous volume (natural gas). We also report the degree of precision to which the units are rounded. The measurement of electricity is constant in million-kilowatt hours. Finally, we report labor to the nearest hour after transforming the amount of cement from short tons to metric tons and multiplying.

We now discuss how we collect data on raw material input prices. Raw material input prices are treated as the unit value or freight on board price of the different goods. These values are collected from the USGS Minerals Yearbook. Limestone and calcareous marl unit values were collected from the crushed stone/stone yearbook entries. For example, the unit values for 1998 were collected from Table 2 in the 1999 crushed stone yearbook entry. The information on prices of both limestone and calcareous marl are not always available before 1993 which is why we restrict to analysis to the years 1993-1998 in the main text. From 1980-1992, the unit values of limestone and calcareous marl are only available on odd years. However, even years from 1980-1992 still contain information on the unit value of all crushed stone. Thus, when we analyze profit maximization for the larger period from 1980-1998, we treat the price of limestone and calcareous marl as the average unit value for all crushed stone in the even years between 1980-1992.

The price of common clay/shale is obtained from the Clay and Shale/Clay yearbook entry from the USGS Minerals yearbook. The yearbook makes no distinction between the prices of these goods, so they are aggregated into a single commodity in the analysis. This information is not recorded in a table and the yearbook entry only contains one year of data. For an example, the unit value of clay/shale from 1998 is collected from the section on Prices under

Type	Units	Reporting Years	Metric Conversion	Rounding
Mass	Thousand Short Tons	1980-1992	0.907185 $\frac{\text{metric ton}}{\text{short ton}}$	Thousand Metric Ton
	Thousand Metric Tons	1993-1998		
Liquid	Thousand 42-gallon Barrels	1980-1992	3.78541 $\frac{\text{liter}}{\text{gallon}}$	Thousand Liter
Volume	Thousand Liters	1993-1998		
Gaseous	Thousand Cubic Feet	1980-1992	0.0283168 $\frac{\text{cubic meter}}{\text{cubic foot}}$	Thousand Cubic Meter
Volume	Thousand Cubic Meters	1993-1998		

Table 5: Units of Measurement in Cement Yearbook

the heading "Common Clay and Shale" in the 1998 yearbook entry.

The price of ferrous material is treated as the average freight-on-board mine value of usable iron ore. This number is obtained from the Iron Ore entry of the USGS Minerals yearbook. For example, the unit value for 1998 is gathered from the first paragraph under the heading "Prices" in the 1998 yearbook entry. The price of sand is treated as freight on board (f.o.b.) price of sand. We obtain the average f.o.b. price of sand from the Construction Sand and Gravel entry of the USGS Minerals Yearbook. This information is generally in a separate section on prices. For example, the 1996 price of sand is the f.o.b. price of sand collected from the subsection on prices in the 1996 yearbook entry. The prices of sand were not reported in even years up to 1992 but were instead estimated. This is another data limitation that motivates looking at the restricted sample from 1993-1998 in the main text.

Lastly, the price of gypsum was taken as the per unit value of uncalcined gypsum used in the portland cement industry. The yearbook entry on gypsum has additional information that allows us to look more closely at the unit value of gypsum for the cement industry. For example, the price of gypsum in 1993 was taken calculating the unit value of uncalcined gypsum used in for portland cement derived from Table 4 in 1994 yearbook entry. As in the case of the cement yearbook entry, many entries switched measurement units from the English/U.S. engineering units to metric units. Most of the conversions are from dollars per short ton to dollars per metric ton, where we use the conversion from Table 5. We also make use of the conversion from long tons to metric tons for iron ore from 1980-1983 where the conversion is $1.01605\frac{\text{metric ton}}{\text{long ton}}$.

We obtain energy prices from the American Energy Reviews Published in 2011, 1998, and 1982. This includes prices for coal, oil, natural gas, and electricity purchase. As with the other data sources, there are discrepancies in prices when one looks across the different publications. We take the entry from the most recent publication in keeping with the previous analysis. The prices of oil for 1995-1998 are recovered from the No. 4 Residual Fuel Oil prices to end users in Table 5.22 of the 2011 American Energy Review. Other prices are recovered from the analogous tables in different American Energy Reviews. There is an exception where prices of oil from 1980-1981 are wholesale prices of No. 4 residual fuel oil as the price to end user was not recorded. These prices are recorded in dollars per gallon which we convert to dollars per liter using the conversion factor in Table 5.

We take the price of coal to be the price of bituminous coal. The prices of coal from 1980-1998 are all recovered from the nominal prices of bituminous coal from Table 7.9 in the 2011 American Energy Review. The prices of coal are recorded in dollars per short ton which we convert to dollars per metric ton using the conversion from Table 5. For electricity consumption, we treat price as the average retail prices of electricity in the industrial sector. The prices from 1980-1998 are all collected from Table 8.10 of the American Energy Review of 2011. These prices are recorded in terms of dollars per kilowatt-hour which agree with the units from the cement yearbook entry.

The final set of prices needed is the price of labor. We treat the price of labor as the yearly average hourly wage for manufacturing employees from the St. Louis Federal Reserve. In particular, we use monthly level data to generate an average yearly hourly wage using data that is not seasonally adjusted. We choose to use this data rather than the seasonally adjusted data so that all units begin in nominal unscaled dollars and then are converted to real prices by a common conversion factor. This data can be obtained from of Labor Statistics (2018a).

Thus far, all of the entries for prices have been nominal prices. To convert prices into real purchasing power, we use the information of the Consumer Price Index (CPI) acquired from the U.S. Beaurau of Labor and Statistics (of Labor Statistics, 2018b). We normalize the value to 1996 dollars. We do this primarily for simplicity although in practice, it is likely more appropriate to use industry level inflation factors. However, as a first approximation we choose to use the CPI since it does not introduce sources of measurement error for each separate industry pricing index. For the computations, we use the linear programming package from CPLEX compatible with Matlab from IBM (IBM, 2019).

Appendix C Extended Analysis 1980-1990 & 1992-1998

We repeat the analysis from Section 4.2, but for data from 1980-1990 & 1992-1998. We leave out 1991 since we do not have energy inputs for this year. We note that over this period there is more entry/exit than in the years from just 1993-1998. In particular, there are 166 distinct firms in the market during this extended time period. All of the information on entry and exit from 1980-1998 is present in Table 6. We include 1991 even though we do not use it in the analysis for completeness. For the years between 1980-1990, entry and exit is much more common than 1993-1998. Since there is more variation from firms, we hypothesize adding these years may have little effect to the analysis.

Year	1980	1981	1982	1983	1984	1985
Number of Firms	146	144	140	140	138	133
Entering Firms	-	7	2	3	1	0
Exiting Firms	-	9	6	3	3	5
Year	1986	1987	1988	1989	1990	1991
Number of Firms	130	129	124	120	116	116
Entering Firms	0	4	1	0	0	0
Exiting Firms	3	5	6	4	4	0
Year	1992	1993	1994	1995	1996	1997
Number of Firms	116	115	115	117	115	115
Entering Firms	1	0	1	2	0	0
Exiting Firms	1	1	1	0	2	0
Year	1998					
Number of Firms	115					
Entering Firms	0					
Exiting Firms	0					

Table 6: Firm Participation from 1980-1998

We show results replicating the analysis from Section 4.2 below in Table 7 and Table 8. We see that the additional data only changes the measures of NPL for the static model of profit maximization with input/output constraints. However, the errors more than double in magnitude when we increase the time period studied. For this expanded dataset, we find a m-NPL of $1.7 billion and a f-NPL of $12.8 million. This shows that as one expands the time period over which the analysis is performed, then the errors will increase in non-trivial magnitudes.

	Unrestricted	Input/Output	Input/Output and Non-negative Profits
Static	348.0	348.0	1,746
Increasing	0	0	109.0

Table 7: m-NPL for full dataset in millions of 1996 dollars

	Unrestricted	Restricted	Restricted and Non-negative Profits
Static	3.026	3.026	12.83
Increasing	0	0	0.948

Table 8: f-NPL for full dataset in millions of 1996 dollars