# Estimating Production Functions When Productivity Change Is Endogenous*

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**Abstract**

Production function estimation on micro data suffers from persistent unobserved shocks that vary within firms and cause bias. This paper presents an estimation model where the firm chooses capital investment and productivity-relevant intangible assets in response to market conditions under partly fixed adjustment costs. Estimation on Brazilian manufacturing firm data suggests that (i) firms' unobserved shocks are associated with productivity responses to competitive conditions and that (ii) a suitable productivity proxy is investment interacted with firm-specific competition variables. Identification does not rely on timing assumptions, and non-positive investment observations can be retained. Bootstraps show that the new proxy yields less dispersed coefficient estimates than alternatives while remedying bias. JEL C51, D24

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# 1 Introduction

Small estimates of capital coefficients and economies of scale trouble estimation of production functions with micro data. Using a fixed effects estimator rather than ordinary least squares does typically not resolve the apparent negative bias but can aggravate it (Griliches and Mairesse 1998). These findings lead to the suspicion that firm-specific but time-varying shocks may distort estimation. Olley and Pakes (1996) and Levinsohn and Petrin (2003), for instance, document that the fixed-effects estimator disagrees markedly with other estimators. This indicates that a persistent shock varies within firm or plant over time but remains untreated in known estimation procedures. Similarly, Blundell and Bond (2000) conclude that persistent input series trouble instruments in first-differenced estimators, whereas lagged first differences in extended GMM perform more reasonably.

I argue that an important component of the unobserved individual shock is a firm's changing expectation about market prospects. The shock correlates closely with observed factor choices because a firm chooses its observed factors as well as its unobserved intangible investments in response to market prospects. The firm's intangible assets govern organizational choice and productivity.

A growing body of micro-econometric research into productivity change offers evidence that the efficiency of plants or firms responds to competitive pressure and rivaling innovations (e.g. Tybout, Melo and Corbo 1991, Nickell 1996, Pavcnik 2002). The business literature abounds with productivity management techniques: more recent terms such as supply-chain management, total quality management, group technology, information-technology enabled organizational change, and lean management (including just-in-time, kaizen, or continuous improvement) now replace older notions such as reorganization or re-engineering and the so-called efficiency-improvement systems of the 1980s (materials requirements planning, kanban, optimized production technology, and flexible manufacturing systems). The idea remains unaltered. Good management continuously optimizes processes in response to competition and business prospects. In short, investment in productivity-relevant assets is under a firm's control, responds to market conditions, and production function estimation should account for a firm's expectations to prevent bias.

My estimation model allows the firm to invest in both physical capital and intangible productivity-relevant assets. Productivity is considered the outcome of intangible and unobserved investments into organizational change. Fixed adjustment costs induce lumpy investments under a $q$-theory approach (Abel and Eberly 1994). This asset model of the firm motivates an extended Olley-Pakes estimation procedure, where a firm's market conditions, interacted with its physical investment, serve as a set of novel proxies in the control function for productivity. The model favors this set of proxies because the firm jointly cultivates physical capital and intangible organizational knowledge, given market conditions. Whenever its market prospects are favorable, the firm has an incentive to expand physical capital and to improve its intangible organizational capital simultaneously. Similar to prior approaches, the estimation model permits resolution of transmission bias (controlling for the simultaneous determination of unobserved firm-level productivity and factor choices), survival bias (using exit-rule estimation on an unbalanced firm panel), and omitted-price bias (removing time-invariant demand components from otherwise confounded productivity estimates). The estimation model achieves the resolution of bias on the basis of a lean set of identifying assumptions with plausible implications for productivity evolution.

Its assumptions and implications set the present estimation model apart from prior approaches. First, identification of the production function does not have to rely on timing assumptions. Productivity shocks need not be fully known to the firm prior to physical investment choice (Olley and Pakes 1996) or variable input choice (Levinsohn and Petrin 2003). Instead, the asset model implies that variables related to a firm's market conditions, and interacted with its physical investment, provide a natural source of identification for the productivity control function as long as an exit rule is estimated alongside. Estimation of an exit rule, as in Olley and Pakes (1996), is crucial if there are fixed costs of investment in organizational change, because the productivity control function for survivors changes strictly monotonically in its arguments only through the exit rule. So, an extended Olley-Pakes procedure is the estimation method of choice under an asset model of the firm.

Beyond sector-level covariates, proxies to market conditions include the firm-specific mean characteristics of each firm's competitors. When applied to a sample of medium-sized to large Brazilian manufacturing companies between 1986 and 1998, the extended Olley-Pakes procedure detects, and removes, frequently suspected biases. Bootstraps show that alternative estimators yield more volatile and less precise estimates than does extended Olley-Pakes estimation.

Second, observations with non-positive investment are permissible for estimation under the asset model of the firm. Non-positive net investments occur frequently in micro data. Common theory of the firm predicts that firms with higher marginal products of capital, and lower marginal products of other factors, invest more so that a restriction to a positive-investments-only sample expectedly results in capital coefficients that exceed those in the full sample. As a consequence, the positive-investments-only subsample does not reflect the average production technology, but an initially less capital-intensive technology. Estimates from the asset model of the firm confirm this prediction in the sample of Brazilian manufacturers.

A third implication of the asset model is that an upward bias in capital coefficients remains consistent with the estimation model. Some estimates in the Brazilian sample of manufacturing firms in this paper exhibit positive bias, similar to positive-bias estimates in other firm samples (Mairesse and Hall 1996, Pavcnik 2002, Levinsohn and Petrin 2003). The reason for a potential positive bias in capital coefficients is that market conditions induce firms to jointly adjust physical capital and intangible productivity-relevant assets. While more frequent survival of capital-rich firms results in a negative bias in capital coefficients, the negative bias may or may not outweigh the positive bias. Fourth, pro-cyclical productivity evolution is ruled out under the prior assumption of exogenous productivity shocks (Olley and Pakes 1996, Levinsohn and Petrin 2003), where favorable market conditions make survivors tolerate lower productivity levels and result in a counter-cyclical evolution. In the present model, in contrast, favorable market conditions are associated with positive physical investments and positive organizational change.

Using investment interacted with sectoral competition to proxy productivity on a sample of Brazilian manufacturing firms yields production function estimates that resemble fixed-effects estimates. This suggests that expectations-proxy estimation largely captures the firm-specific time-variant shocks that used to confound estimation. Capital coefficients from the new estimation method frequently agree with those from fixed-effects estimation (but still detect and remove a negative bias from OLS in many sectors) while variable-input coefficients differ more strongly. This pattern is consistent with the hypothesis that constant components in the firm-specific expectations shock affect capital coefficients most, so that the new estimator agrees with the fixed effects estimator, whereas time-varying components in firm-level expectations affect variable-input coefficients strongly.

# 2 An Asset Model of the Firm

Productivity is the outcome of a firm's investments and product or process innovations. The investments and innovations respond to market conditions and suggest an asset approach to a firm's productivity-relevant knowledge, based on standard theories of monopolistic competition and investment. I draw on Abel and Eberly (1994) to model a firm's investment decisions but choose discrete time for empirical implementation. I derive implications for estimation under selectivity, transmission bias, and omitted price bias. Table 1 provides an overview of the model's primitives and implications. The model does not require any assumption on the firm's timing of decisions to resolve the transmission bias in capital coefficients and permits the inclusion of observations with zero or negative net investments; the model is consistent with an upward bias in the estimated capital

Table 1: $q$-Theory of Investment with Fixed Adjustment Costs

| Variable | Evolution in the model | Data | Olley & Pakes |
|---|---|---|---|
| **State Variables** | | | |
| *TFP*: $(\Omega_{i,t})^\gamma$ | $\Omega_{i,t} = \left[\Omega_{i,t-1}(1-\delta^\Omega) + I^\Omega_{i,t}\right]\tilde{x}_{i,t}$ | no | Markovian[a] |
| Capital $K_{i,t}$ | $K_{i,t} = K_{i,t-1}(1-\delta^K) + I^K_{i,t}$ | yes | same |
| **Control Variables** | | | |
| Investment $I^\Omega_{i,t}$ | before $\tilde{x}_{i,t}$ realized (based on $q^\Omega_{i,t-1}$) | no | absent[a] |
| Investment $I^K_{i,t}$ | before $\tilde{x}_{i,t}$ realized (based on $q^K_{i,t-1}$) | yes | same |
| Survival $\chi_{i,t}$ | after $\tilde{x}_{i,t}$ realized | yes | same |
| Variable inputs $L_{i,t}, M_{i,t}$ | after $\tilde{x}_{i,t}$ realized | yes | same |
| **Implications** | | | |
| Survivors are capital-rich and productive | | yes | yes |
| Observations with non-positive investment permissible[b] | | yes | no |
| Upward bias in capital coefficient consistent with theory | | yes | no |
| Pro-cyclical productivity evolution with demand is possible | | yes | no |
| Transmission bias resolved without timing assumptions[c] | | yes | no |

[a]Olley and Pakes (1996) consider an exogenous Markov process of *TFP* beyond a firm's control. Alternatively, Ericson and Pakes (1995) allow for a binary choice of *TFP* improvement that affects the Markov process.

[b]Partially fixed adjustment costs give rise to lumpy capital investment but market conditions remain valid productivity proxies under zero capital investments.

[c]Identification of transmission bias in Olley and Pakes (1996) is based on the assumption that $I^K_{i,t}$ is chosen in response to $\tilde{x}_{i,t}$. For clarity in the present model, $I^K_{i,t}$ is assumed to be uninformative and chosen before the $\tilde{x}_{i,t}$ realization, and thus uninformative.

coefficient and it is consistent with the observation that industry productivity positively correlates with demand.

## 2.1 Monopolistic competition

Consider a Cobb-Douglas production technology for variety $i$ of good $Z$:

$$Z_{i,t} = (\Omega_{i,t})^\gamma (K_{i,t})^{\beta_K} (L_{i,t} - L_0)^{\beta_L} (M_{i,t})^{\beta_M}, \tag{1}$$

where $Z_{i,t}$ is real output, $K_{i,t}$ is physical capital, $L_{i,t}$ is employment and $M_{i,t}$ denotes intermediate input goods. $L_0$ is a fixed labor input to operate the firm every period. It gives rise to monopolistic competition in equilibrium. Total factor productivity (*TFP*) is specified as

$$TFP_{i,t} = (\Omega_{i,t})^\gamma$$

for some coefficient $\gamma > 0$. The empirical objective is to obtain unbiased estimates of $\beta_K, \beta_L$ and $\beta_M$ that permit inference of $TFP$.

Under monopolistic competition, every firm manufactures a single variety of a good. There are $N$ varieties of good $Z$. Consumers have income $Y_t$ and Dixit-Stiglitz utility $u(Z_1, ...Z_N; C) = (\theta/\eta)\ln(\sum_{n=1}^{N}(Z_n)^\eta) + (1-\theta)\ln C$. So, price elasticity of demand for variety $i$ is approximately $-1/(1-\eta)$ and results in a constant markup $1/\eta$ over marginal cost.[1] With a harmonic price index $\bar{P}_t \equiv [\sum_{n=1}^{N} P_{n,t}^{-\eta/(1-\eta)}]^{-(1-\eta)/\eta}$, similar to a statistical bureau's price index, demand for firm $i$'s variety and its price become

$$Z_{i,t} = \frac{\Theta_t}{\bar{P}_t} \cdot \left(\frac{P_{i,t}}{\bar{P}_t}\right)^{-\frac{1}{1-\eta}} \quad \text{and} \quad P_{i,t} = \left(\bar{P}_t\right)^\eta \left(\frac{\Theta_t}{Z_{i,t}}\right)^{1-\eta}, \tag{2}$$

where $\Theta_t$ is the disposable income that domestic consumers spend on goods $Z$, including imports.

Models of monopolistic competition typically simplify (2) under the assumption that domestic firms operate at common scale and sell their variety at a common price. This simplification is not borne out in the data where considerable heterogeneity in firm size and productivity prevails. The product price ratio $\bar{P}_t/P_{i,t}$ over a firm's individual price captures these differences in efficiencies and marginal costs across firms. So, monopolist $i$ considers revenues $(\bar{P}_t Z_{i,t})^\eta(\Theta_t)^{1-\eta}$ a function $R(Z_{i,t}, \mathbf{D}_{i,t})$, where $\mathbf{D}_{i,t}$ stands for the vector of individual current market conditions that firm $i$ faces.[2]

Demand (2) underlies the later Klette and Griliches (1996) correction for endogenous price. More important, market conditions in (2) provide a natural source of identification that does not require any assumptions on the timing of a firm's investment decisions.

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[1] The precise price elasticity of demand is

$$\varepsilon_{d_{i,t},P_{i,t}} = -\frac{1}{1-\eta}\left[1 - \eta\left(\frac{\bar{P}_t}{P_{i,t}}\right)^{\frac{\eta}{1-\eta}}\right]$$

giving rise to a markup $P_{i,t} \simeq \frac{1}{\eta} MC_{i,t}$ over marginal cost $MC$ for large $N$.

[2] For empirical implementation, $\mathbf{D}_{i,t}$ includes firm $i$'s domestic competitors' mean capital stock (which determines entry and exit and hence competition) and domestic competitors' mean labor productivity (which determines competitors' prices). These two variables affect the product price ratio $\bar{P}_t/P_{i,t}$ differently for every firm. Current trade barriers (which affect the price of competing foreign goods) and foreign competitors' market penetration (which reduces pricing power) are common to all domestic firms and also affect demand through the product price ratio $\bar{P}_t/P_{i,t}$.

## 2.2 Productivity-relevant assets

The firm can invest in two state variables: intangible productivity-relevant assets and physical capital. In addition, firms choose the flow variables labor $L_{i,t}$ and intermediate goods $M_{i,t}$. Finally, firms decide whether to continue in business or exit. If a firm exits, it receives a fixed scrap payment $\Phi$ for its remaining assets.

To adjust its assets, firm $i$ chooses investments into productivity-relevant assets $I^{\Omega}_{i,t+1}$ and physical capital $I^{K}_{i,t+1}$ at the end of period $t$ based on its information then. Investments result in cash outflows at the beginning of period $t+1$ but become fully effective only at the end of period $t+1$ when production is finalized. A firm's capital stock next period is certain, $K_{i,t+1} = K_{i,t}(1-\delta^K) + I^K_{i,t+1}$.

The productivity-relevant assets $\Omega_{i,t}$ include tacit knowledge, organizational skills, and efficiency-related arrangements of the production process. I refer to $\Omega_{i,t}$ as *organizational knowledge*. It is not transferrable from one firm to another but can be accumulated within a firm. It depreciates unless cultivated with investment $I^{\Omega}_{i,t+1}$. As opposed to physical capital accumulation, there is a stochastic factor $x_{i,t+1}$ to the evolution of organizational knowledge:

$$\Omega_{i,t+1} = \left[\Omega_{i,t}(1-\delta^{\Omega}) + I^{\Omega}_{i,t+1}\right] \cdot x_{i,t+1}. \tag{3}$$

The log of $x_{i,t+1}$ is random with firm-fixed mean $\mathbb{E}\left[\ln x_{i,t+1}\right] = \beta_{0,i}/\gamma$. The parameter $\delta^{\Omega}$ expresses the depreciation rate of organizational knowledge. Productivity is an imperfect substitute for physical capital because $(\Omega_{i,t})^{\gamma}$ enters the production function (1) separately and because a firm cannot anticipate the realization $x_{i,t}$. The stochastic factor $x_{i,t}$ captures a firm's efficiency and is assumed to be uncorrelated with past realizations and factor inputs—similar in spirit to Olley and Pakes's (1996) model and in line with Levinsohn and Petrin's (2003) moment conditions.[3]

Investments in assets are costly and not fully productive. I distinguish between adjustment costs and fixed costs of investment and make according assumptions on the shape of the adjustment cost function (similar to Abel and Eberly 1994). These assumptions, in turn, have implications for marginal adjustment costs.

**Assumption 1** (Adjustment Costs) *Adjustment costs are additive of the form $C^K(I^K_{i,t+1}, K_{i,t}) + C^{\Omega}(I^{\Omega}_{i,t+1}, \Omega_{i,t})$, weakly positive, continuous, once differentiable with respect to $K_{i,t}$ and $\Omega_{i,t}$, and twice differentiable with respect to $I^K_{i,t+1}$ and $I^{\Omega}_{i,t+1}$, except possibly at zero investment. The adjustment cost components $C^K(\cdot)$ and $C^{\Omega}(\cdot)$*

[3] The efforts that a firm's management makes to improve efficiency and organizational skills can affect the distribution of $x_{i,t}$ favorably. The reason is that product-market competition alters agents' incentives and may induce effort (Hermalin 1992, Schmidt 1997, Raith 2003). An according extension of the estimation model is omitted here for brevity (see the working paper Muendler (2004) for an implementation that gives rise to similar identification).

1. *are weakly decreasing in the assets:* $C^K_K(\cdot) \leq 0$ *and* $C^\Omega_\Omega(\cdot) \leq 0$,

2. *strictly convex in investments:* $C^K_{I^K,I^K}(\cdot) > 0$ *and* $C^\Omega_{I^\Omega,I^\Omega}(\cdot) > 0$, *and*

3. *attain a minimum of zero at zero investment:* $C^K(0,\cdot) = 0$ *and* $C^\Omega(0,\cdot) = 0$.

I make adjustment costs additively separable for clarity. As a consequence, results will not depend on any *ad hoc* assumptions about the relationship between the cost components. Only market conditions will drive the joint evolution of physical capital and organizational knowledge. A generalization to non-separable adjustment costs complicates the proof of Proposition 1 but does not affect the main result that there are potential ranges of inactivity for Tobin's $q$'s around unity. Assumption 1 allows for a cash outflow when a firm purchases capital goods, and for a potential cash inflow when the firm divests. Investment in organizational knowledge reduces a firm's net cash flow either because workforce training and production rearrangements result in foregone output, or in additional factor payments, or both.

Weakly decreasing adjustment costs in $K_{i,t}$ and $\Omega_{i,t}$ are a sufficient condition for Tobin's $q$'s of physical capital $q^K_{i,t}$ and organizational knowledge $q^\Omega_{i,t}$ to be strictly positive. Convexity of the adjustment cost function in investments is the common assumption in the literature and is necessary and sufficient for optimal investment to increase in Tobin's $q$ in the absence of fixed costs.

For $q$ theory, implications of Assumption 1 for *marginal* adjustment cost are crucial. Together with the assumption on minima at zero, convexity of the cost function implies that the marginal adjustment cost is strictly positive if investment is strictly positive, and strictly negative if investment is strictly negative.[4] If the cost function is differentiable at zero investment then Assumption 1 implies that the marginal cost is zero at zero investment. If the cost function is not differentiable at zero investment, then Assumption 1 implies that the marginal cost is weakly negative as investment approaches zero from below and weakly positive as investment approaches zero from above.[5]

**Assumption 2** (Fixed Costs of Capital Investment) *The left and right limits of adjustment cost component* $C^K(I^K_{i,t+1}, K_{i,t})$ *are* $C^{K,-}(0, K_{i,t}) = C^{K,+}(0, K_{i,t}) \equiv C^K(0, K_{i,t}) > 0$ *as* $I^K_{i,t+1}$ *approaches zero.*

[4] $I^K_{i,t+1} > 0$ implies $C^K_{I^K}(\cdot) > 0$ and $I^K_{i,t+1} < 0$ implies $C^K_{I^K}(\cdot) < 0$. Similarly for organizational change.

[5] If $C^K(\cdot)$ is differentiable at $I^K_{i,t+1} = 0$ then $C^K_{I^K}(0, K_{i,t}) = 0$ by convexity (Assumption 1). Otherwise, and in the absence of fixed costs, convexity (Assumption 1) implies that the left and right limits of marginal adjustment costs (partial derivatives of adjustment costs) at $I^K_{i,t+1} = 0$ are $C^{K,-}_{I^K}(0, K_{i,t}) \leq 0$ and $C^{K,+}_{I^K}(0, K_{i,t}) \geq 0$. Similar implications apply to organizational knowledge.

Recall that the adjustment cost level is zero at zero investment by Assumption 1. But the adjustment cost level discretely jumps to a strictly positive level for arbitrarily small non-zero investment by Assumption 2. So, neither adjustment cost levels nor marginal costs are differentiable at zero investment. For marginal costs, convexity (Assumption 1) and fixed costs (Assumption 2) together imply that, when investment approaches zero from above, the marginal cost is weakly positive, as before. But, when investment approaches zero from below, the marginal cost need no longer be weakly negative because the cost level is strictly positive in this limit. Convexity (Assumption 1) and fixed costs (Assumption 2) continue to imply, however, that the marginal cost limit from below is strictly less than the limit from above as investment goes to zero.[6]

Firm-level data typically exhibit a probability mass of observations with zero net capital investment, consistent with Assumption 2. There is no conclusive evidence on the presence of fixed adjustment costs for organizational change, however.[7] I will therefore derive identification conditions in the presence and absence of fixed costs of organizational change (Assumption 3).

**Assumption 3** (Fixed Costs of Organizational Change) *The left and right limits of adjustment cost component $C^{\Omega}(I^{\Omega}_{i,t+1}, \Omega_{i,t})$ are $C^{\Omega,-}(0, \Omega_{i,t}) = C^{\Omega,+}(0, \Omega_{i,t}) \equiv C^{\Omega}(0, \Omega_{i,t}) > 0$ as $I^{\Omega}_{i,t+1}$ approaches zero.*

[6] $C^K(\cdot)$ is not differentiable at $I^K_{i,t+1} = 0$ by Assumption 2. Assumptions 1 and 2 jointly imply that the left partial derivative $C^{K,-}_{IK}(0, K_{i,t})$ can be positive, zero, or negative, whereas the right partial derivative must satisfy $C^{K,+}_{IK}(0, K_{i,t}) \geq 0$ and $C^{K,+}_{IK}(0, K_{i,t}) \geq C^{K,-}_{IK}(0, K_{i,t})$.

[7] Much empirical work on productivity-relevant investment considers embodied technical change through physical-capital investment (e.g. Power 1998, Sakellaris and Wilson 2004). Cooper and Haltiwanger (2006) document for physical-capital investment that a mix of both convex and sunk adjustment costs fits the data best. However, disembodied organizational change motivates the present $q$-theory of productivity. Ichniowski and Shaw (1995) provide evidence of barriers to transitions between distinct categories of work practices for product lines in the steel industry, consistent with fixed costs of adoption. Evidence from recent studies of organizational change, however, is consistent with adjustment costs under Assumption 1 and the absence of fixed costs: Caroli and Van Reenen (2001) document that organizational change leads to faster productivity change in plants with larger initial skill employment (reminiscent of adjustment costs that decrease in existing organizational knowledge); Gant, Ichniowski and Shaw (2002) report that organizational change requires simultaneous change in informal networks (consistent with convex adjustment costs); Bresnahan, Brynjolfsson and Hitt (2002) find information-technology adoption, organizational change and innovation to reinforce each other (comparable to convex adjustment costs when intangible investments reflect cumulative efforts in the three categories). Consistent with those latter findings, estimates of firm-level productivity change in this paper will not exhibit a probability mass around zero, contrary to physical capital (Section 4.2).

The Bellman equation for the firm's intertemporal decision is

$$
\begin{aligned}
V(\Omega_{i,t}, K_{i,t}) \;\; = \;\; \max\Bigg\{ \Phi, \sup_{I^{\Omega}_{i,t+1}, I^{K}_{i,t+1}, L_{i,t} M_{i,t}} & \Pi(L_{i,t}, M_{i,t}, \Omega_{i,t}, K_{i,t}, \mathbf{D}_{i,t}) \\
& -\mathbf{1}(I^{\Omega}_{i,t+1} \neq 0) \cdot C^{\Omega}(I^{\Omega}_{i,t+1}, \Omega_{i,t}) - \mathbf{1}(I^{K}_{i,t+1} \neq 0) \cdot C^{K}(I^{K}_{i,t+1}, K_{i,t}) \\
& + \frac{1}{R}\,\mathbb{E}\left[V(\Omega_{i,t+1}, K_{i,t+1}) \,|\, \mathcal{F}_{i,t}\right] \Bigg\},
\end{aligned} \tag{4}
$$

where $R \equiv 1+r$ is the real interest factor and $\Pi(L_{i,t}, M_{i,t}, \Omega_{i,t}, K_{i,t}, \mathbf{D}_{i,t}) \equiv P(Z_{i,t}, \mathbf{D}_{i,t})\, Z_{i,t} - w_t L_{i,t} - p_t M_{i,t}$ denotes operational profits given production function (1) and demand (2), with $w_t$ being the wage rate and $p_t$ the intermediate goods price. A firm is uncertain about the realization of future *TFP* and market conditions, and $\mathcal{F}_{i,t}$ is firm $i$'s information set at time $t$. It includes, among other variables, its current market conditions $\mathbf{D}_{i,t}$. The indicator functions $\mathbf{1}(I^{K}_{i,t+1} \neq 0)$ and $\mathbf{1}(I^{\Omega}_{i,t+1} \neq 0)$ are explicit reminders of the fixed adjustment cost: adjustment cost jump from zero to a strictly positive level for non-zero investment under Assumptions 2 and 3, but there need not be a jump in organizational adjustment costs when Assumption 3 is dropped. Under monopolistic competition, every firm considers price a function $P(Z_{i,t}, \mathbf{D}_{i,t})$, where $\mathbf{D}_{i,t}$ stands for the vector of individual market conditions.

To analyze the firm's intertemporal decisions, first consider a firm that stays in business. Tobin's $q$'s for physical capital and organizational knowledge can be defined as the expected marginal values of the respective assets

$$
q^{K}_{i,t} \equiv \mathbb{E}_{i,t}\left[\frac{1}{R}\frac{\partial V(\Omega_{i,t+1}, K_{i,t+1})}{\partial K_{i,t+1}}\right] \text{ and } q^{\Omega}_{i,t} \equiv \mathbb{E}_{i,t}\left[\frac{1}{R}\frac{\partial V(\Omega_{i,t+1}, K_{i,t+1})}{\partial \Omega_{i,t+1}} \cdot x_{i,t+1}\right], \tag{5}
$$

Then the first-order conditions for the Bellman equation (4) imply that

$$
L^{*}_{i,t} = L_0 + \frac{\eta\beta_L}{w_t}\,P(Z_{i,t}, \mathbf{D}_{i,t}) Z_{i,t}, \quad M^{*}_{i,t} = \frac{\eta\beta_M}{p_t}\,P(Z_{i,t}, \mathbf{D}_{i,t}) Z_{i,t} \tag{6}
$$

and that non-zero investments equalize marginal adjustment costs to Tobin's $q$'s

$$
q^{K}_{i,t} = C^{K}_{I^K}(I^{K,*}_{i,t+1}, K_{i,t}) \quad \text{and} \quad q^{\Omega}_{i,t} = C^{\Omega}_{I^\Omega}(I^{\Omega,*}_{i,t+1}, \Omega_{i,t}). \tag{7}
$$

Differentiate the value function with respect to the current state variable $\Omega_{i,t}$ and lead it by one period to find

$$
R\, q^{\Omega}_{i,t} = \mathbb{E}_{i,t}\big[\, \Pi_{\Omega}(\cdot_{i,t+1}) - \mathbf{1}(I^{\Omega}_{i,t+2})\, C^{\Omega}_{\Omega}(\cdot_{i,t+1}) \,\big] + (1-\delta^{\Omega})\, \mathbb{E}_{i,t}\big[q^{\Omega}_{i,t+1}\big]
$$

by (5) and the envelope theorem, where $C^{\Omega}_{\Omega}(\cdot_{i,t+1}) \equiv C^{\Omega}_{\Omega}(I^{\Omega}_{i,t+2}, \Omega_{i,t+1})$ and similar shorthand definitions describe the remaining functions. So, under the usual no-bubble condition,

$$q^K_{i,t} = \frac{1}{1-\delta^K} \sum_{s=t+1}^{\infty} \left(\frac{1-\delta^K}{R}\right)^{s-t} \mathbb{E}\left[\Pi_K(\cdot_{i,s}) - \mathbf{1}(I^K_{i,s+1})\, C^K_K(\cdot_{i,s}) \,|\, \mathcal{F}_{i,t}\right]. \quad (8)$$

and

$$q^{\Omega}_{i,t} = \frac{1}{1-\delta^{\Omega}} \sum_{s=t+1}^{\infty} \left(\frac{1-\delta^{\Omega}}{R}\right)^{s-t} \mathbb{E}\left[\Pi_{\Omega}(\cdot_{i,s}) - \mathbf{1}(I^{\Omega}_{i,s+1})\, C^{\Omega}_{\Omega}(\cdot_{i,s}) \,|\, \mathcal{F}_{i,t}\right] \quad (9)$$

Expected firm characteristics and market fundamentals govern optimal investments. Equations (8) and (9) suggest that market conditions affect the marginal value of both assets—physical capital and organizational knowledge—in a similar way.

**Proposition 1** *Under Assumptions 1 and 2, optimal physical investment follows the rule*

$$I^{K,opt}_{i,t+1} = \begin{cases} I^{K,*}_{i,t+1}(q^K_{i,t}; K_{i,t}) < 0 & \text{if } \; q^K_{i,t} < q^{K,-}(K_{i,t}) \\ 0 & \text{if } \; q^{K,-}(K_{i,t}) \leq q^K_{i,t} \leq q^{K,+}(K_{i,t}) \\ I^{K,*}_{i,t+1}(q^K_{i,t}; K_{i,t}) > 0 & \text{if } \; q^K_{i,t} > q^{K,+}(K_{i,t}) \end{cases} \quad (10)$$

*for some $q^{K,-}(K_{i,t}) < C^{K,-}_{I^K}(0, K_{i,t}) \leq C^{K,+}_{I^K}(0, K_{i,t})$ and some $q^{K,+}(K_{i,t}) > C^{K,+}_{I^K}(0, K_{i,t}) \geq 0$, where $I^{K,*}_{i,t+1}(q^K_{i,t}; K_{i,t})$ satisfies (7) and $q^K_{i,t}$ is given by (8).*

*Under Assumptions 1 and 3, optimal organizational change follows the rule*

$$I^{\Omega,opt}_{i,t+1} = \begin{cases} I^{\Omega,*}_{i,t+1}(q^{\Omega}_{i,t}; \Omega_{i,t}) < 0 & \text{if } \; q^{\Omega}_{i,t} < q^{\Omega,-}(\Omega_{i,t}) \\ 0 & \text{if } \; q^{\Omega,-}(\Omega_{i,t}) \leq q^{\Omega}_{i,t} \leq q^{\Omega,+}(\Omega_{i,t}) \\ I^{\Omega,*}_{i,t+1}(q^{\Omega}_{i,t}; \Omega_{i,t}) > 0 & \text{if } \; q^{\Omega}_{i,t} > q^{\Omega,+}(\Omega_{i,t}) \end{cases} \quad (11)$$

*for some $q^{\Omega,-}(\Omega_{i,t}) < C^{\Omega,-}_{I^{\Omega}}(0, \Omega_{i,t}) \leq C^{\Omega,+}_{I^{\Omega}}(0, \Omega_{i,t})$ and $q^{\Omega,+}(\Omega_{i,t}) > C^{\Omega,+}_{I^{\Omega}}(0, \Omega_{i,t}) \geq 0$, where $I^{\Omega,*}_{i,t+1}(q^{\Omega}_{i,t}; \Omega_{i,t})$ satisfies (7) and $q^{\Omega}_{i,t}$ is given by (9).*

*Under Assumption 1, and if $C^{\Omega}(I^{\Omega}_{i,t+1}, \Omega_{i,t})$ is twice differentiable with respect to $I^{\Omega}_{i,t+1}$ everywhere, $I^{\Omega,opt}_{i,t+1} = I^{\Omega,*}_{i,t+1}(q^{\Omega}_{i,t}; \Omega_{i,t})$, where $I^{\Omega,*}_{i,t+1}(q^{\Omega}_{i,t}; \Omega_{i,t})$ satisfies (7).*

**Proof.** See Appendix A. ■

Optimal investments are zero within the *ranges of inaction* $q^K_{i,t} \in [q^{K,-}, q^{K,+}]$ and $q^{\Omega}_{i,t} \in [q^{\Omega,-}, q^{\Omega,+}]$ and non-zero outside, where they are implicitly given by first-order condition (7). The boundaries of the ranges of inaction may vary with the asset position, depending on the properties of the adjustment cost function. For organizational change, if adjustment costs are smooth around zero investment, then there is no range of inaction (the range shrinks to a singleton). Appendix A presents the proof, extending Abel and Eberly (1994) to discrete time, and a convenient example of functional forms for empirical implementation where marginal and average $q$ are equal even under fixed adjustment costs.

## 2.3 Survival and expected productivity

Some firms exit. The rational shutdown rule depends on the firm's state variables and its information about market prospects. A natural timing of information release and decisions in every period $t$ is: the firm first chooses $I^{\Omega}_{i,t+1}$ and $I^{K}_{i,t+1}$ which take time to implement, then the firm observes its realization of $x_{i,t}$ and the sector-wide realization of $\mathbf{D}_{i,t}$, and finally it decides whether to remain in business or shutdown, and chooses variable inputs if it stays. It is plausible that firms exit immediately after adverse productivity shocks, whereas investments arguably require planning before productivity shocks are observable. The early investment decision, before the productivity shock is realized, also highlights that identification in this model does not depend on the specific timing assumption that productivity observation precedes the investment decision. Because the value function increases in both state variables, there are lower threshold levels for the states below which a firm exits, given market prospects. So, a firm's optimal shutdown rule can be written as a function of the realization of the *TFP* innovation.

After observing the realization of $x_{i,t+1}$, a firm decides whether to exit or continue in business:

$$\chi_{i,t+1} = \begin{cases} 0 & \text{if } \; x_{i,t+1} < \underline{x}(\omega_{i,t}; k_{i,t}, \mathbf{D}_{i,t}) \\ 1 & \text{otherwise,} \end{cases} \tag{12}$$

where $\chi_{i,t+1} = 0$ means that firm $i$ chooses to shutdown before the end of period $t+1$. $\omega_{i,t} \equiv \gamma \ln \Omega_{i,t}$ denotes estimable log productivity. $k_{i,t} \equiv \ln K_{i,t}$ is the log capital stock, and $\mathbf{D}_{i,t}$ the vector of firm $i$'s known market conditions at the time of the exit decision. If the value of current and discounted future profits falls short of the scrap value $\Phi$, the firm has no incentive to produce in the current or any future period. The value function (4) strictly increases in the state variables (organizational knowledge and the capital stock).[8] So, the threshold level $\underline{x}(\cdot)$ strictly decreases in $k_{i,t}$. A capital-rich firm is willing to bear lower *TFP* levels

[8] The expected marginal values of the assets are, by definition, equal to $q^{K}_{i,t-1} > 0$ and $q^{\Omega}_{i,t-1} > 0$ and strictly positive by (8) and (9). Estimates of exit probabilities from the second stage of the estimation algorithm will confirm that capital-rich firms are less likely to exit.

and still continues in business. Call the resulting probability that a firm stays in business through the end of period $t+1$

$$\Pr(\chi_{i,t+1} = 1 |\, \omega_{i,t}; k_{i,t}, \mathbf{D}_{i,t}) = G(\omega_{i,t}; k_{i,t}, \mathbf{D}_{i,t}). \tag{13}$$

If the firm stays in business, it faces a strictly positive relationship between Tobin's $q$'s for its two assets $q^{\Omega}_{i,t}$ and $q^{K}_{i,t}$. By (8) and (9),

$$q^{\Omega}_{i,t} = \rho_{i,t}(\omega_{i,t}; k_{i,t}, \mathbf{D}_{i,t}) \cdot q^{K}_{i,t} \tag{14}$$

where

$$\rho_{i,t}(\omega_{i,t}; k_{i,t}, \mathbf{D}_{i,t}) \equiv \frac{1-\delta^K}{1-\delta^\Omega} \frac{\sum_{s=t+1}^{\infty} \left(\frac{1-\delta^\Omega}{R}\right)^{s-t} \mathbb{E}\left[\, \Pi_\Omega(\cdot_{i,s}) - \mathbf{1}(I^{\Omega}_{i,s+1})\, C^{\Omega}_{\Omega}(\cdot_{i,s}) \,|\, \mathcal{F}_{i,t}\right]}{\sum_{s=t+1}^{\infty} \left(\frac{1-\delta^K}{R}\right)^{s-t} \mathbb{E}\left[\, \Pi_K(\cdot_{i,s}) - \mathbf{1}(I^{K}_{i,s+1})\, C^{K}_{K}(\cdot_{i,s}) \,|\, \mathcal{F}_{i,t}\right]}$$

is strictly positive conditional on survival. Firm $i$'s state variables and market conditions $\mathbf{D}_{i,t}$ enter its information set $\mathcal{F}_{i,t}$.

For the evolution of estimable log productivity $\omega_{i,t+1} \equiv \gamma \ln \Omega_{i,t+1}$, this relationship and Proposition 1 imply that

$$\omega_{i,t+1} = \begin{cases} \quad \textit{unobserved} & \text{if} \quad x_{i,t+1} < \underline{x}(\omega_{i,t}; k_{i,t}, \mathbf{D}_{i,t}), \\ h^0(\omega_{i,t}) + \gamma \ln x_{i,t+1} & \text{if} \;\; q^{\Omega}_{i,t} \in [q^{\Omega,-}, q^{\Omega,+}] \,\wedge\, x_{i,t+1} \geq \underline{x}(\cdot) \\ h^1(\omega_{i,t}; q^{K}_{i,t}, k_{i,t}, \mathbf{D}_{i,t}) + \gamma \ln x_{i,t+1} & \text{if} \;\; q^{\Omega}_{i,t} \notin [q^{\Omega,-}, q^{\Omega,+}] \,\wedge\, x_{i,t+1} \geq \underline{x}(\cdot) \end{cases} \tag{15}$$

by (3), where

$$\begin{aligned} h^0(\omega_{i,t}) \;&\equiv\; \gamma \ln(1-\delta^\Omega) + \omega_{i,t}, \\ h^1(\omega_{i,t}; q^{K}_{i,t}, k_{i,t}, \mathbf{D}_{i,t}) \;&\equiv\; \gamma \ln\left[(1-\delta^\Omega) e^{\omega_{i,t}/\gamma} + I^{\Omega,*}_{i,t+1}\big(\rho_{i,t}(\omega_{i,t}; k_{i,t}, \mathbf{D}_{i,t})\, q^{K}_{i,t};\, e^{\omega_{i,t}/\gamma}\big)\right]. \end{aligned}$$

Note that $h^1(\cdot)$ strictly increases in $q^{K}_{i,t}$ because $\rho_{i,t}(\cdot)$ is strictly positive conditional on survival, and organizational investment strictly increases in $q^{\Omega}_{i,t}$ by strict convexity of adjustment costs (Assumption 1).

Based on these insights, expected organizational knowledge can be defined as a function $h^{\text{OC}}(k_{i,t}, I^{K,\text{opt}}_{i,t+1}, \mathbf{D}_{i,t})$, and a survivor's expected log productivity shock as a function $h^X(k_{i,t}, \mathbf{D}_{i,t})$:

$$\begin{aligned} h^{\text{OC}} \;&\equiv\; \begin{cases} h^1(\omega_{i,t}; C^{K}_{I^K}(I^{K,\text{opt}}_{i,t+1}, e^{k_{i,t}}), k_{i,t}, \mathbf{D}_{i,t}) & \textit{if} \;\; q^{\Omega}_{i,t} \notin [q^{\Omega,-}, q^{\Omega,+}] \,\wedge\, I^{K,\text{opt}}_{i,t+1} \neq 0 \\ h^1(\omega_{i,t}; q^{K}_{i,t}, k_{i,t}, \mathbf{D}_{i,t}) & \textit{if} \;\; q^{\Omega}_{i,t} \notin [q^{\Omega,-}, q^{\Omega,+}] \,\wedge\, I^{K,\text{opt}}_{i,t+1} = 0 \\ h^0(\omega_{i,t}) & \textit{if} \;\; q^{\Omega}_{i,t} \in [q^{\Omega,-}, q^{\Omega,+}], \end{cases} \\ h^X \;&\equiv\; \int_{\gamma \ln \underline{x}(\omega_{i,t}; k_{i,t}, \mathbf{D}_{i,t}) - \beta_{0,i}} \xi_{i,t+1} \frac{f\left(\xi_{i,t+1}\right)}{G(\omega_{i,t}; k_{i,t}, \mathbf{D}_{i,t})}\, d\xi_{i,t+1}, \end{aligned}$$

where $\xi_{i,t+1} \equiv \gamma \ln x_{i,t+1} - \beta_{0,i}$ and $\beta_{0,i} = \gamma \mathbb{E}\left[\ln x_{i,t+1}\right]$. Proposition 2 states the properties.

**Proposition 2** *Under Assumptions 1 and 2, the conditional expectation of log productivity is*

$$\mathbb{E}[\omega_{i,t+1} | \chi_{i,t+1} = 1, k_{i,t}, I^{K,opt}_{i,t+1}, \mathbf{D}_{i,t}] = h^{OC}(k_{i,t}, I^{K,opt}_{i,t+1}, \mathbf{D}_{i,t}) + h^X(k_{i,t}, \mathbf{D}_{i,t}) + \beta_{0,i}. \tag{16}$$

$h^X(\cdot)$ *strictly decreases in* $k_{i,t}$*, and* $h^X(\cdot)$ *changes strictly monotonically in elements of* $\mathbf{D}_{i,t}$ *if and only if the firm's value function changes strictly monotonically in the elements.*

*Under twice differentiable* $C^{\Omega}(I^{\Omega}_{i,t+1}, \Omega_{i,t})$ *with respect to* $I^{\Omega}_{i,t+1}$ *everywhere,* $h^{OC}(\cdot)$ *strictly increases in* $k_{i,t}$ *and* $I^{K,opt}_{i,t+1}$*, and* $h^{OC}(\cdot)$ *changes strictly monotonically in elements of* $\mathbf{D}_{i,t}$ *if and only if the firm's value function changes strictly monotonically in the elements. Under Assumption 3,* $h^{OC}(\cdot)$ *weakly increases in* $k_{i,t}$ *and* $I^{K,opt}_{i,t+1}$*, and* $h^{OC}(\cdot)$ *changes weakly monotonically in elements of* $\mathbf{D}_{i,t}$ *if the firm's value function changes weakly monotonically in the elements.*

**Proof.** See Appendix B ■

Expected log productivity has two components. The component $h^X(\cdot)$ is familiar from Olley and Pakes (1996). But it is now theoretically independent of physical investment after dropping the timing assumption that the productivity-shock realization is fully known before investment decisions are taken. Of course, physical investment can still be considered a proxy to otherwise unobserved components of $\mathbf{D}_{i,t}$ since the econometrician may not observe the firm's complete information set about market conditions. The component $h^X(\cdot)$ includes a vector of current market conditions, which shift the minimum productivity threshold for survivors.

The novel component $h^{\mathrm{OC}}(\cdot)$ is the result of the firm's joint decision on physical and intangible investments, given market conditions, and provides an additional source of identification. If the data are plausibly consistent with the assumption that there are no fixed adjustment cost to organizational change, then identification can exclusively rely on $h^{\mathrm{OC}}(\cdot)$ because it changes strictly monotonically in physical investment and firms' market conditions, and thus permits control-function estimation of expected log productivity without exit-rule estimation. In the presence of fixed adjustment costs to organizational change, however, identification depends on $h^X(\cdot)$ for the range of inaction in organizational change where $h^{\mathrm{OC}}(\cdot)$ does not respond to investment or market conditions, whereas $h^X(\cdot)$ monotonically responds everywhere. Even under fixed costs to organizational change, strict monotonicity of $h^{\mathrm{OC}}(\cdot)$ outside the range of organizational inaction improves efficiency of control-function estimation.

Proposition 2 clarifies that the exit rule is a crucial source of identification, using the firms' current market conditions as control variables, if the econometrician neither wants to rely on timing assumptions nor wants to rule out fixed cost in organizational change. Using the exit rule for identification permits the econometrician to test for the presence of fixed costs to organizational change. Prior evidence on organizational change can be interpreted as consistent with the presence or absence of fixed adjustment cost;[9] empirical results in this paper do not provide evidence in favor of fixed adjustment costs for organizational change (Section 4.2).

Proposition 2 restates in the context of the present model that a transmission bias arises for capital-stock coefficients. The sign is indeterminate, however. The omission of log-productivity controls can either result in negatively biased capital coefficients (if the effect of $k_{i,t}$ on $h^X$ dominates) or positively biased capital coefficients (if the effect of $k_{i,t}$ on $h^{\mathrm{OC}}$ dominates). A positive bias in OLS capital coefficients is often found in micro data, casting doubt on prior models that rule out this possibility. Moreover, Proposition 2 justifies the retention of observations with non-positive net investment as long as variables on market conditions are included alongside.

## 2.4 Identification of variable input coefficients

The first regression equation follows from using the past expectation of (16) in (1),

$$\begin{aligned} z_{i,t} &= \beta_{0,i} + \beta_L\, l_{i,t} + \beta_M\, m_{i,t} + \beta_K\, k_{i,t} + h(I^K_{i,t}, k_{i,t}, \mathbf{D}_{i,t-1}) + \xi_{i,t} + \epsilon_{i,t} \\ &\equiv \beta_{0,i} + \beta_L\, l_{i,t} + \beta_M\, m_{i,t} + \phi(I^K_{i,t}, k_{i,t}, \mathbf{D}_{i,t-1}) + \xi_{i,t} + \epsilon_{i,t}, \end{aligned} \tag{17}$$

where lower-case variables are the logs of their upper-case equivalents, $h(\cdot) \equiv h^{\mathrm{OC}}(\cdot) + h^X(\cdot)$, $l_{i,t}$ excludes managers from the work force to account for fixed factor use, and $\beta_{0,i}$ is a firm-fixed effect. Note that for known $I^K_{i,t}$, we can replace $k_{i,t-1}$ with $k_{i,t}$ in $h(\cdot)$. Prior investment $I^K_{i,t}$ remains nevertheless an independent regressor because it reveals distinct information in a model of adjustment costs, beyond $k_{i,t}$, where past investment is positively related to the magnitude of the past productivity shock $\xi_{i,t-1}$, which is now part of $\omega_{i,t}$.

The term $\phi(\cdot) \equiv \beta_K\, k_{i,t} + h(\cdot)$ arises because the effect of log *TFP* on output cannot be separated from the effect of physical capital on output as long as their correlation is not removed. $h(\cdot)$ is a non-linear function of $(k_{i,t}, I^K_{i,t}, \mathbf{D}_{i,t-1})$ and will be approximated by a higher-order polynomial.[10] The coefficient estimates for $\beta_L$ and $\beta_M$, on the other hand, are consistent if $\phi(\cdot)$ is independently identified. Note that identification does not require perfect foresight of the firm. The

[9] See footnote 7.

[10] Competition can affect the distribution of $x_{i,t}$ (Hermalin 1992, Schmidt 1997, Raith 2003). An according extension of the estimation model (Muendler 2004) shows that more competitive market conditions tend to shift mean $x_{i,t}$.

control function $\phi(I^K_{i,t}, k_{i,t}, \mathbf{D}_{i,t-1})$ is based on observed investments and market-related variables $\mathbf{D}_{i,t-1}$ that are both observable to the researcher and in the firm's information set at the time of its decision.

As long as labor and intermediate inputs are imperfect substitutes in (6), their optimal choice depends on distinct factor prices, or differently weighted combinations of them, and $\beta_L$ and $\beta_M$ are independently identified. Ackerberg, Caves and Frazer (2005) point out, however, that $l_{i,t}$ and $m_{i,t}$ are not identified independently of $\phi(\cdot)$ if and only if the firm chooses $l_{i,t}$ and $m_{i,t}$ as a function of the same factor prices and market conditions as $k_{i,t}$ and $\omega_{i,t}$. So optimal factor choices $l_{i,t} = l(I^K_{i,t}, k_{i,t})$ and $m_{i,t} = m(I^K_{i,t}, k_{i,t})$ are potentially functions of the same variables as $\phi = \phi(I^K_{i,t}, k_{i,t})$. Ackerberg et al. (2005) argue that this potential identification (multi-collinearity) problem affects the Olley and Pakes (1996) procedure less than the Levinsohn and Petrin (2003) approach because firms can hardly alter their choice of the Olley and Pakes productivity proxies $I^K_{i,t}$ and $k_{i,t}$ in response to factor price changes and other news between $t-1$ and $t$. Levinsohn and Petrin's productivity proxy, however, is the present input choice $m_{i,t}$ and does respond to innovations in factor prices and other news between $t-1$ and $t$.

To identify $\beta_L$ and $\beta_M$ from (17), Ackerberg et al. (2005) propose an estimation procedure based on the moment conditions $\mathbb{E}[\xi_{i,t}+\epsilon_{i,t}|k_{i,t}] = \mathbb{E}[\xi_{i,t}+\epsilon_{i,t}|l_{i,t-1}] = \mathbb{E}[\xi_{i,t}+\epsilon_{i,t}|m_{i,t-1}] = 0$. These conditions rely on the assumption that investments are chosen at an earlier time than variable inputs. The according use of lagged variable input choices in the moment conditions is similar in spirit to Levinsohn and Petrin's (2003) over-identifying restrictions and instrumental variable approaches such as those by Blundell and Bond (2000), which also draw on timing assumptions. Concurrent expected values $\mathbb{E}[\xi_{i,t}|l_{i,t}] \neq 0$ and $\mathbb{E}[\xi_{i,t}|m_{i,t-1}] \neq 0$, however, would arguably violate mean independence because firms observe their $\xi_{i,t}$ realization before the choice of variable factors.

Estimation equation (17) in the present estimation framework is identified under equivalent moment conditions to those proposed by Ackerberg et al. (2005). Whereas $I^K_{i,t}$ and $k_{i,t}$ were chosen on the basis of firm $i$'s past information set $\mathcal{F}_{i,t-1}$, including $\mathbf{D}_{i,t-1}$ but not $\xi_{i,t}$, variable input choices $l_{i,t}$ and $m_{i,t}$ respond to $\mathbf{D}_{i,t}$ and $\xi_{i,t}$. In mathematical notation, $\beta_K k_{i,t} + \gamma\omega_{i,t} = \phi(I^K_{i,t}, k_{i,t}, \mathbf{D}_{i,t-1})$ but $l_{i,t} = l(\mathbf{D}_{i,t})$ and $m_{i,t} = m(\mathbf{D}_{i,t})$. These timing assumptions are equivalent to $\mathbb{E}[\xi_{i,t}|l_{i,t}] \neq 0$ and $\mathbb{E}[\xi_{i,t}|m_{i,t-1}] \neq 0$ and $\mathbb{E}[\xi_{i,t}+\epsilon_{i,t}|k_{i,t}] = \mathbb{E}[\xi_{i,t}+\epsilon_{i,t}|l_{i,t-1}] = \mathbb{E}[\xi_{i,t}+\epsilon_{i,t}|m_{i,t-1}] = 0$. Beyond Ackerberg et al.'s (2005) estimation approach, the current framework explicitly accounts for market conditions and endogenous productivity responses to them.

## 2.5 Identification of capital-stock coefficients

A firm's exit rule is an important source of identification in the absence of timing assumptions and in the presence of fixed cost to organizational change. By (13), the probability of survival is

$$\Pr\left(\chi_{i,t+1} = 1|\cdot\right) = G(I^K_{i,t}, k_{i,t}, \mathbf{D}_{i,t}) \tag{18}$$

conditional on observable variables. Equation (18) is the second estimation equation.

To obtain a consistent estimate of the capital coefficient $\beta_K$, use information on the expected contribution of capital to production one period in advance. Consider $z_{i,t+1} - \beta_{0,i} - \beta_L\, l_{i,t+1} - \beta_M\, m_{i,t+1}$. Conditional on survival and past productivity, the expectation of this term is

$$\begin{aligned}\mathbb{E}\left[z_{i,t+1} - \beta_{0,i} - \beta_L\, l_{i,t+1} - \beta_M\, m_{i,t+1}\,|k_{i,t+1}, \omega_{i,t}, \mathbf{D}_{i,t+1}, \chi_{i,t+1} = 1\right] \\ = \beta_K\, k_{i,t+1} + \mathbb{E}[\omega_{i,t+1}|\, \chi_{i,t+1} = 1, k_{i,t+1}, I^K_{i,t+1}, \mathbf{D}_{i,t}]\end{aligned}$$

by (16). The expected value of log productivity one period in advance is a function $g$ of the survival probability $G(\cdot)$ and past productivity $h^{\mathrm{OC}}(\cdot_{i,t}) = \phi(\cdot_{i,t}) - \beta_K\, k_{i,t}$. So,

$$\begin{aligned} & z_{i,t+1} - \beta_{0,i} - \beta_L\, l_{i,t+1} - \beta_M\, m_{i,t+1} \\ & \quad = \beta_K\, k_{i,t+1} + g\left(G(\cdot), \phi(\cdot) - \beta_K\, k_{i,t}\right) + \xi_{i,t+1} + \epsilon_{i,t+1}. \end{aligned} \tag{19}$$

The variable $\xi_{i,t+1}$ is the unanticipated innovation in $\omega_{i,t+1}$. Hence, it is not correlated with net investment $I^K_{i,t+1}$ or tomorrow's log capital stock $k_{i,t+1}$, and the estimate of $\beta_K$ is consistent. $\beta_K$ is independently identified because $k_{i,t+1}$ enters $g(\cdot)$ only in conjunction with predicted survival or market conditions. Equation (19) is the third estimation equation. To resemble Olley and Pakes (1996), I choose a third-order polynomial expansion $\sum_{m=0}^{3} \sum_{n=0}^{3-m} \beta_{m,n} (\hat{G})^m (\hat{h})^n$ to approximate $g\left(G(\cdot), h(\cdot)\right)$ in equation (19).

The capital coefficient enters equation (19) twice: in the additive terms, and through $\hat{h}(\cdot) = \hat{\phi}(\cdot) - \beta_K\, k_{i,t}$. I estimate the equation with non-linear least squares, using fixed-effects estimates of equation (17) as starting values. Subtracting the fixed effect $\beta_{0,i}$ from $z_{i,t}$ on the left hand side reduces the fit in some sectors. The error term, however, needs to be identically distributed for the bootstrap to follow. Moreover, endogenous productivity choice implies by (16) that firm-specific initial productivity levels have to be accounted for. This favors subtraction of $\beta_{0,i}$ from the left-hand side in (19).

## 2.6 Adjustment for omitted price bias

A source of bias remains for estimates of economies of scale because revenues are used to approximate output but price is endogenous in imperfectly competitive markets (Klette and Griliches 1996).[11] The total of a firm's sales and production for inventory, deflated by sector-specific price indices, approximates output. So, the dependent variable in the first regression equation (17) is in fact $p_{i,t}+z_{i,t}-\bar{p}_t$, where $p_{i,t}$ denotes the log of firm $i$'s product price and $\bar{p}_t$ the value of the price index for deflation. By demand (2), the difference between a firm's price and market price is $p_{i,t}-\bar{p}_t = -(1-\eta)d_{i,t}+(1-\eta)(\bar{\theta}_t-\bar{p}_t)$, where $-1/(1-\eta) \in (-\infty, -1)$ approximates price elasticity of demand and $\bar{\theta}_t$ denotes the log of market-wide demand. Because of this relationship and since $d_{i,t} = z_{i,t}$ in equilibrium, the *de facto* regression is

$$\begin{aligned}
(p_{i,t} + z_{i,t} - \bar{p}_t) &= \eta z_{i,t} + (1-\eta)(\bar{\theta}_t - \bar{p}_t) \\
&= \eta\beta_{0,i} + (1-\eta)(\bar{\theta} - \bar{p}) \\
&\quad +\eta\beta_L\, l_{i,t} + \eta\beta_M\, m_{i,t} + \eta\phi(I^K_{i,t}, k_{i,t}, \mathbf{D}_{i,t-1}) \\
&\quad +(1-\eta)(\Delta\bar{\theta}_t - \Delta\bar{p}_t) + \eta\xi_{i,t} + \eta\epsilon_{i,t},
\end{aligned} \tag{20}$$

rather than (17). Here, the log of market-wide demand for close substitutes $(1-\eta)(\bar{\theta}_t - \bar{p}_t)$ is decomposed into a preference based component $(1-\eta)(\bar{\theta} - \bar{p})$ that does not vary over time, and into a time-varying component $(1-\eta)(\Delta\bar{\theta}_t-\Delta\bar{p}_t)$ that moves with the market conditions and the business cycle ($\Delta\bar{\theta}_t \equiv \bar{\theta}_t - \bar{\theta}$ and $\Delta\bar{p}_t \equiv \bar{p}_t - \bar{p}$).

The demand-side parameter $\eta$ confounds the estimate of returns to scale by appearing in front of $z_{i,t}$. Klette and Griliches (1996) propose to use the sum of all firms' sales to approximate market-wide demand and to include it explicitly in the regression. Their purpose is to correct the scale estimate. Here, however, the focus lies on endogenous productivity choice, and there are theoretical and practical reasons not to use Klette and Griliches's full correction but rather a fixed-effects variant. The present estimation framework implies that the fixed-effects estimator $\eta\beta_{0,i}+(1-\eta)(\bar{\theta}-\bar{p})$ absorbs the time-invariant demand component $\bar{\theta}$ and that the time-varying demand component $\Delta\bar{\theta}_t$ becomes part of the expectations proxy $\eta\phi(I^K_{i,t}, k_{i,t}, \mathbf{D}_{i,t-1}) + (1-\eta)(\Delta\bar{\theta}_t - \Delta\bar{p}_t)$.

A firm's investment in organizational knowledge $I^{\Omega}_{i,t+1}$ depends on market expectations by (9) and (11). If these market expectations are rational and firms are able to anticipate demand well, the coefficient on log sector-wide demand,

[11] Harrison (1994) discusses the problem of markups in input prices. This is of less concern in the present context and for Brazilian manufacturing data, in which foreign inputs can be deflated separately from domestic variables. Eslava, Haltiwanger, Kugler and Kugler (2004) treat the markup problem using observed plant-level prices in Colombian data.

which is part of the vector $\mathbf{D}_{i,t-1}$, will capture efficiency choice rather than the omitted price effect. Estimation in Section 4 shows that the coefficient on log aggregate demand would imply unreasonable demand elasticities $-1/(1-\hat{\eta})$ in several sectors. In fact, some coefficient estimates imply $1-\hat{\eta} > 1$ although $\eta > 0$ in theory—an impossibility. This finding indicates that market expectations can go a long way in explaining productivity choice. The coefficient estimate for $(1-\eta)$ likely captures both the price elasticity of demand and the effect of current demand on realizations of productivity choice.

In summary, the estimation framework addresses endogenous investment in productivity-relevant assets and provides a consistent identification approach for production under reasonable and commonly used moment conditions. The approach accounts for selection, transmission bias, and omitted price bias. Up to a correction factor for scale economies, unbiased production function coefficients result. So, while the inference of firm-specific *TFP* levels remains a challenge for research, measures of firm-specific *TFP change* can be constructed.

# 3 Data

The Brazilian statistical bureau *IBGE* surveys manufacturing firms annually in its *Pesquisa Industrial Anual* (*PIA*). The firm sample from 1986 to 1995 (with the year 1991 missing due to a federal austerity program), and its extension through 1998, is representative for medium-sized to large manufacturing companies but not necessarily for the Brazilian manufacturing sector as a whole. This Section summarizes data characteristics and highlights elements of the panel construction. Appendix C provides a more detailed description of the sample.

For brevity of exposition, I restrict the data to the five sectors with the largest number of firm-year observations at *nível 50*: (08) Machinery, equipment and installations; (14) Wood sawing, wood products and furniture; (22) Textiles; (26) Plant product processing (including rice and wheat milling, fruit and vegetable processing, and tobacco); and (31) Other food and beverage manufacturing (including animal feeds, other food and beverage manufacturing). Together, the five largest sectors comprise 24,661 firm-year observations of the total 72,652 observations in 27 manufacturing sectors at *nível 50* in *PIA* 1986-98.

*PIA* offers precise longitudinal information for every firm. Special variables record a firm's state of operation and make sure that observations with missing economic information are not confounded with closure or temporary suspension. Brazilian manufacturers between 1986 and 1998 mothball for extended periods of time. Among the 9,500 firms with valid observations, more than 1,100 state in at least one year that they suspended production temporarily or for the entire year.

Economic variables in *PIA* include sales figures and changes in final goods

Table 2: SUMMARY STATISTICS FOR LARGEST FIVE SECTORS

| | Mean (1) | S.dev. (2) | Median (3) | Obs. (4) |
|---|---|---|---|---|
| *Firm-level variables* | | | | |
| Output | 26.412 | 66.955 | 7.060 | 21,465 |
| Intermediate goods | 12.572 | 33.258 | 2.836 | 20,862 |
| Total employment | 677.266 | 1102.038 | 300.000 | 17,362 |
| Blue-collar employment | 468.528 | 3077.856 | 176.000 | 20,894 |
| White-collar employment | 164.808 | 373.944 | 50.000 | 17,574 |
| Total capital | 14.404 | 41.604 | 3.374 | 17,912 |
| Equipment | 4.367 | 13.145 | .760 | 17,923 |
| Structures | 10.027 | 34.495 | 2.273 | 17,927 |
| Total net investment | 1.540 | 9.521 | .046 | 20,118 |
| Equipment net investment | .508 | 4.653 | .000 | 20,118 |
| Structures net investment | 1.032 | 7.715 | .019 | 20,118 |
| Foreign intm. goods share | .013 | .073 | .000 | 24,123 |
| Foreign equipment share | .023 | .098 | .000 | 18,800 |
| *Firm-level variables related to market conditions* | | | | |
| Investment $\times$ Lagged foreign penetration | .074 | .814 | .0008 | 19,390 |
| Competitors' mean equipment | .759 | .587 | .529 | 24,661 |
| Competitors' mean output/employment | .054 | .021 | .046 | 24,661 |
| *Sector-level variables related to market conditions* | | | | |
| Aggregate demand (billion) | 10.197 | 3.330 | 10.564 | 24,661 |
| Foreign market penetration | .049 | .056 | .026 | 24,661 |
| Nominal tariff | .352 | .246 | .257 | 24,661 |

*Source*: *Pesquisa Industrial Anual* 1986-1998 from sectors (08) Machinery, (14) Wood and furniture, (22) Textiles, (26) Plant products, (31) Other food and beverages.
*Notes*: Economic figures in million Reais, August 1994 (except for aggregate demand); employment in number of persons; foreign input shares, market penetration and tariffs as fractions.

stocks, costs of inputs, employment of blue- and white-collar workers, and several variables related to investment and the capital stock. Firms in *PIA* also report their acquisitions of foreign equipment until 1995 and their purchases of foreign intermediate goods since 1996. Output and domestic inputs are deflated with sector-specific wholesale price indices. Capital stock figures and investments are deflated with economy-wide wholesale price indices. There is no producer price index for Brazil. A perpetual inventory method, which controls for changes to accounting law in 1991, yields the overall capital stock (see Muendler 2005).

Table 2 presents summary statistics for the five largest sectors. A sizable number of observations exhibits missing values for several variables. Except for intermediate steps in the perpetual inventory method for capital stock figures, no variables are imputed. Median investment in equipment is zero, and median investment in structures close to zero. Among the 20,118 firm-year observations in the final estimation sample, 8,574 exhibit zero equipment investment and 5,799 show zero structures investment. Fixed adjustment costs in the theoretical model of Section 2 account for this lumpiness.

Sector classifications in *PIA* would allow for the estimation of production functions at a level that corresponds to three *ISIC* digits (*nível 100*). The large firms in *PIA*, however, are likely to offer product ranges beyond narrowly defined sector limits. Data at more aggregate levels also provide more variation in the cross section because variables related to the market environment become available for two or more subsectors within several sectors. Moreover, switching from the three to the two-digit level increases the number of observations per estimation considerably. So, I carry out estimation at two *ISIC* digits (*nível 50*).

# 4 Production Function Estimation

The model of endogenous physical and intangible investments in Section 2 implies that capital investments interacted with competition variables are principal candidates to capture a firm's individual market expectations and to correct for transmission bias. The model—(17), (18) and (19)—is estimated for constant factor elasticities between 1986 and 1998.

## 4.1 Extended Olley and Pakes procedure

Exit estimation (18) is an important source of identification if the econometrician neither wants to rely on timing assumptions nor wants to rule out fixed cost in organizational change. To estimate survival probability (18), I choose two independent logit and probit functions for the pre-1991 data and for the post-1991 data, taking into account that shutdown probabilities may have changed systematically after trade liberalization in 1990. Contrary to the general finding for estimation of (17) and (19), where time indicators are not significant, the fit improves in this case.[12] The survival probability (18) at $t+1$ is predicted with a fourth-order polynomial in $(I^K_{i,t}, I^S_{i,t}, a_{i,t}, k_{i,t}, s_{i,t})$ and variables $\mathbf{D}_{i,t}$, where $a_{i,t}$ denotes a firm's log age. Capital is decomposed into equipment $k_{i,t}$ and structures $s_{i,t}$, and so is net investment $(I^K_{i,t}, I^S_{i,t})$. Variables $\mathbf{D}_{i,t}$ (nominal tariffs, foreign market penetration, the sectoral real exchange rate and domestic inflation) characterize a firm's market environment at the time of the continuation decision.

[12]No survival probability can be estimated for 1991 but is needed on the third step. In order not to lose all 1992 observations, I impute the survival probability in 1991 as the unweighted average of the 1989, 1990, and 1992 predictions for each firm.

Table 3: OBSERVED AND PREDICTED SURVIVAL

| | Mean | St. dev. | Correlation coeff. | | |
|---|---|---|---|---|---|
| | | | Survival | Probit | Logit |
| Survival, overall[a] | .968 | .177 | | | |
| Survival, estimation sample[b] | .994 | .078 | 1.000 | | |
| Probit prediction[b] | .973 | .081 | .144 | 1.000 | |
| Logit prediction[b] | .973 | .089 | .147 | .914 | 1.000 |

[a]24,661 observations in largest five manufacturing sectors at *nível 50*.
[b]17,253 observations in largest five manufacturing sectors at *nível 50*.

*Source*: *Pesquisa Industrial Anual* 1986-1998 from sectors (08) Machinery, (14) Wood and furniture, (22) Textiles, (26) Plant products, (31) Other food and beverages.

Table 3 shows that both the probit and the logit model predict slightly too few exits as compared to the data, and exhibit slightly more dispersion. Financial variables of the firm such as its debt composition and competitor variables turn out to reduce the fit of the logit and probit models and are left out. Including the vector of market environment variables $\mathbf{D}_{i,t}$ improves the correlation between probabilities (between zero and one) and observed outcomes (either zero or one). Correlation coefficients show that the logit model slightly outperforms probit in the estimation sample of the largest five sectors.[13] Logit estimates are used for the remaining procedure.

The production function on the first step (17) and third step (19) is augmented to account for all factors available in the data and a firm-fixed effect. A polynomial series estimator of third order approximates the part of production $\phi(I^K_{i,t}, I^S_{i,t}, a_{i,t}, k_{i,t}, s_{i,t}; \kappa^f_{i,t}, \mu^f_{i,t}; \mathbf{D}_{i,t-1})$ that is affected by transmission bias. Variables in $\mathbf{D}_{i,t-1}$ characterize a firm's competitive environment to approximate investments in organizational knowledge. The vector includes five variables: firm-specific lags of competitors' mean equipment stock and competitors' mean labor productivity, as well as sector-specific nominal tariffs, foreign market penetration, and aggregate demand. The interaction of these variables with the firms' physical investment in equipment and structures is intended to capture both general business prospects and the firms' individual expectations about them. To reduce measurement error in inputs, the shares of foreign equipment $\kappa^f_{i,t}$ and foreign intermediate inputs $\mu^f_{i,t}$ are included as regressors in $\phi(\cdot)$. The variable $\kappa^f$ is available for 1986 through 1995, and $\mu^f$ from 1996 to 1998; observations are stacked accordingly. Neither a time trend nor year dummies were jointly significant when

[13]In the five largest sectors, correlation coefficients of around .14 are considerably below those in the full sample. The correlation coefficients are .25 (probit) and .26 (logit) in the sample of all 27 manufacturing sectors at *nível 50*.

included. These findings lend support to the assertion that an exogenous drop in the connecting sample in 1996 does not affect production estimates.

Including a set of expectation proxies—individual investments, market environment variables, and their interactions—results in individual significance of some but not all proxy coefficients. Alternative regression specifications showed that polynomial expansions of lower than third order or the omission of regressors would turn more market variables statistically significant. Yet only the joint significance of a combination of these proxy regressors matters for transmission bias correction in the present context. Net investment regressors turn insignificant when the market covariates $\mathbf{D}_{i,t-1}$ are included. This may be evidence that investment in Olley and Pakes (1996) indeed proxies a firm's expectations of the market environment.

Table 4 contrasts production coefficients from the extended Olley-Pakes (EOP) procedure with EOP estimates from a subsample of observations with strictly positive investments in both equipment and structures (EOP $I^K > 0$). Table 4 also reports results from fixed-effect regressions (FE), an alternative estimation method under the behavioral assumptions but usually the most strikingly different estimator, and from OLS.

Several capital coefficients on equipment and structures under the EOP procedure resemble coefficients under the fixed-effects estimators (FE). The agreement between EOP and FE capital coefficient may indicate that capital coefficients mostly suffer from a firm-specific and constant transmission bias. The lacking agreement between EOP and FE labor and intermediate input coefficients, on the other hand, suggests that time-varying elements of transmission bias may affect short-term (variable) factor choices more strongly.

The FE estimator is generally thought to bias capital coefficients downward (e.g. Griliches and Mairesse 1998). In the Brazilian manufacturing sample, however, several capital coefficients on equipment and structures in Table 4 are larger under EOP and FE than under OLS—indicating a positive bias in OLS capital coefficients. The model in Section 2, where simultaneous investment in physical capital and productivity change are driven by market expectations, suggests that a positive association between capital and productivity among survivors may outweigh the negative correlation induced by exit. Other studies encounter positively biased OLS capital coefficients too (Mairesse and Hall 1996, Pavcnik 2002, Levinsohn and Petrin 2003). Table 4 also shows, however, that the OLS equipment coefficient exhibits a negative bias in two out of five sectors (14, 26) and that the OLS structures coefficient has a negative bias in three out of five sectors (08, 14, 22). These latter estimates are consistent with the widely expected negative bias in capital coefficients in micro data.

The original Olley and Pakes procedure requires observations with strictly

Table 4: COMPARISON OF PRODUCTION FUNCTION ESTIMATES

| | EOP | | EOP $I^K>0$ | | FE | | OLS | |
|---|---|---|---|---|---|---|---|---|
| | Coef. | *SE* | Coef. | *SE* | Coef. | *SE* | Coef. | *SE* |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| **(08) Machines** | | | | | | | | |
| Blue-coll. empl. | .398 | .028 | .378 | .092 | .439 | .017 | .243 | .014 |
| White-coll. empl. | .261 | .023 | .224 | .071 | .238 | .016 | .319 | .014 |
| Interm. goods | .231 | .018 | .138 | .025 | .244 | .010 | .365 | .010 |
| Equipment | .013 | .018 | .039 | .037 | .013 | .015 | .069 | .009 |
| Structures | .078 | .016 | .064 | .024 | .077 | .014 | .053 | .011 |
| Obs. | 1,987 | | 1,124 | | 2,629 | | 2,629 | |
| **(14) Wood and furniture** | | | | | | | | |
| Blue-coll. empl. | .460 | .027 | .401 | .069 | .563 | .018 | .367 | .015 |
| White-coll. empl. | .167 | .020 | .066 | .052 | .165 | .015 | .216 | .013 |
| Interm. goods | .224 | .016 | .097 | .023 | .232 | .010 | .335 | .009 |
| Equipment | .163 | .022 | .171 | .034 | .178 | .015 | .085 | .010 |
| Structures | .059 | .015 | .092 | .024 | .060 | .015 | .039 | .010 |
| Obs. | 2,014 | | 975 | | 2,731 | | 2,731 | |
| **(22) Textiles** | | | | | | | | |
| Blue-coll. empl. | .394 | .034 | .272 | .062 | .473 | .015 | .256 | .012 |
| White-coll. empl. | .164 | .022 | .134 | .040 | .177 | .015 | .209 | .012 |
| Interm. goods | .310 | .023 | .124 | .026 | .311 | .009 | .457 | .008 |
| Equipment | .031 | .018 | .111 | .055 | .030 | .013 | .041 | .008 |
| Structures | .079 | .017 | .130 | .043 | .080 | .012 | .042 | .009 |
| Obs. | 2,444 | | 1,181 | | 3,197 | | 3,197 | |
| **(26) Plant products** | | | | | | | | |
| Blue-coll. empl. | .347 | .031 | .313 | .095 | .395 | .018 | .250 | .015 |
| White-coll. empl. | .216 | .022 | .172 | .061 | .238 | .017 | .243 | .014 |
| Interm. goods | .239 | .023 | .164 | .028 | .230 | .009 | .385 | .008 |
| Equipment | .085 | .020 | .071 | .042 | .084 | .016 | .055 | .011 |
| Structures | .059 | .024 | .184 | .061 | .057 | .015 | .126 | .012 |
| Obs. | 2,092 | | 967 | | 2,745 | | 2,745 | |
| **(31) Other food and beverages** | | | | | | | | |
| Blue-coll. empl. | .410 | .037 | .253 | .068 | .490 | .016 | .273 | .013 |
| White-coll. empl. | .188 | .017 | .152 | .036 | .209 | .013 | .229 | .011 |
| Interm. goods | .199 | .015 | .153 | .022 | .179 | .008 | .338 | .008 |
| Equipment | .068 | .015 | .041 | .026 | .068 | .014 | .085 | .010 |
| Structures | .038 | .015 | .102 | .027 | .038 | .012 | .081 | .011 |
| Obs. | 2,562 | | 1,303 | | 3,367 | | 3,367 | |

*Data*: *Pesquisa Industrial Anual* 1986-98. Variables in logs.
*Note*: Standard errors from 200 bootstraps.

positive investments because zero or negative investment is not invertible in its determinants when productivity is assumed to be exogenous. Table 4 presents results for the subsample of observations with both strictly positive equipment investment and strictly positive structures investment. Every coefficient on a factor other than capital is smaller in the positive-investment sample (column 3) than in the full sample (column 1), whereas most coefficients on capital goods exceed those in the full sample. Economic theory suggests this pattern. Firms with higher marginal products of capital, and lower marginal products of other factors, invest to raise their capital stock. So, the positive-investment subsample does not reflect the average production technology within a sector but an initially less capital-intensive technology. The firm's model in this paper justifies the retention of observations with zero and negative investment in the extended EOP procedure. It avoids the bias towards high marginal products on capital that would result form a restriction to a positive-investment subsample.

## 4.2 Checks on assumptions and implications

The distribution of estimated *TFP* and its association with other variables provide insight into the validity of model and estimation assumptions. Given production function estimates, the logarithm of total factor productivity at the firm level $\ln TFP_{i,t} = \beta_{0,i} + \xi_{i,t} + \epsilon_{i,t}$ becomes

$$\begin{aligned} \eta \ln TFP_{i,t} &= y_{i,t} - \widehat{(1-\eta)(\bar{\theta}_t - \bar{p}_t)} \\ &\quad - \left( \hat{\beta}_{bl}\, l_{i,t}^{bl} + \hat{\beta}_{wh}\, l_{i,t}^{wh} + \hat{\beta}_K\, k_{i,t} + \hat{\beta}_S\, s_{i,t} + \hat{\beta}_M\, m_{i,t} \right), \end{aligned} \tag{21}$$

by (20), where $y_{i,t} = (p_{i,t} - \bar{p}_t) + z_{i,t}$ denotes the total of deflated sales and production for inventory. The term $(1-\eta)(\bar{\theta}_t - \bar{p}_t)$ is the sector-average firm-fixed effect $\overline{\beta_{0,i}}$ from production function estimates (17). It corrects for sector-specific and time-invariant demand-side effects that affect productivity estimates through price $p_{i,t}$ in $y_{i,t}$ (Section 2.6). Under monopolistic competition, the time-invariant demand-side parameter $\eta$ scales $\log TFP_{i,t}$ up or down (where $-1/(1-\eta)$ is price elasticity of demand). Up to this scaling parameter, however, firm-specific and sector-wide log productivity change can be inferred.

Several implications are common to both the present estimation model and the original Olley and Pakes (1996) estimation model. Table 1 at the outset of Section 2 listed five major model implications. First, survivors are predicted to be capital-rich and productive. Table 5 confirms that exiting firms have strictly lower capital stocks than survivors in all five sectors, and strictly lower *TFP* levels in four out of five sectors (with no clear difference in the remaining sector).

Other assumptions and implications set the present estimation model apart from the original Olley and Pakes (1996) estimation model. The discussion above

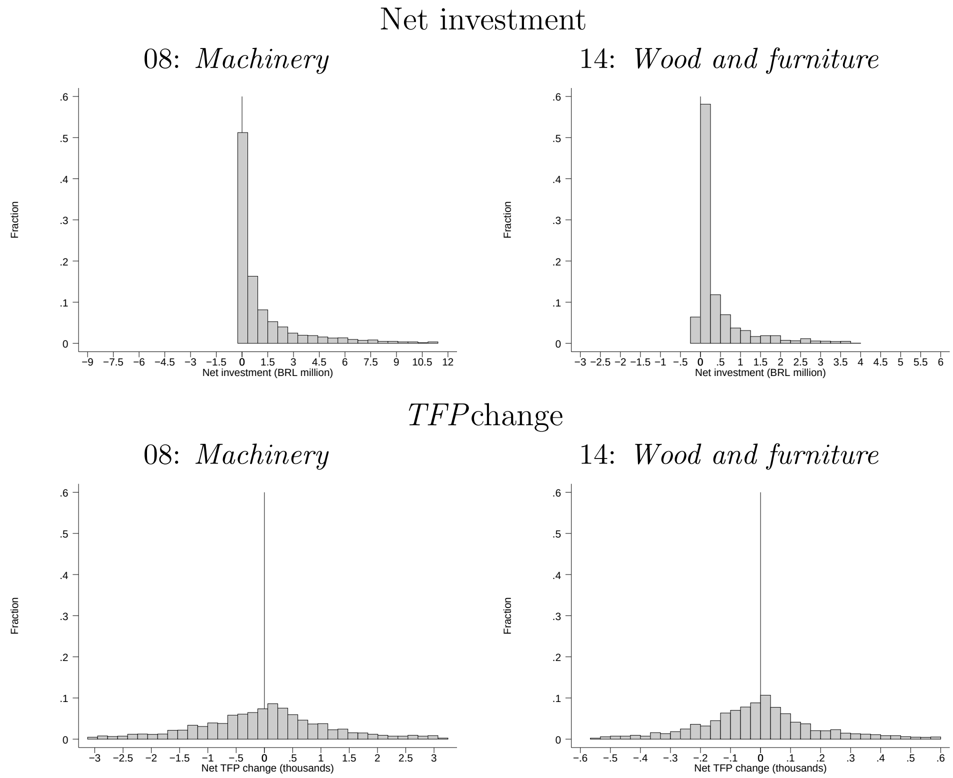
Table 5: CHECKS ON $q$-THEORY IMPLICATIONS

| | Machines (08) | Wood & furniture (14) | Textiles (22) | Plant products (26) | Food & beverages (31) |
|---|---|---|---|---|---|
| Exiter-survivor capital diff. | -10.612 | -7.958 | -6.623 | -4.780 | -6.557 |
| Exiter-survivor *TFP* diff. | -.957 | .019 | -.351 | -1.463 | -.003 |
| OLS bias in equipment coeff. | .056 | -.084 | .011 | -.028 | .018 |
| OLS bias in structures coeff. | -.024 | -.021 | -.039 | .069 | .043 |
| *TFP*-demand correl. coeff. | .061 | .301 | .101 | .069 | .111 |

*Data*: *Pesquisa Industrial Anual* 1986-98.
*Note*: Statistics based on estimates from Table 4. Total capital (in million Reais) includes equipment and structures. Productivity is *TFP* (in thousands) as in equation (21).

has already highlighted the importance of the second implication that observations with non-positive investment are permissible for estimation. A third implication of the present model is that an upward bias in capital coefficients may occur. Table 5 summarizes the differences between equipment and structures coefficients, half of which exhibit positive and half negative signs. Fourth, a procyclical productivity evolution is ruled out in the original Olley and Pakes (1996) estimation model, where favorable market conditions only affect exit and make survivors tolerate lower productivity levels, but do not impact within-firm productivity. The implication is counter-cyclical productivity. In the present model, in contrast, favorable market conditions are associated with positive physical investments and positive organizational change. Table 5 shows for the Brazilian manufacturing sample that demand is indeed positively correlated with productivity.

There is no evidence in the Brazilian manufacturing sample that intangible investments into productivity change are subject to large fixed costs. Figure 1 plots the distributions of annual physical investment (the sum of equipment and structures investments) and annual *TFP* change (the annual difference between exponentiated log *TFP*) for the two largest sectors. While physical investment exhibits the expected lumpiness around zero investment, *TFP* change is smoothly distributed. This pattern is the same in the remaining sectors. Though estimation of a firm's exit rule is important for identification under the suspected presence of fixed costs, the lacking evidence for fixed costs after estimation suggests that the production function is also identified in shorter estimation procedures. This provides a rationale for the direct comparison, in the following Section, between common proxy variables under a popular GMM estimator with no exit rule. That comparison will finally shed light on the fifth and last major implication




*Source*: *Pesquisa Industrial Anual* 1986-1998.
*Note*: Net investment includes structures and equipment investment. Firm-level *TFP* changes inferred from EOP production-function estimates. Observations below the fifth and above the 95th percentile are removed.

Figure 1: **Distributions of net investment and *TFP* change**

that transmission bias can be resolved without timing assumptions, using market conditions.

Overall, the EOP procedure provides evidence why firm-specific but time-variant effects distort production function estimation: firms respond to expected market conditions with physical investments and simultaneous investments in productivity change. An extension of the Olley and Pakes algorithm (EOP) to endogenous productivity change, and the use of investments interacted with firm-specific competition variables as productivity proxies, yields plausible estimates. Retention of positive-investment observations is justified and allows for the estimation of a sector's mean production technology, where returns on capital are expectedly smaller than in the positive-investments-only subsample. The EOP algorithm tends to find and mitigate a commonly suspected negative bias in OLS capital coefficients in several cases, but is also consistent with a sometimes observed positive bias. The EOP coefficients resemble fixed-effects estimates and therefore plausibly control for firms' time-invariant productivity conditions.

# 5 Comparison to Alternative Estimators

The model of this paper posits that transmission bias can be resolved without timing assumptions, under the alternative identifying assumption that a firm's chosen productivity change endogenously responds to expected market conditions. The present Section subjects this maintained assumption to scrutiny and compares the new market-expectations proxy—investment interacted with competition—to only investment as proxy (as proposed by Olley and Pakes), to intermediate inputs as a proxy (proposed by Levinsohn and Petrin), and to the ordinary least squares estimator. To focus the comparison, estimation is based on the short Levinsohn and Petrin (2003) GMM algorithm, which does not include exit-rule estimation (see Appendix D). The implicit identifying assumption is that productivity change does not exhibit a probability mass around zero (as confirmed in Figure 1 after full EOP estimation). To gain a sense of the precision of estimates under the four alternatives, I compare distributions of bootstrapped estimates.

Table 6 presents GMM results under the four alternative proxy variables. In the original Levinsohn and Petrin (2003) GMM procedure, intermediate inputs enter the estimator on the first stage to proxy productivity and on the final stage as regressor. For comparability, I also include the other proxy variables on the final stage. The market-conditions proxy and the investments proxy show a final-stage coefficient that is significantly different from zero in several but not all sectors (significant difference from zero in sectors 14 and 26 for the market-conditions proxy, 14 and 22 for the investments proxy). The small magnitude of the proxy coefficient is encouraging: coefficients on physical factor inputs account for almost all of the variation in output. Neither proxy takes away from that, while it still helps clear the coefficient estimates of transmission bias on the first stage.

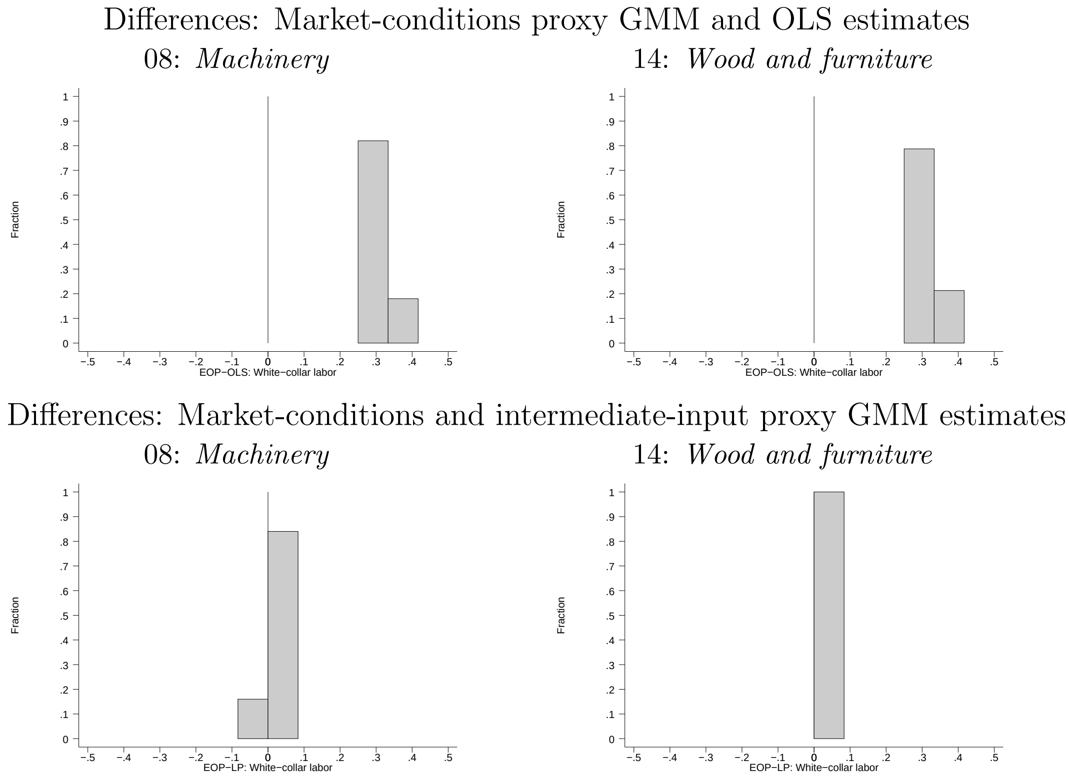
The short Levinsohn and Petrin algorithm generally detects a surprising positive bias in OLS capital coefficients, whereas the extended Olley-Pakes algorithm in the previous Section pointed to frequent negative bias in OLS capital coefficients (Table 6). Note that a negative transmission bias in capital coefficients results from different exit rules for capital-rich firms, which are more likely to survive adverse productivity shocks. This suggests that the inclusion of exit-rule estimation in the Olley and Pakes (1996) algorithm, which Levinsohn and Petrin (2003) omit, may more adequately resolve negative biases in capital coefficients.

For white-collar labor, OLS estimates exhibit the most pronounced downward bias, with implausibly negative coefficients in all five sectors. GMM under any of

Table 6: Comparison of Proxies under GMM Estimation

| Proxy: | Mkt. Conditions | | Investments | | Materials | | None (OLS) | |
|---|---|---|---|---|---|---|---|---|
| | Coef. | *SE* | Coef. | *SE* | Coef. | *SE* | Coef. | *SE* |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| **(08) Machines** | | | | | | | | |
| Blue-coll. empl. | .251 | .031 | .257 | .031 | .254 | .033 | .221 | .041 |
| White-coll. empl. | .297 | .024 | .289 | .025 | .287 | .025 | -.008 | .027 |
| Interm. goods | .378 | .021 | .374 | .021 | .000 | .212 | .605 | .030 |
| Capital | .153 | .304 | .127 | .317 | .373 | .239 | .376 | .033 |
| Proxy | 3.8e-07 | .010 | 3.2e-08 | .019 | | | | |
| Obs. | 2,621 | | 2,694 | | 2,694 | | 2,694 | |
| **(14) Wood and furniture** | | | | | | | | |
| Blue-coll. empl. | .379 | .023 | .380 | .025 | .365 | .026 | .364 | .034 |
| White-coll. empl. | .221 | .021 | .212 | .018 | .199 | .018 | -.083 | .027 |
| Interm. goods | .341 | .019 | .339 | .019 | .087 | .169 | .616 | .026 |
| Capital | .001 | .281 | .101 | .026 | .213 | .102 | .334 | .023 |
| Proxy | .00006 | .00002 | 4.4e-07 | 1.3e-07 | | | | |
| Obs. | 2,721 | | 2,835 | | 2,835 | | 2,835 | |
| **(22) Textiles** | | | | | | | | |
| Blue-coll. empl. | .267 | .026 | .256 | .026 | .281 | .026 | .224 | .030 |
| White-coll. empl. | .221 | .023 | .220 | .023 | .203 | .023 | -.061 | .023 |
| Interm. goods | .460 | .025 | .460 | .023 | .124 | .086 | .679 | .022 |
| Capital | .084 | .071 | .063 | .022 | .197 | .056 | .310 | .021 |
| Proxy | 4.0e-07 | .00002 | 1.4e-07 | 4.7e-08 | | | | |
| Obs. | 3,199 | | 3,258 | | 3,258 | | 3,258 | |
| **(26) Plant products** | | | | | | | | |
| Blue-coll. empl. | .253 | .030 | .253 | .032 | .211 | .032 | .288 | .034 |
| White-coll. empl. | .244 | .023 | .241 | .024 | .228 | .023 | -.092 | .028 |
| Interm. goods | .384 | .017 | .381 | .018 | .655 | .207 | .549 | .022 |
| Capital | .050 | .036 | .153 | .038 | .000 | .148 | .449 | .024 |
| Proxy | 5.0e-06 | 1.2e-06 | 2.1e-07 | .002 | | | | |
| Obs. | 2,730 | | 2,764 | | 2,764 | | 2,764 | |
| **(31) Other food and beverages** | | | | | | | | |
| Blue-coll. empl. | .269 | .025 | .272 | .026 | .232 | .026 | .221 | .032 |
| White-coll. empl. | .224 | .021 | .224 | .022 | .210 | .022 | -.029 | .025 |
| Interm. goods | .337 | .023 | .340 | .022 | .557 | .218 | .608 | .028 |
| Capital | .178 | .036 | .161 | .019 | .060 | .141 | .391 | .029 |
| Proxy | 3.0e-07 | 6.1e-07 | 3.4e-08 | 4.1e-08 | | | | |
| Obs. | 3,353 | | 3,431 | | 3,431 | | 3,431 | |

*Source*: *Pesquisa Industrial Anual* 1986-1998.
*Notes*: GMM estimates (Levinsohn and Petrin 2003). Variables in logs except for investment. Proxy variables: Market conditions are investment × lagged foreign market penetration (col. 1 and 2); investments are net physical capital investment (as in Olley and Pakes 1996, col. 3 and 4); materials are intermediate inputs (as in Levinsohn and Petrin 2003, col. 5 and 6). Standard errors based on 50 bootstraps.



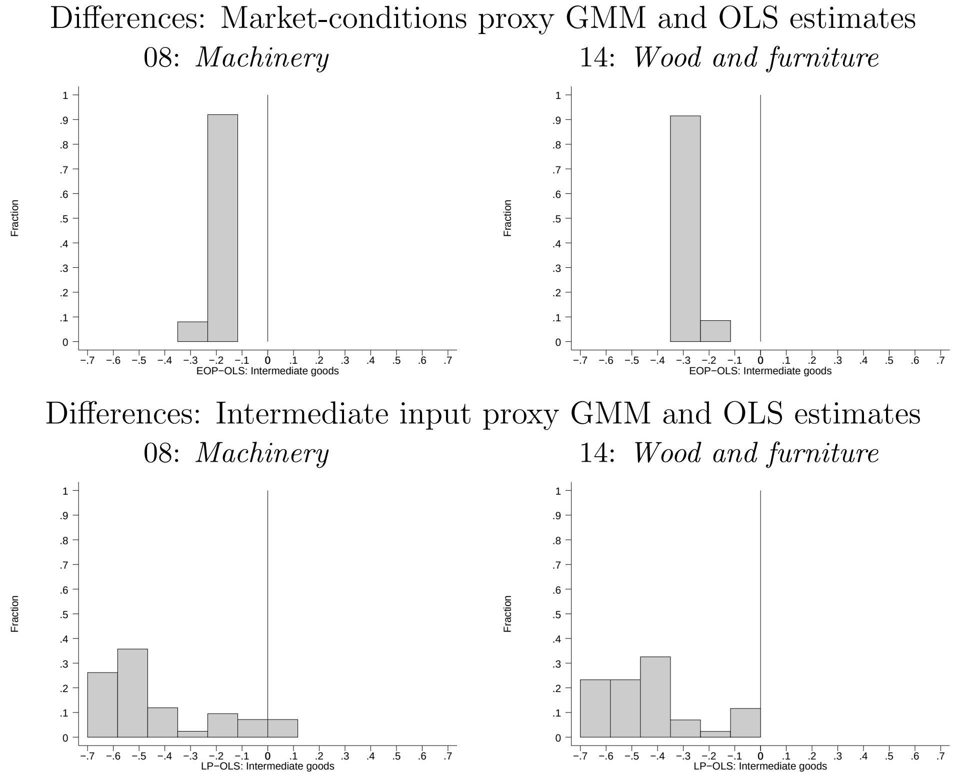

*Source*: *Pesquisa Industrial Anual* 1986-1998.
*Note*: GMM and OLS estimates from 50 bootstraps.

Figure 2: **Bootstrapped white-collar labor coefficients**

the three productivity proxies turns the white-collar coefficients positive. Figure 2 displays histograms of white-collar labor coefficient estimates from 50 bootstraps of OLS as well as market-conditions and variable-input proxy GMM estimators for the machinery (08) and the wood and furniture (14) sectors. Whereas the market-conditions proxy and OLS estimates differ sharply, the market-conditions and variable-input proxy estimates exhibit hardly any difference at all. So, both the market-conditions and variable-input proxy estimators seem to remove the negative bias from the white-collar labor coefficient to a similar degree.

Intermediate input coefficients are lower under the market-conditions proxy and the variable-input proxy than in OLS (the variable-input proxy GMM in sector 26 being the only exception in Table 6).[14] The market-conditions proxy

[14]This revealed positive bias in OLS estimates might reflect the fact that surviving manufacturers who engage in outsourcing to a larger degree also tend to be more efficient. Outsourcing (*terceirização*) became a widely discussed and often pursued business strategy during the 1990s




*Source*: *Pesquisa Industrial Anual* 1986-1998.
*Note*: GMM and OLS estimates from 50 bootstraps.

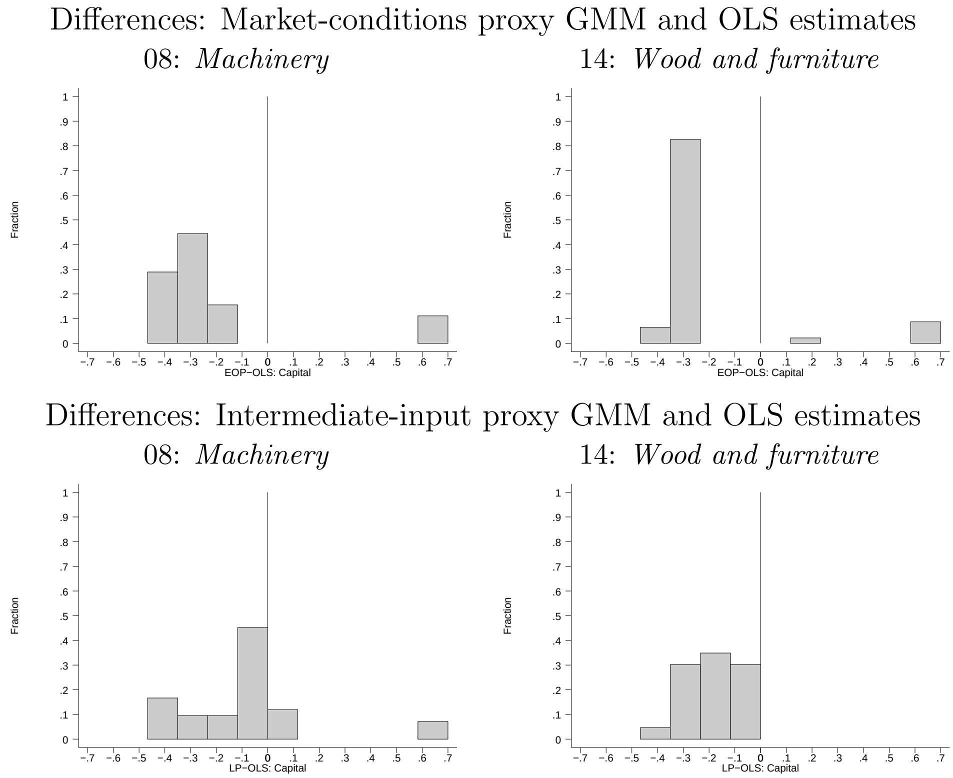
Figure 3: **Bootstrapped intermediate goods coefficients**

and variable-input proxy estimators largely agree on intermediate input coefficients themselves. Variable-input proxy estimates, however, can widely differ from estimates under the other two procedures and yield partly implausible coefficients (zero in sector 08). Figure 3 shows that the market-conditions proxy also yields considerably sharper and less volatile estimates than does the variable-input proxy. So, the market-conditions proxy seems to clear transmission bias from intermediate inputs more consistently.

Capital coefficients exhibit a bias similar to that of intermediate inputs. OLS capital coefficients exceed those of the other three estimators in all five sectors (Table 6). Similar to intermediate input coefficients, Figure 4 illustrates for capital coefficients that the market-conditions proxy yields sharper and less volatile estimates.

In summary, the new single-variable proxy to productivity—investment in-

in Brazil.




*Source*: *Pesquisa Industrial Anual* 1986-1998.
*Note*: GMM and OLS estimates from 50 bootstraps.

Figure 4: **Bootstrapped capital coefficients**

teracted with lagged competition variables—yields similar but sharper and less volatile coefficient estimates than the alternative Levinsohn and Petrin proxy (intermediate goods). In comparison to a pure, not interacted investment proxy as in the original Olley and Pakes procedure, coefficient estimates on factors other than capital largely agree, while capital coefficients may be larger or smaller with the new proxy. These findings establish the expectations proxy as a viable alternative to remove transmission bias but also call for a complete survival-based treatment of capital coefficients under the extended Olley-Pakes procedure (Section 4).

# 6 Conclusion

Managers streamline processes and improve efficiency, they invest in productivity-relevant assets, and respond to individual market prospects. Recent empirical evidence is consistent with the hypothesis that product-market competition tends to exert discipline on managers and to instill efficiency improvements. Prior estimation techniques, however, do not model productivity as endogenous to market conditions.

This paper presents an estimation framework similar to Olley and Pakes (1996) but based on endogenous productivity responses. The model of the firm implies that variables that characterize a firm's competitive environment, interacted with the firm's individual investments, are suitable proxies to endogenous productivity change. The new proxies help explain why fixed-effects estimators frequently disagree with other estimators: a persistent firm-specific but time-varying shock correlates with inputs. This unobservable shock is closely related to firms' expectations about the competitive environment and to input responses.

Contrary to most prior research, the estimation framework does not need to rely on the identifying assumption that firms learn productivity realizations and decide on asset investments before they choose inputs. Beyond prior methods, the estimation framework permits the inclusion of observations with non-positive investment so that the sector-mean technology can be estimated more precisely. Inference of firm-level productivity change, however, is only based on a partial adjustment for firms' endogenous price setting so that productivity change is measurable only under the assumption of constant markups. The adjustment cannot accommodate firm-specific or time-varying markups so that individual markups could confound measures of productivity change. In the absence of firm-level price data, a separation of firm-specific markups from productivity measures is a difficult but potentially fruitful task for research.

# Appendix

## A Proof of Proposition 1

This Appendix presents a proof of the optimal investment rule in organizational knowledge

$$I_{i,t+1}^{\Omega,\text{opt}} = \begin{cases} I_{i,t+1}^{\Omega,*}(q_{i,t}^{\Omega};\Omega_{i,t}) < 0 & \text{if} \quad q_{i,t}^{\Omega} < q^{\Omega,-}(\Omega_{i,t}) \\ 0 & \text{if} \quad q^{\Omega,-}(\Omega_{i,t}) \le q_{i,t}^{\Omega} \le q^{\Omega,+}(\Omega_{i,t}) \\ I_{i,t+1}^{\Omega,*}(q_{i,t}^{\Omega};\Omega_{i,t}) > 0 & \text{if} \quad q_{i,t}^{\Omega} > q^{\Omega,+}(\Omega_{i,t}) \end{cases}$$

under Assumptions 1 and 3. The proof follows Abel and Eberly (1994). By additive separability of the adjustment cost function, the same proof applies to organizational knowledge under Assumptions 1 and 2.

First consider Assumption 1 in the absence of fixed costs. The left and right limits of the adjustment costs are zero: $C^{K,-}(0,K_{i,t}) = C^{K,+}(0,K_{i,t}) \equiv C^{K}(0,K_{i,t}) = 0$ as $I_{i,t+1}^{K}$ approaches zero. Assumption 1 implies that the left and right limits of marginal adjustment costs (partial derivatives of adjustment costs) at $I_{i,t+1}^{K} = 0$ are $C_{I^K}^{K,-}(0,K_{i,t}) \le 0$ and $C_{I^K}^{K,+}(0,K_{i,t}) \ge 0$. Hence, if $q_{i,t}^{K}$ falls outside the interval $q_{i,t}^{K} \notin [C_{I^K}^{K,-}(0,K_{i,t}), C_{I^K}^{K,+}(0,K_{i,t})]$, then first-order condition (7) implicitly determines a unique optimal investment level $I_{i,t+1}^{K,*}(q_{i,t}^{K};K_{i,t})$. Conversely, if $q_{i,t}^{K}$ falls within the interval $[C_{I^K}^{K,-}(0,K_{i,t}), C_{I^K}^{K,+}(0,K_{i,t})]$, then $I_{i,t+1}^{K,*} = 0$ because the marginal adjustment cost is weakly negative as investment approaches zero from below and weakly positive as investment approaches zero from above. I call $[C_{I^K}^{K,-}(0,K_{i,t}), C_{I^K}^{K,+}(0,K_{i,t})]$ the inner interval of inaction. It shrinks to a singleton if $C^{K}(\cdot)$ is twice differentiable with respect to $I_{i,t+1}^{K}$ at zero. Outside the inner interval of inaction, investment strictly increases in $q$ with $\partial I_{i,t+1}^{K,*}(\cdot)/\partial q_{i,t}^{K} > 0$ by (7) because adjustment costs are strictly convex in $I_{i,t+1}^{K,*}$ under Assumption 1. If $q_{i,t}^{K} < C_{I^K}^{K,-}(0,K_{i,t})$ then $I_{i,t+1}^{K,*} < 0$ and if $q_{i,t}^{K} > C_{I^K}^{K,+}(0,K_{i,t})$ then $I_{i,t+1}^{K,*} > 0$.

Turn to fixed costs and suppose that Assumption 2 holds in addition to Assumption 1. The Bellman equation (4) is maximized in $I_{i,t+1}^{K,*}$ if and only if the alternate function

$$\Psi^{K}(q_{i,t}^{K};K_{i,t}) \equiv -\mathbf{1}(I_{i,t+1}^{K} \neq 0) \cdot C^{K}(I_{i,t+1}^{K,*},K_{i,t}) + q_{i,t}^{K} \cdot I_{i,t+1}^{K,*} \tag{A.1}$$

is maximized given $q_{i,t}^{K}$. To understand the properties of (A.1), ignore the possibility of zero investment for a moment and set the indicator function $\mathbf{1}(\cdot)$ to one. This provides insight into adjustment cost outcomes in optimum. In the neighborhood of zero investment as $I_{i,t+1}^{K,*} = 0$ approaches zero, $\Psi^{K}(\cdot)$ approaches $-C^{K}(0,K_{i,t}) < 0$, which is strictly negative by Assumption 2. If $q_{i,t}^{K}$ is within the inner interval of inaction $[C_{I^K}^{K,-}(0,K_{i,t}), C_{I^K}^{K,+}(0,K_{i,t})]$ then $\Psi^{K}(\cdot)$ cannot be below $-C^{K}(0,K_{i,t})$ because the firm can always choose investment of zero. Neither can $\Psi^{K}(\cdot)$ be above $-C^{K}(0,K_{i,t}) = -C^{K,-}(0,K_{i,t}) = -C^{K,+}(0,K_{i,t})$ by Assumption (2).

Finally turn to inaction with zero investment under fixed adjustment cost. The *de facto* lower bound on $\Psi^K(q^K_{i,t}; K_{i,t})$ is zero at zero investment by (A.1), and $\Psi^K(\cdot) > 0$ is strictly positive only if $I^{K,*}_{i,t+1} \neq 0$. For what range of $q^K_{i,t}$ does the firm optimally choose zero investment? The range of optimal inaction must include the inner interval of inaction $[C^{K,-}_{IK}(0, K_{i,t}), C^{K,+}_{IK}(0, K_{i,t})]$. Fixed costs enlarge the interval to the full range of inaction. Note that $\Psi^K(q^K_{i,t}; K_{i,t})$ becomes unboundedly positive as $q^K_{i,t}$ becomes arbitrarily large or small (hypothetically negative): $\partial\Psi^K/\partial q^K_{i,t} = I^{K,*}_{i,t+1}$ by (A.1) so $\Psi^K(\cdot)$ strictly increases in $q^K_{i,t}$ as $q^K_{i,t}$ drops below $C^{K,-}_{IK}(0, K_{i,t})$ and strictly increases in $q^K_{i,t}$ as $q^K_{i,t}$ rises above $C^{K,+}_{IK}(0, K_{i,t})$. The function $\Psi^K(q^K_{i,t}; K_{i,t})$ must therefore have two roots, one (negative or positive) root $q^{K,-} < C^{K,-}_{IK}(\cdot) \leq C^{K,+}_{IK}(\cdot)$, and one strictly positive root $q^{K,+} > C^{K,+}_{IK}(\cdot) \geq 0$. If the lower root $q^{K,-}$ is weakly negative, then the range of inaction includes zero and implies that a firm will never optimally choose to divest. Within the range of inaction $q^K_{i,t} \in [q^{K,-}, q^{K,+}]$, zero investment is the optimal choice. Outside the range of inaction, optimal non-zero investment is implicitly determined by first-order condition (7), where $q^K_{i,t}$ is given by expected firm characteristics and market fundamentals in (9).

If $C^\Omega(I^\Omega_{i,t+1}, \Omega_{i,t})$ is twice differentiable with respect to $I^\Omega_{i,t+1}$ everywhere, contrary to Assumption 3, then the range of inaction shrinks to the singleton $q^{\Omega,-}(\Omega_{i,t}) = q^{\Omega,+}(\Omega_{i,t})$ and the investment rule 11 simplifies to $I^{\Omega,\mathrm{opt}}_{i,t+1} = I^{\Omega,*}_{i,t+1}(q^\Omega_{i,t}; \Omega_{i,t})$, where $I^{\Omega,*}_{i,t+1}(q^\Omega_{i,t}; \Omega_{i,t})$ satisfies (7).

**Example 1** *Firm i faces quadratic adjustment costs for investments in physical capital $\zeta^K(I^K_{i,t+1})^2/(2K_{i,t})$ and for organizational change $\zeta^\Omega(I^\Omega_{i,t+1})^2/(2\Omega_{i,t})$, similar to a textbook model of Tobin's q. But a firm also incurs a fixed investment cost $F^K = f^K K_{i,t}$, proportional to installed capital, when net physical investment is non-zero, and $F^\Omega = f^\Omega\,\Omega_{i,t}$ when net organizational investment is non-zero. Proportionality to existing stocks is convenient for empirical implementation because it makes the fixed adjustment cost a linearly homogeneous function so that marginal and average q are equal at any scale of operation. Investments, however, are zero unless Tobin's q's satisfy the break-even conditions*

$$q^K_{i,t} I^K_{i,t+1} \geq I^K_{i,t+1} + \frac{\zeta^K}{2}\frac{(I^K_{i,t+1})^2}{K_{i,t}} + f^K K_{i,t} \text{ and } q^\Omega_{i,t} I^\Omega_{i,t+1} \geq I^\Omega_{i,t+1} + \frac{\zeta^\Omega}{2}\frac{(I^\Omega_{i,t+1})^2}{\Omega_{i,t}} + f^\Omega \Omega_{i,t}$$

*so that rewards from investments weakly exceed the costs. Using (7) shows that a firm chooses zero investment in capital $I^K_{i,s+1} = 0$ if $q^K_{i,t}$ falls into the range of inaction $q^K_{i,t} \in [1 - \sqrt{2\zeta^K f^K}, 1 + \sqrt{2\zeta^K f^K}]$, where the average reward from investing falls short of its average cost. A similar condition holds for organizational change under Assumption 3. The terms in the expectations operator reflect the marginal value of the respective state variable including the marginal revenue $\gamma\eta P(Z_{i,s}, \mathbf{D}_s)\, Z_{i,s}/K_{i,s}$, the marginal reduction in future adjustment costs $(I^K_{i,s+1})^2/(K_{i,s})^2$, and the marginal increase in adjustment fixed costs $\mathbf{1}(I^K_{i,s+1}{\neq}0) f^K$ from an increase in the state variable.*

# B Proof of Proposition 2

If $I^{K,\text{opt}}_{i,t+1} \neq 0$ then $I^{K,\text{opt}}_{i,t+1} = I^{K,*}_{i,t+1}$ is implicitly given by (7) so that Tobin's $q$ is inferrable as $q^K_{i,t} = C^K_{I^K}(I^{K,\text{opt}}_{i,t+1}, e^{k_{i,t}})$. Using this insight in (15) establishes

$$\mathbb{E}[\omega_{i,t+1} | \chi_{i,t+1} = 1, k_{i,t}, I^{K,\text{opt}}_{i,t+1}, \mathbf{D}_{i,t}] = h^{\text{OC}}(k_{i,t}, I^{K,\text{opt}}_{i,t+1}, \mathbf{D}_{i,t}) + h^X(k_{i,t}, \mathbf{D}_{i,t}) + \beta_{0,i}$$

for

$$h^{\text{OC}} \equiv \begin{cases} h^1(\omega_{i,t}; C^K_{I^K}(I^{K,\text{opt}}_{i,t+1}, e^{k_{i,t}}), k_{i,t}, \mathbf{D}_{i,t}) & \textit{if} \;\; q^\Omega_{i,t} \notin [q^{\Omega,-}, q^{\Omega,+}] \wedge I^{K,\text{opt}}_{i,t+1} \neq 0 \\ h^1(\omega_{i,t}; q^K_{i,t}, k_{i,t}, \mathbf{D}_{i,t}) & \textit{if} \;\; q^\Omega_{i,t} \notin [q^{\Omega,-}, q^{\Omega,+}] \wedge I^{K,\text{opt}}_{i,t+1} = 0 \\ h^0(\omega_{i,t}) & \textit{if} \;\; q^\Omega_{i,t} \in [q^{\Omega,-}, q^{\Omega,+}], \end{cases}$$

$$h^X \equiv \int_{\gamma \ln \underline{x}(\omega_{i,t}; k_{i,t}, \mathbf{D}_{i,t}) - \beta_{0,i}} \xi_{i,t+1} \frac{f(\xi_{i,t+1})}{G(\omega_{i,t}; k_{i,t}, \mathbf{D}_{i,t})} d\xi_{i,t+1},$$

where $\xi_{i,t+1} \equiv \gamma \ln x_{i,t+1} - \beta_{0,i}$ and $\beta_{0,i} = \gamma \mathbb{E}[\ln x_{i,t+1}]$.

The firm's expected value change in response to a marginal change in $k_{i,t}$ is, by definition, $q^K_{i,t-1} > 0$ and strictly positive by (8) so that $\partial \underline{x}(\cdot)/\partial k_{i,t} < 0$ and $\partial G(\cdot)/\partial k_{i,t} > 0$; hence $h^X(\cdot)$ strictly increases in $k_{i,t} > 0$. If the firm's expected value change in response to a marginal change in an element of $\mathbf{D}_{i,t}$ is strictly monotonic, then marginal change in $\underline{x}(\cdot)$ and $G(\cdot)$ is strictly monotonic and $h^X(\cdot)$ changes strictly monotonically. Conversely, if $h^X(\cdot)$ changes strictly monotonically with an element of $\mathbf{D}_{i,t}$ then either $\underline{x}(\cdot)$ or $G(\cdot)$ must be strictly monotonic in the changing element and the firm's expected value must be strictly monotonic in the element of $\mathbf{D}_{i,t}$.

Note that $\partial I^{\Omega,*}_{i,t+1}/\partial q^\Omega_{i,t} > 0$ by Assumption 1. So, for Hicks-neutral $\Omega_{i,t}$ as in (1), or for factor-augmenting productivity, $\partial q^\Omega_{i,t}/\partial k_{i,t} > 0$ by (9) implies that $\partial I^{\Omega,*}_{i,t+1}/\partial k_{i,t} = (\partial I^{\Omega,*}_{i,t+1}/\partial q^\Omega_{i,t})(\partial q^\Omega_{i,t}/\partial k_{i,t}) > 0$; hence $h^{\text{OC}}(\cdot)$ strictly increases in $k_{i,t}$ unless $I^{\Omega,\text{opt}}_{i,t+1} = 0$ in the range of inaction. Similarly, $\partial q^\Omega_{i,t}/\partial I^{K,*}_{i,t+1} > 0$ by Assumption 1 and (14) implies that $\partial I^{\Omega,*}_{i,t+1}/\partial I^{K,\text{opt}}_{i,t+1} = (\partial I^{\Omega,*}_{i,t+1}/\partial q^\Omega_{i,t})(\partial q^\Omega_{i,t}/\partial I^{K,*}_{i,t+1}) > 0$; hence $h^{\text{OC}}(\cdot)$ strictly increases in $I^{K,\text{opt}}_{i,t+1}$ unless $I^{\Omega,\text{opt}}_{i,t+1} = 0$ in the range of inaction.

If the firm's expected value change in response to a marginal change in an element of $\mathbf{D}_{i,t}$ is strictly (weakly) monotonic, then the marginal change in $q^\Omega_{i,t}$ is strictly (weakly) monotonic by (9); hence $h^{\text{OC}}(\cdot)$ strictly (weakly) monotonically changes in the element of $\mathbf{D}_{i,t}$ unless $I^{\Omega,\text{opt}}_{i,t+1} = 0$ in the range of inaction. Conversely, if $h^{\text{OC}}(\cdot)$ changes strictly monotonically with an element of $\mathbf{D}_{i,t}$ then $q^\Omega_{i,t}$ must be strictly monotonic in the changing element and the firm's expected value must be strictly monotonic in the element of $\mathbf{D}_{i,t}$.

# C The *Pesquisa Industrial Anual* Sample

The Brazilian statistical bureau (*IBGE*) conducts an annual survey of mining and manufacturing firms, called *Pesquisa Industrial Anual* (*PIA*). The survey consists of a sample of formally established, medium-sized to large Brazilian firms for the years 1986 to 1990, 1992 to 1995, and 1996 to the present. This Appendix summarizes properties of the data.[15]

A firm qualifies for *PIA* if at least half of its revenues stem from manufacturing and if it is tax registered. In 1986, the initial *PIA* sample was constructed from three strata: (1) A non-random sample of the largest Brazilian manufacturers with output corresponding to at least 200 million Reais in 1995 (around 200 million US dollars in 1995). There were roughly 800 of them. (2) A random sample among medium-sized firms whose annual output in 1985 exceeded a value corresponding to R$ 100,000 in 1995 (around USD 100,000 in 1995). More than 6,900 firms made it into *PIA* this way. (3) A non-random selection of newly founded firms. *PIA* only included new firms that surpassed an annual average employment level of at least 100 persons. Around 1,800 firms were identified this way until 1993, when the inclusion process ended.

Departing from its initial 1986 sample, *PIA* identifies more than 9,500 active firms over the years. A firm that ever enters *PIA* through one of the selection criteria remains in the sample unless it is legally extinct. Moreover, if an existing firm in *PIA* reports the creation of a new firm as a subsidiary or spin-off, or a merger, this new firm enters *PIA* too. No sample was taken in 1991 due to a federal austerity program. The sampling method changed in 1996, and no capital stock figures are reported since. Therefore, the dataset of this paper only embraces firms after 1995 that were present in *PIA* earlier or that were longitudinally related to an earlier firm. Their capital stock is inferred with a perpetual inventory method. Following the change in sampling, there is a drop in the sample in 1996. Tests at various stages of the estimation prove it to be exogenous. Table 7 documents sample exit and sample attrition for the five largest sectors in *PIA*, on which the present analysis is based.

Output and domestic inputs are deflated with sector-specific price indices (constructed on the basis of Brazilian wholesale price indices and input-output matrices). Capital stock figures and investments are deflated with economy-wide price indices (constructed on the basis of Brazilian wholesale price indices and economy-wide capital formation vectors). Two steps are used to deflate foreign equipment acquisitions and foreign intermediate inputs. First, sector-specific series of import-weighted foreign producer prices, adjusted for nominal exchange rate fluctuations relative to the US-Dollar, are applied. Then, (investment-weighted) nominal tariffs on foreign machinery and (sector-specific input-weighted) nominal tariffs on intermediates are removed from equipment acquisitions and intermediate inputs.

To check for sensitivity, the data were deflated with three different price indices. The sector-specific wholesale price index *IPA-OG* underlies all results in this paper. Another sector-specific wholesale price index, *IPA-DI* (excluding imports), and the

[15]Muendler (2005) documents the construction of an unbalanced panel data set from *PIA* in detail—including the establishment of longitudinal relations between firms (such as entry, creation, exit, and mergers or acquisitions), consistency adjustments for economic variables due to questionnaire changes, price deflation of the economic variables, and the derivation of consistent capital stock series.

Table 7: SAMPLE EXIT AND ATTRITION IN LARGEST FIVE SECTORS

| | Observations | Survivors through 1998 |
|---|---|---|
| | (1) | (2) |
| 1986 | 1,945 | 685 |
| 1987 | 1,966 | 692 |
| 1988 | 2,365 | 730 |
| 1989 | 2,373 | 742 |
| 1990 | 2,313 | 747 |
| 1992 | 1,889 | 791 |
| 1993 | 1,838 | 817 |
| 1994 | 1,753 | 841 |
| 1995 | 1,653 | 854 |
| 1996 | 1,186 | 955 |
| 1997 | 1,150 | 989 |
| Observations | 21,465 | |
| Firm panels | 2,942 | |

*Data*: *Pesquisa Industrial Anual* 1986-1998. Sectors: (08) Machinery, (14) Wood and furniture, (22) Textiles, (26) Plant products, (31) Other food and beverages.

economy-wide price index *IGP-DI* (a combined wholesale and consumer price index) do not yield substantially different results. There is no producer price index for Brazil.

The overall capital stock is inferred under a perpetual inventory method that controls for changes to accounting law in 1991. Both investments and book values of capital goods are reported in *PIA* until 1995. Investments are assumed to become productive parts of the capital stock within the year of their reporting. They are used to infer typical depreciation rates through regression analysis. Foreign equipment levels are inferred from foreign equipment acquisitions and overall retirements. The non-equipment part in total capital also includes all rented capital goods. These stocks of rented capital goods are inferred from reported rental rates, which are taken to equal the (time-varying) user cost of capital. Consistency adjustments are made under the perpetual inventory method when stock changes are observed that differ from net investments (different deflators can cause this). Usually, simple averages are used. Because sector-wide depreciation rates are applied, the resulting capital stock series for 1986-1998 are smoother across firms and over time than the raw series.

# D Levinsohn and Petrin estimation

Instead of approximating firm-level productivity through a polynomial in covariates as in equation (17), Levinsohn and Petrin (2003) regress the output variable and all transmission-biased input variables on intermediate goods (the proxy variable) and the capital stock. Levinsohn and Petrin propose to subtract the predictions from the observed variables and run the according short regression of the production function

$$z_{i,t} - \hat{z}_{i,t} \quad = \quad \beta_{bl}\,(l^{bl}_{i,t} - \hat{l}^{bl}_{i,t}) + \beta_{wh}\,(l^{wh}_{i,t} - \hat{l}^{wh}_{i,t}) + \epsilon_{i,t}, \tag{D.1}$$

where variables with hats denote predictions from a linear regression on $m_{i,t}$ and $k_{i,t}$. Labor is split into blue-collar and white-collar employment.

To obtain consistent coefficient estimates for intermediate inputs and capital, according moment conditions can be applied: Under the assumptions made, productivity shocks are orthogonal to the current capital stock and lagged variable inputs (intermediate goods, labor). The conditional mean of the unpredictable part of productivity ($\widehat{\gamma\omega_{i,t}}(\check{\beta}_M, \check{\beta}_K) = z_{i,t} - \widehat{\beta}_{bl}\, l^{bl}_{i,t} - \hat{\beta}_{wh}\, l^{wh}_{i,t} - \check{\beta}_M\, m_{i,t} - \check{\beta}_K\, k_{i,t}$ from the first stage) given the current capital stock or any lagged variable input is restricted to be zero. The according GMM estimator minimizes

$$Q(\beta_M, \beta_K) = \min_{\beta_M, \beta_K} \sum_{j=1}^{4} \left( \sum_i \sum_t \gamma\omega_{i,t}(\check{\beta}_M, \check{\beta}_K) \cdot a_{j;i,t} \right)^2 \tag{D.2}$$

over estimates of $\beta_M$ and $\beta_K$, where $a_{j;i,t}$ $(j = 1, \ldots, 4)$ stands for the three common instrumental variables $k_{i,t}, l^{bl}_{i,t-1}$, and $l^{wh}_{i,t-1}$ and the fourth instrument $m_{i,t-1}$ (Levinsohn and Petrin) or $I^K_{i,t} \cdot D_{i,t-1}$ (expectations-proxy estimation with one market-related regressor $D_{i,t-1}$). Starting values for $\check{\beta}_M$ and $\check{\beta}_K$ are estimates from the $\hat{z}_{i,t}$ regression at the outset of the first step.

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