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Guy MEUNIER

Jean-pierre PONSSARD

Catherine THOMAS

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DEPARTEMENT D'ECONOMIE

Route de Saclay
91128 PALAISEAU CEDEX
(33) 1 69333033
http://www.economie.polytechnique.edu/
mailto:chantal.poujouly@polytechnique.edu

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Guy Meunier

INRA & Ecole Polytechnique

Jean-Pierre Ponssard

CNRS & Ecole Polytechnique

Catherine Thomas

London School of Economics†

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†Email: Guy.Meunier@polytechnique.edu, Jean-Pierre.Ponssard@polytechnique.edu and c.m.thomas@lse.ac.uk.

Abstract

Demand uncertainty is thought to influence irreversible capacity decisions. Suppose local demand can be sourced from domestic (rigid) production or from (flexible) imports. This paper shows that the optimal domestic capacity is either increasing or decreasing with demand uncertainty depending on the relative level of the costs of domestic production and imports. This relationship is tested with data on the U.S. cement industry, where, because cement is costly to transport over land, the difference in marginal cost between domestic production and imports varies across local U.S. markets. Industry data for 1999 to 2010 are consistent with the predictions of the model. The introduction of two technologies to the production set—one rigid and one flexible—is crucial in understanding the relationship between capacity choice and uncertainty in this industry because there is no relationship at the aggregated U.S. data. The analysis presented in the paper reveals that the relationship is negative for coastal districts, and significantly more positive in landlocked districts.

1 Introduction

The relationship between uncertainty and investment decisions has been the subject of academic debate since the early work of Jorgenson (1971). As summarized in Abel et al. (1996), theoretical arguments can be made to ensure either a positive or a negative relationship between demand uncertainty and investment. A mean-preserving increase in the variance of demand may induce a positive effect on the value of a marginal unit of capital, and, hence, on investment, due to the increased probability of high demand states. There may also be a counteracting negative effect when there is an option to delay investment until uncertainty is partly resolved (Dixit and Pindyck, 1992). The findings in the empirical literature reflect the ambiguity of these theoretical results (Carruth et al., 2000).

We build on the framework developed by Rothschild and Stiglitz (1971) in a model adapted to characteristics of the cement industry, and then explore the theoretical predictions in data from the U.S. in the early 2000s. In this industry, local demand for cement can be met by the output from two technologies: capital-intensive local production or imports from abroad. Imports are a more flexible and less capital-intensive alternative source of production to the output from local capacity, and the ability to import to a market affects firms' local investment decisions. The main contribution of the paper is to explicate the role of the production set in the relationship between uncertainty and investment.

There are three main reasons why the U.S. cement industry is an attractive industry in which to study this relationship: First, capacity decisions are major firm-level decisions in this industry because cement production is very capital-intensive. Second, the industry is regionally segmented in terms of supply and demand, and the market structure is quite concentrated within each region. At the start of the 2000s there were 114 active cement plants operating across the U.S. Regions vary in the extent of local demand uncertainty because it is affected by both the general business cycle and the local cycles typical of the construction industry. Third, long-haul maritime imports are responsive to fluctuations in U.S. domestic demand, and regional demand is often met by a mix of local production capacity and imports from overseas controlled by domestic cement producers.[1]

We develop a theoretical model which captures these three characteristics. Each firm in a local market has to make two decisions in sequence under imperfect Cournot competition. First, it decides its local capacity. Second, after the level of demand in the following period is revealed, the firm decides its production mix from its domestic capacity and imports. In the context of the model, domestic capacity and imports can be considered substitutable inputs, and they play similar roles to capital and labor in Rothschild and Stiglitz's model (Rothschild and Stiglitz, 1971). We extend their results and show that the domestic capacity choice is either increasing or decreasing in the level of uncertainty, depending on the relative marginal cost of the domestic versus the import technology. Specifically, capacity is increasing with uncertainty if the cost of imports is relatively large, and decreasing if the cost of imports is relatively small.

Our empirical analysis of the US cement industry between 1999 and 2010 confirms this contingent property: The nature of the relationship between demand uncertainty and investment is related to local access to the flexible production technology—imports from abroad. An increase in local demand uncertainty is associated with a significant decrease in production capacity and average plant size only in coastal districts, and significantly more positive in landlocked districts. We also show that, at the country-level, the data reveal no clear

[1] The USGS notes that, in the U.S. "...since the early 1990s, the majority of cement imports have been controlled by domestic cement producers, and they import only as needed to make up for production shortfalls." (USGS, 2006, p.166).

aggregate relationship between uncertainty and investment. These results suggest that firms respond to an increase in uncertainty about future returns from an investment by choosing to make smaller irreversible investments only when imports are relatively cheap.

The significance of our empirical contribution comes from the fact that there is a monotonic relationship between uncertainty and investment only when accounting for variation in production-set flexibility across geographic markets. The model provides a theoretical rationale for this fact, and the empirical evidence reveals that, without controlling for production set flexibility, the role of demand uncertainty would be obscured.

The rest of the paper is organized as follows: Section 2 develops the analytical model. Section 3 reviews the literature related to both the model and empirical work in this industrial setting. It also includes a calibration of the model to some key industry facts. Section 4 describes the data used in the paper. Section 5 develops the methodology employed and gives the empirical results. Section 6 discusses some of the implications of these results and concludes.

2 An Analytical Model

2.1 Set Up

The inverse demand function for a given market is $p(q, \theta)$, in which p is the price and q the quantity sold in the market. Uncertainty is introduced through the random variable θ, which is assumed to be distributed on the interval $[\underline{\theta}; \bar{\theta}]$, where the cumulative distribution of θ is given by F, assumed to be differentiable. The inverse demand function $p(q, \theta)$ is assumed to be twice differentiable and strictly decreasing w.r.t. the quantity q when q is positive. We also make the standard assumption that

$$\frac{\partial p}{\partial q} + q\frac{\partial^2 p}{\partial q^2} < 0 \tag{A1}$$

which, when the market is served by a monopoly producer, ensures that the revenue of the firm is concave w.r.t. to its production. When the market is served by an oligopoly, this assumption implies that the revenue of a firm is concave whatever the production of its competitor, and that this marginal revenue is decreasing w.r.t. to the production of its competitor.[2]

To ensure that both the revenue and the marginal revenue are increasing with respect to the draw θ from the distribution F, where θ can be interpreted as a demand shock, it is assumed that:

$$\frac{\partial p}{\partial \theta}(q,\theta) > 0 \text{ and } \frac{\partial p}{\partial \theta} + \frac{\partial^2 p}{\partial \theta \partial q}q > 0 \tag{A2}$$

This assumption will hold whenever uncertainty is additive or if uncertainty pertains to, for example, incomplete information about market size.[3]

Turning to the supply side, a firm's cost function for the home technology consists of two terms: a linear per unit investment cost c_k for a capacity choice denoted k, and a linear per unit production cost c_h.[4] The firm is unable to produce more than its capacity with the home technology. For the foreign technology, there is no unit investment cost. This technology is assumed to have a linear per unit production cost c_f that varies across local markets. In the case of no uncertainty, the home technology is preferred to the foreign, that

[2]This ensures the uniqueness of the Cournot equilibrium in the oligopoly case.

[3]This assumption rules out the possibility that a monopolist would reduce its output under a higher draw of θ. Note that if $p(q,\theta) = p(q/\theta)$, the second part of A2 is equivalent to A1.

[4]For simplicity, we assume there is no fixed component to investment or production costs. Introducing fixed costs does not affect the predictions of the model as long as investing remains profitable, which we assume all through the model.

is, it is assumed that: $c_h + c_k < c_f$. Finally, it is assumed that local demand is high enough to make some domestic investment worthwhile, so $\int_{\underline{\theta}}^{\bar{\theta}} p(0,\theta)dF > c_h + c_k$, and that, in all realized demand states, it is worth producing with the home technology: $p(0,\theta) > c_h$, $\forall\theta$.

The game has three stages, with firm decisions being made at the first and third stage. First, the firm decides its local capacity k relative to the home technology. Second, uncertainty is resolved, and the realized value of θ is revealed to the firm. Third, the firm makes production decisions (q_h, q_f) using the home and foreign technologies respectively, subject to the constraint $q_h \leq k$. The optimal capacity is denoted k^* and is a function of both the distribution of demand states and the local relevant import cost c_f.

2.2 Demand Uncertainty and Optimal Local Capacity for a Monopoly Firm

We first look at the capacity choice of a firm that has a production monopoly in the local market and then generalize to the oligopoly setting. The short-term profit of a monopoly firm is:

$$\pi(k,\theta) = \max_{q_h \leq k, q_f} [p(q,\theta)q - c_h q_h - c_f q_f]$$

and the expected long-term monopoly profit is the expected short-term profit minus the investment cost:

$$\Pi(k) = \int_{\underline{\theta}}^{\bar{\theta}} \pi(k,\theta)dF(\theta) - c_k k$$

Since $c_h + c_k < c_f$, the optimal capacity in the case of no uncertainty is simply the monopoly capacity with marginal cost $c_h + c_k$. Production is equal to capacity, both are independent of c_f, and there are no imports.

With sufficiently large uncertainty, however, production and capacity become uncoupled. In low realized demand states, the firm has excess capacity, and production is determined by the home plant's variable cost. For high realized demand states, the firm imports to satisfy demand in excess of capacity, and the quantity sold is determined by the import cost. Capacity is equal to production only over a range of intermediate levels of the realized demand shock.

The bounds of this range are denoted θ^- and θ^+ respectively. At θ^- and θ^+, the marginal revenue of local production at capacity is equal to the home variable production cost and to the import cost, respectively:

$$p(k,\theta^-) + \frac{\partial p}{\partial q}(k,\theta^-)k = c_h \text{ and } p(k,\theta^+) + \frac{\partial p}{\partial q}(k,\theta^+)k = c_f. \tag{1}$$

The relationship between k, home production and imports in the short term for different ranges of the realized demand shock θ, are given by Table (1), which also shows, in the second row, the corresponding marginal ex post profit associated with additional capacity for each range:

$\theta^\dagger$	$\underline{\theta} \le \theta \le \theta^-$	$\theta^- \le \theta \le \theta^+$	$\theta^+ \le \theta \le \bar{\theta}$
q_h, q_f	$q_h < k,\ q_f = 0$	$q_h = k,\ q_f = 0$	$q_h = k,\ q_f > 0$
$\partial\pi/\partial k$	0	$p(k,\theta) + \frac{\partial p}{\partial q}(k,\theta)k - c_h$	$c_f - c_h$

†The two thresholds θ^-, θ^+ are defined by equation (1).

Table 1: The level of demand, θ, determines whether the firm is at full capacity and whether it imports; and also the short-term marginal profit of an additional capacity.

Capacity choice is derived from maximizing the expected long-term profit given the distribution of possible demand states, F. The derivative of expected long-term profit with respect to k is

$$\frac{\partial \Pi}{\partial k} = \int_{\underline{\theta}}^{\bar{\theta}} \left[\frac{\partial \pi}{\partial k} - c_k \right] dF(\theta) \tag{2}$$

The effect of an increase in risk *à la* Rothschild and Stiglitz (1970) on the long-term marginal profit depends on the shape of $\partial\pi/\partial k$ with respect to θ. If the short-term marginal profit is concave (resp. convex) with respect to θ then an increase in risk reduces (resp. increases) the optimal investment.[5]

In the present framework, and as summarized in Table (1), the short-term marginal profit is neither concave nor convex and depends on the realized value of θ. For $(\theta < \theta^-)$, short-term marginal profit is constant (equal to zero); for $(\theta^- < \theta < \theta^+)$, short term marginal profit is increasing in capacity; for $(\theta^+ < \theta)$, it is once again constant.

Without further assumptions on either the revenue function or the distribution of demand states, an increase in risk has an ambiguous effect on the equilibrium capacity. However, with a uniform distribution of demand states, the effect of an increase of uncertainty on the optimal capacity is clear, and depends on the magnitude of relative costs.

Proposition 1 *If θ is uniformly distributed over $[-\lambda, \lambda]$, then the equilibrium capacity is increasing (resp. decreasing) with respect to λ if $c_f > c_h + 2c_k$ (resp. $c_f < c_h + 2c_k$)*

Proof. Using the expressions in the second row of Table 1, and including the capital costs which are relevant in the long term, we can write the long-term marginal profit as:

$$\frac{\partial \Pi}{\partial k} = \int_{\underline{\theta}}^{\theta^-} -c_k dF(\theta) + \int_{\theta^-}^{\theta^+} \left[\frac{\partial r}{\partial q}(k,\theta) - c_h - c_k \right] dF(\theta) + \int_{\theta^+}^{\bar{\theta}} (c_f - c_h - c_k) dF(\theta) \tag{3}$$

[5] This is a possible definition of an increase in risk: any risk-averse decision maker, with a concave utility function, prefers a less risky distribution. Intuitively, an increase in risk increases the probability of extreme demand states, with a concave function the weight of lower states are larger than the weight of higher states, so that an increase in risk reduces the expectation.

The equilibrium capacity $k^*(\lambda)$ is thus the solution of the equation:

$$0 = \frac{\partial \Pi}{\partial k} = \frac{1}{2\lambda}\left\{\int_{-\lambda}^{\theta-} -c_k d\theta + \int_{\theta-}^{\theta+}\left[p(k,\theta) + \frac{\partial p}{\partial q}(k,\theta)k - c_h - c_k\right] d\theta + \int_{\theta+}^{\lambda}(c_f - c_h - c_k)d\theta\right\}$$

Then, the derivative of $\frac{\partial \Pi}{\partial k}$ with respect to λ at $k^*(\lambda)$ is:

$$\frac{\partial \Pi^2}{\partial \lambda \partial k} = -\frac{1}{2\lambda}\frac{\partial \Pi}{\partial k} + \frac{1}{2\lambda}\left[(c_f - c_h - c_k) - c_k\right] = \frac{1}{2\lambda}(c_f - c_h - 2c_k).$$

Therefore, the sign of $\partial k^*/\partial \lambda$ is the sign of $c_f - c_h - 2c_k$. ■

The simplicity of the condition on the cost components is appealing; the precise nature of the demand function does not affect the result. With uniformity, the weight of interior demand states – in which the firm produces at capacity – is constant, and the relative weights of each range of demand states do not change when uncertainty increases.

The nature of the impact of the import cost on the direction of the relationship between capacity and demand uncertainty can be made more general in the following way: On the one hand, when the import cost is so high that the firm never imports, an increase in uncertainty increases the incentive to invest to satisfy high demand realizations. On the other hand, the lower the import cost, the more flexible is the firm in its ability to face uncertainty. This flexibility intuitively leads to a negative relationship between uncertainty and investment. This intuition, while developed above using the uniform class of distribution functions, is likely to hold for a broader set of possible demand distribution functions.

2.3 The Oligopoly Case

We now extend the analytical results to different market structures. Specifically, we move to an oligopolistic setting, and then include a competitive fringe of importers. Together with the monopoly case, these market structures describe the set of local markets considered in our empirical application.

In a standard static Cournot model, each firm's best response can be viewed as the monopoly response to a residual demand curve. This interpretation remains true in our dynamic model as long as we make the assumption that the production decisions of any given firm do not depend on the capacity of its competitors. This rules out preemptive motives for capacity investment. [6]

Making the further assumption that firms have similar cost structures we can show that while the number of firms in the market does influence the magnitude of the relationship between uncertainty and capacity, it does not affect its sign. The proof of this Lemma is in Appendix 1.[7] Consider now the introduction of a competitive fringe of price-taking importers: The oligopolists continue to face a residual demand function and the analytical results developed so far continue to hold. Thus, the contingent nature of the relationship between uncertainty and capacity, depending on the relative cost of imports, is robust to the local market structure.

[6] In other words, this does not allow the possibility that firms operate with excess capacity to deter entry. There have been several theoretical contributions that could motivate such strategic behavior, such as Spence (1977) and Dixit (1980). A number of empirical studies have tested this hypothesis in specific industry studies; see, for example, Ghemawat (1984) and Mathis and Koscianski (1997). As noted by Lieberman (1987), the empirical results provide limited supporting evidence of this type of behavior.

[7] Note that this symmetry assumption extends to the firms's technology mix. We conjecture that the relationship stated in Proposition 1 should be restated as a progressive shift from being negative to positive when the fraction of firms with importing capability in the market increases. Since the investment cost associated to an import cement terminal is low as compared to the investment cost in a cement plant we may assume that there are no entry barrier for terminals so that this fraction is large in our empirical analysis.

The oligopoly result is, however, obtained assuming an exogenous market structure, and may not generalize to settings where the number of firms is endogenous to the level of demand uncertainty. However, the market size relative to economies of scale tends to be the primary determinant of market structure in a capital intensive industry, and demand uncertainty as such certainly plays a limited role. As a consequence, the contingent property of the model may be tested as long as the observed market structure is relatively stable. In our review of literature we provide indirect confirmation that market structure is relatively static during the time period under study.[8]

Altogether, we think that Proposition 1 can be seen as a relatively robust property that can be evaluated empirically at the market level, rather than the firm level. Figure 2.3 illustrates how the optimal capacity k^* is predicted to depend on both demand uncertainty and the relative cost of imports. Suppose that for a landlocked district, we have $c_f \geq 2c_k + c_h$, while the reverse is true for a coastal district. The line AB traces out the predicted relationship between capacity and demand uncertainty in landlocked districts, and the line CD does the same for coastal districts. Proposition 1 states that the slope of AB is positive and the slope of CD is negative.

[8]We do not have data on the number of firms, but our data do contain the number of plants in each district in each year. We include the number of plants in each market as a control variable in our main analysis, controlling for changes in market structure resulting from the entry of new plants and changes in market structure due to ownership consolidation. We also see that the number of plants within a district is uncorrelated with demand variability in the data overall.

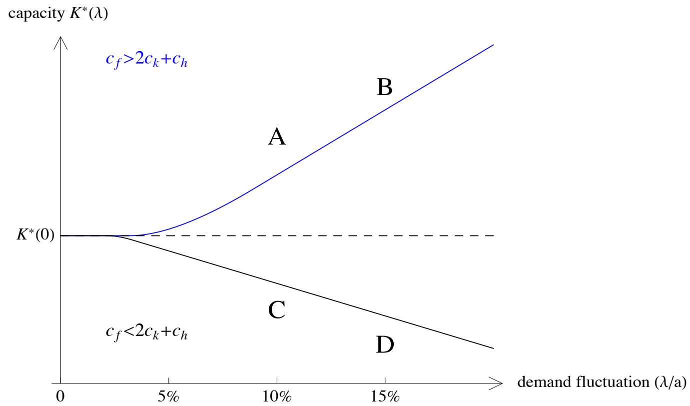


Figure 1: The influence of uncertainty on the equilibrium capacity.

3 Relevant literature and Simple Model Calibration

3.1 Review of the literature

This study relates to several distinct literatures. First, we review the relevant literatures on option value and on capacity and uncertainty in industrial organization, pointing out the contribution made by this paper. Then, we review the papers that are specifically about the cement industry, and use some empirical findings from these papers to discuss the relevance of our model.

The result of Proposition 1 can be directly interpreted in terms of options (Dixit and Pindyck, 1992; Abel et al., 1996). There are two valuable options in this model when demand is uncertain. Investing in an additional unit of capacity creates the put option to produce less than installed capacity for a benefit of c_h but eliminates the call option to import at a cost of c_f. An increase in uncertainty increases the value of each of these two options, and the overall effect on investment depends on the comparison of these changes.[9]

[9] Our framework could be compared with the one presented in Abel et al. (1996). The possibility of producing less than capacity in our model could be compared to the possibility of divesting capacity in their model, and the possibility of importing is comparable to the possibility of (immediately) expanding capacity in their model. Abel et al. (1996) points out the ambiguity of the effect of uncertainty on irreversible

Our model can also be related to two theoretical industrial organization papers. Demers (1991) analyzes capacity choice in a dynamic oligopolistic Markov model and shows that the equilibrium capacity is decreasing with uncertainty. In his model, the firm is constrained to always produce as much as its earlier capacity commitment—possibly more with a penalty cost—but never less. Gabszewicz and Poddar (1997) consider a two-stage game and show that firms invest more with uncertainty. In their framework, firms can produce less and not more than their capacity. Capacity is increasing with uncertainty. Our model combines these two models into one unified framework – firms may produce more than capacity (through imports) or produce less than capacity – and extends their results, so that the relative level of the domestic production and import costs explains when capacity is increasing or decreasing with uncertainty.

Previous empirical studies have reached mixed conclusions about the influence of different types of uncertainty on investment. Goldberg (1993) shows that there is a negative relationship between investment and exchange rate variability in some sectors in the United States, but then Campa and Goldberg (1995) find that exchange rate variability has no significant effect on investment levels in manufacturing. Bell and Campa (1997) find no relationship between product demand uncertainty at the country level and capacity investment in the chemical processing industry. Ghosal and Loungani (1996, 2000) find a negative relationship between investment and uncertainty, focusing on the role of concentration ratios and whether industries are dominated by small firms. Our findings from the U.S. cement industry support the suggestion made by Carruth et al. (2000) that production set flexibility is a possible explanation for the ambiguous results obtained in previous studies.

We now come to the papers that directly model the cement industry, focusing on the U.S.

investment in the general case, while we provide a clear-cut comparison with a specific distribution.

so as to relate empirical findings to our context.[10] Ryan (2012) models a dynamic Markov game in the tradition of Ericson and Pakes (1995), where the stage game involves an investment phase (entry or exit, and choice of capacity for the next stage), followed by a Cournot competition production phase under capacity constraints for incumbents. This model is estimated using data from geographic areas which are similar to ours (U.S. districts). Fowlie et al. (2012) extends the Markov framework developed in Ryan (2012) to include a competitive fringe of importers. Perez-Saiz (2011) also draws on Ryan (2012) but this time allows for mergers and acquisitions. These papers note that the U.S. market structure at the district level has a lot of inertia, and (Ryan, 2012) introduces the possibility of heterogenous firms, but the estimation shows that there are no significant differences in cost functions across firms. Our model shares the same underlying features (investment and production with capacity constraint, symmetric firms). It directly assumes an exogenous market structure with identical cost functions and is robust to the introduction of a competitive fringe. These three papers neither allow for demand uncertainty nor for the capability of domestic firms to import, which are the two characteristics we study here.

It is worth noting that, according to our model, these two characteristics are the primary factors to explain the disproportionate response of cement imports to market demand fluctuations. We shall come back to this point in Section 4.

Since the firms in U.S. cement markets are often large multinationals that produce cement in many markets and also often own the major import terminals in the U.S., our paper also relates to the theory model set out in Rob and Vettas (2003). In their model, as in ours, firms have the choice between home and foreign production to satisfy an uncertain demand.

[10] Salvo (2010) studies the cement industry in Brazil, where, unlike in the U.S., there are limited imports. This paper also models importers as a competitive fringe and tests the potential threat of fringe on the domestic market even in the absence of imports.

Their paper focuses on the optimal strategy mix between local production and imports as local demand grows over time. In contrast, we focus on the optimal strategy mix under demand uncertainty and varying costs of imports. In both models, domestic production and imports may co-exist.[11] Our model provides another explanation to the observation that under some circumstances firms serve a given market through both imports and local production (Blonigen (2001)).

3.2 Analytical Model Calibration

Before evaluating the empirical predictions generated in the analytical model, we make a rough calibration to test its empirical relevance for the U.S. cement industry. Our main source of information is provided by the industry analysts Jefferies, in their Industrials Building Materials Report (August, 2012). The model's prediction is based on two inequalities. The first one states that building home production is cheaper than import, $c_k + c_h < c_f$. The second one says that the sign of the relationship between demand uncertainty and local capacity hinges on the sign of $c_f - c_h - 2c_k$. In coastal markets the sign is expected to be negative while it is expected to be positive in landlocked markets.

Taking each variable in turn: For import cost, insurance, and freight value (CIF value) for cement arriving at U.S. ports Jefferies provides an estimate of \$70 to \$80 per ton (page 158). The additional costs incurred for transporting the cement to final markets are very different by region. We rely on Lafarge, the largest global cement producer, to have estimates of these costs to various U.S. districts. On average, we arrive at \$10 per ton to coastal markets and at \$40 per ton for inland markets. This generates estimates of c_f in the range [80,90] for

[11] Kogut and Kulatilaka (1994) show how the value of joint ownership of production facilities in more than one country can be related to the operating flexibility this offers under exchange rate uncertainty. When firms have local capacity constraints, their model can also generate the predictions that firms simultaneously export to and produce in a given market.

coastal regions and c_f in the range [110, 120] for landlocked regions.

Second, to estimate the costs of local production, c_h, Jefferies provide EBITDA margins of 20 to 30 percent of price per ton (p 186). They estimate price per ton at \$70 to \$80, which gives us a local production cost estimate of c_h of between \$49 and \$64 per ton.

Third, for capital costs, the Jefferies Report estimates an investment cost per ton of \$250 (page 153). At an annual cost of capital of 8 percent, this gives us an estimate of c_k of \$20.

Turning now to the two inequalities underlying the prediction. We first note that $c_h + c_k < c_f$ for landlocked districts is well satisfied, while in some easily accessible coastal locations it may be not be profitable to build new capacity ($c_h + c_k = 84 > c_f = 80$). These extreme cases should not endanger our analysis. Secondly, we note that for coastal regions, this calibration gives an estimate of $c_f - c_h - 2c_k$ of between -24 and 1. For landlocked regions, the estimate of $c_f - c_h - 2c_k$ is between 16 and 41. Altogether we think that this calibration gives some reassurance about the relevance of our model to move to the empirical analysis.

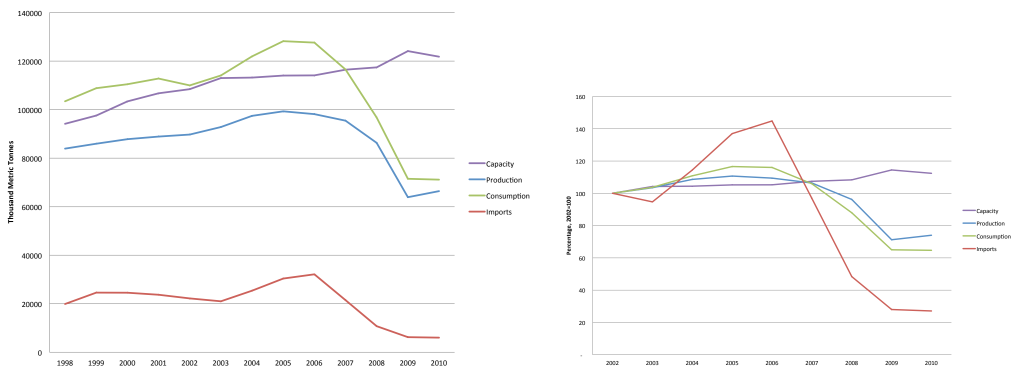
4 Data

We now evaluate whether the empirical predictions of the model developed in Section 2 are consistent with investment in capacity in the U.S. cement industry over the 2000s, when construction activity cycles, as mentioned in the introduction, led to substantial localized demand volatility. Figure 2(a) shows the U.S.-wide levels of cement consumption, capacity, production and imports for each year between 1998 and 2010. Consumption increased in each year up to 2007, at which point it fell off dramatically. The figure reveals that imports also saw a big reduction from 2007 onwards. We note that exports of cement production were very low throughout the period, less than one twentieth of import levels when imports were at their lowest. For this reason, we abstract from any incentive to invest in local production to serve export markets, in the model and in the empirical work.

Figure 2(b) plots each of the same series as in Figure 2(a) relative to each of their 2002 levels. The percentage increase in cement imports up to 2006 was far larger than the percentage increase in consumption, and the percentage drop off in imports after 2006 was, in turn, larger than the percentage decrease in consumption. Over the same time period, aggregate capacity increased at a steady rate up to 2007, at which point this trend reversed. The large percentage decline in aggregate imports from 2007, relative to the decline in GDP, is consistent with the overall picture in global manufacturing and trade around this time, often referred to as "The Great Trade Collapse" (Baldwin (2009); Bems, Johnson, Yi (2012)). Our model contributes to the explanation of the disproportionately large fall in imports in the cement industry, where imports and local production are perfect substitutes: When demand falls in coastal regions, a larger share of that decreased demand can be satisfied with local production rather than imports.[12]

The empirical analysis presented in the paper examines localized variation in these aggregate patterns. The three main variables of interest are: local capacity, the relative marginal cost of imports, and demand uncertainty. We discuss each of these in turn:

[12]To the best of our knowledge, this mechanism has not been previously discussed as a contributory factor to The Great Trade Collapse. Other papers, as summarized in Bems, Johnson, Yi (2012), have studied the roles of product durability, inventory adjustments, and trade financing constraints.



(a) Evolutions of capacity, production and imports.

(b) Evolutions relative to the 2002 level (The Great Trade Collapse)

Figure 2: The evolution of the US cement markets.

4.1 Capacity and Capacity Investment

The USGS publishes an annual Minerals Yearbook containing detailed data about the cement industry at the region, or district, level. The district-level capacity is given for different local regions, defined mostly by state-lines and consisting of groups of states. To account for changes in the market-level boundaries over time, we group the data into 23 different districts, where the outer boundaries of the 23 district groupings are constant over time. In some cases, these districts are divided differently into two or more separate regions at some point during the data, and the set of 23 allows for consistency over time in the states that are included in each. In addition, since the USGS divides California and Texas into two districts in each case, and we want to match the capacity data with state-level data about demand and other control variables, we group up the capacity data to the state level. This leaves us with 21 districts altogether, as listed in the first column of Table 2.[13]

[13]We note that the USGS also divides Pennsylvania into two districts, Eastern and Western. We have matched the state-level variables for New Jersey to the USGS capacity-related data for Eastern Pennsylvania and the state-level variables for Pennsylvania to the USGS capacity-related data for Western Pennsylvania. This is a more accurate matching than grouping Eastern and Western Pennsylvania together and matching it with demand and other variables in Pennsylvania as a whole.

District-level capacity is measured in the data as the finish grinding capacity in thousands of metric tons, and is based on the grinding capacity required to produce the district's plants' normal output mix, including both portland and masonry cement, allowing for downtime for routine maintenance. Production, in thousands of metric tons, includes cement produced using imported clinker. The USGS Minerals Yearbook also reports data on the number of active plants by district, which permits a measure of the average plant size for each district in each year. Table 2 summarizes the levels of capacity in each district in 2002, which is the first year of capacity data that we use as the dependent variable in the analysis. California had the largest installed base of cement capacity, with over 13 million tons, and the district containing Alaska, Hawaii, Oregon and Washington had the lowest level of capacity, at 2.5 million tons. Michigan and Wisconsin had the largest plants, at an average of 1.3 million tons each, and the plants in the district containing Idaho, Montana, Nevada and Utah averaged just over half a million tons each. Over the eight years from 2002 to 2010, 19 of these 21 districts experienced both annual increases and annual decreases in total installed capacity. Each of the 21 districts experienced both increases and decreases in average plant size from year to year.[14]

4.2 Relative Marginal Costs of Flexible Production

Imports of cement to areas such as Florida, California, New York, and Texas had increased steadily since improvements in shipping technology in the 1970s, with imports coming from South America, Europe, and Asia. The industry association Cembureau now estimates that it is now less costly for cement to cross the Atlantic Ocean than to truck it 300km overland.[15]

[14] While regulation may play a role in capacity decisions, it is more likely to act as a very local constraint (at the city or town level) and is unlikely to matter differently in landlocked and coastal districts.

[15] See: http://www.cembureau.be/about-cement/cement-industry-main-characteristics

In the early 2000s, according to industry sources, global cement firms such as Cemex, Holcim, Lafarge, and Lehigh (Heidelberger) operated import terminals located on the East Coast, and Lafarge, Lehigh (Heidelberger) and Taiheiyo on the West Coast. The USGS breaks down total imports of cement and clinker into the U.S. by customs district. Major import terminals include Tampa, FL, New Orleans, LA, Los Angeles, CA, Miami, FL, and Houston-Galveston, TX. Smaller import terminals are spread out over the East Coast of the US and include Baltimore, MD, New York City, NY, Norfolk, VA, and Philadelphia, PA.[16] In each year, there are also imports to Detroit, MI and other northern Midwestern districts from Canada.

The final column of Table 2 indicates our classification of districts into landlocked or coastal regions. This classification is based on overland distance from the coast and, specifically, distance from a port where cement is imported.[17] Figure 3 represents this classification graphically. The empirical analysis investigates whether or not the relationship between investment and demand uncertainty differs significantly between the two district groups. Import costs are not included as explanatory variables for two main reasons: Firstly, import terminals were built prior to the time period of analysis, so the landlocked-coastal classification is quite robust over the data period. Secondly, as described in Section 3.2, interviews with managers at Lafarge suggested that local investment decisions across the U.S. depended critically on whether there was nearby access to a deep water harbor. This suggests that it is not the precise value of the import cost that matters for the investment decision but whether the district is coastal or landlocked.

The relative cost of local production is also, of course, affected by any district-level

[16] This list is not comprehensive. Annual statistics can be found in Table 18 of the Cement Yearbook.

[17] Section 6 includes a set of robustness tests to different definitions of district groupings and classifications.

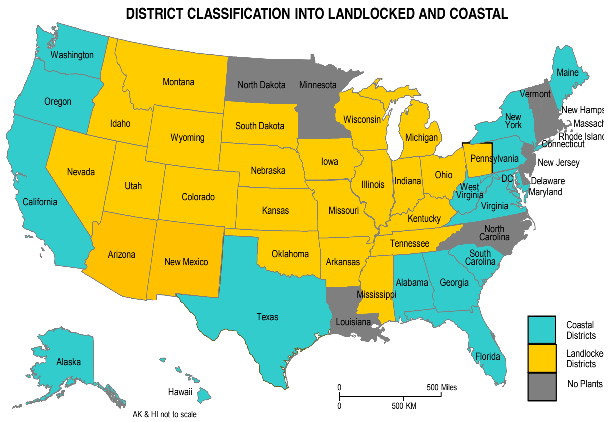


Figure 3: Base Case Classification of Districts into Coastal and Landlocked

production cost shocks. The largest variable cost in cement production is energy costs, and the majority of U.S. kilns are coal-powered (USGS, 2011). The U.S. Energy Information Administration publishes data on coal prices delivered to Other Industrial Plants (other than Electric Utilities) in each state in each year. We include nominal coal price data, aggregated up across states to the geographic district boundaries, as a control variable in the anaysis.

4.3 Demand Uncertainty

One of the key variables in the theoretical model set out in Section 2 is market-level demand uncertainty at the time when capacity investment decisions are made. In the model, this variable is the parameter that measures the variance in demand over the productive lifetime of the investment. In taking this to the data, we seek to measure managers' expectations about future demand variability in a district.

Cement is an intermediate input into different types of construction. The Portland Cement Association constructs a demand index for cement by construction activity, taking into account both the amount of activity in that sector and the intensity with which the sector uses cement.[18] In 2010, at the end of the period analyzed, residential construction made up 32 percent of the demand for cement; non-residential construction made up 31 percent; and the remaining 37 percent was in public construction. These figures varied considerably in the years preceeding 2010 as residential construction is strongly pro-cyclical, and public expenditure counter-cyclical. The total quantity of cement used in a district is an endogenous outcome reflecting local demand conditions, and local supply conditions, including capacity, which is treated in our model as another endogenous variable.

To focus in on the expected variance in demand, we turn to measures of local construction activity, over the recent past, current and future years. Using data from the Occupational Employment Statistics, published by the Bureau of Labor Statistics, we collect the state-level number of construction laborers from 1999 to 2010.[19] Of the different types of employment in this sector, we anticipate that laborers are the most flexible part of the construction workforce, often employed on short-term contracts on an as needed basis. As a proxy for district-level cement demand, we aggregate the state-level data on the number of construction laborers employed across states to the district-level, where the districts are as listed in Table 2. As a proxy for district-level demand uncertainty, we calculate the variance in the demand measure in each district over the current and past four years.

We make two further adjustments to this uncertainty measure: We use de-trended data to account for changes in employment levels that are consistent with patterns that are arguably predictable and would, otherwise, lead us to overstate uncertainty in fast-growing, or fast-shrinking, districts. Specifically, we regress employment by district over the past five years on a constant term. The larger the residuals from this regression on a trend, the

[18] See http://www.cement.org/econ/pdf/CementInvue102010.pdf
[19] See http://www.bls.gov/oes/tables.htm

less informative are recent employment levels in predicting current demand. To measure the average difficulty of predicting current employment demand using the data from recent years, we take the standard deviation of the residual values over the current year and the prior four years.

Second, since this measure of demand variation is increasing in the level of employment in a district, we also normalize the standard deviation by the mean employment level over the five years in question. This normalized standard deviation measure summarizes the extent of recent employment volatility across districts, adjusting for differences in district size. Our intent is to capture the plant manager's view about the difficulty in predicting the local demand level in any one upcoming year using information about past construction activity.[20]

We note that this measure of demand uncertainty is backwards-looking since it is constructed using district-level data from the current and last four years.[21] Any increase in volatility in a given year within a district is due to the level of demand in the current year being less similar to the level of demand for the past three years than is the level of demand four years ago to the prior three years.

While this measure of recent demand uncertainty has been adjusted to account for differences in the average growth rates by district by de-trending, predictable demand growth, or decline, is also likely to have an independent effect on investment decisions and, hence, on capacity levels within a district. We construct a measure of recent employment growth within a district at any point in time as the average percentage change in the level of construction

[20] Section 6 presents a series of robustness tests measuring cement demand volatility in alternative ways: using different data on construction activity, and using different models of expectation formation.

[21] Carruth et al. (2000) contain a discussion about the relative merits of different measures of uncertainty. Guiso and Parigi (1999) is one of very few studies that uses survey data on manager's certainty about future demand as a measure of firm-level uncertainty.

employment over the prior four years. This measure is included as a control variable in our main regressions.

5 Empirical Analysis

In this empirical setting, as described in Section 3, the investment in local cement production capacity incurs high fixed costs and relatively low variable production costs. The alternative production technology of importing cement has low fixed costs, and a variable production cost that varies by geography. We now investigate whether observed investment decisions in local cement production capacity in the U.S. over the 2000s are consistent with the model's prediction that the relationship between local investment decisions and demand uncertainty depends on the relative marginal costs of the capital intensive and alternative production technologies.

5.1 Estimation Strategy

We exploit the panel nature of the data to investigate the relationship between capacity and uncertainty. The estimated equation is:

$$y_{i,t} = \alpha + (\beta + \gamma L_i)\left(V_{i,t} + \mathbf{X}_{i,t}\right) + \mu D_i + i.Year_t + \varepsilon_{i,t} \tag{4}$$

where i denotes one of the 21 districts, and t denotes the year. The key variable of interest on the right hand side of equation (4) is $V_{i,t}$, the measure of demand uncertainty, measured as the level of recent demand volatility in the number of construction laborers in district i in year t, as described in Section 4.3. L_i indicates whether district i is landlocked, so that the association between demand uncertainty and the dependent variable $y_{i,t}$ is allowed to vary with whether or not the district is landlocked.

$\mathbf{X}_{i,t}$ is a vector of time-varying district-level control variables, namely demand growth and the number of plants. The association of these variables with the dependent variable is also allowed to depend on whether the district is landlocked. α is a constant term, D_i are district fixed effects, and $Year_t$ are year fixed effects.

The dependent variable in equation (4) is one of three measures of capacity: The first dependent variable is the installed capacity in the district. The second is a weighted measure of installed capacity that is intended to take account of differences in size across districts. It is calculated as the installed capacity in each year minus the mean district-level production over the entire time period and then divided by installed annual capacity. It is a measure of capacity in excess of the quantity locally produced in a typical year. We note that as a consequence of using mean production in the denominator, variation over time in this excess capacity measure within a district is due entirely to changes in capacity, that is, due to the investment decisions that we want to study. The third dependent variable used is the average plant size in a district.

As is common in the analysis of panel data, the observations are likely to be correlated within groups, in our case, within districts. In addition to the clustering problem arising from the fact that observations within a district are likely to share some unobserved variable, our measure of demand uncertainty in any year is based on the variance in local demand levels over that year and the past four years. This introduces serial correlation in the observations from a given district. We estimate the fixed effects and first differences specifications using OLS regressions and report Newey-West standard errors with a maximum lag order of correlation within a district of four years (Newey and West, 1987). This correction addresses the serial correlation in the errors resulting from how we measure local demand uncertainty.

Having estimated the coefficients in each specification, we then test whether linear combinations of the estimated coefficients are significantly different from zero, and significantly different from each other, in ways that are consistent with the predictions of the model. Specifically, to test whether a change in demand uncertainty is associated with a change in capacity in coastal districts, we examine the significance of the coefficient estimate for demand uncertainty. To test whether a change in demand uncertainty is associated with a change in capacity in landlocked districts, we test whether the linear combination of the coefficients on demand uncertainty and the interaction of demand uncertainty and the landlocked indicator is significantly different from zero. We then test whether changes in demand uncertainty have significantly different effects on capacity in coastal versus landlocked districts.

5.2 Results

The results of estimating equation (4) are given in Tables 4a, 4b and 4c. In Table 4a, the dependent variable is the level of capacity. Column 1 reveals that, when we do not allow for differences between landlocked and coastal districts, there is no significant relationship between changes in demand uncertainty and investment in capacity across all U.S. districts over this time period.

Columns 2 and 3 presents the first test of the predictions of the model by allowing this relationship to depend on whether the district is landlocked or coastal. There is a negative association between demand uncertainty and investment in coastal districts in Column 2, although the estimated coefficients is insignificantly different from zero. Column 3 includes the control variables of demand growth interacted with the landlocked indicator variable.

After including these controls, the negative coefficient on demand uncertainty becomes significantly different from zero. The coefficient on the interaction of landlocked and demand uncertainty is now positive and significant. This suggests that the relationship between capacity and uncertainty does vary with proximity to the coast.

Columns 4 to 6 of Table 4a add further control variables. First, we include the district-level coal price. We allow the relationship between local coal price and capacity to vary with whether or not a district is landlocked. Including these controls does not affect the nature of the relationship between uncertainty and capacity investment, which is negative in coastal districts and positive in landlocked districts.

We next include the number of plants as an additional control. This variable is intended to control for any changes in market structure within a district over time. As mentioned in Section 2, we would like to control for changes in the number of firms, but in the absence of this data, the number of plants in a district in each year takes account of any market-level consolidation or expansion. Column 5 includes this control, and allows its role to vary with whether the district is landlocked. Column 6 includes both the number of plant controls and the coal price controls from Column 4. In each case, the main result remains—the coefficient on demand volatility in coastal districts is negative and significant and the coefficient on the interaction of the landlocked indicator variable and demand volatility is positive and significant, both at the one-percent level.

The first two columns of Table 4a, Panel B report the estimated change in local capacity associated with a one standard deviation increase in local demand uncertainty, using the coefficient estimates from Column 3 of Panel A. In coastal districts, this increase in demand volatility is associated with a decrease in capacity of 260 thousand metric tons. The average district capacity (Table 2) is 5.2 million metric tons. Hence, this corresponds to a decrease of around five percent. In landlocked districts, the same increase in demand uncertainty is associated with an increase in capacity of 113 thousand metric tons, although this number is not significantly different from zero at conventional significance levels. Column 3 of the panel shows that the difference in the response to changes in uncertainty between landlocked and coastal districts is significant at the one-percent level—the relationship is significantly more positive in landlocked districts than in coastal districts.

Table 4b shows the results for the same analysis with the measure of excess capacity as a dependent variable.[22] As in Table 4a, Column 1 of Table 4b shows that there is no significant association between local demand uncertainty and excess capacity without accounting for geographic differences. Allowing the relationship to vary between landlocked and coastal districts, in Columns 2 to 6, reveals that there is a negative and significant association in coastal districts and a positive and significant association in landlocked districts.

Panel B of Table 4b demonstrates that the relationship is significantly different from zero in each case, and significantly different between coastal and landlocked districts. The mean level of the excess capacity variable over all districts between 2002 and 2010 is 1.41. Hence, the coefficient of -0.07 suggests a one standard deviation increase in uncertainty is associated with a five-percent reduction in excess capacity in coastal regions. The coefficient of 0.04 in the next column suggests that the same increase in uncertainty is associated with around a three-percent increase in excess capacity in landlocked districts.

Table 4c repeats the key analyses with average plant size as the dependent variable. Across all districts, there is no discernable relationship between plant size and uncertainty. In coastal districts, however, the relationship is negative and significant and, in landlocked

[22] This specification is intended to take account of the large differences in size across districts since this variable can be interpreted as the average percentage of installed capacity that is unused in a year.

districts it is positive, although insignificantly different from zero.[23] The nature of the relationship differs significantly between the coastal and landlocked districts. In this specification too, a one standard deviation increase in uncertainty is associated with a five-percent reduction in the capacity measure, in this case, average plant size.

Together, these results show that investment is negatively associated with an increase in demand uncertainty, but only in coastal districts. With reference to Figure 2.3, the findings establish that the line AB has a slope that is not significantly different from zero, although positive in sign. This line is the elasticity of capacity choice with respect to demand uncertainty. In contrast, the elasticity of capacity choice with respect to demand uncertainty in coastal districts, given by line CD, has a negative slope that is significantly different from zero. Moreover, the slope of the line AB is significantly more positive than the slope of the line CD. This suggests that the flexibility offered by a choice between two different production technologies (in this case, local production and imports), where the technologies differ in the amount of investment required, has a significant role in determining the overall relationship between demand volatility and investment.

6 Robustness Tests

6.1 Demand Uncertainty

We first examine whether the results in Section 4 are robust to different measures of district-level uncertainty. As a reminder, uncertainty, in the model in Section 2, is the variance of the possible demand realizations, θ. In Section 4, we make the assumption that the managers

[23]We have not included the number of plants as a control in this specification to ensure the estimated coefficients reflect plant-level, rather than district-level, decisions.

of the cement firms making investment decisions form a belief about demand volatility in future demand using the variance in construction activity in recent history: the last four years and current year.

Table 5 presents an investigation of robustness about this assumption of how manager form beliefs about upcoming demand uncertainty. We first give them a shorter memory: We measure local demand uncertainty using the variance in the number of local construction laborers over the last two years and current year, that is, over a three-year period.[24] The first three columns of Table 5 show the results of the specification given in Column 3 of Table 4a, 4b, and 4c, but with this shorter time period taken into consideration. In each case, the coefficient on demand uncertainty for coastal districts is negative and significant and positive and significant in the case of demand uncertainty in landlocked districts. Moreover, these coefficients are significantly different from each other, all at the one-percent level. That is, assuming managers are have shorter memories when considering the nature of future demand leads to results that are also consistent with the empirical predictions in the model.

Columns 4 to 6 of Table 5 allow managers some foresight. Demand uncertainty in these columns is measured using five years of employment data, centered on the current year in question. That is, it assumes managers anticipate ongoing demand uncertainty that reflects the volatility seen around the current year. In these specifications, the coefficients related to uncertainty and investment have the same signs as in the earlier tests; negative for coastal regions and positive for landlocked regions. However, these coefficients are not significantly different from zero. Columns 7 to 9 assume managers are able to anticipate construction activity over the current year and the following four years and use this to approximate market

[24] This robustness test also allows us to include one more year of data in the analysis, since it allows us to construct a measure of recent demand volatility for 2001. This adds 21 observations to the analysis.

uncertainty when making investment decisions. In this case, the data do not provide any support for the empirical predictions of the model.

In sum, Columns 4 to 9 suggests that managers' investment decisions are either inconsistent with the predictions of the model or that managers decisions did not correctly anticipate future market-level demand uncertainty. We feel it is reasonable to think that managers did not fully anticipate the ex post observed level of volatility in construction activity during the 2000s. Hence, the fact that the findings based on forward-looking expectations of uncertainty do not support the model does not, therefore, undermine the validity of the model, which is supported with backwards-looking expectation formation.

6.2 Landlocked classification

Our second set of robustness tests redefines how districts are classified into landlocked and coastal districts. We do three sets of tests, each one relaxing a different assumption made in Sections 3 and 4.

First, we reclassify the Great Lakes regions as coastal. Michigan and Wisonsin, and Ohio districts, are able to import cement from Canada via the Great Lakes. While Canadian cement is likely to have a local production cost that is similar to U.S. Cement, the relative import cost may vary over time to make imports viable. The results for this reclassification are given in Table 6, Columns 1 to 3. Each column replicates the specification Column 3 from Table 4, with the three different dependent variables (capacity, excess capacity, and average plant size). The findings are strengthened, relative to the base case.

Next, we relax the assumption that each of the 21 districts is a well-defined segmented market. In particular, in the USGS data, Michigan and Wisconsin are classified as a single market in the base case, despite the fact that they are separated by Illinois and and Indiana, which are recorded as two separate districts. In addition, Missouri and Illinois are treated as separate districts, when much economic and, hence, construction activity, takes place along their shared border. We redefine the district classification in our data, to group Michigan and Wisconsin with Illinois and Indiana, and also with Missouri, as one large landlocked district. This leaves us with 18 districts in total. Columns 4 to 6 of Table 6 replicate again the specification from Column 3 of Table 4. There remains a significant difference between the landlocked and coastal districts, in all columns.

Finally, we explore variation among the set of coastal markets in the relative price of imports. Of the 8 districts classified as coastal in Table 1, we divide them into those with large import terminals, where the local cost of imports, c_f is likely to be particularly low, and those without large terminals. The import terminal districts are California, Florida and Texas. In this set of robustness tests, we define only these three districts as coastal, and group the remaining five districts with the landlocked districts. Repeating the estimation given in Column 3 of Table 4 yields results that are very similar to the base case. The estimated coefficients take on the same signs, and while the difference in the relationship is not significant at conventional levels for capacity levels, there remains a significant difference in the relationship between excess capacity and average plant size and local demand uncertainty between landlocked and coastal regions.

6.3 Estimation approach: First differences

Our last set of robustness tests relates to the econometric specification of equation (4). The estimated equation in the benchmark specification, as presented in Section 4, controls for any non-time varying observable and unobservable characteristics correlated with capacity in a district and demand uncertainty by including district fixed effects. It also controls for time-varying factors, such as changes in average import costs over time, with year fixed effects. As an alternative specification, we also estimate equation (4) in first differences, where the estimated coefficients measure the association between yearly changes in capacity and yearly changes in demand uncertainty.

The results for this specification are presented in Table 7. In each case, the data continue to provide empirical support for the model's main prediction: There is a significant difference between the relationship between uncertainty and investment in coastal and landlocked districts, with the relationship being significantly more positive in landlocked districts. In contrast to the fixed effects specifications, the slope for landlocked districts is positive and significantly different from zero. The slope for coastal districts is negative, but not significantly different from zero.

With reference to Figure 2.3, this specification suggests that line AB is positive and line CD is negative. In the main fixed effects specifications, AB is not significantly different from zero and CD is negative. Nonetheless, the specification offers further support for the prediction that the slope of AB is significantly more positive than the slope of CD. That is, the relationship between capacity and uncertainty is significantly more positive relationship in landlocked districts.

7 Concluding Comments

This paper contributes to the literature on the theory of irreversible decisions under uncertainty. While the theory has elaborated general conditions under which the relationship between investment and uncertainty can be expected to be increasing or decreasing, these conditions remained to be empirically tested at the industry level. The US cement industry provides a unique opportunity to carry on the test. We have developed a model in line with the theory and show that the empirical findings are consistent with our model. The key factor in our analysis is the existence of a production set involving two technologies: a rigid one and a flexible one. The rigid technology is domestic production and the flexible technology is imports. The fact that cement transportation is high over land routes while it is low over maritime routes generates significant changes in the opportunity cost of the two technologies as one consider landlocked versus coastal markets. The relationship is shown to be decreasing in coastal markets and significantly more increasing in landlocked markets.

The paper provides a number of directions for future research. The model remains simple. The two stage setting could be extended to a Markov framework such as the one introduced in Ryan (2012). This would allow for endogenous market structures. Another direction would be to allow for some asymmetry among firms, in particular relative to their importing capabilities. Data sets for the US cement industry are pretty exhaustive so that the empirical analysis could encompass some of these added characteristics. It would be interesting to explore our finding in this extended framework.

On the application side, the ideas developed in this paper have direct implications to understand the leakage risk associated to a unilateral climate regulation in a sector such as cement. Indeed cement is a highly carbon intensive industry, a unilateral climate policy can be expected to affect trade patterns. This sector is a recurrent topic in the leakage literature Droege, S. and Cooper, S. (2009). Building on the model presented here, Meunier and Ponssard (Meunier and Ponssard (2013)) differentiate between short term and long term leakage, depending on whether or not the investment decisions have taken into account the change in the climate policy. Without capacity adaptation there is no leakage, but there is with capacity adaptation since the increased in domestic cost will reduce the future capacity.

The larger the demand uncertainty the larger this decrease. These considerations remain to be integrated in empirical analysis. For instance, using the Markov framework, Fowlie et al. (Fowlie et al. (2012)) empirically explore the leakage risk for the US cement industry. Introducing demand uncertainty in this analysis, an uncertainty which is large in the case of the US market, would certainly magnify the risk leakage they identify.

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Appendix 1: Proofs

The Oligopoly Case

We consider that there is a set I of n firms. The decision process takes place in two steps. First, each firm $i \in I$ chooses both k^i and a production plan $q_h^i(\theta), q_f^i(\theta)$ with $q_h^i(\theta) \leq k^i$, then θ^i becomes known and each firm produces.

The short-term profit of a firm i depends on its production and the sum of its rivals' production, denoted q^{-i}: $\pi^i = \max_{q_h^i \leq k^i, q_f^i} p(q^i + q^{-i}, \theta)q^i - c_h q_h^i - c_f q_f^i$ and the long-term profit is $\Pi^i = \int_{\underline{\theta}}^{\bar{\theta}} \pi^i dF(\theta) - c_k k^i$.

For any vector of capacity $(k^i)_{i \in I}$, in any state θ firms play a Cournot game with capacity constraints. Thanks to our assumption $A1$, there is a unique equilibrium in all demand states. The production of each firm is increasing with respect to θ (this is due to assumption $A2$ and cost symmetry). In low demand states, the equilibrium is symmetric, each firm has excess capacity; as θ increases each firm's capacity starts to bind, in increasing order (the smallest firm first). For each firm we can define two thresholds $\theta^{i-}$and θ^{i+} as function of the vector of capacities, such that $q_h^i < k^i$ iff $\theta < \theta^{i-}$ and $q_f > 0$ iff $\theta > \theta^{i+}$.

Lemma 1 *With n firms, there is a unique equilibrium which is symmetric.*

Proof. We first show that any equilibrium of the game is symmetric; then, we prove uniqueness of the equilibrium.

• To show symmetry we proceed by contradiction. Let us assume that there is an equilibrium in which two firms A and B have different capacity $k^A < k^B$. In that case, $\theta^{A-} < \theta^{B-}$ and $\theta^{A+} < \theta^{B+}$, the comparison between θ^{A+} and θ^{B-} is ambiguous.

Let us show that, in each demand state, the marginal short-term profit of firm A is larger than that of firm B because:

- in low demand states in which both firms have excess capacity and in high demand states in which both import, their marginal revenues are equal;

- in intermediary states in which both produce at full capacity $p + \frac{\partial p}{\partial q} k^A > p + \frac{\partial p}{\partial q} k^B$ because p is decreasing with respect to q.

- if firm A has excess capacity but firm B does not, or firm A imports but firm B does not, the marginal revenue of firm A is strictly higher than that of firm B.

Therefore, the expected marginal short-term profit of firm A is strictly larger than that of firm B and since, at equilibrium, both should be equal, this is a contradiction.

• Then we show uniqueness by showing that at a symmetric equilibrium the total capacity is a solution of an equation that admit a unique solution.

At a symmetric equilibrium, with total capacity k^*, in low demand states, firms play a Cournot game with identical marginal cost c_h. All firms capacity constraint start being binding simultaneously in a state θ^- such that the individual marginal revenue is equal to the marginal cost: $p(k^*, \theta^-) + \frac{\partial p}{\partial q}(k^*, \theta^-)\frac{k^*}{n} = c_h$; and they start importing simultaneously in the same state θ^+ in which the individual marginal revenue is equal to the import price;

in higher demand states each firm total production is equal to the Cournot production with marginal cost c_f. Consequently, the equilibrium total capacity k^* is the solution of the first order condition:

$$0 = \int_{\underline{\theta}}^{\theta^-} -c_k d\theta + \int_{\theta^-}^{\theta^+} \left[p(k,\theta) + \frac{\partial p}{\partial q}(k,\theta)\frac{k}{n} - c_h - c_k \right] d\theta + \int_{\theta^+}^{\bar{\theta}} (c_f - c_h - c_k) d\theta.$$

By assumption (A1), there is a unique solution to this equation.

• Finally, existence is proved by construction. The solution of the above equation exists and this capacity together with Cournot quantities are an equilibrium. ■

Corollary 1 *With n firms, if θ is homogeneously distributed over $[-\lambda, \lambda]$, the equilibrium capacity is increasing (resp. decreasing) with respect to λ if $c_f \leq c_h + 2c_k$ (resp. $c_f \geq c_f - 3c_k$).*

Proof.

The proof is similar to the monopoly case, rewriting the first order condition for an homogeneous distribution:

$$0 = \int_{-\lambda}^{\theta^-} -c_k d\theta + \int_{\theta^-}^{\theta^+} \left[p(k,\theta) + \frac{\partial p}{\partial q}(k,\theta)\frac{k}{n} - c_h - c_k \right] d\theta + \int_{\theta^+}^{\lambda} (c_f - c_h - c_k) d\theta.$$

■