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Technology Adoption Under Relative Factor Price Uncertainty: The Putty-Clay Investment Model

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Abstract

A plant has more flexibility in choosing among different technologies before undertaking an investment than after installing a specific machine. This paper argues that the irreversibility of factor intensity choice may play an important role in explaining the dynamics of investment in the presence of relative factor price uncertainty. A higher degree of irreversibility in the choice of factor intensity—characterized by the *ex ante* elasticity of substitution between different factors—leads to a larger negative effect of uncertainty in relative factor prices on investment. The empirical implications of the putty-clay investment model are examined using the plant-level Chilean manufacturing data for the period of time-varying exchange rate volatility. The econometric results show that the elasticity of substitution between imported materials and domestic materials is substantially higher at the time of a large investment and suggest that the irreversibility of factor intensity choice may potentially play an important role in explaining the impact of exchange rate volatility on investment.

JEL No. D81, E22, O33

Keywords: irreversible investment; putty-clay; technology adoption; uncertainty.

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1 Introduction

Understanding the response of investment to uncertainty is a crucial factor in understanding macroeconomic fluctuations (e.g., Bernanke, 1983). A growing literature has shown that, when uncertainty is present, the irreversibility of investment expenditure plays a major role in determining investment spending. Few studies have carefully considered, however, the role of the irreversibility of technology choice in explaining the relationship between investment and uncertainty. A plant has more flexibility in choosing among different technologies before undertaking an investment than after installing a specific machine. Explicit consideration of the limited *ex post* substitutability between factors provides a realistic formation of investment decisions. The theoretical contribution of this paper is to clarify the role of irreversible factor intensity choice in determining the impact of relative factor price uncertainty on investment. I also provide plant-level evidence on the importance of the irreversibility of factor intensity choice in explaining the effect of exchange rate volatility on investment.

The theoretical model studied here embeds putty-clay technology and relative factor price uncertainty in the machine replacement model studied by Jovanovich and Rob (1998) and Cooper, Haltiwanger, and Power (1999). Before an investment is made, a plant's technology is flexibly chosen from the *ex ante* technology menu. Once a machine is installed, however, a plant cannot change the factor intensity: the *ex post* production function is Leontief. This irreversibility of factor intensity choice has important implications for investment decisions if future relative factor prices are uncertain. When a plant makes an irreversible factor intensity choice, it gives up the option of waiting for new information on future relative factor prices that may affect the desired factor intensity choice. An increase in relative price uncertainty increases the option value of waiting and slows machine replacement. Furthermore, the effect of relative factor price uncertainty on replacement timing depends crucially on the *ex ante* elasticity of substitution between different factors. If the *ex ante* production function is Leontief, then relative factor price uncertainty may not affect replacement timing because the desired factor intensity choice is fixed regardless of the realization of relative factor prices. If the *ex ante* production function is close to linear, uncertainty in relative factor prices may have a large negative impact on investment since the appropriate choice of factor intensity may drastically differ across realizations.[1]

[1]This paper's model belongs to the class of (S,s) adjustment models, which are often found to be relatively

The interplay between irreversible investment decisions and uncertainty in demand and prices has been well studied from the viewpoint of an "option value."[2] Many of the irreversible investment models previously studied analyze *irreversible capacity choice*—or irreversible adjustment of (homogenous) capital stock—under uncertainty and have shown that, in the presence of decreasing marginal returns to capital, greater uncertainty in demand and prices tends to make irreversible adjustments of the capital stock less desirable. Few studies have examined, however, the implications of *irreversible technology choice*—or irreversible factor intensity choice—on investment decisions under uncertainty.[3] The previous irreversible investment literature implicitly assumes that the *ex ante* and *ex post* substitution possibilities are identical.

Recent research based on the putty-clay technology model includes Gilchrist and Williams (2000) who demonstrate a significant role for putty-clay capital in explaining key business cycle facts.[4] In the Gilchrist and Williams's model, however, uncertainty is assumed to be resolved only *after* the investment decision is made; this assumption rules out an important channel through which uncertainty may affect irreversible investment—there is no option value of waiting. The current paper, in contrast, emphasizes the option value of waiting for new information regarding the desired factor intensity choice.

I empirically examine the main predictions of the putty-clay investment model using Chilean plant-level data. The empirical analysis focuses on factor intensity choice between imported materials and domestic materials, on the one hand, and real exchange rate volatility and its effect on investment, on the other. Despite the long history of economists' interest in limited

successful in explaining aggregate investment dynamics (e.g., Caballero, Engel, and Haltiwanger, 1995; Caballero and Engel, 1999). One notable feature of this paper's model is that the state variables include the desired and the current factor intensity. The incentive to adopt the desired factor intensity increases with the distance between the desired and the current factor intensity; hence, the size of the "range of inaction" (i.e., the range of no investment) decreases with the distance.

[2]See Pindyck (1988), Caballero (1991), Bertola and Caballero (1994), Abel and Eberly (1994), and Dixit and Pindyck (1994).

[3]Abel (1983a) and Kon (1983) have studied how uncertainty in output and factor prices affect investment decisions. In their models, however, uncertainty is resolved only after investment decisions are made and thus firms do not have the option to wait. Ando , Modigliani, Rasche, and Turnovsky (1974) discuss the role of price expectation in investment decisions but, focusing on the overall trend, they do not analyze the role of uncertainty in relative factor prices in determining the timing of investment.

[4]Other studies based on putty-clay technology include Atkeson and Kehoe (1999), Pessoa and Rob (2002), and Wei (2003).

ex post substitutability between factors, there are few previous empirical studies on putty-clay technology using plant-level data.[5] One of the important advantages of focusing on Chile is the availability of detailed plant-level panel data. The plant-level data allows one to directly examine the plant-level—as opposed to aggregate—implications of the putty-clay model. The second advantage is that Chile experienced periods of both high and low exchange rate volatility during the sample period. The time-series variation in exchange rate volatility together with cross-sectional plant variation permits the identification of how the impact of exchange rate volatility on investment depends on plant/industry characteristics.[6]

The econometric results support the basic hypothesis of putty-clay technology and suggest its potential importance, relative to other factors emphasized by alternative investment models, in explaining the impact of exchange rate volatility on investment. The following findings are of particular interest. First, I find that the elasticity of substitution between imported materials and domestic materials is substantially higher at the time of a large investment. This finding provides direct plant-level evidence for the limited *ex post* substitution possibilities. Second, the results support the key prediction that differentiates this paper's putty-clay investment model from other irreversible investment models regarding the volatility effect: the negative impact of exchange rate volatility on investment is larger among plants with a higher *ex ante* elasticity of substitution. The results suggest that the irreversibility of factor intensity choice plays an quantitatively important role in explaining the effect of exchange rate volatility on investment.

This paper is organized as follows. In Section 2, the theoretical model is developed and analyzed. The main result is Proposition 2.5 which states that temporary uncertainty in relative factor prices discourages machine replacement. Empirical analysis is provided in Section 3. Finding plant-level evidence for the irreversibility of factor intensity choice in Section 3.2, I

[5] The putty-clay model has been introduced by Johansen (1959) and studied especially in the context of growth theory (e.g., Solow, 1962; Bliss ,1968) and investment (e.g., Ando et al., 1974; Abel, 1983a; Kon, 1983). The only empirical studies on putty-clay technology *using micro-level data* the author is aware of are Fuss (1977) and Sakellaris (1997). The empirical studies on putty-clay technology *using aggregate data* include Struckmeyer (1987), Atkeson and Kehoe (1999), Gilchrist and Williams (2000), and Wei (2003). The previous empirical studies on the impact of uncertainty on investment using microdata (e.g., Leahy and Whited, 1996; Guiso and Parigi, 1999; Bloom, Bond, and Van Reenen, 2000) have not examined the implications of the putty-clay technology.

[6] The previous empirical studies on the effect of exchange rate volatility on investment use industry-level data (e.g., Goldberg, 1993; Campa and Goldberg, 1995).

further investigate the extent to which the cross-sectional variation in the degree of irreversibility in the choice of factor intensity explains the variation in the impact of exchange rate volatility on investment in Section 3.3. The final section concludes the paper.

2 The Model

2.1 Environment

Consider a risk-neutral producer who owns a single plant with the following production technology. The *ex ante* production function is given by:

$$Y = AF(X_1, X_2),$$

where $F(X_1, X_2)$ is assumed to be continuous, strictly increasing, quasi-concave, and homogenous of degree one; X_1 and X_2 are two different factors. Technology is embodied in capital, where the capital stock is implicit in the technology level A.

There are two sources of *ex post* fixity in the production function.[7] First, without technology adoption, the technology level A is fixed even if the best technology available in the economy, denoted by A^*, changes over time. The value of A essentially reflects the "vintage" of technology embodied in capital. Second, the *ex post* production function is Leontief:

$$Y = Af(x) \min \left\{ \frac{X_1}{x}, X_2 \right\}, \tag{1}$$

where $f(x) \equiv F(x, 1)$; x is the *ex post* factor intensity which has to be chosen at the time of technology adoption.[8] Once the *ex post* factor intensity is chosen, a producer cannot change its factor intensity unless it switches to a new technology.

The marginal cost under the Leontief production function (1) is $A^{-1}c(\mathbf{w}, x)$ with

$$c(\mathbf{w}, x) \equiv \frac{w_1 x + w_2}{f(x)}, \tag{2}$$

[7] Gilchrist and Williams (2000) emphasize the *ex post* fixity of a capacity constraint together with endogenous capacity utilization as a key feature of the putty-clay technology. In this paper, in order to highlight the role of the *ex post* fixity of "technology choice" characterized by factor intensity as opposed to a capacity constraint, the *ex post* fixity of the capacity constraint as well as endogenous capacity utilization is abstracted from the theoretical model.

[8] The assumption that the *ex post* production function is Leontief provides a useful reference point. The model can be generalized—with substantial complications—by considering that the *ex post* elasticity of substitution is not zero but lower than the *ex ante* elasticity of substitution.

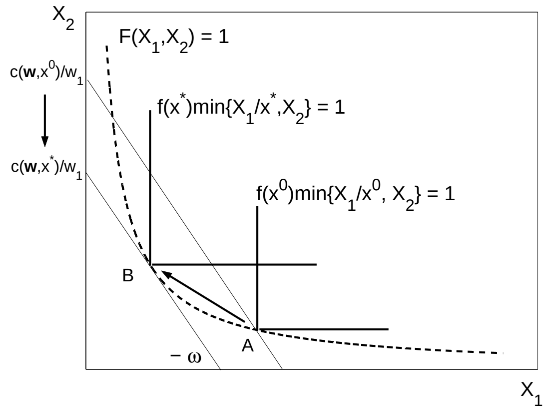

Figure 1: Technology Adoption Reduces Marginal Cost

where w_1 and w_2 are the unit prices of X_1 and X_2, respectively, both of which are assumed to be given exogenously. Let $\mathbf{w} \equiv (w_1, w_2)$ be the factor price vector and denote the relative factor prices by ω:

$$\omega \equiv \frac{w_1}{w_2}.$$

Given $\mathbf{w}$, the factor intensity that minimizes the *ex post* cost function is uniquely determined and only depends on the relative factor prices ω,

$$x^*(\omega) \equiv \underset{x}{argmin}\, c(\mathbf{w}, x), \tag{3}$$

where $x^*(\omega)$ is the **appropriate factor intensity**. Because of its fixity, the actual *ex post* factor intensity could be different from $x^*(\omega)$ when factor prices change over time. The marginal cost (2) is increasing as the "distance" between x and $x^*(\omega)$ gets larger and is lowest at the appropriate factor intensity $x^*(\omega)$.

The producer's technology is completely characterized by a pair (x, A). The concept of **technology adoption** is formalized in the model by a change in a producer's technology, say from (x, A) to (x', A'). By adopting a new technology, the marginal cost may decrease for two reasons. First, if a producer upgrades its technology to the frontier, higher productivity leads to a reduction in marginal cost. Second, by adopting the *appropriate factor intensity*, the marginal cost falls.

To see how the *ex post* fixity of factor intensity is related to the determination of marginal cost, consider the case of no technological change and no depreciation by assuming $A_t^* = A_t = 1$

for all t. Figure 1 presents the isoquant of the *ex post* production function under two different factor intensity choices as well as the isoquant of the *ex ante* production function. Factor prices are given by $\mathbf{w}$. By switching technology from A to B, a producer changes its factor intensity from x^0 to the appropriate factor intensity x^*. Adoption of the appropriate technology reduces its marginal cost from $c(\mathbf{w}, x^0)$ to $c(\mathbf{w}, x^*)$. If the benefit of the marginal cost reduction is large enough to compensate for the cost of technology adoption, the producer would adopt the new technology *even if there were no change in the technology level.*

The frontier technology level A_t^* grows at the rate g so that $A_{t+1}^* = (1+g)A_t^*$. A producer's technology level depreciates at the rate d so that $A_{t+1} = (1-d)A_t$ *without any technology adoption.* There is a fixed cost of technology adoption $\tilde{\kappa}(A^*)$ which depends on the frontier technology. This cost is interpreted as the machine replacement cost when the scrap value of the old machine is zero.[9]

The market is monopolistically competitive with many producers and each producer is too small to strategically affect other producers' decisions. Specifically, each producer faces the inverse demand function: $P(Y) = (Y/z)^{-\frac{1}{\theta}}$, where $\theta \in (1, \infty)$ is the price elasticity of demand and z captures the various factors that affect the product demand (e.g., other products' prices and the exchange rate). Given this inverse demand function and the cost function, the *gross* profit flow is expressed as: $\Pi(c(\mathbf{w}, x), A, z) = z\theta^{-\theta}(\theta-1)^{\theta-1}c(\mathbf{w}, x)^{1-\theta}A^{\theta-1}$.

2.2 Technology Adoption under Certainty

In this section, it is assumed that the factor price vector is fixed at $\mathbf{w}$, and that all producers possess the appropriate technology $x^*(\omega)$. These assumptions essentially void the putty-clay nature of the model; however, they provide a useful benchmark for the model with uncertain relative prices in the next section, where the putty-clay assumption plays a major role.

A producer maximizes the present value of the expected total sum of profits. At the beginning of every period, a producer makes a discrete choice between adopting a different technology and continuing to use the current technology. The value of a plant with the technology level A when

[9] Another possible adjustment cost is the opportunity cost of shutting down a plant at the time of retooling. See Caballero and Engel (1999), Cooper et al. (1999), and Cooper and Haltiwanger (2000) for related arguments. Here, for simplicity, I consider only the fixed cost associated with the purchase of new machines.

the frontier technology level is A^* is recursively given by:

$$V(A, A^*) = \max\{V^*(A, A^*), V^*(A^*, A^*) - \tilde{\kappa}(A^*)\} \quad (4)$$

$$V^*(A, A^*) = \Pi(c(\mathbf{w}, x^*), A, \mathbf{z}) + BV^*((1-d)A, (1+g)A^*) \quad (5)$$

where B is a discount factor, $V(A, A^*)$ is the value of a plant at the beginning of period before adjustment, and $V^*(A, A^*)$ is the value of a plant after adjustment.

Due to the underlying technological change in the frontier technology, the infinite sequence problem implied by the above Bellman equations is non-stationary. I consider the stationary version of the problem below. Assume that $\kappa \equiv \tilde{\kappa}(A_t^*)/A_t^{*\theta-1}$ is constant over time. With this assumption, the profit and adjustment cost functions are homogenous of degree one with respect to $A_t^{*\theta-1}$ and the number of state variables can be reduced by relating the problem in terms of the value of $A_t^{*\theta-1}$. It is convenient to define a **technology position** $s_t \in \mathbf{R}_-$ as follows:

$$s_t \equiv \ln\left(\frac{A_t}{A_t^*}\right).$$

By defining $v(s) \equiv V(A, A^*)/A^{*\theta-1} = V(exp(s), 1)$ and $v^*(s) \equiv V^*(A, A^*)/A^{*\theta-1} = V^*(exp(s), 1)$, the Bellman equations (4)-(5) may be rewritten as:[10]

$$v(s) = \max\{v^*(s), v^*(0) - \kappa\} \quad (6)$$

$$v^*(s) = \pi(s) + \beta v(s - \delta) \quad (7)$$

where $\pi(s) \equiv z\theta^{-\theta}(\theta-1)^{\theta-1}c(\mathbf{w}, x^*)^{1-\theta}\exp((\theta-1)s)$, $\beta \equiv B(1+g)^{\theta-1} \in (0,1)$ and $\delta \equiv \ln\left(\frac{1-d}{1+g}\right) \in (0,1)$. The following proposition states that the optimal technology adoption policy associated with the unique solution to the functional equation obtained by substituting (7) into (6) is a version of (S, s) policy.[11] All proofs of the propositions are found in the Appendix.

Proposition 2.1: *There exists a unique $s^* \in (-\infty, 0]$ such that the producer will update to the frontier technology whenever its technology position falls below s^*.*

[10] More precisely, $V(\cdot)$ defined by the fixed point of (4) is homogenous of degree one with respect to $(A^{\theta-1}, A^{*\theta-1})$. It follows that $V(A, A^*) = V(A/A^*, 1)A^{*\theta-1}$. Thus, the number of states can be reduced by considering $s = \ln(A/A^*)$ instead of (A, A^*).

[11] Propositions 2.1-2.2 in this paper are analogous to Proposition 1 of Jovanovich and Rob (1998). A stochastic version is found in Cooper et al. (1999).

The timing of technology adoption is characterized by the threshold value s^* implicitly defined by $v^*(s^*) = v^*(0) - \kappa$. Since $v^*(s)$ is strictly increasing in s, as shown in the Appendix, there exists a unique s^* such that $v^*(s) \leq v^*(0) - \kappa$ for $s \leq s^*$ and $v^*(s) > v^*(0) - \kappa$ for $s > s^*$. Given the threshold value s^*, the **optimal waiting time** is defined as the largest integer T^* in the set $\{T \in \mathbf{N} : \; s^* \geq -\delta T\}$. The optimal waiting time T^* is another way of characterizing a producer's optimal policy. The next proposition summarizes how the threshold value of s^* depends on replacement cost, demand conditions, and factor price levels.

Proposition 2.2: *The threshold value of technology position, s^*, is strictly decreasing in κ, strictly increasing in z, and strictly decreasing in τ where $\mathbf{w} = \tau \mathbf{w_0}$ for a fixed $\mathbf{w_0}$.*

The timing of replacement is determined by equating the marginal benefit and the marginal cost of postponing. The benefit of postponing is that a producer can save the present value of replacement cost, $(1 - \beta)\kappa$, since a producer discounts the future. On the other hand, by postponing replacement, a producer incurs an opportunity cost that is equal to the difference between the profits with the current (old) technology and the profits that the producer would have had with the new technology, $\pi(s) - \pi(0)$. Reflecting an increase in the opportunity cost of using the old technology over time, the policy rule follows the (S,s) policy as stated in Proposition 2.1. An increase in the replacement cost by $\Delta\kappa$ leads to an increase in the marginal benefit of postponing by $(1-\beta)\Delta\kappa$ and hence implies a longer optimal waiting time (i.e., a lower value of s^*). An improvement in the demand conditions by $\Delta z > 0$ increases the opportunity cost of postponing and thus leads to a shorter optimal waiting time (i.e., a higher value of s^*). Similarly, a decrease in factor price levels increases the opportunity cost of postponing and leads to a shorter optimal waiting time.

2.3 Uncertainty in Relative Factor Prices

To analyze the effect of *relative* factor price uncertainty on the timing of technology adoption, consider the announcement effect of uncertainty regarding future (one-time) changes in *relative* factor prices. Specifically, consider the following stochastic process of relative factor prices. Before Time 0, the factor price is fixed at $\bar{\mathbf{w}} = (\bar{w}_1, \bar{w}_2)$ and is believed to be fixed in the future; the relative factor price is denoted as $\bar{\omega} \equiv \frac{\bar{w}_1}{\bar{w}_2}$. At the beginning of Time 0, there is an "unexpected" announcement that, after Time 1, the factor price will be $\mathbf{w}^L = (w_1^L, w_2^L)$ with probability $\lambda \in (0,1)$ and $\mathbf{w}^H = (w_1^H, w_2^H)$ with probability $1-\lambda$. Assume that $\omega^H > \omega^L$, where $\omega^i \equiv \frac{w_1^i}{w_2^i}$ for $i = L, H$. At Time 1, the factor price is realized; and there will be no changes in factor prices after Time 1.

To focus on the effect of *relative* factor price uncertainty—as opposed to factor price *level* uncertainty—on the replacement timing, the following assumption is imposed in this section:

Assumption C (Cost): $\bar{\mathbf{w}}, \mathbf{w}^L, \mathbf{w}^H \in \mathcal{W}(\bar{c}) \equiv \{\mathbf{w}' : \ \bar{c} = c(\mathbf{w}', x^*(\omega'))\}$, *where* $\bar{c} > 0$ *is a given constant; and* $c(\mathbf{w}, x^*(\omega))$ *is given by (2) together with (3).*

$\mathcal{W}(\bar{c})$ is the *isocost curve* under the *ex ante* production function; thus, $\mathbf{w}^L$, $\mathbf{w}^H$, and $\bar{\mathbf{w}}$ are on the same *ex ante* isocost curve. If a producer's factor intensity is appropriate, profit flows under $\mathbf{w}^L$ and $\mathbf{w}^H$ are identical to a profit flow under $\bar{\mathbf{w}}$. Assumption C, therefore, abstracts from uncertainty in the *level* of factor prices. This allows one to analyze the impact of the *relative* factor price uncertainty separately from that of factor price level uncertainty.[12]

Before Time 0, all producers are assumed to possess the *appropriate* technology $x^*(\bar{\omega})$ defined by equation (3). Since each producer believes that factor prices are fixed over time, the only relevant state variable is the technology position s. Thus, the producer's behavior is characterized by the Bellman equations (6)-(7). A producer follows the (S, s) technology adoption policy as stated in Proposition 2.1. Denote the threshold value before Time 0 by $s^*(x^*(\bar{\omega}), \bar{\mathbf{w}})$.

At the beginning of Time 1, factor prices are realized. After Time 1, there are no factor price changes. Hence, any producer adopting technology after Time 1 chooses the appropriate factor intensity: $x^*(\omega^i)$ if $\mathbf{w}^i$ is realized $(i = L, H)$. The Bellman equations after Time 1 are:

$$v(s, x, \mathbf{w}^i) \quad = \quad \max\{v^*(s, x, \mathbf{w}^i), v^*(0, x^*(\omega^i), \mathbf{w}^i) - \kappa\} \tag{8}$$

$$v^*(s, x, \mathbf{w}^i) \quad = \quad \pi(s, x, \mathbf{w}^i) + \beta v(s - \delta, x, \mathbf{w}^i) \tag{9}$$

for $i = L, H$. The threshold value of technology adoption, denoted by $s^*(x, \mathbf{w}^i)$, is implicitly

[12] A change in factor prices may be decomposed into a change in the relative factor prices (i.e., a change along the *ex ante* isocost curve) and a change in the level of factor prices (i.e., a change from one *ex ante* isocost curve to another). Accordingly, the effect of uncertainty in factor prices on the timing of technology adoption can be decomposed into two effects: the effect of uncertainty in *relative* factor prices and the *levels* of factor prices.

characterized by:

$$v^*(s^*(x,\mathbf{w}^i),x,\mathbf{w}^i) = v^*(0,x^*(\omega^i),\mathbf{w}^i) - \kappa \tag{10}$$

Once the appropriate technology is adopted, the threshold value s^* is the same across different realizations by Assumption C. On the other hand, if a factor intensity x is not appropriate, then the per-period profit $\pi(s,x,\mathbf{w}^i)$ is less than $\pi(s,x^*(\omega^i),\mathbf{w}^i)$. In such a case, profit increases after technology adoption not only are due to the adoption of the frontier technology but also due to the adoption of the *appropriate factor intensity*. The latter provides an extra motivation for technology adoption and leads to the following proposition.

Proposition 2.3: *$s^*(x,\mathbf{w}^i)$ defined by (10) is strictly decreasing in x if $x < x^*(\omega^i)$ and strictly increasing in x if $x > x^*(\omega^i)$.*

The above proposition essentially states that, the larger the "distance" between a producer's *ex post* factor intensity and the appropriate factor intensity, the shorter the timing of technology adoption. The reason is that the benefit from technology adoption is increasing in the distance between the current *ex post* factor intensity and the *appropriate factor intensity*, as implied in Figure 1. The following corollary is a trivial consequence of Proposition 2.3:

Corollary 2.4: *$s^*(x,\mathbf{w}^i) > s^*(x^*(\omega^i),\mathbf{w}^i)$ if $x \neq x^*(\omega^i)$ for $i = L,H$.*

Therefore, once uncertainty is resolved, producers adopt new technology sooner since they possess inappropriate technology due to the *ex post* change in relative factor prices.

At the beginning of Time 0, a producer unexpectedly realizes that there will be a change in factor prices after Time 1: $\mathbf{w}^L$ with probability λ and $\mathbf{w}^H$ with probability $1-\lambda$. The producer's behavior at the beginning of Time 0 is described by:

$$v_0(s,x^*(\bar{\omega}),\bar{\mathbf{w}}) = \max\{v_0^*(s,x^*(\bar{\omega}),\bar{\mathbf{w}}), \max_{x'} v_0^*(0,x',\bar{\mathbf{w}}) - \kappa\} \tag{11}$$

$$v_0^*(s,x,\bar{\mathbf{w}}) = \pi(s,x,\bar{\mathbf{w}}) + \beta[\lambda v(s-\delta,x,\mathbf{w}^L) + (1-\lambda)v(s-\delta,x,\mathbf{w}^H)] \tag{12}$$

where $v(s-\delta,x,\mathbf{w}^i)$ for $i = L,H$ in (12) is defined by (8). Denote the threshold value of technology adoption at Time 0 by s_0^*.

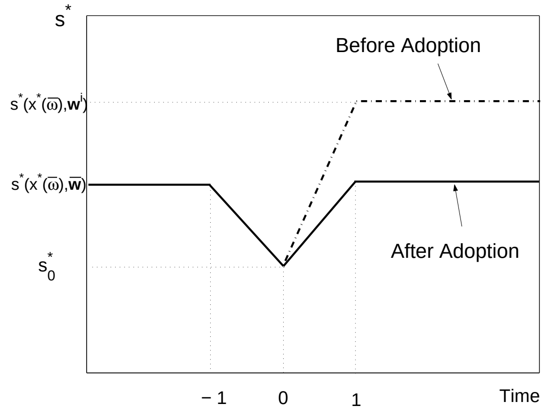

Figure 2: Uncertainty Delays Technology Adoption

The next proposition is the main result, which states that the presence of temporary uncertainty in future relative factor prices at Time 0 tends to delay technology adoption. The *ex post* fixity of factor intensity is responsible for this result. By adopting technology before knowing relative factor prices, a producer's choice of factor intensity may become inappropriate *ex post.* On the other hand, by waiting one more period for the uncertainty to be resolved, a producer can make sure of adopting the appropriate technology. The possibility of the future resolution of relative factor price uncertainty provides an incentive for a producer to delay making an irreversible factor intensity choice at Time 0.

Proposition 2.5: *The threshold value of technology adoption at Time* 0 *is lower than before Time* 0*, i.e.* $s_0^* < s^*(x^*(\bar{\omega}), \bar{\mathbf{w}})$.

Figure 2 depicts how the threshold value of technology adoption s^* changes over time. Before Time 0, the value of s^* stays the same, $s^*(x^*(\bar{\omega}), \bar{\mathbf{w}})$. Upon the announcement of future uncertainty in relative factor prices at Time 0, the value of s^* drops from $s^*(x^*(\bar{\omega}), \bar{\mathbf{w}})$ to s_0^* as stated in Proposition 2.5. At Time 1, relative factor prices are realized. After Time 1, those producers that have not adopted new technology possess inappropriate technology; thus, the threshold values of their technology positions are higher than those that have adopted, as implied by Corollary 2.4. Once a producer adopts the appropriate technology, the threshold value is the same as before Time 0 since $s^*(x^*(\omega^i), \mathbf{w}^i) = s^*(x^*(\bar{\omega}), \bar{\mathbf{w}})$ by Assumption C.

2.4 Ex-ante Elasticity of Substitution and Uncertainty

In this section, to obtain further insight of the role of putty-clay technology, I numerically analyze the model with a regime switching process in factor prices under a CES production function.

Consider the *ex ante* CES production function:

$$Y_t = A_t[\alpha X_{1,t}^{\frac{\gamma-1}{\gamma}} + (1-\alpha)X_{2,t}^{\frac{\gamma-1}{\gamma}}]^{\frac{\gamma}{\gamma-1}}, \tag{13}$$

where $\gamma > 0$ is the *ex ante* elasticity of substitution. The *ex post* cost function is:

$$c(\mathbf{w_t}, x_t) = \frac{w_{1,t}x_t + w_{2,t}}{[\alpha x_t^{\frac{\gamma-1}{\gamma}} + (1-\alpha)]^{\frac{\gamma}{\gamma-1}}}$$

The *appropriate factor intensity* is given by $x^*(\omega) = \left[\frac{1-\alpha}{\alpha}\omega\right]^{-\gamma}$.

Assume there are two regimes, Regime H and Regime L, where *relative* factor prices are more volatile in Regime H than in Regime L. Specifically, assume that relative factor prices, ω, follow a geometric random walk:

$$\ln \omega_{t+1} = \ln \omega_t + \sigma_\omega(r_t)\epsilon_t, \tag{14}$$

where ϵ_t is an i.i.d. standard normal random variable. The degree of volatility in relative factor prices in Regime $r_t \in \{L, H\}$ is characterized by $\sigma_\omega(r_t)$, with $\sigma_\omega(H) > \sigma_\omega(L) \geq 0$. The stochastic process of regimes follows a Markov process with the transition matrix:

$$\begin{pmatrix} p_L & 1-p_L \\ 1-p_H & p_H \end{pmatrix},$$

where $Prob(r_{t+1} = i | r_t = i) = p_i$ for $i = L, H$.[13]

To focus on the impact of *relative* factor price uncertainty—as opposed to uncertainty in factor price *level*—on technology adoption, I impose Assumption C by assuming that $w_{1,t}$ and $w_{2,t}$ are given by: $w_{1,t} = \frac{A[\alpha x^*(\omega_t)^{\frac{\gamma-1}{\gamma}} + (1-\alpha)]^{\frac{\gamma}{\gamma-1}}}{x^*(\omega_t) + \omega_t^{-1}}\bar{c}$ and $w_{2,t} = \frac{A[\alpha x^*(\omega_t)^{\frac{\gamma-1}{\gamma}} + (1-\alpha)]^{\frac{\gamma}{\gamma-1}}}{\omega_t x^*(\omega_t) + 1}\bar{c}$.

The Bellman equation is written as

$$\begin{aligned} v(s, x, \mathbf{w}, r) &= \max\{v^*(s, x, \mathbf{w}, r), \max_{x'} v^*(0, x', \mathbf{w}, r) - \kappa\}, \\ v^*(s, x, \mathbf{w}, r) &= \pi(s, x, \mathbf{w}) + \beta E[v(s-\delta, x, \mathbf{w}', r')|\mathbf{w}, r]. \end{aligned} \tag{15}$$

[13] The analysis in Section 2.3 may be interpreted as the limiting case of $p_L \to 1$, $p_H \to 0$, and $\sigma_\omega(L) \to 0$.

I numerically examine how changes in the parameter values of γ, $\sigma_\omega(H)$, and p_H, affect the optimal waiting time *when a producer possesses the appropriate factor intensity.*[14] The Appendix provides a detailed description of the numerical dynamic programming procedure. Baseline parameter values are set to: $\delta = 0.1$; $\beta = 0.95$; $\alpha = 0.5$; $\kappa = 2$; $\theta = 2$; $z = \theta^\theta(\theta-1)^{1-\theta}$; $\sigma_\omega^H = 0.5$; $\sigma_\omega^L = 0$; $\bar{c} = 2$; $p_L = 1$; $p_H = 0.1$. Symmetry between the two factors in the production function (13) is assumed with $\alpha = 0.5$. Relative factor prices fluctuate in Regime H while they do not in Regime L. Regime L is an absorbing state while Regime H is a transient state. Let T_L^* and T_H^* be the optimal waiting times in Regime L and H, respectively, for a producer with the appropriate factor intensity.

Figure 3 illustrates how the value of the *ex ante* elasticity of substitution γ is related to T_L^* and T_H^*. The solid line represents Regime H and the dashed line represents Regime L. The difference between T_H^* and T_L^* measures the impact of uncertainty on the optimal waiting time. Figure 3 shows that a higher *ex ante* elasticity of substitution leads to slower machine replacement in Regime H. The reason for slower machine replacement is that the *ex ante* elasticity of substitution determines the sensitivity of the *appropriate factor intensity* with respect to a change in relative factor price. When the elasticity of substitution is high, the difference in the *appropriate factor intensity* under two different factor prices (i.e., the "distance" between $x^*(\omega^L)$ and $x^*(\omega^H)$) is large. Thus, if a producer chooses its factor intensity in Regime H, the high elasticity of substitution results in a higher expected deviation of *ex post* factor intensity from the *appropriate factor intensity*, which, in turn, lowers the marginal benefit of technology adoption when the economy is in Regime H.

Figure 4 shows that an increase in uncertainty also delays the timing of technology adoption. As $\sigma_\omega(H)$ increases, the optimal waiting time of Regime H, T_H^*, increases. The reason is that the expected deviation of *ex post* factor intensity from the appropriate factor intensity increases as the spread of the distribution of future relative factor prices increases. This, in turn, increases the option value of waiting in Regime H and delays the timing of technology adoption.

Figure 5 presents how the degree of "persistence" in Regime H, measured by p_H, affects the

[14] As Proposition 2.3 implies, the optimal waiting time of technology adoption also depends on the "distance" between the current factor intensity and the appropriate factor intensity. To compare the effects of uncertainty across different parameter values, the optimal waiting time under the appropriate factor intensity provides a useful reference point.

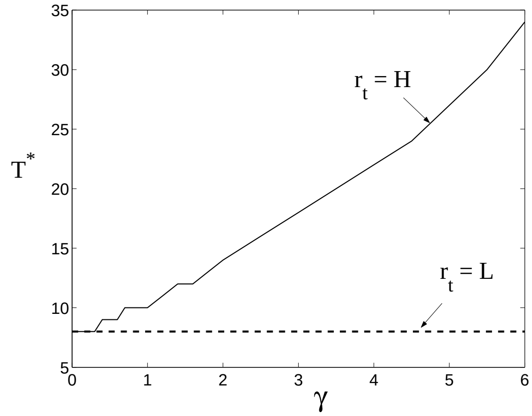

Figure 3: The Higher Elasticity of Substitution Increases Optional Waiting Time

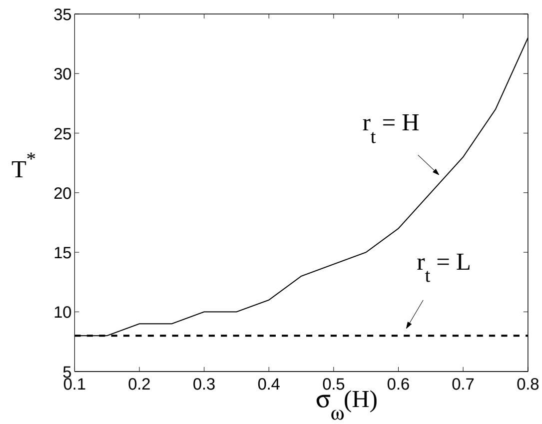

Figure 4: Higher Uncertainty Increases Optimal Waiting Time

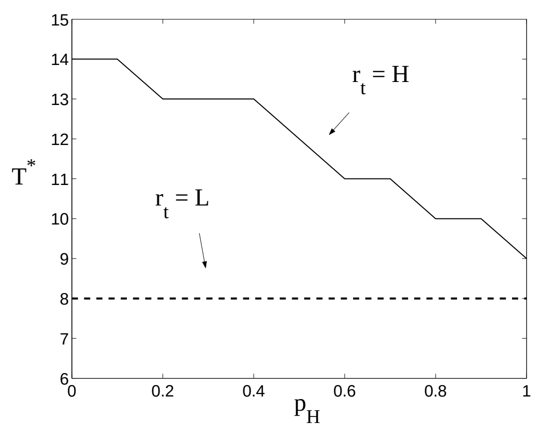

Figure 5: Temporariness Increases Optimal Waiting Time

timing of technology adoption. The result shows that the *temporary* uncertainty magnifies the negative impact of volatility on replacement timing. It is the possibility of the arrival of new information on the desired factor intensity that makes a producer reluctant to adopt technology in Regime H. If Regime H is temporary (i.e., $p_H \approx 0$), then the expectation of the future resolution of uncertainty provides a higher incentive to wait since, by waiting, a producer can make sure of adopting the appropriate technology.

3 An Empirical Application: Real Exchange Rate Volatility

This section examines the key empirical implications of putty-clay technology in the context of real exchange rate volatility, using plant-level Chilean manufacturing data for 1979-1986. The empirical analysis focuses on the irreversibility of factor intensity choice between imported materials and domestic materials and its importance in explaining the effect of *relative* factor price uncertainty induced by exchange rate volatility on investment. Since materials occupy a large share of the total cost of production, the irreversibility in the choice of imported materials intensity—if it exists—may play an important role in determining investment decisions.

3.1 Data

The data set is based on a census of Chilean manufacturing plants by Chile's Instituto Nacional de Estadistica (INE).[15] Attention is focused on the collection of plants present for all sample years. After cleaning the data, the balanced panel data set contains 2116 plants for the period of 1979-1986. The Appendix describes the details of the sample selection criteria and the construction of the variables used in the regressions together with their descriptive statistics.

Table 1 presents the level and the volatility of the real exchange rate—two of the key macroeconomic variables in the empirical analysis—for Chile over the period of 1980-1986. Chile changed its exchange rate system from a fixed exchange rate to a flexible exchange rate in 1982. Reflecting the overvalued Chilean peso under the fixed exchange rate before 1982, real exchange rates depreciated substantially between 1982 and 1986. On the other hand, the real exchange rate volatility is especially high in 1982 and 1985. The time-series variation in the exchange rate level and volatility together with cross-sectional variation in plant characteristics allows the

[15] Empirical studies based on this data set include Tybout (1996) and Pavcnik (2002).

Table 1: Real Exchange Rate of Chile

Year	1980	1981	1982	1983	1984	1985	1986
Real Exchange Rate Level (p_t)	1.000	0.844	0.935	1.143	1.152	1.453	1.698
Real Exchange Rate Volatility (σ_t)	0.0150	0.0198	0.0505	0.0235	0.0262	0.0748	0.0136

Notes: "Real Exchange Rate Level" is the average of the monthly Real Effective Exchange Rates over 12 months. An increase implies a depreciation. "Real Exchange Rate Volatility" is computed as the standard error of the log of the first differences in the monthly real exchange rate over 12 months.

identification of some of the key parameters in the empirical models as discussed below.

3.2 Evidence on the Irreversibility of Factor Intensity Choice

I first examine whether there is evidence that a large current investment leads to a higher elasticity of substitution between factors by estimating the following equation:

$$\begin{aligned} \ln x_{it} &= \alpha_0 I_{it} + \alpha_1 I_{it} \ln p_t + \eta_i + \xi_t + u_{it}, \qquad (16) \\ u_{it} &= \rho u_{i,t-1} + e_{it} \end{aligned}$$

where x_{it} is the factor intensity of imported materials relative to domestic materials of plant i in year t, I_{it} represents an investment variable that indicates a machine replacement decision, $\ln p_t$ is the logarithm of the price of imported materials relative to the price of domestic materials, approximated by the logarithm of the real exchange rate (an increase implies depreciation), η_i is a plant-specific effect, ξ_t is a year-specific intercept, u_{it} is a possibly autoregressive shock with $|\rho| < 1$, and e_{it} is a serially uncorrelated shock.

The coefficient α_0 captures the degree of "imported-material" biased technological change embodied in machines over time. The year-specific effect, ξ_t, includes the effect of the relative prices $\ln p_t$ *without* machine replacement; $-\alpha_1$ measures the difference between the elasticity of substitution *with* machine replacement and the elasticity of substitution *without* machine replacement. I examine whether a large investment leads to a higher elasticity of substitution between factors by testing whether $\alpha_1 < 0$.

The coefficient on the interaction between I_{it} and $\ln p_t$ is further specified as:

$$\alpha_1 = \varphi_0 + \varphi_1 \gamma_i, \qquad (17)$$

where γ_i is the measure of the *ex ante* elasticity of substitution for the industry to which plant i belongs. In practice, the standard error of the imported material ratio measured in logarithms within the four-digit industry level is used as a proxy for the industry-specific *ex ante* elasticity of substitution. This approach is motivated by the consideration that, under putty-clay technology (i.e., zero *ex post* elasticity of substitution), the variability of factor intensities across plants will necessarily capture the *ex ante* elasticity of substitution. If this proxy does not capture the difference between the *ex ante* elasticity of substitution and the *ex post* elasticity of substitution at the industry level, then $\varphi_1 = 0$. The validity of the proxy is testable, therefore, by examining if $\varphi_1 < 0$.

Finally, since the industry-specific measure of the *ex ante* elasticity of substitution γ_i might be correlated with a plant-specific effect, the following correlated random-effects specification is adopted: $\eta_i = \alpha_3 \gamma_i + \tilde{\eta}_i$.

Using a dynamic common factor representation, (16) can be rewritten as:

$$\ln x_{it} = \pi_1 I_{it} + \pi_2 I_{i,t-1} + (\pi_3 + \pi_4 \gamma_i) I_{it} \ln p_t + (\pi_5 + \pi_6 \gamma_i) I_{i,t-1} \ln p_{t-1} + \pi_7 \ln x_{i,t-1} + \pi_8 \gamma_i + \xi_t^* + \eta_i^* + e_{it}, \tag{18}$$

where $\pi_1 = \alpha_0$, $\pi_2 = -\rho\alpha_0$, $\pi_3 = \varphi_0$, $\pi_4 = \varphi_1$, $\pi_5 = -\rho\varphi_0$, $\pi_6 = -\rho\varphi_1$, $\pi_7 = -\rho$, $\pi_8 = (1-\rho)\alpha_3$, $\xi_t^* = \xi_t - \rho\xi_{t-1}$, and $\eta_i^* = (1-\rho)\tilde{\eta}_i$.

I estimate the unrestricted parameter vector $\pi = (\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8)'$ of (18) by one-step GMM, for which inference is more reliable than two-step GMM (c.f., Blundell and Bond, 1998), and then obtain the restricted parameter vector $\theta = (\alpha_0, \alpha_3, \varphi_0, \varphi_1, \rho)'$ using minimum distance (c.f., Chamberlain, 1982).[16] The moment conditions are:

$$E[\gamma_i \Delta e_{it}] = 0 \quad \text{for } t = 2, ..., T, \tag{19}$$

$$E[z_{i,t-s} \Delta e_{it}] = 0 \quad \text{for } s \geq 3 \text{ and } t = 2, ..., T, \tag{20}$$

$$E[\Delta z_{i,t-s}(\eta_i^* + e_{it})] = 0 \quad \text{for } s = 2 \text{ and } t = 2, ..., T, \tag{21}$$

[16] To estimate the unrestricted parameter vector π and its heteroscedasticity-consistent variance-covariance matrix, denoted by Ω, using one-step GMM, I closely follow the procedure described in Doornik, Bond, and Arellano (2002). The restricted parameter θ is then estimated by minimizing $[\hat{\pi} - h(\theta)]'\hat{\Omega}^{-1}[\hat{\pi} - h(\theta)]$ with respect to θ, where $\hat{\pi}$ and $\hat{\Omega}$ are the one-step GMM estimates and $\pi = h(\theta)$ represents the nonlinear restriction between π and θ. The variance covariance matrix for $\sqrt{N}(\hat{\theta} - \theta)$ is computed as $(\hat{H}'\hat{\Omega}^{-1}\hat{H})^{-1}$, where $\hat{H} = \frac{\partial h}{\partial \theta'}|_{\theta=\hat{\theta}}$. Blundell and Bond (2000) estimated production functions using a similar procedure.

where $z_{it} = (I_{it}, \ln x_{it})$ and $\Delta z_{it} = z_{it} - z_{i,t-1}$. While the moment conditions (20) are the standard moment conditions in first differenced GMM estimation (c.f., Arellano and Bond, 1991), the moment conditions (19) are valid if plant's four-digit industry classification is predetermined at the beginning of the sample period. I also consider additional moment conditions (21), assuming that $E[\Delta I_{it}\eta_i^*] = 0$ and that the initial conditions $E[\Delta \ln x_{i,1}\eta_i^*] = 0$.[17]

The following two alternative measures are used for a plant's investment variable, I_{it}: (A) a discrete investment variable, denoted by I_{it}^A, that is equal to one if the gross investment rate, defined by the ratio of gross machinery investment in year t to the machinery capital stock at the beginning of year t, is greater than 0.2 and equal to zero otherwise, (B) a continuous investment variable, denoted by I_{it}^B, that is the gross investment rate defined above.[18] The measurement of I_{it}^A is motivated by the empirical fact that investment is lumpy at the plant level (e.g., Doms and Dunne, 1998) and is more consistent with the theory developed here in which a plant makes a discrete investment choice. On the other hand, the choice of a threshold value of 0.2 to construct I_{it}^A is somewhat arbitrary and a continuous investment variable I_{it}^B may provide better information regarding a relevant plant's investment decision. Using the continuous investment variable I_{it}^B might be more appropriate than using the discrete investment variable I_{it}^A if, for example, a plant has multiple production lines, each of which has a different replacement cycle.

Table 2 presents the results of estimating the factor intensity choice equation (16) with both specifications of I_{it}. In all cases, the validity of instruments are not rejected by the Sargan-Hansen test of overidentifying restrictions.[19] The estimates of the coefficient of the investment variable are positive and significant in all four cases, providing evidence that a large current investment tends to increase the use of imported materials relative to domestic ones.

As shown in columns (1) and (3) of Table 2, the estimated coefficients of interaction of

[17]Blundell and Bond (1998) find that exploiting additional moment conditions like (21) may lead to dramatic reductions in finite sample bias. Moreover, the moment conditions (21) allow the identification of the parameter α_3 of the correlated random-effects specification.

[18]To be consistent with machine replacement, I have set the maximum of I_{it}^B to 1 by replacing the values of any observation with a gross investment rate of more than 100% by 1. Dropping plant observations with gross investment rates above 100% leads to results similar to those presented in Table 2.

[19]I have also estimated equation (16) using lagged levels dated $t-2$ as instruments in the first-differenced equations, combined with lagged first differences dated $t-1$ as instruments in the levels equations. P-values of the Sargan-Hansen statistics are less than 0.05 in all cases, rejecting the validity of instruments. This is consistent with the presence of measurement errors in the dependent variable (c.f., Blundell and Bond, 2000).

Table 2: Estimates of Imported Materials Intensity Equation (16)

	I_{it}^A		I_{it}^B	
	(1)	(2)	(3)	(4)
I_{it}	1.021*	0.972*	1.727*	2.185**
	(0.581)	(0.544)	(0.983)	(0.991)
$I_{it} \ln p_t$	-2.808**	0.206	-4.813*	-0.706
	(1.368)	(1.790)	(2.651)	(3.410)
$\gamma_i I_{it} \ln p_t$		-1.597**		-2.178*
		(0.707)		(1.129)
ρ	0.596**	0.466**	0.616**	0.456**
	(0.095)	(0.194)	(0.097)	(0.143)
Sargan-Hansen	0.799	0.888	0.934	0.919

Notes: Dependent variable = the ratio of imported materials to domestic materials measured in logarithm. Heteroscedasticity-consistent standard errors are in parentheses. The superscripts ** and * indicate that the estimate is significantly different from zero at the 5% and 10% levels, respectively. Year dummies are included in all columns; the industry variable γ_i is also included in columns (2) and (4). The instruments used in the differenced equations for columns (1) and (3) are $I_{i,t-2}, I_{i,t-3}, ..., I_{i,1}$; $\ln x_{i,t-2}, \ln x_{i,t-3}, ..., \ln x_{i,1}$; additional instruments γ_i are added for columns (2) and (4). For all columns, the instruments used in the level equations are $\Delta I_{i,t-2}$ and $\Delta \ln x_{i,t-2}$. Instrument validity is tested using a Sargan-Hansen test of the over-identifying restrictions for the two step GMM estimator and the P-values are reported.

investment with the relative factor prices are negative and significant. The point estimate of column (1) implies the elasticity of substitution between imported materials and domestic materials for a plant replacing its machine is higher by 2.81 points than for a plant not replacing its machine. According to the point estimate in column (3), plants with a 100% gross investment rate experience a higher elasticity of substitution by 4.81 points as compared to plants with no investment. The results indicate that the extent to which an investment facilitates the adjustment of plant's factor intensities is quantitatively large.

In columns (2) and (4) of Table 2, the estimated coefficients for the interaction between the proxy for the *ex ante* elasticity of substitution, investment, and the relative factor prices, are negative and significant. On the other hand, the coefficients of interaction of investment with the relative factor prices are no longer significant. The results support the validity of the proxy for the *ex ante* elasticity of substitution since the proxy captures the cross-industry differences well in the elasticity of substitution at the time of a large investment. The validity of the proxy is important since I extensively use this industry-specific measure of the *ex ante* elasticity of substitution to examine the implications of the putty-clay investment model in the next section.

3.3 Investment and Exchange Rate Volatility

The previous section provided some evidence of the irreversibility of factor intensity choice between imported and domestic materials. This section investigates to what extent this irreversibility of factor intensity choice explains the impact of exchange rate volatility on investment.

Consider the following specification of plant investment decisions:

$$I_{it} = \beta_{\sigma,i}\sigma_t + \beta_{p,i}\ln p_t + \beta_k k_{i,t-1} + \beta_{\Delta x}(\ln x^*_{it} - \ln x_{i,t-1})^2 + \beta_c \frac{C_{it}}{K_{i,t-1}} + \mu_i + \zeta_t + \epsilon_{it}, \quad (22)$$

$$\epsilon_{it} = \phi\epsilon_{i,t-1} + v_{it} \quad (23)$$

where σ_t is the measure of the real exchange rate volatility in year t and $\ln p_t$ is the real exchange rate level measured in logarithm in year t. I allow the coefficients of σ_t and $\ln p_t$ to differ across plants so that $\beta_{\sigma,i}$ represents the plant-specific coefficient on the real exchange rate volatility while $\beta_{p,i}$ represents the plant-specific coefficient on the real exchange rate level. Other regressors include the logarithm of capital-output ratio lagged one period $k_{i,t-1} = \ln \frac{K_{i,t-1}}{Y_{i,t-1}}$, the distance between the *appropriate* factor intensity and the actual factor intensity $(\ln x^*_{it} - \ln x_{i,t-1})^2$, and cash flow normalized by capital stock $\frac{C_{it}}{K_{i,t-1}}$. A plant-specific component, μ_i, captures time-invariant productivity, price and demand factors, while ζ_t is a year-specific intercept, which captures macroeconomic shocks such as machine prices and aggregate productivity shocks. Finally, ϵ_{it} is an autoregressive shock, which captures transitory shocks in productivity, price and demand, with $|\phi| < 1$, and v_{it} is a serially uncorrelated shock.

The main empirical question is: what factors determine the impact of real exchange rate volatility on investment decisions? Possibly important channels through which the real exchange rate volatility may affect investment decisions are: (i) relative factor prices between imported materials and domestic materials, (ii) market demands, (iii) factor price levels. While this paper highlights (i), others in the irreversible investment literature emphasize (ii) and (iii). To examine the relative importance of these channels in explaining the volatility effect of the real exchange rate, the coefficient of the real exchange rate volatility $\beta_{\sigma,i}$ is specified as:

$$\beta_{\sigma,i} = \beta_{\sigma,\gamma}\gamma_i + \beta_{\sigma,e}E_i + \beta_{\sigma,m}M_i + \beta_{\sigma,x}X_i, \quad (24)$$

where γ_i is the industry-specific measure of the *ex ante* elasticity of substitution to which plant i belongs. I use the standard error of the imported material ratio within the four-digit industry level as a proxy. As Columns (2) and (4) of Table 2 show, this proxy captures the elasticity of substitution well at the time of a large investment. E_i is the ratio of aggregate export to aggregate domestic output for the industry, M_i is the import penetration rate, defined as the ratio of aggregate imports to the sum of aggregate imports and aggregate domestic output for the industry, and X_i is the ratio of aggregate imported materials to aggregate total materials for the industry. E_i, M_i, and X_i are measured at the four-digit industry level over the period of 1979-1986. The identification of the parameters $(\beta_{\sigma,\gamma}, \beta_{\sigma,e}, \beta_{\sigma,m}, \beta_{\sigma,x})$ comes from comparing the cross-sectional differences in the response of investment to changes in real exchange rate volatility to the cross-sectional differences in industry-characteristics $(\gamma_i, E_i, M_i, X_i)$. Therefore, both the time-series variation in exchange rate volatility and the cross-sectional variation in γ_i, E_i, M_i, and X_i are important for identification.

The key prediction that differentiates this paper's putty-clay investment model from other irreversible investment models is $\beta_{\sigma,\gamma} < 0$. It is consistent with the model's prediction that a higher *ex ante* elasticity of substitution leads to a larger negative effect of volatility in relative factor prices. The importance of demand uncertainty on investment emphasized by the irreversible investment literature can be tested by examining $\beta_{\sigma,e}, \beta_{\sigma,m} < 0$ since a change in real exchange rates affects demand for tradable sectors more than non-tradable sectors. The depressing effect of imported price level volatility due to the irreversibility of investment can be tested by examining $\beta_{\sigma,x} < 0$ as plants that belong to an industry with a larger share of imported materials would experience a larger negative impact from cost uncertainty induced by the real exchange rate volatility.

It is worth noting that, contrary to the prediction of the irreversible investment models, the models of Hartman (1972, 1976) and Abel (1983b) predict a positive effect of uncertainty. In their models, the marginal revenue product of capital is convex in demand or prices and hence a mean-preserving spread in the distribution of demand or prices has a positive effect on investment by increasing the expected marginal revenue product of capital. The sign condition of $(\beta_{\sigma,e}, \beta_{\sigma,m}, \beta_{\sigma,m})$ is, therefore, ambiguous a priori and will depend on the relative importance of different channels through which uncertainty affects investment.

A change in real exchange rate *levels* may also affect investment decisions by inducing a change in market demands and factor prices. Analogous to (24), I specify the coefficient of the real exchange rate level, $\beta_{p,i}$, in (22) as

$$\beta_{p,i} = \beta_{p,\gamma}\gamma_i + \beta_{p,e}E_i + \beta_{p,m}M_i + \beta_{p,x}X_i.$$

Positive demand effects from exchange rate depreciation for plants belonging to tradable sectors are implied by $\beta_{p,e} > 0$ and $\beta_{p,m} > 0$. The importance of a negative input price effect from depreciation is examined by testing if $\beta_{p,x} < 0$. I also include the term γ_i to control for the effect of the interaction between the ex ante elasticity of substitution and the real exchange rate levels so as not to mistake uncertainty effects of γ_i captured by the coefficient $\beta_{\sigma,\gamma}$ for omitted price level effects.

The third and the fourth terms on the right-hand-side of the equation (22) are two of key micro-level determinants of investment decisions in the putty-clay investment model. In the third term, $k_{i,t-1} = \ln \frac{K_{i,t-1}}{Y_{i,t-1}}$ is included as an explanatory variable to control for the technology position at the beginning of the period t. If the high value of capital-output ratio indicates a recent large investment and hence a low value of technology position, we would expect $\beta_k < 0$ in view of Proposition 2.1. The fourth term, $(\ln x^*_{it} - \ln x_{i,t-1})^2$, measures a quadratic distance between the *appropriate* factor intensity and the actual factor intensity at the beginning of year t. As implied by Proposition 2.3, the benefit from machine replacement increases as this distance increases, and therefore we would expect that $\beta_{\Delta x} > 0$.

It is important to emphasize that other investment models—notably the linear error correction models (e.g., Bond, Harhoff, and Van Reenen, 1999)—also predict the negative sign on capital-output ratio. However, the prediction of a positive sign on the distance between the *appropriate* factor intensity and the actual factor intensity distinguishes this paper's putty-clay investment model from other investment models. For this reason, the positive sign of $\beta_{\Delta x}$ may be viewed as particularly important evidence for the putty-clay model.

Many previous papers have found that cash flow, possibly capturing the effects from liquidity constraints, is significant in investment regressions (e.g., Fazzari, Hubbard and Petersen, 1988). Although examining the effects of liquidity constraints is not the focus here, the exclusion of cash flow measures may lead to an omitted-variable bias. To check the robustness of the results, I also include cash flow, denoted by $\frac{C_{it}}{K_{i,t-1}}$, in the investment equation (22). Finally, since observed industry characteristics (i.e., γ_i, E_i, M_i, and X_i) might be correlated with unobserved time-invariant productivity, price and demand factors, the following correlated random-effects specification is adopted: $\mu_i = \beta_\gamma \gamma_i + \beta_e E_i + \beta_m M_i + \beta_x X_i + \tilde{\mu}_i$.

In estimating (22), real exchange rate volatility σ_t and the *appropriate* factor intensity $\ln x^*_{it}$ must be measured. For σ_t, the standard errors of the first differences in the logarithm of the monthly real exchange rate over 12 months at the year t are used. This measure can be interpreted as the estimate of the year-specific standard deviation of innovation term when the real exchange rate follows a geometric random walk similar to equation (14). The *appropriate* factor intensity $\ln x^*_{it}$ is constructed based on the estimated version of equation (16). Specifically, by assuming that plants with a large investment (i.e., $I_{it} = 1$) will adopt the *appropriate* factor intensity, $\ln x^*_{it}$ is measured as $\hat{\alpha}_0 + (\hat{\varphi}_0 + \hat{\varphi}_1) \ln p_t + \hat{\xi}_t + \hat{\eta}_i$, where $(\hat{\alpha}_0, \hat{\varphi}_0, \hat{\varphi}_1, \hat{\xi}_t, \hat{\eta}_i)$ is the estimate of the parameter vector $(\alpha_0, \varphi_0, \varphi_1, \xi_t, \eta_i)$. See the Appendix for details.

As before, I use two alternative measures of investment variables: I^A_{it} and I^B_{it}. If the discrete investment variable I^A_{it} is used, then the equation (22) is a linear probability model specification. While the linear probability model has the disadvantage that the predicted probabilities may not be constrained to the unit interval, the linear model has the advantage over, say, a random effects probit model in that it is robust to the form of unobserved heterogeneity and that it can incorporate predetermined endogenous regressors in the presence of serially correlated errors. The latter point is particularly important in this context since predetermined endogenous regressors, $k_{i,t-1}$ and $(\ln x^*_{it} - \ln x_{i,t-1})^2$, are present in the specification (22) and there is evidence for serial correlation in the transitory errors as shown in Table 3.[20] For a comparison, the estimates of a random effects probit model—in which $k_{i,t-1}$ and $(\ln x^*_{it} - \ln x_{i,t-1})^2$ are treated as strictly exogenous variables—are presented in the Appendix.

Analogous to equation (18), equation (22) can be written using dynamic common factor representations. I estimate their unrestricted parameter vectors by one-step GMM and then obtain the restricted parameter vector estimate using minimum distance. The following moment

[20] It is difficult to incorporate predetermined endogenous variables into binary choice models with serially correlated errors. Relative to the linear models, fewer results are available on binary choice models with predetermined explanatory variables. Honore and Lewbel (2002) present a binary choice model with fixed effects and predetermined explanatory variables but require one of the explanatory variables to be continuous and strictly exogenous to consistently estimate the parameters. Arellano and Carrasco (2003) develop semi-parametric random effects binary choice models with predetermined variables but their model does not allow for the standard patterns of autocorrelation in transitory shocks (e.g., AR(1) like equation (23)).

conditions, similar to the moment conditions (19)-(21), are used:

$$E[W_i \Delta v_{it}] = 0 \quad \text{for } t \geq 2, ..., T, \tag{25}$$

$$E[w_{i,t-s} \Delta v_{it}] = 0 \quad \text{for } s \geq 3 \text{ and } t \geq 2, ..., T, \tag{26}$$

$$E[\Delta w_{i,t-s}(\mu_i^* + v_{it})] = 0 \quad \text{for } s = 2 \text{ and } t \geq 2, ..., T \tag{27}$$

where $W_i = (\gamma_i, E_i, M_i, X_i)$, $w_{it} = (I_{it}, k_{it-1}, (\ln x_{it}^* - \ln x_{i,t-1})^2, \frac{C_{it}}{K_{i,t-1}})$, $\Delta w_{it} = w_{it} - w_{i,t-1}$, and $\mu_i^* = (1-\phi)\tilde{\mu}_i$.

Table 3 presents the results of estimating the investment decision, equation (22), for different sets of explanatory variables. Comparing the p-values for the Sargan-Hansen test of overidentifying restrictions between columns (2) and (3), I find that the inclusion of a cash flow term is important for the validity of the instruments when the discrete investment variable I^A is used as a dependent variable. The coefficients on the cash flow term are positive as expected although not significant [columns (3) and (6)]. The estimates of the $AR(1)$ coefficient ϕ for transitory shocks are mostly positive and significant, suggesting the presence of serially correlated transitory shocks.

The most important finding is the significant negative coefficient on the interaction between the *ex ante* elasticity of substitution γ_i and the volatility term σ_t throughout all columns. This result suggests, consistent with the putty-clay investment model, that exchange rate volatility has a larger negative effect on investment among plants with a higher *ex ante* elasticity of substitution. The following example provides a sense of the magnitude of this negative effect. Chile experienced high volatility in its real exchange rates in 1982 and 1985. What would have happened to the average investment rates in 1982 and 1985 if the *ex ante* elasticity of substitution measured by γ_i were zero (i.e., no irreversibility in factor intensity choices) for all plants? Using the point estimate of column (3) (i.e., $\hat{\beta}_{\gamma,\sigma} = 0.793$), dropping the average *ex ante* elasticity of substitution measured by γ_i from the actual sample average of 1.12 to 0 would have increased the average investment rates in 1982 and 1985 by 4.53 ($0.051 \times 0.793 \times 1.12$) percent and 6.66 ($0.075 \times 0.793 \times 1.12$) percent, respectively. These numbers suggest the quantitative importance of the interaction between exchange rate volatility and the irreversibility of factor intensity choice in determining investment dynamics.

On the other hand, the results are not consistent with a negative volatility effect from demand and input price level uncertainty. The estimated coefficients of interaction between the volatility

Table 3: Estimates of Investment Equation (22)

	Dependent Variable					
	I^A			I^B		
	(1)	(2)	(3)	(4)	(5)	(6)
$\gamma_i \sigma_t$	-1.093**	-0.743**	-0.793**	-0.833**	-0.322**	-0.554**
	(0.474)	(0.261)	(0.257)	(0.246)	(0.152)	(0.149)
$E_i \sigma_t$	0.378	0.599	0.595	0.022	0.128	0.089
	(0.567)	(0.527)	(0.536)	(0.254)	(0.258)	(0.254)
$M_i \sigma_t$	0.496	0.197	0.036	0.114	-0.016	0.057
	(0.736)	(0.777)	(0.754)	(0.425)	(0.488)	(0.479)
$X_i \sigma_t$	3.303**	3.089**	3.505**	1.724**	0.678	1.839**
	(1.100)	(1.109)	(1.114)	(0.606)	(0.662)	(0.656)
$\gamma_i \ln p_t$	-0.167	0.073	0.062	0.117	0.038	0.006
	(0.178)	(0.067)	(0.068)	(0.090)	(0.039)	(0.039)
$E_i \ln p_t$	0.051	0.096	0.062	0.067	0.024	0.012
	(0.140)	(0.131)	(0.133)	(0.075)	(0.064)	(0.065)
$M_i \ln p_t$	0.368**	0.346**	0.340*	0.131	0.170*	0.169
	(0.186)	(0.168)	(0.191)	(0.107)	(0.101)	(0.114)
$X_i \ln p_t$	0.001	-0.551**	-0.486*	-0.323**	-0.292**	-0.106
	(0.312)	(0.265)	(0.279)	(0.157)	(0.137)	(0.144)
$\ln k_{i,t-1}$		-0.0125	-0.0449		-0.0315	-0.0453*
		(0.0499)	(0.0468)		(0.0284)	(0.0263)
$(\ln x^*_{i,t} - \ln x_{i,t-1})^2$		0.0146	0.0232*		0.0022	0.0046
		(0.0138)	(0.0140)		(0.0040)	(0.0038)
$C_{it}/K_{i,t-1}$			0.0096			0.0015
			(0.0177)			(0.0100)
ϕ	0.342**	0.269**	0.239**	-0.002	0.270**	0.240**
	(0.133)	(0.095)	(0.091)	(0.145)	(0.084)	(0.082)
Sargan-Hansen	0.407	0.037	0.128	0.698	0.193	0.310

Notes: I^A = a discrete investment variable equal to one if the gross investment rate is greater than 0.2 and equal to zero, otherwise. I^B = the gross investment rate. Year dummies and industry variables $(\gamma_i, E_i, M_i, X_i)$ are included in all specifications. Heteroscedasticity-consistent standard errors are in parentheses. The superscripts ** and * indicate that the estimate is significantly different from zero at the 5% and 10% levels, respectively. The instruments used in the differenced equations for columns (1) and (4) are $(\gamma_i, E_i, M_i, X_i)$ and $I_{i,t-s}$ for $s = 2, 3, ..., t-1$. The instruments $\ln k_{i,t-1-s}$ and $(\ln x^*_{i,t-s} - \ln x_{i,t-s-1})^2$ for $s = 2, 3, ..., t-1$ are added for columns (2)-(3) and (5)-(6); the further additional instruments $C_{i,t-s}/K_{i,t-1-s}$ for $s = 2, 3, ..., t-1$ are used for columns (3) and (6). The instrument used in level equations is $\Delta I_{i,t-2}$ for columns (1) and (4); the instruments $\Delta \ln k_{i,t-3}$ and $\Delta(\ln x^*_{i,t-2} - \ln x_{i,t-3})^2$ are added for columns (2)-(3) and (5)-(6); and the further additional instrument $\Delta C_{i,t-2}/K_{i,t-3}$ is used for columns (3) and (6). Instrument validity for both difference and level equations is tested using a Sargan-Hansen test of the over-identifying restrictions for the two step GMM estimator and the P-values are reported.

term σ_t and trade orientation variables E_i and M_i, or the share of imported materials X_i, are mostly *positive*. In particular, the significant positive signs on the coefficients of interaction between the volatility term and the share of imported materials suggest that exchange rate volatility has a larger *positive* effect on investment among those belonging to a sector with a high share of imported materials. This result is more consistent with the investment models with convex returns of Hartman (1972,1976) and Abel (1983b) than irreversible investment models.

The results on the differential impacts of a exchange rate depreciation across industry-characteristics (i.e., E_i, M_i, and X_i) are largely as expected. The positive and significant coefficients on $M_i \ln p_t$ suggest that a depreciation induces a positive demand effect for import-competing sectors. The estimated coefficients on $E_i \ln p_t$ are positive, small in magnitude and not statistically significant, providing rather weak evidence of a positive demand effect from a depreciation for export-oriented sectors. Finally, the negative and significant coefficients on $X_i \ln p_t$ indicate that a depreciation has a negative impact on investment in the sectors that use imported materials intensively.

The coefficient on the capital-output ratio is negative throughout columns (2)-(3) and (5)-(6). To the extent that the high value of the capital-output ratio captures the low value of technology position s_{it}, the result is largely consistent with the model's prediction although a lack of robustness in terms of statistical significance makes the evidence weak.

Another interesting finding is the positive coefficient on $(\ln x^*_{i,t} - \ln x_{i,t-1})^2$ for all columns (2)-(3) and (5)-(6). The positive sign pattern suggests that the possible adoption of the *appropriate* factor intensity provides an extra incentive to invest. To examine its magnitude, consider the following hypothetical question: What would have happened to the average investment rate if all plants had possessed the *appropriate* factor intensity? The sample average of $(\ln x^*_{i,t} - \ln x_{i,t-1})^2$ is 1.342. Using the point estimate of column (3), decreasing the average distance of $(\ln x^*_{i,t} - \ln x_{i,t-1})^2$ from 1.342 to 0 would have decreased the average investment rate by more than 3 percent $(1.342 \times 0.0232 = 0.0311)$.[21] Although such a number should be cautiously interpreted

[21] As discussed in the Appendix, my construction of the *appropriate* factor intensity depends on whether I use I^A or I^B. Here 1.342 is the sample average of $(\ln x^*_{i,t} - \ln x_{i,t-1})^2$ that is computed using I^A. Alternatively, the sample average of $(\ln x^*_{i,t} - \ln x_{i,t-1})^2$ that is computed using I^B is 4.148. Then, according to the point estimate of column (6), decreasing the average distance of $(\ln x^*_{i,t} - \ln x_{i,t-1})^2$ from 4.148 to 0 would decrease the average investment rate by 1.91 (4.148×0.0046) percent.

given the relatively large standard errors, it suggests that the distance between the *appropriate* and the actual factor intensity might be quantitatively important in explaining investment.

4 Conclusion

The machine replacement model with the putty-clay technology developed in this paper provides a theoretical framework to analyze how uncertainty in relative factor prices delays technology adoption. Due to the *ex post* fixity in the choice of factor intensity, a plant confronting relative factor price uncertainty delays technology adoption.

The empirical analysis supports the main implications of the putty-clay investment model. First, I find that the elasticity of substitution between imported materials and domestic materials is substantially higher at the time of lumpy investment; thus, a choice of factor intensity is closely related to the type of machine a plant is using. This finding presents evidence against the view—which is implicitly adopted in many irreversible investment models—that *ex ante* and *ex post* production possibilities are identical. Second, the results indicate that this irreversibility of factor intensity choice plays a potentially important role in determining investment dynamics when exchange rates are volatile. Specifically, the negative volatility effect on investment is found to be larger among plants with a higher *ex ante* elasticity of substitution between imported and domestic materials. These findings highlight the importance of the irreversibility of factor intensity choice in understanding the response of investment to exchange rate volatility.

There are caveats. In my empirical study, I have used the linear specification for the investment variable. From a theoretical viewpoint, the relationship between the investment variable and the regressors must be nonlinear. Thus, we should be careful about interpreting the regression results since the investment equation is subject to mis-specification. Furthermore, my approach does not provide an explicit link between the estimates and the underlying structural parameters of the model. Estimating the structural parameters from the plant-level panel data (c.f., Rust, 1987) is an important topic for future research. This seems especially important in quantitatively evaluating the role of expectations (e.g., temporary vs. permanent changes) in determining investment and factor demands.

While the effects of real exchange rate volatility are examined in this paper, the model provides insights into the effects of uncertainty induced by policy reforms. Many policy reforms induce a change in *relative* factor prices (e.g., a change in tax structure, trade policy, and energy policy). Further, at the outset of reform, there often exists uncertainty as to the timing and the magnitude of the new policy reform. This model should prove useful in analyzing the role of credibility and uncertainty in a variety of major policy reforms.

A Appendix

A.1 Proof of Proposition 2.1

By using the standard argument found in Stokey and Lucas with Prescott (1989), one may prove that there exists an unique solution to the functional equation (6)-(7) and that the unique solution is a function that is bounded, continuous, and strictly increasing in s. Then, while $\pi(s)+\beta v(s-\delta)$ is strictly increasing in s, $\pi(0)-\kappa+\beta v(-\delta)$ is constant in s. Thus, there exists a unique s^* implicitly defined by $\pi(s^*)+\beta v(s^*-\delta) = \pi(0)-\kappa+\beta v(-\delta)$ such that if $s > s^*$ then $\pi(s)+\beta v(s-\delta) > \pi(0)-\kappa+\beta v(-\delta)$ and if $s < s^*$ then $\pi(s)+\beta v(s-\delta) < \pi(0)-\kappa+\beta v(-\delta)$. Therefore, the plant will adopt the frontier technology whenever its technology position is no more than s^*. ∎

A.2 Proof of Proposition 2.2

Let $C(\mathbf{X}\times\mathbf{K})$ be the space of bounded and continuous functions which are non-decreasing in the first argument and non-increasing in the second argument with support $\mathbf{X}\times\mathbf{K} \subset \mathbf{R}_{-}\times\mathbf{R}_{+}$. Define an operator T mapping $C(\mathbf{X}\times\mathbf{K})$ into itself by $(Tv)(s,\kappa) \equiv \max\{\pi(s)-\beta v(s-\delta,\kappa), \pi(0)-\kappa+\beta v(-\delta,\kappa)\}$. Then, by using the standard argument found in Stokey and Lucas with Prescott (1989), one may prove that an unique fixed point of $Tv = v$ exists and the unique fixed point $v(s,\kappa)$ is strictly decreasing in κ.

For each value of κ, the threshold value $s^*(\kappa)$ is characterized by $\pi(s^*(\kappa)) - \beta v(s^*(\kappa)-\delta,\kappa) = \pi(0)-\kappa+\beta v(-\delta,\kappa)$. Plug $v(s^*(\kappa)-\delta,\kappa) = \pi(0)-\kappa+\beta v(-\delta,\kappa)$, which is implied by Proposition 1 with $s^*-\delta < s^*$, into this equation, one obtains

$$\pi(s^*(\kappa)) = (1-\beta)[\pi(0)-\kappa+\beta v(0,\kappa)]. \tag{28}$$

Note that the right-hand side of equation (28) is strictly decreasing in κ and thus $\pi(s^*(\kappa))$ is strictly decreasing in κ. This implies that $s^*(\kappa)$ is strictly decreasing in κ.

To prove that s^* is strictly increasing in z and is strictly decreasing in τ, I first show that the value function is homogenous of degree one with respect to $(\kappa, z\tau^{1-\theta})$. By plugging $\mathbf{w} = \tau\mathbf{w}_0$ into the profit function (**??**), one obtains $\pi(s; z\tau^{1-\theta}) = z\theta^{-\theta}(\theta-1)^{\theta-1}c(\tau\mathbf{w}_0, x^*)^{1-\theta}exp((\theta-1)s) = (z\tau^{1-\theta})c_0 exp((\theta-1)s)$, where $c_0 \equiv \theta^{-\theta}(\theta-1)^{\theta-1}c(\mathbf{w}_0, x^*)^{1-\theta}$. This profit function $\pi(s; z\tau^{1-\theta})$ is homogenous of degree one with respect to $z\tau^{1-\theta}$. Consider the Bellman equation that corresponds to (6)-(7): $v(s;\kappa, z\tau^{1-\theta}) =$

$\max\{\pi(s; z\tau^{1-\theta}) + \beta v(s-\delta; \kappa, z\tau^{1-\theta}), \pi(0; z\tau^{1-\theta}) - \kappa + \beta v(-\delta; \kappa, z\tau^{1-\theta})\}$. The right-hand side of the Bellman equation defines an operator that maps the space of functions that are homogenous of degree one with respect to $(\kappa, z\tau^{1-\theta})$ into itself; the fixed point of the operator is homogenous of degree one with respect to $(\kappa, z\tau^{1-\theta})$. Hence, one may consider the following Bellman equation normalized in terms of the value $z\tau^{1-\theta}$:

$$\tilde{v}(s, \kappa/z\tau^{1-\theta}) = \max\{\tilde{\pi}(s) + \beta\tilde{v}(s-\delta, \kappa/z\tau^{1-\theta}), \tilde{\pi}(0) - \kappa/z\tau^{1-\theta} + \beta\tilde{v}(-\delta, \kappa/z\tau^{1-\theta})\}$$

where $\tilde{v}(s, \kappa/z\tau^{1-\theta}) \equiv v(s, \kappa, z\tau^{1-\theta})/z\tau^{1-\theta}$ and $\tilde{\pi}(s) \equiv \pi(s; z\tau^{1-\theta})/z\tau^{1-\theta} = c_0 e^s$. The threshold value s^* satisfies the equation corresponding to (28): $\tilde{\pi}(s^*) = (1-\beta)[\tilde{\pi}(0) - \kappa/z\tau^{1-\theta} + \beta\tilde{v}(0, \kappa/z\tau^{1-\theta})]$. One may show that $\tilde{v}(s, \kappa/z\tau^{1-\theta})$ is strictly decreasing in the second argument and hence the right-hand side of this equation is strictly increasing in z and strictly decreasing in τ when $\theta > 1$. This implies that s^* is strictly increasing in z and strictly decreasing in τ. ∎

A.3 Proof of Proposition 2.3

Suppose that $x \neq x^*(\omega^i)$. Note that $s^*(x, \mathbf{w}^i)$ is implicitly defined by the following equation corresponding to (28):

$$\pi(s^*(x, \mathbf{w}^i), x, \mathbf{w}^i) = (1-\beta)[\pi(0, x^*(\omega^i), \mathbf{w}^i) - \kappa + \beta v(-\delta, x^*(\omega^i), \mathbf{w}^i)].$$

Note that the right hand side does not depend on x. Together with the fact that $\pi(s, x, \mathbf{w}^i)$ is strictly increasing in s, strictly increasing in x if $x < x(\omega^i)$, and strictly decreasing in x if $x > x(\omega^i)$, this implies that $s^*(x, \mathbf{w}^i)$ is strictly decreasing in x if $x < x(\omega^i)$ and strictly increasing in x if $x > x(\omega^i)$.

A.4 Proof of Proposition 2.5

For the proof of Proposition 2.5, I first prove the following lemma.

Lemma A2.5

For each fixed x and $\mathbf{w}^i$, $v(s, x, \mathbf{w}^i)$ defined by the equations (8)-(9) is strictly increasing in s. For each fixed $s \in [0, 1]$ and $\mathbf{w}^i$, $v(s, x, \mathbf{w}^i)$ is strictly increasing in x if $x < x^*(\omega^i)$ and strictly decreasing in x if $x > x^*(\omega^i)$.

Proof of Lemma A2.5 The proof for the first statement is standard and therefore omitted. The second statement is proved analogously as follows. Define the operator T by

$$(Tv)(s, x, \mathbf{w}^i) = \max\{\pi(s, x, \mathbf{w}^i) + \beta v(s-\delta, x, \mathbf{w}^i), \pi(0, x, \mathbf{w}^i) - \kappa + \beta v(-\delta)\}$$

Let $C^*(\mathbf{X})$ be the space of functions on $\mathbf{X}$ which are: (i) bounded; (ii) continuous; and (iii) non-decreasing for $x < x^*(\omega^i)$ and non-increasing for $x > x^*(\omega^i)$. $C^*(\mathbf{X})$ equipped with the sup norm is a complete metric space. Then, T maps $C^*(\mathbf{X})$ into itself and satisfies Blackwell's conditions for a contraction mapping and, therefore, there exists a unique solution to the functional equation $Tv = v$ in $C^*(\mathbf{X})$. Further, let $C^{**}(\mathbf{X}) \subset C^*(\mathbf{X})$ be the space of functions with the following additional property: strictly increasing for $x < x^*(\omega^i)$ and strictly decreasing for $x > x^*(\omega^i)$. Since $\pi(s, x, \mathbf{w}^i)$ is strictly increasing for $x < x^*(\omega^i)$ and strictly decreasing for $x > x^*(\omega^i)$, $T[C^*(\mathbf{X})] \subset C^{**}(\mathbf{X})$. It follows that the unique solution is in $C^{**}(\mathbf{X})$ by Corollary 1 of Theorem 3.2 in Stokey and Lucas (1989, p.52). ∎

Proof of Proposition 2.5 It suffices to show that a plant with technology position $s^*(x^*(\bar{\omega}), \bar{\mathbf{w}})$ does not adopt technology at Time 0. For brevity, denote $\bar{s}^* \equiv s^*(x^*(\bar{\omega}), \bar{\mathbf{w}})$. Consider a plant with technology position $\bar{s}^*$ at the beginning of Time 0. In the following, it is shown that the plant's value when it does not adopt technology at Time 0 is larger than the value when the plant adopts technology at Time 0.

By *not adopting* technology at Time 0, the plant's value at Time 0 is

$$
\begin{aligned}
v_{0,n}(\bar{s}^*, x^*(\bar{\omega}), \bar{\mathbf{w}}) &= \pi(\bar{s}^*, x^*(\bar{\omega}), \bar{\mathbf{w}}) + \beta[\lambda v(\bar{s}^* - \delta, x^*(\bar{\omega}), \mathbf{w}^L) + (1-\lambda) v(\bar{s}^* - \delta, x^*(\bar{\omega}), \mathbf{w}^H)] \\
&= \pi(\bar{s}^*, x^*(\bar{\omega}), \bar{\mathbf{w}}) + \beta\lambda[\pi(0, x^*(\omega^L), \mathbf{w}^L) - \kappa + \beta v(-\delta, x^*(\omega^L), \mathbf{w}^L)] \\
&\quad + \beta(1-\lambda)[\pi(0, x^*(\omega^H), \mathbf{w}^H) - \kappa + \beta v(-\delta, x^*(\omega^H), \mathbf{w}^H)] \\
&= \pi(\bar{s}^*, x^*(\bar{\omega}), \bar{\mathbf{w}}) + \beta[\pi(0, x^*(\bar{\omega}), \bar{\mathbf{w}}) - \kappa + \beta v(-\delta, x^*(\bar{\omega}), \bar{\mathbf{w}})] \\
&= \pi(\bar{s}^*, x^*(\bar{\omega}), \bar{\mathbf{w}}) + \beta v(\bar{s}^* - \delta, x^*(\bar{\omega}), \bar{\mathbf{w}}) \\
&= \pi(0, x^*(\bar{\omega}), \bar{\mathbf{w}}) - \kappa + \beta v(-\delta, x^*(\bar{\omega}), \bar{\mathbf{w}})
\end{aligned}
$$

where the second equality uses the result of Corollary 2.4; the third equality follows from $v^*(0, x^*(\omega^L), \mathbf{w}^L) = v^*(0, x^*(\omega^H), \mathbf{w}^H) = v^*(0, x^*(\bar{\omega}), \bar{\mathbf{w}})$ owing to Assumption C; the fourth equality follows from $\bar{s}^* - \delta < \bar{s}^*$ and hence a plant updates its machine, implying that $v(\bar{s}^* - \delta, x^*(\bar{\omega}), \bar{\mathbf{w}}) = \pi(0, x^*(\bar{\omega}), \bar{\mathbf{w}}) - \kappa + \beta v(-\delta, x^*(\bar{\omega}), \bar{\mathbf{w}})$; the last equality uses the characterization of $\bar{s}^*$: $v^*(0, x^*(\bar{\omega}), \bar{\mathbf{w}}) - \kappa = v^*(\bar{s}^*, x^*(\bar{\omega}), \bar{\mathbf{w}})$ $\Rightarrow \pi(0, x^*(\bar{\omega}), \bar{\mathbf{w}}) - \kappa + \beta v(-\delta, x^*(\bar{\omega}), \bar{\mathbf{w}}) = \pi(\bar{s}^*, x^*(\bar{\omega}), \bar{\mathbf{w}}) + \beta v(\bar{s}^* - \delta, x^*(\bar{\omega}), \bar{\mathbf{w}})$.

By *adopting* technology at Time 0, the plant's value at Time 0 is

$$
v_{0,a}(\bar{s}^*, x^*(\bar{\omega}), \bar{\mathbf{w}}) = \max_{x' \in \mathbf{X}} \pi(0, x', \bar{\mathbf{w}}) - \kappa + \beta[\lambda v(-\delta, x', \mathbf{w}^L) + (1-\lambda) v(-\delta, x', \mathbf{w}^H)].
$$

In the following, it will be shown that $v_{0,n}(\bar{s}^*, x^*(\bar{\omega}), \bar{\mathbf{w}}) > v_{0,a}(\bar{s}^*, x^*(\bar{\omega}), \bar{\mathbf{w}})$. First, note that $\pi(0, x^*(\bar{\mathbf{w}}), \bar{\mathbf{w}}) \geq \pi(0, x', \bar{\mathbf{w}})$ for all $x' \in \mathbf{X}$ where the inequality is strict when $x' \neq x^*(\bar{\omega})$. Second, $v(-\delta, x^*(\bar{\omega}), \bar{\mathbf{w}}) > \lambda v(-\delta, x', \mathbf{w}^L) + (1-\lambda) v(-\delta, x', \mathbf{w}^H)$ for all $x' \in \mathbf{X}$ under the assumption that $\mathbf{w}^L \neq \mathbf{w}^H$ since $v^*(-\delta, x^*(\bar{\omega}), \bar{\mathbf{w}}) = v(-\delta, x^*(\omega^i), \mathbf{w}^i) > v^*(-\delta, x', \mathbf{w}^i)$ for $i = L, H$ if $x' \neq x^*(\omega^i)$, where the first equality follows from Assumption C and the second inequality follows from Lemma A2.5. This implies that $v^*_{0,n} - v^*_{0,a} > 0$. Hence, a plant with technology position $\bar{s}^*$ does not adopt technology at Time 0. It follows that $s^*_0 < \bar{s}^*$. ∎

A.5 Numerical Dynamic Programming

The value function iteration method with discrete approximation is used. The state space of s is naturally discretized as $[0, -\delta, -2\delta, \ldots]$. For relative prices, $\ln \omega$, I use a uniform grid consisting of equi-spaced points between $-M\sigma_\omega(H)$ and $M\sigma_\omega(H)$. By choosing $\Delta \ln \omega \equiv 2M\sigma_\omega(H)/(m-1)$, my discretization for $\ln \omega$ will be $\ln \omega(j) = -M\sigma_\omega(H) + (j-1)\Delta \ln \omega$ for $j = 1, 2, ..., m$. I set $M = 25$ and $m = 51$. I also experimented with $M = 50$ and $m = 101$ in some cases and found that results changed little. The grid for relative factor intensity choice measured in logarithm, $\ln x$, is generated from the grid for $\ln \omega$ using the formula for appropriate factor intensity with $\alpha = 0.5$, i.e., $\ln x^*(\omega) = -\gamma \ln \omega$; thus, it is a uniform grid consisting of equi-spaced points between $-M\gamma\sigma_\omega(H)$ and $M\gamma\sigma_\omega(H)$. The optimal waiting times reported in figures 5, 7, and 8 are optimal waiting times when the state is $(\ln x, \ln \omega) = (0, 0)$ so that a plant possesses the appropriate factor intensity corresponding to the relative factor prices that are equal to one. The transition probability of relative factor prices from the ith state $\ln \omega(i)$ to the jth state $\ln \omega(j)$ under Regime H, denoted by $q_H(i,j) = P[\ln \omega_t = \ln \omega(j) | \ln \omega_{t-1} = \ln \omega(i)]$, is approximated as: $q_H(i,j) = \frac{\phi([\ln \omega(j) - \ln \omega(i)]/\sigma_\omega(H))/\sigma_\omega(H)}{\sum_{j'=1}^{m} \phi([\ln \omega(j') - \ln \omega(i)]/\sigma_\omega(H))/\sigma_\omega(H)}$, where ϕ is the standard normal density function. The normalization insures that $q_H(i,j)$ is a well defined probability density. The Matlab program generating Figures 4-6 is available on request from the author.

A.6 Data and Variable Definitions

The data set is based on a census of Chilean manufacturing plants by Chile's Instituto Nacional de Estadistica (INE). The sample selection criteria is as follows. I focus my attention on the collection of plants present for all sample years. I exclude plants for which any of the data for investment, capital stocks, domestic materials, and imported materials are not available. In particular, plants that do not report book values of their capital stocks in any year are excluded since constructing capital stocks for these plants is impossible. I also exclude plants with strictly negative values of capital stocks or domestic materials, considering them as mis-coded or mis-reported. Finally, the plants that change their four-digit industry classifications within the sample period are omitted since I extensively use the explanatory variables based on plant's four-digit industry classification in the regression analysis. After cleaning the data, the balanced panel data set contains 2116 plants for the period of 1979-1986. Table A.1 reports descriptive statistics. In the following, I describe the variables used in the regressions.

Investment Variables (I_{it}^A and I_{it}^B): The continuous investment variable I^B is the gross investment rate defined as the real gross investment in capital goods in year t divided by the real capital stock at the end of year $t-1$. The discrete investment variable I^A is equal to one if the gross investment rate is greater than 20 percent and equal to zero otherwise. The measure of gross investment includes machinery and equipment and vehicles but excludes buildings. I also exclude the sales of used capital

Table A.1: Descriptive Statistics of the 2116 plants

Variable	Mean	S.E.	Min	Max	Variable	Mean	S.E.	Min	Max
I_{it}^A	0.17	0.37	0.00	1.00	$\ln k_{it}$	-2.13	1.16	-9.96	8.69
I_{it}^B	0.11	0.22	0.00	1.00	$\frac{C_{it}}{K_{i,t-1}}$	2.58	3.55	-1.24	13.36
$\ln x_{it}$	-3.50	1.59	-4.33	1.34	$\ln x_{it}^{*A}$	-2.89	1.38	-5.54	2.77
γ_i	1.12	0.66	0.00	2.65	$\ln x_{it}^{*B}$	-1.96	1.48	-5.82	4.23
E_i	0.08	0.23	0.00	5.39	$(\ln x_{it}^{*A} - \ln x_{i,t-1})^2$	1.11	2.10	0.00	33.67
M_i	0.12	0.16	0.00	0.98	$(\ln x_{it}^{*B} - \ln x_{i,t-1})^2$	3.49	3.56	0.00	54.18
X_i	0.16	0.14	0.00	0.62					

Notes: "S.E." indicates the standard errors. $\ln x_{it}^{*A}$ is the *appropriate factor intensity* that is constructed based on the discrete investment variable I^A. $\ln x_{it}^{*B}$ is the *appropriate factor intensity* that is constructed based on the discrete investment variable I^B.

from the measurement of gross investment given my focus on technology adoption through a *positive* investment. The capital stock at the end of year $t-1$, denoted by $K_{i,t}$, is constructed from the 1980 book value of capital (the 1981 book value if the 1980 book value is not available) using the perpetual inventory method.[22]

Ratio of Imported Materials to Domestic Materials ($\ln x_{it}$): The logarithm of the factor intensity of imported materials relative to domestic materials. The data set provides the nominal purchase values of imported materials as well as those of total materials. The nominal values of domestically produced materials is constructed by subtracting the purchase values of imported materials from those of total materials. They are put in constant 1980 prices by deflating all nominal magnitudes by their respective price deflators.[23] There are a large number of plant-time observations that report zero purchases of imported materials. This is problematic since the logarithm of factor intensity becomes negative infinity for observations with zero imported materials. One way to proceed is to exclude those observations with zero purchases of imported materials. There are at least two problems with this approach. First, to the extent that plants endogenously choose zero imported materials given relative factor prices, such a procedure may lead to serious selection biases. Second, a substantial portion of plants—699 plants out of 969 plants that use imported materials within the sample period—switched from non-users of imported materials to users of imported materials, or vice-versa, at least once within the sample period. Hence, much of the information used to identify the effect of investment on factor intensity adjustment would

[22]Since the reported book values are evaluated at the end of year t, the book values of capital are deflated by the (geometric) average deflator of machinery and equipment for years t and t+1. Depreciation rates are set to 10 % for machinery and equipment and 20% for vehicles.

[23]For domestic materials, intermediate material input price deflators at the three-digit industry level are used. For imported materials, the import price deflator (in pesos) obtained from the International Financial Statistics is used.

be lost by excluding those observations with zero purchases of imported materials. For these reasons, I use the following alternative procedure. Let q_α be the sample α percentile of $\ln x_{it}$ among plant-time observations that have strictly positive purchases of imported materials. I set $q_\alpha \leq \ln x_{it} \leq q_{1-\alpha}$ by replacing the observations with extreme low values with q_α and those with extreme high values with $q_{1-\alpha}$. In practice, I use $\alpha = 0.05$. When the alternative values of $\alpha = 0.01$ or 0.10 are used, the results, which are available on request from the author, are similar to those reported in Tables 2 and 3.

Proxy for the Ex-ante Elasticity of Substitution (γ_i): The standard errors of $\ln x_{it}$, plant-level factor intensity measured in logarithms, within the four-digit industry level. To compute this measure, I first split the balanced panel sample according to the four-digit industry classification. Then, for each industry, the standard errors of $\ln x_{it}$ defined in the previous paragraph are computed to obtain the industry-specific measure of the standard errors of plant-level factor intensity.

Export-Output Ratio (E_i): The ratio of aggregate exports to aggregate domestic output at the four-digit industry level over the period of 1979-1986, obtained from Pavcnik (2002).

Import-Penetration Rate (M_i): The ratio of aggregate imports to the sum of aggregate imports and aggregate domestic output at the four-digit industry level over the period of 1979-1986, obtained from Pavcnik (2002).

Imported Material Ratio (X_i): The ratio of aggregate imported materials to aggregate total materials at the four-digit industry level over the period of 1979-1986; aggregate imported materials and aggregate total materials are computed for each four-digit industry by summing up plant-level imported materials and total materials over plant-time observations that belong to the industry using a full sample of the original data set. *Relative Factor Prices or Real Exchange Rate Level* (p_t): The average of the monthly real effective exchange rates over the 12 months in year t, obtained from the International Financial Statistics. An increase implies a depreciation.

Real Exchange Rate Volatility (σ_t): The standard errors of the first differences in the logarithm of the monthly real effective exchange rate over the 12 months in year t.

Capital-Output Ratio ($\ln k_{it-1}$): The logarithm of the capital-output ratio, $\ln k_{i,t-1} = \ln \frac{K_{i,t-1}}{Y_{i,t-1}}$, where K_{it-1} is the capital stock at the end of year $t-1$ and Y_{it-1} is the total sales in 1980 price in year $t-1$.

Cash Flow ($C_{it}/K_{i,t-1}$): The ratio of the net operating profit, denoted by C_{it}, to the capital stock at the end of the previous period. C_{it} is constructed using the data: sales, wage, and materials. Specifically, the nominal values of C_{it} are computed according to the formula C_{it} = [Sales] - [Total Wage Payments] - [Purchase Values of Total Materials]; then, they are put in constant 1980 prices using the three-digit industry output deflators. I trim the variable using the sample 5th percentile and the sample 95th percentile of $C_{it}/K_{i,t-1}$, which are equal to -1.24 and 13.36, respectively; that is, values below -1.24 are set to -1.24 and values above 13.36 are set equal to 13.36.

Appropriate Factor Intensity ($\ln x^*_{it}$): I construct the *appropriate* factor intensity, $\ln x^*_{it}$, as $\hat{\alpha}_0 +$

Table A.2: Estimates of Random Effects Probit Model (29)

$\gamma_i \sigma_t$	-5.685*	-4.649*
	(3.105)	(2.564)
$E_i \sigma_t$	1.145	0.898
	(4.439)	(4.503)
$M_i \sigma_t$	-3.772	-2.636
	(7.593)	(7.585)
$X_i \sigma_t$	29.10**	28.45**
	(11.72)	(11.32)
$\gamma_i \ln p_t$	0.667**	0.554**
	(0.287)	(0.237)
$E_i \ln p_t$	-0.067	-0.070
	(0.333)	(0.327)
$M_i \ln p_t$	2.315**	2.200**
	(0.705)	(0.711)
$X_i \ln p_t$	-2.902**	-2.738**
	(1.059)	(1.024)
$\ln k_{i,t-1}$	-0.474**	-0.379**
	(0.023)	(0.028)
$(\ln x^*_{i,t} - \ln x_{i,t-1})^2$	-0.050**	-0.027**
	(0.014)	(0.010)
$\frac{C_{it}}{K_{i,t-1}}$		0.049**
		(0.008)
$\frac{\sigma_v}{\sigma_\mu}$	1.548**	1.548**
	(0.065)	(0.066)

Notes: Year dummies and industry variables $(\gamma_i, E_i, M_i, X_i)$ are included in all specifications. The superscripts ** and * indicate that the estimate is significantly different from zero at the 5% and 10% levels respectively.

$(\hat{\varphi}_0 + \hat{\varphi}_1) \ln p_t + \hat{\xi}_t + \hat{\alpha}_3\gamma_i + \hat{\tilde{\eta}}_i$, where $(\hat{\alpha}_0, \hat{\varphi}_0, \hat{\varphi}_1, \hat{\alpha}_3, \hat{\xi}_t, \hat{\tilde{\eta}}_i)$ is the estimate of the parameter vector $(\alpha_0, \varphi_0, \varphi_1, \alpha_3, \xi_t, \tilde{\eta}_i)$ of equation (16). The estimate of $(\hat{\alpha}_0, \hat{\varphi}_0, \hat{\varphi}_1, \hat{\alpha}_3)$ is obtained by the procedure discussed in the main text and depends on which investment variable (i.e., I^A or I^B) is used. The estimates $(\xi_t, \tilde{\eta}_i)$ for $i = 1, ..., N$ and $t = 1, ..., T$ are obtained as follows. First, define a residual $\hat{\varepsilon}_{it} = lnx_{it} - \hat{\alpha}_0 I_{it} - (\hat{\varphi}_0 + \hat{\varphi}_1 I_{it}) \ln p_t - \hat{\alpha}_3\gamma_i$, where $I_{it} = I^A_{it}$ or I^B_{it}. Then, the estimate of the time-specific component is computed as $\hat{\xi}_t = \sum_{i=1}^N \hat{\varepsilon}_{it}/N$. Finally, the estimate of the plant-specific component is computed as $\hat{\tilde{\eta}}_i = \sum_{t=1}^T (\hat{\varepsilon}_{it} - \hat{\xi}_t)/T$. I use the *appropriate factor intensity* that is constructed based on the discrete investment variable I^A for estimating the columns (1)-(3) of Table 3, while the *appropriate factor intensity* that is constructed based on the continuous investment variable I^B is used for estimating the columns (4)-(6) of Table 3.

A.7 Additional Estimates: Random Effects Probit Model

In this appendix, I present the additional estimates from the following random effects probit model for investment:

$$\begin{aligned} I_{it} &= 1(I^*_{it} > 0) \qquad (29) \\ I^*_{it} &= \beta_{\sigma,i}\sigma_t + \beta_{p,i} \ln p_t + \beta_k k_{i,t-1} + \beta_{\Delta x}(\ln x^*_{it} - \ln x_{i,t-1})^2 + \beta_c \frac{C_{it}}{K_{i,t-1}} + \mu_i + \zeta_t + v_{it}, \end{aligned}$$

where, as before, $\beta_{\sigma,i} = \beta_{\sigma,\gamma}\gamma_i + \beta_{\sigma,e}E_i + \beta_{\sigma,m}M_i + \beta_{\sigma,x}X_i$, $\beta_{p,i} = \beta_{p,\gamma}\gamma_i + \beta_{p,e}E_i + \beta_{p,m}M_i + \beta_{p,x}X_i$, and $\mu_i = \beta_\gamma\gamma_i + \beta_e E_i + \beta_m M_i + \beta_x X_i + \tilde{\mu}_i$. Assume that $\tilde{\mu}_i$ is distributed, conditional on regressors, as $N(0, \sigma^2_\mu)$. v_{it} is orthogonal to $\tilde{\mu}_i$ and distributed as $N(0, \sigma^2_v)$. For identification, assume that $\sigma_\mu = 1$. I estimate (29) by maximum likelihood, where the integral with respect to $\tilde{\mu}_i$ is numerically evaluated by using Gaussian quadrature technique with 10 nodes. The standard errors are computed using the outer-products of gradients estimator. The validity of this random effects probit specification requires, in addition to the distributional assumption on unobserved heterogeneity, that all regressors are strictly exogenous. However, $k_{i,t-1}$ and $(\ln x^*_{it} - \ln x_{i,t-1})^2$ are predetermined endogenous regressors and are likely to be correlated with $\tilde{\mu}_i$. For this reason, the results for the random effects probit model should be interpreted with caution. Table A.2 contains the results. The sign conditions are largely similar to those of the linear probability model presented in columns (2)-(3) of Table 3. In particular,I reconfirm one of the main empirical results in this paper: the coefficient on the interaction between the *ex ante* elasticity of substitution γ_i and the volatility term σ_t is negative and significant. One important exception to the similarity between the linear probability model and the probit model is the significant negative coefficient on $(\ln x^*_{i,t} - \ln x_{i,t-1})^2$. This contradictory result might be due to the treatment of $(\ln x^*_{it} - \ln x_{i,t-1})^2$ as a strictly exogenous variable in my probit specification where in fact it is a predetermined endogenous variable.

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