

## The Slow Growth of New Plants: Learning about Demand?\*

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### **Abstract**

One of the most consistent findings in the literature using business-level microdata is that average plant sizes vary considerably with age. New plants tend to be much smaller than established plants in the same industry, and their size convergence tends to be slow—taking well over a decade in some cases. We show that this is not due to productivity gaps. Indeed, new plants are just as technically efficient as, if not more than, older plants. They are small in spite of their prices, not because of them. The size patterns thus appear to be tied to differences in demand-side fundamentals. New plants start with a considerable demand deficit and only slowly erase it over time (if they survive). We document the patterns in plants' idiosyncratic demand levels, and explore the sources of their variance across plants and growth rates within them. We estimate a dynamic model of plant growth behavior in the presence of a "demand accumulation" process (e.g., building a customer base) that is affected by plants' past production decisions. We find interesting differences in the levels and growth rates of plants depending on the types of firms that own them.

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## 1. Introduction

The large literature using business-level microdata to study various aspects of production behavior has, without exception, found considerable differences between producers in a given industry. Enormous heterogeneity has been documented along many dimensions. One of the more consistent findings is that entrants are different than incumbents, with particular regard to size. New plants tend to be considerably smaller than plants that are already established in the industry (e.g., Dunne, Roberts, and Samuelson (1989), Caves (1998)). These patterns are tied to several facets industry evolution, from features of industry lifecycles to how the growth of individual producers impacts industry aggregates.

In this paper, we look more closely at the sources of the size gaps between young and old plants. While earlier work has focused on productivity/cost differences as an explanation (see Bahk and Gort (1993), for example), this does not seem likely to be an explanation. We found in Foster, Haltiwanger, and Syverson (2008) that new plants' physical total factor productivity levels are as high as—and often even slightly higher than—older plants'. That is, entrants are just as technically efficient as their more experienced competition. They are small *in spite of* their prices, not because of them. (Their prices in fact actually tend to be lower.)

This similarity in supply-side fundamentals points to the likelihood of idiosyncratic demand factors explaining plant size differences. We document some evidence of this importance in our earlier work. There is a clear dichotomy between the age profiles of plants' productivity and demand-side fundamentals. Unlike their closeness to established plants in technical efficiency, young plants' idiosyncratic demand levels are much lower. In addition to the large size of the idiosyncratic demand gaps, these gaps converge very slowly over time. There is no such slow convergence in supply side fundamentals.

These patterns can be seen in Table 1, which is an extract from Table 5 in Foster, Haltiwanger, and Syverson (2008). It shows the evolution of physical total factor productivity (TFP)—i.e., units of output per unit input—and idiosyncratic demand across plants of various ages. Plant-level demand can be thought of as the units of output a plant would sell relative to other plants in its industry, if all plants charged a common, fixed price. (Further details of the construction of the sample and the variables follow below.) We use four age categories.

“Entrants” are plants appearing for the first time in the Census of Manufactures (CM).<sup>1</sup> “Young” establishments are those that first appeared in the census prior to the current time period; that is, they were entrants in the previous census. Establishments first appearing two censuses back are “medium” aged, and establishments that first appeared three or more censuses prior are classified as “old.” Plants that will exit (die) by the next CM are placed in their own category. We separately regress plants’ TFP and idiosyncratic demand levels on dummies for each age category (old plants are the excluded category), along with a full set of industry-year fixed effects.

The results indicate that entering plants have physical TFP levels slightly above established (“old”) incumbents. This TFP advantage is indistinct from zero, however, by the time plants are at least five years old. (Consistent with a large literature, we also find that exiters of any age are less efficient than incumbents.) The patterns are very different for plants’ idiosyncratic demands. The estimate on the entrant dummy implies that at the same price, a new plant will sell only 57 percent ( $e^{-0.5557} = 0.574$ ; the demand measure’s units are logged output) the output of a plant more than 15 years old. This gap closes very slowly. Young plants (five to nine years old) would sell 67 percent of the output of an old plant, and even plants 10-15 years old would only sell 73 percent as much.

We explore the sources of this demand gap and its slow convergence here. Our proposed explanation involves dynamic demand side forces—growth of a customer base or building a reputation, for example—that take considerable time to play out. Caminal and Vives (1999) and Radner (2003) model examples of such processes. These forces lead to gradual growth of an entrant’s “demand stock” (at least among entrants good enough to survive). The uncertainties tied to such processes may also create an option value to the plant of waiting to expand until further information about the demand process is revealed (e.g., Dixit and Pindyck (1994)). It is also likely that the rate of demand stock growth and the level of uncertainty are related to the characteristics of a plant or the firm that owns it.

Our view of the customer learning that would drive demand stock growth is much broader than the simple process of discovering the existence of a producer. While spotty information about mere existence might be consistent with the large gaps in idiosyncratic

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<sup>1</sup> Because the CM includes all manufacturing plants in the U.S., we observe all entry and exit, though only at five-year intervals.

demand present at plants' births, it seems unlikely to explain why convergence takes upwards of 15 years. We posit that learning involves much deeper components, like details of producers' product attributes, the quality and quantity of their bundled services, the consistency of their operations, their expected longevity, and so on. Having to learn about these features can impart considerable inertia into producers' demand stocks.

This paper fits into a new line of research (e.g., Eslava et al. (2006); Das, Roberts, and Tybout (2007); and Foster, Haltiwanger, and Syverson (2008)) that has extended the large literature tying productivity to plant and firm survival (see Bartelsman and Doms (2000) for an earlier literature summary) to explicitly account for demand-side effects on the growth and survival of plants. Further, this literature also suggests a reinterpretation of productivity's effects as inferred from standard measures, because typical productivity measures incorporate demand-side shocks through their (often necessary because of data limitations) inclusion of producer prices in the output measure.

Our empirical analysis is two-pronged. We first document the evolution of plants' idiosyncratic demand fundamentals in an atheoretic way. Once these facts are established, we posit a simple dynamic model of producers' decisions in the face of a dynamic demand process, and estimate the model using producers' behavior in our data. In the model, producers observe realizations of a stochastic demand process and then choose output levels that in turn feed back into future sales through a demand stock accumulation process. The model generates an Euler equation describing establishments' incentives for investing in this sort of demand capital. We then use the Euler equation and the demand specification to estimate the model's parameters. These models are informative about the sources of demand growth as well as their relative magnitudes, and allow us to run counterfactual simulations.

Our preliminary results show that while almost all entrants have lower idiosyncratic demand levels than incumbents, the gap is especially large for those owned by small or less experienced firms. Demand convergence rates do differ across plants in different types of firms, but all exhibit limited speed of catching up to their more established competitors. Perhaps these patterns reflect large or established firms' pre-existing "brand capital" imparting higher initial demand levels and perhaps faster customer base growth.

The paper proceeds as follows. The next section describes data and measurement issues. Section 3 documents basic empirical facts about the evolution of producers' idiosyncratic

demands in our sample. Section 4 describes the empirical model that we estimate using plants' dynamic choices. The results are discussed in Section 5, and Section 6 concludes.

## 2. Data and Measurement Issues

This paper uses the same data set of homogenous goods producers we used in Foster, Haltiwanger, and Syverson (2008). Details on the selection of our sample and construction of the variables we use are in that paper as well as the Appendix, so we only highlight key points here.

The data is an extract of the U.S. Census of Manufactures (CM). The CM covers the universe of manufacturing plants and is conducted quinquennially in years ending in "2" and "7". We use the 1977, 1982, 1987, 1992, and 1997 CMs in our sample based upon the availability and quality of physical output data. Information on plants' production in physical units is important because we must be able to observe plants' output quantities and prices, not just total revenue (which is often the only output measure available in producer microdata). The CM collects information on plants' shipments in dollar value and physical units by seven-digit SIC product category.<sup>2</sup>

The 17,669 plant-year observations in the sample include producers of one of eleven products: corrugated and solid fiber boxes (which we will refer to as "boxes" from now on), white pan bread (bread), carbon black, roasted coffee beans (coffee), ready-mixed concrete (concrete), oak flooring (flooring), gasoline, block ice, processed ice, hardwood plywood (plywood), and raw cane sugar (sugar).<sup>3</sup> These products were chosen because their physical

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<sup>2</sup> A problem with CMs prior to our sample is that it is more difficult to identify balancing product codes (these are used to make sure the sum of the plant's product-specific shipment values equals the plant's separately reported total value of shipments). Having reliable product codes is necessary to obtain accurate information on plants' separate quantities and prices, important inputs into our empirical work below. A related problem is that there are erratic time series patterns in the number of establishments reporting physical quantities, especially in early CMs. We thus choose to focus on the data in 1977 and beyond. However, we do use revenue data from prior censuses as far back as 1963 when constructing plants' ages and demand stocks  $Z_t$ .

<sup>3</sup> Our product definitions are built up from the seven-digit SIC product classification system. Some of our eleven products are the only seven-digit product in their respective four-digit SIC industry, and thus the product defines the industry. This is true of, for example, ready-mixed concrete. Others are single seven-digit products that are parts of industries that make multiple products. Raw cane sugar, for instance, is one seven-digit product produced by the four-digit sugar and confectionary products industry. Finally, some of our eleven products are combinations of seven-digit products within the same four-digit industry. For example, the product we call boxes is actually comprised of roughly ten seven-digit products. In cases where we combine products, we base the decision on our impression of the available physical quantity metric's ability to capture output variations across the seven-digit

homogeneity. This allows plants' output quantities and unit prices to be more meaningfully compared.

Note that physical homogeneity does not necessarily imply that producers operate in an undifferentiated product market. Prices vary within industries because, for instance, geographic demand variations or webs of history-laden relationships between particular consumers and producers that create producer-specific demand shifts. Further, as we have already shown, quantities sold differ tremendously even holding price fixed. Trying to explain *why* they differ is the very point of our analysis. Our quantity data are meaningful not due to the complete absence of differentiation, but rather because there is no differentiation along the dimension in which we measure output—the physical unit. The notion behind the selection of our sample products is that a consumer should be roughly indifferent between unlabeled units of the industry output. But that does not rule out consumers view as equivalent other products or services (real or perceived) that are tied to those units of output. Much of such differentiation, we argue in our earlier work, is horizontal rather than vertical in nature.

## 2.1. Idiosyncratic Demand: Concept and Measurement

The plant-level idiosyncratic demand measures that we used in Table 1 above and that we will use in our descriptive analysis in the next section are obtained by estimating demand for each of the eleven products in our sample. We describe this process briefly here; again, details can be found in Foster, Haltiwanger, and Syverson (2008).

We begin by estimating the following demand system separately for each of our eleven products:

$$(1) \quad \ln q_{it} = \alpha_o + \alpha_1 \ln p_{it} + \sum \alpha_t YEAR_t + \alpha_2 \ln(INCOME_{mt}) + \eta_{it},$$

where  $q_{it}$  is the physical output of plant  $i$  in year  $t$ ,  $p_{it}$  is the plant's price, and  $\eta_{it}$  is a plant-year specific disturbance term. We also control for a set of demand shifters, including a set of year dummies ( $YEAR_t$ ), which adjust for any economy-wide variation in the demand for the product, as well as the average income in the plant's local market  $m$ . We define local markets using the

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products without introducing serious measurement problems due to product differentiation. The exact definition of the eleven products can be found in the Appendix.

Bureau of Economic Analysis' Economic Areas (EAs).<sup>4</sup>

Plant quantities are simply their reported output in physical units. We calculate unit prices for each producer using their reported revenue and physical output.<sup>5</sup> These prices are then adjusted to a common 1987 basis using the revenue-weighted geometric mean of the product price across all of the plants producing the product in our sample.

Of course, estimating the above equation using ordinary least squares (OLS) methods could lead to positively biased estimates of the price elasticity  $\alpha_1$ . Producers may optimally respond to demand shocks in  $\eta_{it}$  by raising prices, creating a positive correlation between the error term and  $p_{it}$ . A solution to this is to instrument for  $p_{it}$  using supply-side (cost) influences on prices. While such instruments can sometimes be hard to come by in practice, we believe we have very suitable instruments at hand: namely, plants' physical TFP levels. These embody producers' idiosyncratic technical efficiency levels—their physical production costs. As such, they should have explanatory power over prices. They do. The correlation between plants' physical TFP and prices in our sample is -0.54. Further, it is unlikely they will be correlated with any short-run plant-specific demand shocks embodied in  $\eta_{it}$ . Hence they appear quite suitable as instruments for plant prices.<sup>6</sup>

The price and income elasticity estimates from the above demand equation are not reported here for space reasons, but are available in Foster, Haltiwanger, and Syverson (2008). The estimates are reassuring about our estimation strategy. All estimated price elasticities are negative, and for all but carbon black, they exceed one in absolute value. This is what one should expect; price-setting producers should be operating in the elastic portion of their demand curves. (Carbon black's inelastic point estimate may be due to the small number of producers of that product in our sample; we cannot in fact reject that carbon black producers face elastic

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<sup>4</sup> EAs are collections of counties usually, but not always, centered on Metropolitan Statistical Areas. The 172 EAs that are mutually exclusive and exhaustive of the land area of the United States. See U.S. Bureau of Economic Analysis (1995) for detailed information.

<sup>5</sup> The reported revenues and physical quantities are annual aggregates, so the unit price is an annual average. This is equivalent to a quantity-weighted average of all transaction prices charged by the plant during the year.

<sup>6</sup> There are two potential problems with using physical TFP as an instrument. The first is that selection on profitability can lead to a correlation between TFP and demand at the plant level, even if the innovations to both series are orthogonal as assumed. Producers with a higher TFP draws can tolerate lower demand draws (and vice versa) while still remaining profitable. The second potential problem is measurement error. We compute prices by dividing reported revenue by quantity and any measurement error in physical quantities will overstate the negative correlation between prices and physical TFP, potentially contaminating the first stage of the IV estimation. We describe in Foster, Haltiwanger, and Syverson (2008) how we deal with these issues. We found the patterns of demand estimates to be quite robust, reducing concerns about either measurement issue.

demand.) Further, all products, again except for carbon black, have more elastic IV demand estimates than in the OLS estimations. This is consistent with the theorized simultaneity bias present in the OLS results as well as the ability of TFPQ to instrument for endogenous prices.

The idiosyncratic demand estimates for our sample plants are simply the residual from this IV demand estimation, along with the estimated contribution of local income added back in. Thus the measure essentially captures across-plant output variation that reflects shifts in the demand curve rather than movements along the demand curve.

The dispersion of our producer-specific demand measure is huge. Its within-product-year standard deviation is 1.16 (recall the measure's units are logged output). This implies that a plant sells 3.2 times as much output at a given price as another in its industry that is one standard deviation lower in the idiosyncratic demand distribution. By way of comparison, the comparable standard deviations of logged physical TFP and logged prices are 0.26 and 0.18, respectively.

### **3. Facts about Plants' Idiosyncratic Demands**

In this section, we expand on the exercise done in Table 1 to explore how the relative levels and convergence of idiosyncratic demand levels change with plants' attributes. As briefly mentioned above, a possible source of differences in idiosyncratic demand patterns are the types of firms that own the plants. Dynamic demand effects from customer learning or other similar processes might be impacted by the type and form firms to which plants are tied.

Consider the following example. Two new plants are built in an industry. One is a *de novo* entry by a firm with no prior experience; the other is opened by a firm with considerable history in the industry (though perhaps in a different local market). We might expect that the latter will enter with a higher idiosyncratic demand, because customers may already be familiar with the plant's product (or at least its firm). This might also impact the speed at which demand convergence occurs.

To begin exploring these possibilities, we again project plants' idiosyncratic demand measures on plant age indicators, but this time interact those indicators with variables tied to characteristics of the firms that own the plants. In the first specification, we will simply allow the age dummies to differ for plants that are part of a multi-plant firm. (The firm's other plants need not make the same product, or even be manufacturers for that matter.) This is a crude proxy for firm size. The second specification will use a series of dummies for the age of *the*



*firm*, defined as the age of the firm's oldest plant. These will be interacted with the plant age dummies. The notion is that plants of older, more established firms may start larger and grow faster than those of newer firms. (Again, the remainder of the firm's activities need not be in the same industry. In future drafts, we will break this out specifically, allowing not only firm age, but the firm's length of producing the plant's particular product, to affect plant idiosyncratic demand.)

The results looking at the impact of multi-unit firm status are shown in Table 2. The upper row shows the coefficients on the age categories, the lower those for the age categories interacted with the multi-plant firm indicator. Hence the upper row reflects the evolution of idiosyncratic demand for single-unit plant/firms, while the column-wise sum of the two rows' values shows the same evolution for plants in multi-plant firms (multi-plant firms account for 59 percent of the observations in our sample). Note here that the excluded group is different from that in Table 1. There, it was all "old" plants (those having first appeared three or more CMs prior, and who are therefore at least 15 years old). Here, it is only old plants in single unit firms. Hence the age coefficients show groups' average idiosyncratic demands relative to this group rather than all old plants. Since, as we will see, old plants in multi-plant firms are the largest plants in our sample, their separation from the excluded group will be noticeable.

The results are interesting. Single-unit plants exhibit similar patterns to those seen before. Entrants have considerably smaller idiosyncratic demand levels than do established incumbents; they sell 27 percent less output at a given price than do old single-unit plants, and undersell old multi-unit plants by 58 percent. There is some convergence between entry and being 5-9 years old ("young"), where single-unit plants have demand levels 16 percent below old single-unit plants. But then convergence largely stalls; medium-aged plants still have 14 percent demand deficits.

For plants in multi-plant firms, similar qualitative relationships are present, but their demand levels are higher than single-unit plants at every age. That said, they're still considerably smaller than old plants in multi-unit firms, with average demand levels that are only two-thirds that of their older counterparts. Convergence is similarly slow among multi-unit plants. (Interestingly exiting plants in multi-unit firms have lower average demand levels than single-unit exiters. We will see this inversion again below in the interaction with firm age.)

It therefore appears that new plants in small firms (by our crude measure) face significantly lower idiosyncratic demand levels than do their new competitors in multi-plant firms. Nevertheless, both types of plants see the inertial convergence patterns observed in the broader sample, suggesting demand dynamics are at work in both cases.<sup>7</sup>

Estimating the interactions between firm and plant age yields the results in Table 3. A fully interacted model with four plant and firm age categories each, for both single- and multi-unit firms, would unfortunately create some subsample cells that are too small to be useful for identification and would possibly violate data confidentiality standards. We therefore pool some categories together. First, we only break out firm age effects for plants in multi-unit firms. Further, we pool firms that are young- or medium-aged (i.e., whose first plant was observed either one or two CMs prior). Note also that some plant-firm-age categories cannot exist by definition, and are such missing from the estimation. There cannot be a medium-aged plant in an entering or young firm, for example. Old plants in single-unit firms are again the excluded group.

Focusing on the multi-unit plant results in the bottom three rows, we see that among firms that are at least 15 years old, the basic convergence patterns seen before hold here as well. Entering plants of old firms have demand levels that are 63 percent of old plants in this type of firm. Growth is slow for the first five years: old firms' young plants have 65 percent of the demand level. Demand growth accelerates after this somewhat, but medium-aged plants still have notably (24 percent) lower demand levels.

For young- and medium-aged firms, we also observe that entrants are smaller than longer-lived plants in such firms (though there can be no old plants in these firms). Notice, too, that plants in young- and medium-aged firms have lower demands than plants of the same age in older firms. The only result that is not in accordance with these general patterns across firm and plant ages involves entering plants in entering multi-unit firms. While as might be expected their demand levels are smaller than that of old plants in old firms (on average 68 percent of the level), they have higher idiosyncratic demands than entering plants in older firms. Another

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<sup>7</sup> Of course, single-unit plants are not restricted to remaining in single-unit firms their entire life, nor for that matter are multi-unit plants restricted to those type of firms. The more common transformation between these is for a plant in a single-unit firm to become part of a multi-unit firm, either through acquisition by another firm or through its own firm acquiring additional plants. From this perspective, the low demand levels and slow convergence of single-unit entrants becomes even starker, vis-à-vis their demand levels relative to old plants in multi-unit firms.

interesting result is that exiting plants in old firms tend to be exceptionally small—smaller, in fact than entering single-unit plants.

The results in Table 3 show there are nontrivial distinctions in the levels and growth of plant demand in firms of different ages. The broadest pattern is one of older firms being tied to higher demand levels at any plant age, just as with firm size again. But also as with the firm-size results above, the demand gaps are still large within any firm type, and these diffuse demands close only slowly over time.

While these results themselves do not uniquely identify an explanation for the patterns seen in the evolution of plants' idiosyncratic demand levels, they are consistent with the dynamic demand model. We will explore more specific possibilities further in future drafts in exercises like those above done with a greater array of firm attributes. There are several possible avenues. We will, for example, see if distinctions in plant demand growth exist between firms not just of different ages, but with different prior experiences in making the plant's particular product. (We observe the product-by-product production history of every plant, making this measurement possible.) When a new plant's firm already makes the same product at other locations, consumers' familiarity with the firm and its ability to make the new plant's product should make demand spillovers more likely, and lead to faster demand growth if these spillovers matter. This product-level effect may be distinct from the broader firm-level mechanisms hinted at in our Table 3 results above.

Another approach is to account for geography explicitly. Several of our sample products have localized markets (e.g., concrete, ice, and boxes). We can measure whether new producers are in marginal locations by comparing their sales to more established producers in the same area within the market. Further, if other evidence suggests demand spillovers in customer bases are important, we will be able to see the role that physical proximity to the firms' other plants plays in determining their magnitudes.

#### **4. Model**

The analysis above shows various relationships between the attributes of plants and firms and the evolution of producers' idiosyncratic demand levels. Many of the patterns suggest dynamic demand factors are at play—perhaps involved with producers having to build a customer base or reputation, for instance. To address the inherent dynamics more directly, we

now pose a model that explicitly builds in a dynamic demand process that has both exogenous components and a component that is affected by the producer's choices. We will estimate this model using the growth patterns of producers in our dataset to obtain guidance as to the specific sources of demand growth.

We assume the plant faces an isoelastic contemporaneous demand curve:

$$(2) \quad q_t = \theta_t \text{Age}_t^\phi Z_t^\gamma p_t^{-\eta},$$

where  $p_t$  is the current price charged by the plant. Several factors shift the demand curve.  $\theta_t$  is an exogenous demand shock that we assume follows an AR(1) process.  $\text{Age}_t$  is the plant's age. Along with parameter  $\phi$ , this accounts for deterministic changes in plants' demand as they age. Finally,  $Z_t$  is a demand shifter that with parameter  $\gamma$  links a plant's current activity to its future expected demand level. Specifically, we assume that  $Z_t$  evolves according to the following process:

$$(3) \quad Z_t = (1 - \delta)Z_{t-1} + (1 - \delta)R_{t-1}.$$

Thus,  $Z_t$  is a sort of operating history of the plant. It grows with past plant sales  $R_t$  (defined as  $p_t q_t$ ), subject to depreciation at a rate  $\delta$ . This process captures dynamic demand processes where a plant's *potential* customer base is related to its past sales activity. For instance, the process embodies many types of "word of mouth" effects consumers are more likely to have heard about a producer or its product if it has operated more in the past. This specification of learning nests the specification common in the literature where learning depends on cumulative output by setting  $\delta=0$ . We consider both the latter and the more general specification in our estimation.

The plant's production function is given by

$$(4) \quad q_t = A_t x_t,$$

where  $q_t$  is the plant's output,  $A_t$  is its TFP level, and  $x_t$  is its input choice. This input can be thought of as a composite of labor, capital, energy, and materials inputs, weighted appropriately. (For example, if the technology is Cobb-Douglas and there are constant returns to scale, the composite would be the plant's inputs raised to their respective input elasticities.)

The plant faces two costs: a factor cost of  $c_t$  per unit of  $x_t$  and a fixed operating cost of  $f$  per period. This, along with the production function, implies the plant's periodic profit function is

$$(5) \quad \pi_t = p_t A_t x_t - c_t x_t - f.$$

Using the demand curve to substitute in for price and simplifying, we have

$$(5a) \quad \pi_t = \theta_t^\eta \text{Age}_t^\eta Z_t^\eta (A_t x_t)^{1-\frac{1}{\eta}} - c_t x_t - f.$$

The plant manager maximizes the present value of the plant's operating profits.<sup>8</sup> This problem can be expressed recursively as follows:

$$(6) V(Z_t, A_t, \text{Age}_t, \theta_t) = \max \left\{ 0, \sup_{x_t} \theta_t^\eta \text{Age}_t^\eta Z_t^\eta A_t^{1-\frac{1}{\eta}} x_t^{1-\frac{1}{\eta}} - c_t x_t - f + \beta EV(Z_{t+1}, A_{t+1}, \text{Age}_{t+1}, \theta_{t+1}) \right\},$$

where  $V(\cdot)$  is the plant's value given state variables.  $Z$  is endogenously affected by the plant's input choices; the plant's age, TFP, and demand shock  $\theta_t$  evolve exogenously. The future is discounted by a factor of  $\beta < 1$ .

The plant's continuation decision is made explicit in (6): it can operate and earn the profits this entails (the second item in the braces), or it can exit and earn the outside option (normalized to zero here). If it chooses to operate, it takes as given its past operating history as summarized in  $Z_t$  and chooses current inputs  $x_t$  to maximize its present value. Because of the form of the production function and the demand curve, this choice of  $x_t$  simultaneously pins down the plant's output and its price as well.

The dynamics inherent in the plant's choice problem are apparent: by producing more today, the plant can shift out its demand curve tomorrow. The optimal production level (equivalently: the optimal price) in this case will be higher (lower) than that implied by a purely static problem where current price is not tied to future demand. This is consistent with what we found in Foster, Haltiwanger, and Syverson (2008): young plants had lower average prices than older plants in the same industry.

Optimal dynamic behavior (the plant's  $x_t$  trajectory) conditional on survival is given by the Euler equation implied by the supremum in (6):

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<sup>8</sup> We abstract from any agency issues that may arise between plants' managers and the owners of these establishments (if they are different people).

$$\begin{aligned}
(7) \quad & \frac{c_t}{(1-\delta)p_t A_t} - \frac{1}{1-\delta} \left(1 - \frac{1}{\eta}\right) \theta_t^\eta \text{Age}_t^\eta Z_t^\eta (A_t x_t)^{-\frac{1}{\eta}} p_t^{-1} \\
& = \beta E \left\{ \theta_{t+1}^\eta \text{Age}_{t+1}^\eta Z_{t+1}^\eta (A_{t+1} x_{t+1})^{-\frac{1}{\eta}} p_{t+1}^{-1} \left[ \frac{\gamma}{\eta} \frac{p_{t+1} A_{t+1} x_{t+1}}{Z_{t+1}} - \left(1 - \frac{1}{\eta}\right) \right] + \frac{c_{t+1}}{p_{t+1} A_{t+1}} \right\}.
\end{aligned}$$

This expression is slightly unwieldy. Moreover, it includes a state variable  $\theta_t$  that is observable to the plant manager but unobserved by us.<sup>9</sup> While there are techniques for estimating Euler equations with unobserved state variables, it is preferable to work only with observables.

Fortunately, we use the demand curve to substitute for the unobservable. We solve (2) for  $\theta_t$  and substitute the result into (7). This yields, after some algebra,

$$(7a) \quad \frac{c_t}{p_t A_t} - \left(1 - \frac{1}{\eta}\right) = \frac{\beta(1-\delta)\gamma}{\eta} \frac{1}{Z_{t+1}} E[R_{t+1}] + \beta(1-\delta) \left\{ E \left[ \frac{c_{t+1}}{p_{t+1} A_{t+1}} \right] - \left(1 - \frac{1}{\eta}\right) \right\}.$$

The intuition behind the plant's optimal dynamic behavior can be seen in this simplified Euler equation. The first term on the left hand side is the inverse of the plant's price-cost ratio (note that the production function implies the plant's marginal cost is  $c_t/A_t$ ). The second term is a function of the elasticity of demand familiar as the inverse of the optimal markup for a firm facing a residual demand elasticity of  $-\eta$ . Thus the left hand side of the equation, in a completely static production/pricing optimization problem, would be zero. It is not generally so here, and that is because of the dynamics discussed above. Since the plant shifts out its demand curve tomorrow by making more sales today, it will want to markup price less over marginal cost than it would in a static world to induce extra sales. (Another way to think about this is that its marginal revenue now isn't just that implied by the contemporaneous demand function, but now also includes the discounted expected increase in future demand from the growth in "demand stock"  $Z$ ). With a lower markup than implied by the static markup rule, the cost-price ratio in the first term will be larger than the second term, and thus the left hand side generally positive.

The first right-hand-side term is a parameter-dependent constant multiplied by the ratio of the plant's expected next-period revenue and its operating history captured in  $Z_{t+1}$ . ( $Z_{t+1}$  is not

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<sup>9</sup> We observe all the other state variables in our dataset, the Census of Manufactures (CM) microdata. Age, by five-year categories, is available because we have a census of all establishments every fifth year.  $A$ , total factor productivity, can be measured from the plant's reported output and inputs.  $Z$ , the plant's sales history, can be constructed (given a value for  $\delta$ ) from the plant's sales reported in past CMs.

preceded by an expectation operator because it is solely a function of period- $t$  values; see (3).) This term is positive as long as the exogenous impact of age on demand is positive.

The second term on the right hand side is the same markup function as that on the left hand side of the Euler equation, except it is for prices and costs in the next period. Of course, being in the future, it is affected by discounting and the depreciation of  $Z_t$ , and it holds in expectation rather than ex-post. Again, this term would be zero in a static setting but is positive here.

When the first right-hand-side term is positive, the second term will be less than the current-period inverse markup expression. Thus it is possible that the future markup expression in the braces will be lower than its current-period counterpart—i.e., the price-cost ratio will be higher in the next period. Thus the plant reduces the extent to which it underprices for future demand. As the plant ages, the ratio of its next period revenue to its demand stock  $Z_{t+1}$  will fall. This will drive the first right-hand-side term toward zero. In the limit, the only stable dynamic path will be for the plant to set its markup equal to the static rule, setting all terms in the Euler equation equal to zero. Thus we should expect young plants to have the smallest margins, and then see them rise to the short-term optimum as the plant ages. How fast margins rise is a function of the depreciation rate of the plant's demand stock.

#### 4.1. Estimation

To estimate the model's parameters we consider two complementary approaches. First, we consider estimating the key demand parameters from the demand equation (2) alone. This approach has the virtue that all of the parameters of interest are potentially identified from estimation of the demand equation alone. We then impose the additional structure from equation (7a), the Euler equation. The Euler equation exploits different variation in the data and imposes additional structure but as will become clear below not all of the parameters are identified by the Euler equation alone.

A basic measurement and estimation issue for both the demand and Euler equations is to construct measures of the demand stock,  $Z$ . Here we note that that we observe plant revenues in every Census of Manufactures back to 1963. Thus  $R_t$  is directly observable and past revenues can be used to construct the plant's demand stock  $Z_t$  as a function of past sales and the depreciation rate:

$$(3a) \quad Z_t = (1 - \delta)^\tau Z_{t-\tau} + \sum_{i=1}^{\tau} (1 - \delta)^i R_{t-i},$$

where  $\tau$  is the number of periods the plant has operated.<sup>10</sup>

Now consider the measurement and econometric issues specific to estimating the demand equation (2). One reason for needing to estimate the demand equation as well is that the effect of age on plant demand  $\phi$  in the simplified Euler equation (7a) is missing. Note that while equation (7) —the version of the Euler equation with the plant’s unobservable state variable  $\theta_t$ — includes all of the model’s parameters, equation (7a) is missing  $\phi$ , the effect of age on plant demand. Substituting out for  $\theta_t$  using the demand curve caused the  $Age_t$  terms to cancel. However, we can still recover  $\phi$  as well as impose additional structure on the data to estimate the other model parameters by estimating the demand equation.

In considering estimating the demand equation (2), we must address the issue of endogeneity. The RHS variables of (2) include endogenous plant level prices as well as state variables  $Z$  and age that in the presence of serially correlated demand shocks are correlated with the unobserved demand shock. To deal with these issues, we first take logs of (2) which yields:

$$(2a) \quad \ln q_{t+1} = \theta_{t+1} + \phi \ln Age_{t+1} + \gamma \ln Z_{t+1} - \eta \ln p_{t+1}$$

where we have dated the demand equation in  $t+1$  without loss of generality to keep the timing of the estimation of the demand equation consistent with the Euler equation. We assume that the unobserved demand shock follows an AR1 process:

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<sup>10</sup> We face a number of practical constraints in the construction of  $Z_t$ . The first is that while our sample estimation period focuses on the 1982-97 period there are some plants that have been in existence since 1963 so that our measures of  $Z$  are left-censored. This is an issue that is mitigated by depreciation but still a real issue since about a third of our plant-year observations are left-censored in 1963 in this fashion. To deal with this issue in this draft we simply estimate the model with and without left censored cases to obtain a sense of the importance of this issue. A second estimation issue is that we do not observe plant sales in the four years between censuses. Hence we can only build  $Z$  stocks using observed revenues. Essentially, we are assuming that sales are constant between censuses and ignore the impact of depreciation in the intervening years. We expect the fact that the cross-sectional variation in sales tends to swamp any intertemporal variation within plants to mitigate this measurement problem. Third, our Euler and Demand estimation approaches is based on plants observed in years  $t$  and  $t+1$  and in an associated fashion plants that have all variables in equations (2b) and (7c) available in periods  $t$  and  $t+1$ . As we discuss in the text, this implies that we need to deal with such selection in the estimation of (2b) and (7c) which we plan to address in future drafts. A related measurement issue is how to initialize  $Z$  for entrants. In this draft, we finesse this issue since we base the estimation on plants that exist in periods  $t$  and  $t+1$  and also have positive lagged revenue in both of those periods. As such, only plants with positive revenue in period  $t-1$  are included in the estimation so that in both  $t$  and  $t+1$   $Z$  is well defined based on cumulative lagged revenue.



$$(8) \quad \theta_{t+1} = \rho\theta_t + v_{t+1}$$

where  $v_{t+1}$  is iid. We then quasi-difference the demand equation (2a) so that we have:

$$(2b) \quad \ln q_{t+1} = \rho \ln q_t + \phi \ln Age_{t+1} - \rho\phi \ln Age_t + \gamma \ln Z_{t+1} - \rho\gamma \ln Z_t - \eta \ln p_{t+1} + \rho\eta \ln p_t + v_{t+1}$$

The residual from the quasi-differenced demand equation (2b),  $v_{t+1}$ , is the innovation to the unobserved demand shock and as such will be uncorrelated with variables dated  $t$  and earlier and also uncorrelated with instruments dated in  $t+1$  that are correlated with the RHS variables of (2b) but uncorrelated with the innovation to demand shocks. As discussed (and implemented) in section 2.1, a valid instrument for plant-level prices in the demand equation is physical productivity (what we refer to as TFPQ) and we use this instrument here as well. We note that demand estimation relies on variations (both across plants and within plants over time) in age, past revenues, and cost-driven price shifts for identification. A challenge in the estimation of (2b) is to obtain sufficient variation in the data to identify separately the dynamics of the unobserved demand shock, the role of plant age and the role of learning about demand through experience. It is partly for these identification challenges that we seek to also exploit the variation important for identification of the Euler equation, (7a).

For the estimation of (7a), we note that it can be further simplified by multiplying both the numerator and the denominator of the cost-price ratio by the plant's quantity – then the ratio becomes the plant's total variable costs as a share of revenue. That is,

$$(7b) \quad \frac{C_t}{R_t} - \left(1 - \frac{1}{\eta}\right) = \frac{\beta(1-\delta)\gamma}{\eta} \frac{1}{Z_{t+1}} E[R_{t+1}] + \beta(1-\delta) \left\{ E\left[\frac{C_{t+1}}{R_{t+1}}\right] - \left(1 - \frac{1}{\eta}\right) \right\},$$

where  $C_t$  are total variable costs. Both plants' variable costs and revenues are readily observable in our data.<sup>11</sup> Thus we can observe in our data all of the components of the Euler equation, up to parameters.

To estimate the Euler equation, we assume that the expectation errors are additively separable, and that their mean is zero at the true parameter values. This gives us the moment condition:

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<sup>11</sup> Though we have to make an assumption about the size of fixed costs.

$$(7c) \quad E[\varepsilon_{t+1}] = \frac{C_t}{R_t} - \left(1 - \frac{1}{\eta}\right) - \frac{\beta(1-\delta)\gamma}{\eta} \frac{R_{t+1}}{Z_{t+1}} - \beta(1-\delta) \left( \frac{C_{t+1}}{R_{t+1}} - \left(1 - \frac{1}{\eta}\right) \right) = 0.$$

We use this moment condition and instruments that are orthogonal to the expectation error to estimate the model's parameters by GMM. The instruments we use for the Euler equation are variables dated  $t$  and earlier and include cost-revenue ratios and lagged revenue (as well as age dummies). We note that unlike the demand equation, the Euler equation identifies parameters from changes in plants' cost-revenue and revenue-demand-stock ratios.

In what follows, we report results on estimating (2b) alone and (2b) and (7c) jointly. One potentially important econometric issue in estimating both equations (2b) and (7c) is selection. Estimation of each of these equations requires plants that are present in both  $t$  and  $t+1$  and accompanying measurement of all variables in both equations in  $t$  and  $t+1$ . Since the five year mean exit rate for our data sample is around 20 percent, selection is an important empirical issue. As we know from our earlier work, Foster, Haltiwanger and Syverson (2008), selection is non-random and related to plant-level fundamentals including physical productivity and demand shocks. In our earlier work, for example, we find that a one standard deviation increase in the demand shock (which in this paper reflects the combined influence of unobserved shocks, age and  $Z$  effects) decreases the probability of exit by 5 percent. In future drafts, we plan to address the issue of selection directly by considering estimation approaches that correct for selection. Given that we are neglecting this potentially important issue in this draft, the results from the estimation presented below should be viewed with appropriate caution.

## 4.2. Discussion

The comparison between the estimates of  $\phi$  and  $\gamma$ , which respectively parameterize the influence of plant age and past output on demand, will be informative about the sources of the dynamics of the demand process discussed above. Age captures deterministic demand shifts that would happen regardless of the level of a plant's past activity.  $Z_t$ , on the other hand, captures past activity's influence directly. Models that posit dynamic demand linkages through passive consumer learning imply that the influence of plant age will be greater, while those emphasizing learning (or habit formation, perhaps) driven by activity will show a large influence of  $Z_t$ . We can distinguish between these possibilities in the data—or perhaps more precisely, we can measure the relative importance of each.

In future versions of the paper, we will estimate the model for separate subsamples of plants. The subsamples will be chosen, as with those explored in Section 3, based on plant attributes that one might expect will affect the speed or nature of the dynamic demand process.

## 5. Results and Discussion

We have begun preliminary estimation of the parameters using the demand only model (equation (2b)) and joint estimation of the demand and Euler equations (equations (2b) and (7c)). As we have noted above, we base our estimates on plants that exist in periods  $t$  and  $t+1$  and have not yet accounted for selection that may impact the results.<sup>12</sup>

For this draft of the paper, we focus on concrete plants only and for the sample period 1977-1992.<sup>13</sup> We use the variable construction as described above but note that we use capture the age variable in (2b) non-parametrically with a young dummy that is equal to one if the plant in period  $t$  is one census period old, a medium age dummy that is equal to one if the plant in period  $t$  is two census periods old, and the omitted group are mature plants that are at least three census periods old in period  $t$ .

We consider the estimation of the models first setting the depreciation rate of the demand stock to zero so that the demand stock reflects cumulative real revenue. The results of the estimation are reported in Table 4. The first two columns show the results of demand estimation alone. The second two columns show the results of the joint estimation of the demand equation and the Euler equation. For both specifications, we report results excluding the 1963 cohort (so excluding left censored cases) and including the 1963 cohort.

In terms of the main parameters of interest, we find evidence of positive and significant effects of “learning by doing” in terms of the effect of the demand stock or demand experience. The elasticities with respect to demand stock range from 0.57 to 0.67. In contrast, we find evidence that, having controlled for demand stock, that there is a negative effect from “learning by being”. That is, the coefficients on the young and medium dummies are both positive and

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<sup>12</sup> While selection effects are likely to be important, we note that the patterns we have emphasized in section 2 hold even for the subset of plant-year observations for which we based our estimation of (2b) and (7c). That is, restricting the sample to plants in period  $t$  that are not entrants (so they have data in  $t-1$ ) and survive to the next Census (so have data in  $t+1$ ) and estimating the level demand specification (1) yields results consistent with those reported in section 2. That is, plants that are young (entered in  $t-1$ ) have lower demand than plants that are medium-aged (entered in  $t-1$ ) who in turn have lower demand than mature plants (plants that entered in  $t-3$  or earlier).

<sup>13</sup> We don't estimate  $\beta$  in the Euler equation but rather set it to be consistent with annual discount factor of 0.98.

significant with the estimated young coefficient larger than the estimated medium aged coefficient. Since the omitted group is the oldest plants, there is a monotonically decreasing impact of age. Both the “learning by doing” and “learning by being effects” are estimated while controlling for the potential presence of positive serially correlated unobserved demand shocks. For the latter, we estimate a five-year AR(1) coefficient in the range 0.4 to 0.45. These five year persistence rates correspond to an annual rates in the range 0.83 to 0.85. We also note that we find plausible estimated price elasticities of demand that are in the range -4 to -4.5.<sup>14</sup>

Turning to the more complex specification that attempts to also estimate the depreciation rate of the demand stock, we find in Table 5 similar results on some key dimensions but also some difficulty in estimating the depreciation rate. The patterns in Table 5 are similar to those in Table 4 for the elasticity with respect to the demand stock (the “learning by doing” effect) and for the estimated price elasticities of demand. The elasticity with respect to the demand stock is in the range 0.59 to 0.78 -- so if anything this effect is even larger in this specification. The price elasticities of demand are in the range -3.7 to -5.

For the remaining parameters, we find some sensitivity to sample and specification. For the demand only specification, we find rates of depreciation that are large, positive (around 0.5) and significant. For the joint estimation, the rates of depreciation are much smaller and not significantly different from zero. As such, for the joint estimation the other parameters such as the age effects and the persistence parameter,  $\rho$ , are similar to those in Table 4. However, for the demand only estimation, the age effects are smaller in magnitude as is the persistence rate. In combination, there is some sensitivity and tradeoff between a higher estimated depreciation rate and lower age and persistence effects.

These very early results are encouraging in that they indicate we should be able to identify and estimate the main parameters of interest given the available data. The early results are also quite striking in that they suggest that higher demand of mature plants shown in section 2 is driven by a positive learning by doing effect, which is at least partly offset by a negative learning by being effect. We are reluctant to draw strong inferences from these promising early results since they are based on a limited sample and most importantly do not control for

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<sup>14</sup> Both the price elasticities and the persistence rates are consistent with those reported in Foster, Haltiwanger and Syverson (2008). The latter is especially interesting since the persistence rate in the earlier work reflected the persistence of the combined demand shock without separating out the influence of learning by doing and learning by being.

selection.

## **6. Conclusion**

To be written.

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Table 1. Evolution of Productivity and Demand across Plant Ages

Variable	Plant Age Dummies			
	Entrant	Young	Medium	Exiter
Physical TFP	0.0128 (0.0053)	0.0046 (0.0058)	-0.0039 (0.0062)	-0.0186 (0.0050)
Demand Shock	-0.5557 (0.0264)	-0.3985 (0.0263)	-0.3183 (0.0267)	-0.3466 (0.0227)

Note: This table is an extract from Table 5 in Foster, Haltiwanger, and Syverson (2008). It shows the coefficients on indicator variables for exiting, entering, and continuing plants of two age cohorts (shown by column; “young” establishments first appeared in the census five years ago, “medium” establishments first appeared in the census ten years ago) when we regress plant-level productivity and demand levels on these indicators and a full set of product-year fixed effects. The excluded category is plants that appeared three or more censuses prior. The sample includes 17,314 plant-year observations for from the 1977, 82, 87, and 92 Census of Manufactures. Standard errors, clustered by plant, are in parentheses.

Table 2. Evolution of Demand across Plant Ages—Interactions with Firm’s Multi-Unit Status

Variable	Plant age dummies				
	Entrant	Young	Medium	Old	Exiter
Demand shock	-0.316 (0.034)	-0.172 (0.035)	-0.149 (0.038)	Excl.	-0.179 (0.031)
Demand shock x multi-unit firm indicator	0.111 (0.038)	0.131 (0.041)	0.245 (0.045)	0.547 (0.026)	-0.293 (0.023)

Note: This table repeats the analysis of Table 1, but now allows plant age effects to vary with the multi-unit status of the plant’s owning firm. The excluded category includes plants in single-unit firms that appeared three or more censuses prior. N = 17,314 plant-year observations. Standard errors, clustered by plant, are in parentheses.



Table 3. Evolution of Demand across Plant Ages—Interactions with Firm’s Age

Variable	Plant age dummies				
	Entrant	Young	Medium	Old	Exiter
Demand shock	-0.316 (0.034)	-0.175 (0.034)	-0.144 (0.036)	Excl.	-0.179 (0.031)
Demand shock x firm is multi-unit and an entrant	0.176 (0.066)	N/A	N/A	N/A	-0.179 (0.110)
Demand shock x firm is multi-unit and young or medium	0.007 (0.041)	N/A	0.130 (0.044)	N/A	-0.116 (0.077)
Demand shock x firm is multi-unit and old	0.096 (0.042)	0.126 (0.044)	0.279 (0.047)	0.555 (0.026)	-0.342 (0.045)

Note: This table repeats the analysis of Table 1, but now allows plant age effects to vary with the multi-unit status and age of the plant’s owning firm. The excluded category includes plants that appeared three or more censuses prior. N = 17,314 plant-year observations. Standard errors, clustered by plant, are in parentheses.

**Table 4 Estimated Coefficients for Cumulative Revenue Learning Model**

Estimated Coefficient	Demand Estimation Only		Joint Demand and Euler Equation Estimation	
	$\gamma$	0.586 (0.059)	0.634 (0.035)	0.642 (0.034)
$\eta$	4.512 (0.565)	3.952 (0.430)	4.398 (0.346)	3.960 (0.254)
Young Dummy	0.477 (0.110)	0.626 (0.083)	0.450 (0.099)	0.646 (0.077)
Medium Age Dummy	0.165 (0.051)	0.261 (0.044)	0.142 (0.047)	0.260 (0.041)
$\rho$	0.412 (0.056)	0.409 (0.037)	0.439 (0.044)	0.449 (0.032)
Including 1963 cohort	No	Yes	No	Yes

Notes: Demand Estimation Only model is based on estimation of equation (2b). Joint Demand and Euler Estimation is based on joint estimation of equations (2b) and (7c). Demand equation also includes year dummies (not reported) and control for local demand (local BEA economic area income). Young plants here refer to plants that are present in the current and prior Economic Census. Medium age plants are those that have been present for at least two Economic censuses. The omitted age group is mature plants that have been present for at least three Economic Censuses. The instruments for demand equation include  $\log(\text{TFPQ})$ , lagged revenues (up to six lags), lagged price, local income, age and year dummies. Instruments for Euler equation include lagged revenue (up to six lags), lagged cost/revenue ratios (up to two lags), lagged price (up to two lags), and age dummies. Standard errors in parentheses.

**Table 5 Estimated Coefficients for Learning with Depreciation Model**

Estimated Coefficient	Demand Estimation Only		Joint Demand and Euler Equation Estimation	
	$\gamma$	0.694 (0.052)	0.776 (0.031)	0.589 (0.048)
$\delta$	0.530 (0.205)	0.528 (0.098)	-0.051 (0.032)	0.016 (0.022)
$\eta$	3.737 (0.532)	3.239 (0.378)	4.951 (0.563)	4.144 (0.358)
Young Dummy	0.268 (0.162)	0.367 (0.106)	0.425 (0.107)	0.620 (0.079)
Medium Age Dummy	0.043 (0.074)	0.084 (0.057)	0.138 (0.050)	0.249 (0.042)
$\rho$	0.235 (0.090)	0.170 (0.065)	0.464 (0.045)	0.442 (0.033)
Including 1963 cohort	No	Yes	No	Yes

Notes: Demand Estimation Only model is based on estimation of equation (2b). Joint Demand and Euler Estimation is based on joint estimation of equations (2b) and (7c). Demand equation also includes year dummies (not reported) and control for local demand (local BEA economic area income). Young plants here refer to plants that are present in the current and prior Economic Census. Medium age plants are those that have been present for at least two Economic censuses. The omitted age group is mature plants that have been present for at least three Economic Censuses. The instruments for demand equation include  $\log(\text{TFPQ})$ , lagged revenues (up to six lags), lagged price, local income, age and year dummies. Instruments for Euler equation include lagged revenue (up to six lags), lagged cost/revenue ratios (up to two lags), lagged price (up to two lags), and age dummies. Standard errors in parentheses.

# Appendix

## A.1. Defining Our Products

As background to how we define our products, it is first necessary to understand the product coding scheme that Census uses. There are three types of codes that we highlight. First, Census codes flags products from administrative records (AR) sources. We exclude all of these AR products from our analysis. (Including in our measures of PPSR since it is obviously not possible to assign these AR products to a single 7-digit code.) Second, Census uses balancing codes to correct cases in which the sum of the total value of shipments of reported individual products does not sum to the reported total value of shipments. Census identified these balancing codes using special suffixes for the product codes in every census year except in 1987. Where balancing codes are identified, they have been deleted. Finally, Census collects data on receipts for contract work, miscellaneous receipts, and resales of products. These products are excluded from our calculations of PPSR (again, because it is obviously not possible to assign these AR products to a single 7-digit code). As a final exclusion, we did not include any products in that have a negative value since these are presumably balancing codes. The precise definitions of our eleven products are listed below (with 7-digit product codes in parentheses).

*Boxes* is defined as the sum of boxes classified by their end use and boxes classified by their materials. Boxes classified by end use are: food and beverages (2653012), paper and allied products (2653013), carryout boxes for retail food (2653014 category starts in 1987) glass, clay, and stone products (2653015), metal products, machinery, equipment, and supplies except electrical (2653016), electrical machinery, equipment, supplies, and appliances (2653018), chemicals and drugs, including paints, varnishes, cosmetics, and soap (2653021), lumber and wood products, including furniture (2653029), and all other ends uses not specified above (2653029 in 1977 and 1982, 2653030 in 1987). Boxes classified by their materials are: solid fiber (2653051), corrugated paperboard in sheets and rolls, lined and unlined (2653067), and corrugated and solid fiber pallets, pads and partitions (2653068). The physical data for boxes is measured in short tons.

*Bread* is defined as one 7-digit product, white pan bread (2051111), until 1992 when it was split into two products white pan bread, except frozen (2051121) and frozen white pan bread (2051122). The physical data for bread is measured in thousands of pounds.

*Carbon Black* is defined as one 7-digit product, carbon black (2895011 in 1977, 2895000 thereafter). The physical data for carbon black is measured in thousands of pounds.

*Coffee* is the sum of whole bean (2095111), ground and extended yield (2095117 and 2095118 in 1982 and 2095115 thereafter), and ground coffee mixtures (2095121). The physical data for coffee is measured in thousands of pounds.

*Concrete* is defined as one 7-digit product, ready-mix concrete (3273000), over our entire sample. Some of the products coded as 3273000 in 1987 were in fact census balancing codes and thus were deleted from our sample. The physical data for concrete is measured in thousands of cubic yards.

*Flooring* is defined as one 7-digit product, hardwood oak flooring (2426111), over our entire sample. The physical data for flooring is measured in thousands of board feet.

*Gasoline* is defined as one 7-digit product, motor gasoline (2911131), over our entire sample. The physical data for gasoline is measured in thousands of barrels.

*Block Ice* is defined as one 7-digit product, can or block ice (2097011), over our entire sample. The physical data for block ice is measured in short tons.

*Processed Ice* is defined as one 7-digit product, cubed, crushed, or other processed ice (2097051), over our entire sample. The physical data for processed ice is measured in short tons.

*Plywood* is defined as one 7-digit product, hardwood plywood (2435100), over 1977-1987. Starting in 1992, plywood is the sum of veneer core (2435101), particleboard core (2435105), medium density fiberboard core

(2435107), and other core (2435147). The physical data for plywood is measured in thousands of square feet surface measure.

*Sugar* is defined as one 7-digit product, raw cane sugar (2061011), over our entire sample. The physical data for sugar is measured in short tons.

## **A.2. Measurement of input levels and input elasticities in the TFP indexes.**

This section reports details on the measurement of input levels and elasticities in the TFP measures described in Section 3.

Labor inputs are measured as plants' reported production-worker hours adjusted using the method of Baily, Hulten and Campbell (1992). This involves multiplying the production-worker hours by the ratio of total payroll to payroll for production workers. Prior work has shown this measure to be highly correlated with Davis and Haltiwanger's (1991) more direct imputation of nonproduction workers, which multiplies a plant's number of nonproduction workers by the average annual hours for nonproduction workers in the corresponding two-digit industry calculated from the CPS. Capital inputs are plants' reported book values for their structure and equipment capital stocks deflated to 1987 levels using sector-specific deflators from the Bureau of Economic Analysis. The method is detailed in Foster, Haltiwanger and Krizan (2001). Materials and energy inputs are simply plants' reported expenditures on each deflated using the corresponding input price indices from the NBER Productivity Database.

To compute the industry-level cost shares that we use to measure the input elasticities  $\alpha_j$ , we use the materials and energy expenditures along with payments to labor to measure the costs of these three inputs. We construct the cost of capital by multiplying real capital stock value by the capital rental rates for the plant's respective two-digit industry. These rental rates are from unpublished data constructed and used by the Bureau of Labor Statistics in computing their Multifactor Productivity series. Formulas, related methodology, and data sources are described in U.S. Bureau of Labor Statistics (1983) and Harper, Berndt, and Wood (1989).

## **A.3. Rules for Inclusion in the Sample**

While the Economic Census data we use is very rich, it still has limitations that make necessary three restrictions on the set of producers included in our sample. First, we exclude plants in a small number of product-years for which physical output data are not available due to Census decisions to not collect it or obvious recording problems. Second, we exclude establishments whose production information appears to be imputed (imputes are not always identifiable in the CM) or suffering from gross reporting errors. Third, we impose a product specialization criterion: a plant must obtain at least 50% of its revenue from sales of our product of interest. This restriction reduces measurement problems in computing physical TFP. Because plants' factor inputs are not reported separately by product but rather at the plant level, we must for multi-product plants apportion the share of inputs used to make our product of interest. Operationally, we make this adjustment by dividing the plant's reported output of the product of interest by that product's share of plant sales. This restriction is not very binding in seven of our products whose establishments are on average quite specialized. Bread, flooring, gasoline, and block ice producers are less specialized, however, so care must be taken in interpreting our sample as being representative of all producers of those products. We test below the sensitivity of our results to the inclusion of less specialized producers.<sup>15</sup> Characteristics of the final sample can be seen in Table A.1.

Census reports physical product data for only a subset of the 11,000 products reported in the Census of Manufactures. While we use only products for which physical output is reported, the collection of this data has changed over time for two of our products. (See Table A.1.) Census did not collect physical output for ready-mix concrete in 1997, and the unit of measurement for boxes changed over our sample period in a way that makes the

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<sup>15</sup> This input-adjustment method in effect assumes inputs are used proportionately to each product's revenue share. For example, a plant producing 1000 cubic yards of ready-mixed concrete accounting for 80% of its shipment revenues will have the same physical TFP value as a completely specialized plant producing 1250 cubic yards of concrete, assuming they employ the same measured inputs. Without adjusting the output, the first plant would appear less productive because the inputs it uses its other products would be instead attributed entirely to ready-mixed production. The average share of our sample plants' values of shipments accounted for by the corresponding product is given in parentheses: boxes (93), bread (39), carbon black (96), coffee (86), concrete (92), flooring (46), gasoline (49), block ice (37), processed ice (76), plywood (64), and sugar (90).

1992 and 1997 data incomparable to the earlier periods. Additionally, there are recording flaws in the 1992 quantity data for processed ice that make using it unfeasible.

The Census Bureau relies on administrative record data for very small establishments (typically with less than five employees). In these cases all production data except total revenues and the number of employees are imputed, and production operations are classified only up to the four-digit industry level. Since our unit of analysis is more detailed than the four-digit industry, we cannot determine whether a particular administrative record establishment actually produces the product of interest. For these reasons, we exclude administrative records cases from our sample. While about one-third of CM establishments are administrative records, their output and employment shares are much less because they are such small plants.

We also exclude establishments whose data appear to be imputed or suffer from reporting or recording errors. The Census Bureau imputes physical quantities when product-level data are not fully reported. Unfortunately, imputed data are not explicitly identified. To distinguish and remove imputed product-level data from the sample, we use techniques similar to those employed by Roberts and Supina (1996, 2000). To minimize the influence of reporting and recording errors, we also remove a small number of plants reporting physical quantities that imply prices greater than ten times or less than one-tenth the median price in a given year. In order to maintain the same sample over all exercises, we delete observations that are missing any one of the main regression variables. We also delete observations when the plant's labor or materials cost share is less than one-tenth of the corresponding industry's average cost share for that year, or when the cost share is more than one. Finally, we still find a relatively small number of obvious outliers in physical quantity measures, so we trim the one-percent tails of the physical productivity (TFPQ) distribution.

Our product specialization criterion requires that plants obtain at least 50% of their revenue from our product of interest. The text discusses the measurement reasons for imposing this restriction as well as describing a robustness check with respect to this product specialization cutoff.

#### **A.4. Characteristics of Establishments by Product**

In this section we briefly characterize some of the relevant properties of the establishments that produce our products. Table A.1 shows characteristics of the sample by product. The first five columns show the number of establishments in our sample by year for each product. The second to last column shows the real revenue shares of each product. Real revenue is the weight used in our weighted regressions. Concrete clearly dominates our sample in terms of the number of establishments while gasoline dominates in terms of the revenue share. The table's last column shows mean logged income (income is taken from Census reports for the county in which the plant is located) for each product in our sample. Concrete has the highest mean log income while carbon black has the lowest.

Table A.2 shows the entry and exit rates by product for the data pooled over all available years. Entry rates range from a low of 3.9 for sugar to a high of 26.6 for concrete, while exit rates range from a low of 9.0 for gasoline and to a high of 27.7 for processed ice. Some products appear to be in a period of retrenchment or consolidation. Sugar for example, has a very low entry rate (3.9) but a high exit rate (17.0). The number of plants in the sugar and confectionary products industry (SIC 2061) has fallen from 66 in 1977 to 39 in 1997. Other products appear to simply have a high degree of churning. For example, concrete and both types of ice products all have entry rates and exit rates that exceed 20 percent. The number of establishments in ready-mixed concrete (SIC 3273) industry increases over our sample period, while the number of establishments in the block and processed ice industry (SIC 2097) falls somewhat over our sample, from 675 establishments in 1977 to 582 establishments in 1997.

#### **A.5. Robustness of Demand Estimates**

There are two potential problems with using TFPQ as an instrument. We have explored both and found our results to be robust. We briefly describe these potential issues here.

The first regards how selection on profitability impacts the assumption that TFPQ is uncorrelated with demand shocks at the plant level. This assumption, which is necessary for TFPQ to be a valid instrument in the demand estimation, strikes us as quite reasonable for *innovations* to the dynamic plant-level TFPQ and demand processes. Hence for entering plants, which get their initial idiosyncratic productivity and demand levels as draws from the respective innovation processes, the assumption of no correlation is likely to hold. However, TFPQ and demand levels may be correlated for *continuing* plants (those operating in both the current and previous periods) because of selection. Here is why. A producer continues operation if it is profitable, which depends on idiosyncratic productivity and demand. Since a producer with a higher TFPQ draw can tolerate lower demand draws (and vice versa) while remaining profitable, those producers that chose in the previous period to continue operations into the current period—i.e., the continuing plants—will tend to have negatively correlated lagged TFPQ

and lagged demand levels. The correlation arises in the lagged values because the plants' decisions to continue operating into the current period were conditioned on that information. But because both of these processes are persistent, their current values could be correlated as well, making the orthogonality assumption necessary for consistent demand elasticity estimation questionable.

To explore the sensitivity of our results to this issue, we estimated product demand curves (10) using an alternative instrument for price that is based only upon innovations to TFPQ. For entrants, this was simply the observed level of TFPQ (after taking out product-year fixed effects). For continuers, on the other hand, we regressed the plants' current TFPQ levels on their lagged values (again including product-year fixed effects), and used the residual from this to instrument for price. In this way, we use the innovation to producers' productivity levels—information that was plausibly not included in their decision in the previous period to continue operations, but that should affect current costs—to gain exogenous variation in current prices. (The fact that we only observe plants every five years makes necessary some assumptions of timing here. The first is that the period when plants have received their idiosyncratic profitability draws but have yet to decide whether to exit, which is instantaneous in our two-stage model, can in reality actually correspond to a period of a few years. The entering plants in our sample are assumed to be in this stage. The second is that the TFPQ innovation does not impact producers' exit decisions in intercensal years.)

When we use this alternative TFPQ-innovation-based instrument, we find that the pattern of elasticities and even more importantly the pattern of demand shocks to be very robust. We also find the results that depend upon demand shocks in Tables 3-6 to be virtually unaffected. These results are available upon request.

A second potential problem is measurement error. We compute prices by dividing reported revenue by quantity and any measurement error in physical quantities will overstate the negative correlation between prices and TFPQ. Since the first stage of the IV estimation regresses plants' prices on their TFP levels, measurement error would yield biased estimates of the fitted prices used in the second stage, possibly leading in turn to biased price elasticities and idiosyncratic demand measures. To address this concern, we estimated a specification that should be robust to measurement error, implemented as follows. Rather than using current plant TFP directly as an instrument, we use a "fitted" value constructed as a projection of current TFP on several values expected to be correlated with plant productivity but orthogonal to measurement error. These include the plant's lagged TFP, lead TFP, the average TFP of the *other* plants in the same industry owned by the plant's firm (these three variables are used as available, depending on the plant), a set of birth-cohort-by-industry dummies, and a set of "survival-cohort"-by-industry dummies denoting how many more CMs a plant exists before exiting (or if it survives until the end of our sample).

All of these variables should have predictive power over a plant's current TFP level but be orthogonal to classical measurement error in quantity. Lag and lead TFP values are relevant to current TFP because of productivity persistence, the average TFP of other plants owned by the same firm because of management-driven productivity spillovers or assortative matching of plants, and the birth and survival cohort indicators because of age-specific productivity evolutions and because future survival is determined by current productivity. Second, besides this fitted TFP value, we also include the local average wage as an instrument in the first stage. This factor price is of course an additional cost shifter for the plant.

As with the other robustness check above, the results of this alternative demand estimation procedure yield demand estimates that closely track those obtained in our benchmark specification. Moreover, the subsequent results using the estimated demand shocks from this alternative estimation are very similar to those reported in the paper. Again, we do not report these here for space reasons.

In considering these two robustness checks, we note that they employ essentially opposite strategies: one uses the transitory variation in TFPQ while the other uses the permanent component. We are reassured by the fact that the results are robust to using either component of TFPQ variation. If either potential problem was a major driver of our results, we would expect the demand estimates to be quite sensitive to these distinctions.

Table A.1: Characteristics of the Sample by Product

Product	Number of Observations					Real Revenue Share (%)	Mean (log) Income
	1977	1982	1987	1992	1997		
Boxes	936	905	1045	NA	NA	7.9	17.4
Bread	195	142	110	92	92	2.4	17.0
Carbon Black	31	23	22	21	18	0.7	16.2
Coffee	61	84	79	77	77	4.7	18.0
Concrete	2184	3316	3236	3427	NA	7.0	17.1
Hardwood Flooring	8	10	16	25	24	0.2	16.7
Gasoline	99	99	94	95	71	75.0	17.1
Block Ice	40	43	26	23	10	0.0	16.9
Processed Ice	87	155	144	NA	NA	0.1	16.8
Plywood	71	68	42	42	37	0.6	16.5
Sugar	40	36	30	35	26	1.3	16.6

Note: This table shows the number of establishments in our sample by product and year, as well as each product's share of total real revenue in the sample (pooled across all years). Mean log income, used in our demand estimation procedure, is for plants' corresponding Economic Areas (see text for details) based on data pooled over all years.



Table A.2: Entry and Exit Rates by Product

Products	Entry Rates	Exit Rates
All Products	22.3	19.6
By Product:		
Boxes	12.4	12.2
Bread	7.6	18.9
Carbon Black	4.8	13.4
Coffee	9.1	15.6
Concrete	26.6	21.8
Hardwood Flooring	18.7	11.9
Gasoline	4.2	9.0
Block Ice	24.5	26.5
Processed Ice	23.1	27.7
Plywood	7.4	10.3
Sugar	3.9	17.0

Note: This table shows the plant entry and exit rates (averaged across all years in the sample). Entry (exit) is determined by plants' first (last) appearance in a CM. See text for details. Entry rates for gasoline reflect a small number (less than five) births in the 1987, 1992, and 1997 CMs, even though the Energy Information Administration reports no new refineries were built during that period. It is not clear why there is a discrepancy in the Census data, but for the sake of consistency and given the low entry rate in the industry overall, we defined these new plants as entrants.