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ENTRY, EXIT, EMBODIED TECHNOLOGY, AND BUSINESS CYCLES

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ABSTRACT

This paper studies the entry and exit of U.S. manufacturing plants over the business cycle and compares the results with those from a vintage capital model augmented to reproduce observed features of the plant life cycle. Looking at the entry and exit of plants provides new evidence supporting the hypothesis that shocks to embodied technological change are a significant source of economic fluctuations. In the U.S. economy, the entry rate covaries positively with output and total factor productivity growth, and the exit rate leads all three of these. A vintage capital model in which all technological progress is embodied in new plants reproduces these patterns. In the model economy, a persistent improvement to embodied technology induces obsolete plants to cease production, causing exit to rise. Later, as entering plants embodying the new technology become operational, both output and productivity increase.

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1. Introduction

This paper studies the entry and exit of U.S. manufacturing plants over the business cycle and compares the results with those from a vintage capital model augmented with plant level productivity uncertainty. Looking at the entry and exit of plants provides new evidence supporting the hypothesis that shocks to embodied technological change are a significant source of economic fluctuations. In the U.S. economy, the entry rate covaries positively with output and total factor productivity growth, and the exit rate leads all three of these. A vintage capital model in which all technological progress is embodied in new plants reproduces these patterns. In the model economy, a persistent improvement to embodied technology induces obsolete plants to cease production, causing exit to rise. Later, as entering plants embodying the new technology become operational, both output and productivity increase.

In most vintage capital frameworks, changes machine retirement and replacement decisions play critical roles in generating business cycles. Except in specific cases, such as that studied by Cooper and Haltiwanger(1993), individual machine retirement and replacement is difficult to observe. However, the entry and exit of individual plants is somewhat easier to observe. Using the Longitudinal Research Database, Davis, Haltiwanger, and Schuh(1996) produced quarterly employment weighted entry and exit rates for the U.S. manufacturing sector for a period of 16 years. Because much technological change is embodied in plants as well as machines, examining this data is a natural first step towards understanding patterns of machine retirement and replacement over the business cycle.[2] The next section of this paper presents such an examination. The entry and exit rates both

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[2] For an example technical change embodied in plants, see the description of the titanium dioxide industry in Dobson, Shepherd, and Stoner (1994)

exhibit considerable fluctuations over the sample period, and their fluctuations have noticeable relationships with each other and the business cycle. Peaks in the exit rate tend to lead peaks in the entry rate by about 5 quarters. As might be expected, entry is procyclical and exit is countercyclical. Entry is positively correlated with current productivity growth and exit is positively correlated with future productivity growth.

To determine whether the observed fluctuations in entry and exit could be caused by shocks to the rate of embodied technological progress, the remainder of this paper studies a general equilibrium model of growth, entry, and exit in which all technological progress is embodied in new plants. The studies of Oley and Pakes(1996) and Bartelsman and Dhrymes(1993), which find that average productivity growth at existing plants is trivial, justify this assumption. As in the models of Greenwood, Hercowitz, and Huffman(1988) and Greenwood, Hercowitz, and Krusell(1997), the sole source of aggregate uncertainty is the price of capital goods relative to consumption goods. Because capital goods in this model are identified with plants, features of plant level data sets, most notably idiosyncratic productivity uncertainty, are added to a vintage capital model. The model augments King, Plosser, and Rebelo's(1988) general equilibrium business cycle framework with a selection model of entry and exit resembling Hopenhayn's(1992)

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The inclusion of idiosyncratic uncertainty significantly influences both microeconomic decisions and macroeconomic outcomes. As in the investment models of Pindyck(1988) and Abel and Eberly(1994), irreversibility of exit and ongoing productivity uncertainty induce agents to rationally delay plant exit. An extremely unproductive plant is kept in operation in the hope that a favorable idiosyncratic productivity shock will improve its value. The responses of such plants to technology shocks determine the aggregate exit rate's fluctuations. As embodied technology continually improves, it becomes less likely that an older plant will receive a technology shock favorable enough to justify its long run operation. A positive innovation to embodied technology hastens this obsolescence process and induces marginal plants to exit. The increase in the aggregate exit rate is followed by increases in entry, productivity, and output as new plants embodying the innovation become productive. Thus, the model economy reproduces the cyclical features of the entry and exit data: Exit is countercyclical and leads output and productivity growth, which both accompany entry.

The remainder of the paper proceeds as follows: The next section presents the empirical study of entry and exit. Section 3 presents the model economy, and Section 4 characterizes the competitive equilibrium for a parameterized version of the model and compares the model economy's characteristics to those of the U.S. data. Section 5 offers concluding remarks.

2. Entry, Exit, and Business Cycles

This section documents the cyclical properties of the plant entry and exit rates, showing that the plant entry rate covaries positively with output and total factor productivity growth and that the exit rate is countercyclical and leads all three of these series. These conclusions are based on an examination of the correlations of the entry and exit rates with each other and with current, future, and past output and total factor productivity growth. To correctly interpret the empirical results, it is essential to understand how the data on entry and exit were constructed. Accordingly, this section begins with a description of the data construction procedure.

2.1 Data Construction

To produce the Annual Survey of Manufacturers, the U.S. Department of Census compiles a plant level data set covering the population of large plants and a probability sample of small plants in the manufacturing sector.[3] With quarterly employment observations from the ASM panel data set, Davis, Haltiwanger, and Schuh(1996) compiled aggregate time series for job creation and destruction, total employment expansion at growing plants and total employment contraction at shrinking plants. Dividing these measurements by total manufacturing employment yields job creation and destruction rates.

Davis, Haltiwanger, and Schuh(1996) consider two types of job creation, that which occurs at plants which were previously active, and that which occurs at entering plants. Similarly, they divide job destruction into that at plants which remain in production and that at plants which close down. The job creation rate at entering plants, employment at all entering plants divided by total employment, forms an employment weighted entry rate. The job destruction rate at exiting plants, in a like fashion, forms an employment weighted exit rate.

Two features of the data collection process influence its interpretation. First, the definitions of quarters are not standard. Each year, each respondent plant in the ASM panel reports its employment in the previous four quarters, but the year's first quarter begins on November 15 of the *previous* year. Furthermore, the quarters are not all of equal length. Davis, Haltiwanger, and Schuh(1996) correct their reported time series to make their quarters of comparable length, but can not account for the non-standard quarterly timing. This implies that,

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[3] **Dunne(1992) provides details of the linking process for the ASM panel.**

when looking for a contemporaneous relationship between either the entry or exit rate and a conventionally measured macroeconomic aggregate, it is important to examine both their contemporaneous correlation and the correlation of the rate with the aggregate lagged one quarter.

The second important feature regards the measurement of entry itself. To account for attrition from the ASM panel, the Department of Census collects observations of plant start-ups from the Company Organization Survey and the Social Security Administration. It seems likely that these sources would tend to identify plant start-ups after, rather than before, their actual births. In this case, it is best to view the measured entry rate as a linear combination of the current and past true entry rates. The implications of this for empirical work are the same as those of the series' quarterly timing: To find evidence of a contemporaneous relationship between entry and another variable, it is important to look at both the contemporaneous correlation and its correlations with that variable in the past.[4]

2.2 The Cyclicality of Entry and Exit

To gauge the cyclicality of entry and exit using the quarterly series, figure 1 plots them and table 1 reports their summary statistics.[5] A standard error, estimated using Newey and West's(1987) procedure, appears below each estimated moment in parentheses.[6] The observations begin in the second quarter of 1972 and end in the last quarter of 1988.

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[4] For further details concerning the construction of the entry and exit data, see Davis, Haltiwanger, and Schuh(1996).

[5] The original series of Davis, Haltiwanger, and Schuh were seasonally adjusted by removing quarterly means to produce the series used in this paper. The first moments of the adjusted and unadjusted series are identical by construction.

[6] Eight sample autocovariances were used to calculate all of the standard errors reported in this paper.

Variable	Mean	Std. Dev.
Entry Rate	0.62% (0.04%)	0.23% (0.04%)
Exit Rate	0.83% (0.06%)	0.26% (0.04%)

Table 1: Summary Statistics

The quarterly entry and exit rates reflect the constant restructuring of the U.S. manufacturing sector. Their sample averages, 0.62% and 0.83%, are high. Furthermore, they are quite volatile. Their standard deviations are 0.23% and 0.26%. The cyclical behavior of entry and exit is evident in the data plot. Exit rises during recessions, and entry follows it, increasing during the subsequent recovery. This pattern fits the recession of 1974-75 and those occurring from 1980 to 1982. In spite of these cyclical variations, it is clear that not all of the series' fluctuations can be attributed to any particular recession. This is particularly true for entry's rise during 1978 and exit's during the mid 1980's.

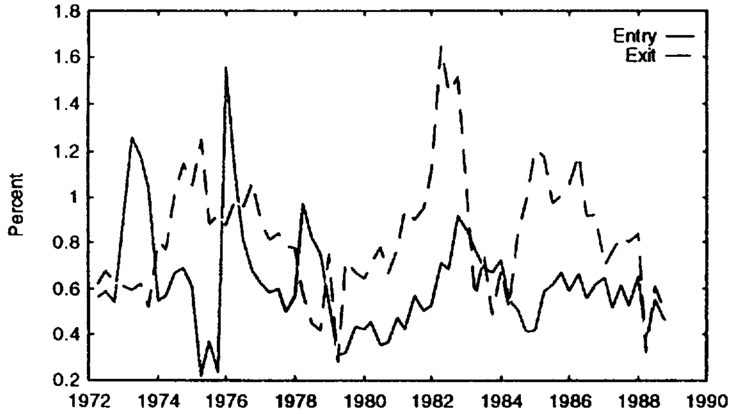

Figure 1: Employment Weighted Entry and Exit Rates

To verify the conjectures regarding the entry and exit rates' cyclicality, figures 2 and 3 plot the correlations of entry and exit with the past, current, and future per-capita growth rates of non-farm, non-government gross domestic product, GDP. Figure 4 plots the correlations of exit with future and past entry. The figures also present asymptotic 95% confidence intervals for each point on the graph. They were produced with the same procedure used to construct the standard errors in table 1.

The entry rate's dynamic correlations confirm its procyclical nature. Although its contemporaneous correlation with GDP growth is small and insignificant, its correlation with GDP growth one period ago is larger, 0.28, and statistically significant. Although neither of entry's correlations with GDP growth two or three quarters ago are statistically significant, their point estimates are large, 0.25 and 0.26. The exit rate's dynamic correlations also reflect the cyclical pattern found in the data plot. The exit rate is countercyclical, and its correlations with future GDP growth are positive, large, and statistically significant. The correlation between the exit rate and GDP growth four quarters hence is 0.51. This positive relationship is persistent: the sample correlation is still large and significant eight quarters into the future. Finally, the exit rate has no significant correlation with the current or past entry rates, but it is positively correlated with the entry rate five to seven quarters in the future. These three correlations are 0.30, 0.30, and 0.21. All three of these correlations are individually statistically significant.

If cyclical fluctuations in entry and exit are caused by shocks to the rate of embodied technological progress, then it is possible that these series will exhibit significant correlation with the growth of measured total factor productivity, TFP. Figures 5 and 6 plot the dynamic correlations of the entry and exit rates with total

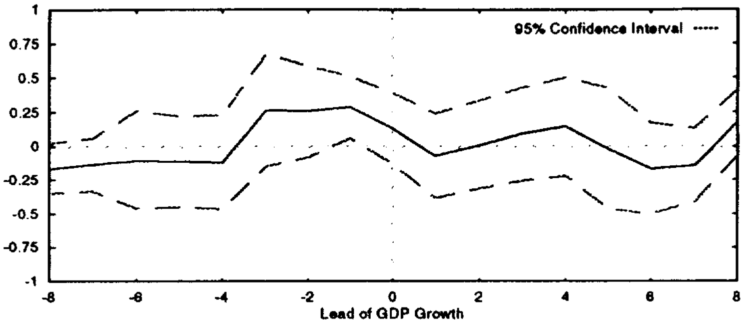

Figure 2: Dynamic Correlations of Entry Rate with ΔGDP

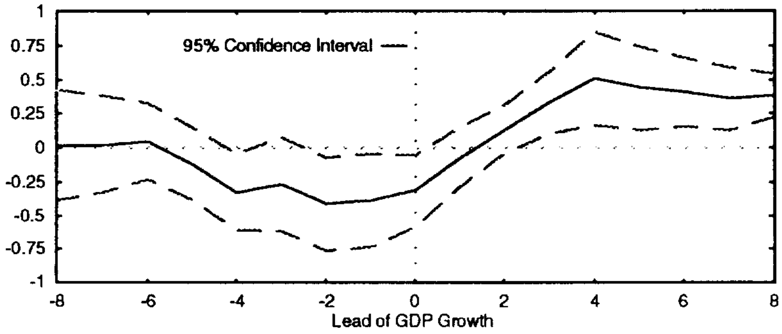

Figure 3: Dynamic Correlations of Exit Rate with ΔGDP

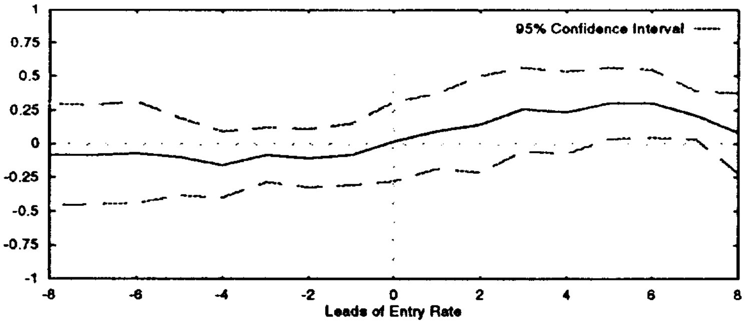

Figure 4: Dynamic Correlations of Exit Rate with Entry Rate

factor productivity growth, which is conventionally measured using the definition

$$z_t \equiv y_t - \alpha n_t - (1-\alpha)k_t.$$

The growth rates of per-capita non-farm, non-government gross domestic product, hours worked, and the capital stock are y_t, n_t, and k_t. The elasticity of output with respect to labor input, α, is estimated with labor's average share of output, as in Solow(1957).[7] These correlations are strikingly similar to the analogous correlations with GDP growth. First, the dynamic correlations indicate that entry covaries positively with contemporaneous TFP growth. Although the contemporaneous correlation is small, 0.08, and statistically insignificant, the correlation with TFP growth one quarter ago is larger, 0.20, and statistically significant. Although the correlations two and three quarters in the past are statistically insignificant, their point estimates are large, 0.18 and 0.34. Second, the exit rate covaries positively with future productivity growth. Its correlations with TFP growth three, four, and five quarters hence are 0.38, 0.45, and 0.32. These point estimates are all statistically significant. Whereas exit covaries negatively with contemporaneous GDP growth, it does not covary at all with contemporaneous TFP growth.

The above empirical results reveal significant relationships of entry and exit with output and productivity growth. The remainder of this paper carries the investigation further by constructing and analyzing a vintage capital model in which fluctuations in entry, exit, output, and productivity reflect shocks to the pace of embodied technological progress.

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[7] To account for the presence of measurement error in hours worked, the variance of TFP growth is estimated using the covariance of two separate measures. The first uses hours data based on the survey of establishment payrolls, and the second uses hours data based on the survey of households. All covariances of TFP with another series are measured using the establishment hours data.

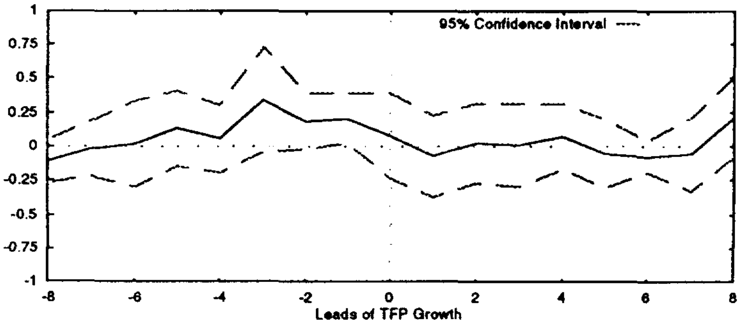

Figure 5: Dynamic Correlations of Entry Rate with ΔTFP

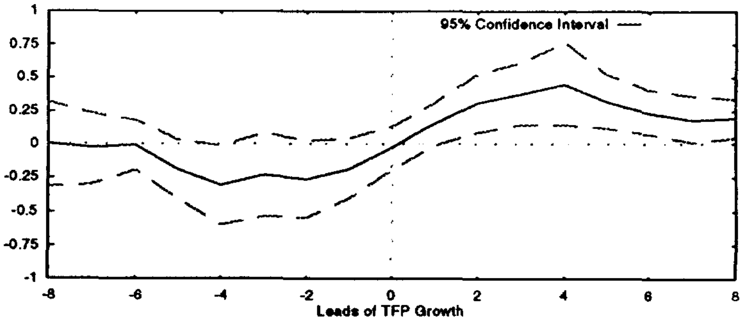

Figure 6: Dynamic Correlations of Exit Rate with ΔTFP

3. The Model

The model of this section differs from a standard vintage capital framework by explicitly modeling the idiosyncratic uncertainty which drives entry and exit. Investing one unit of an aggregate good yields a unit mass of plants. Plant construction requires time to deliver. As in the vintage capital models of Solow(1960) and Cooley, Greenwood and Yorukoglu(1996), only newly constructed plants have access to the leading edge technology. The technology a plant uses is fixed throughout its lifetime, but different plants implement the same technology with varying degrees of success. After birth, plants are subject to ongoing idiosyncratic productivity shocks. Any plant can be retired to recover a fraction of its capital stock as scrap. This scrap value does not depend on a plant's productivity, so only relatively unproductive plants will exit.

The remainder of the model is standard. There are many identical consumers who provide the economy's labor and own its equity. Capital goods are traded in complete markets. A single representative firm purchases all available capital goods from the consumers at the beginning of the period and liquidates after production. Its manager chooses the allocation of labor among the plants and makes plant exit decisions to maximize the firm's profits. The constant returns to scale technology ensures that profits are zero in a competitive equilibrium.

3.1 The Production Sector

A continuum of atomistic plants populates the economy's production sector. A plant uses labor to produce an aggregate good, which can be used for either consumption or new plant construction. A Cobb-Douglas production function characterizes each plant's technology.

$$y = (ke^{v_t})^{1-\alpha} n^{\alpha}.$$

The plant's capital is k; its labor input is n; and its output of the aggregate good is y. The plant's idiosyncratic productivity level is v_t. The elasticity of output with respect to labor input, $0 < \alpha < 1$, is common across plants. Because this technology obeys constant returns to scale, the plants' size distribution (as measured by capital) does not affect the economy's aggregate production possibilities. The production sets available to a single plant with one unit of capital and N otherwise identical plants, each with $k = 1/N$, are the same. This allows considerable simplification of the economy by restricting the size of all plants to equal 1.

New plant construction requires time to deliver. Investing a unit of the aggregate good in construction yields a plant in T^i periods. A new plant has access to the leading edge production process when its construction begins. After its construction, a plant may not update its technology or add to its capital stock. A plant's initial idiosyncratic productivity level reflects its success or failure at implementing this technology. The initial productivity level, v_{t+T^i}, of a plant begun in period t is a random variable with a normal distribution.

$$v_{t+T^i} \sim N(z_t, \sigma_e^2)$$

The productivity of a plant with an average implementation of the leading edge production process is z_t. This is an index of embodied technology. It follows a random walk with a positive drift.

$$\begin{aligned} z_t &= \mu_z + z_{t-1} + \varepsilon_t^z \\ \varepsilon_t^z &\sim N(0, \sigma_z^2) \end{aligned}$$

The exogenous technological progress is the model economy's only source of growth and aggregate uncertainty. After a new plant's entry, nothing distinguishes it from an incumbent with an identical productivity level.

After production takes place, a plant may either remain in place until the next period or be retired. If it is retired, η units of the aggregate good are recovered as its scrap value. The scrap value is positive but less than one. Alternatively, the plant may be left intact. In that case, it receives an idiosyncratic shock to its productivity level before the next period.

$$\begin{aligned} v_{t+1} &= v_t + \varepsilon_{t+1} \\ \varepsilon_{t+1} &\sim N(0, \sigma^2) \end{aligned}$$

That is, the plant's idiosyncratic productivity level follows a random walk. The random walk's innovation is *i.i.d.* across time and across plants. It has zero mean, so an average plant's productivity does not rise over its lifetime. The unit root in the plant productivity process implies that the level of the leading edge production technology during its construction, z_t, will have a permanent effect on its productivity. In this sense, the model includes a vintage capital structure.

3.2 Consumers

There are many identical, infinitely lived consumers who value two goods, consumption and leisure. Each consumer has a time endowment of one unit each period, which she must allocate between leisure and labor. The utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t u(c_t, 1 - n_t)$$

represents her preferences over state contingent sequences of these two goods. Her discount factor is β, which lies strictly between zero and one. Her momentary utility function, $u(c_t, 1 - n_t)$, is

$$u(c_t, 1 - n_t) = \ln(c_t) + \kappa(1 - n_t)$$

where $\kappa > 0$. Hansen(1985) justifies this functional form for preferences in a real business cycle model in which labor is indivisible and consumers trade lotteries over employment outcomes.

3.3 Market Structure

In a competitive equilibrium, firms and consumers trade the aggregate good, labor, and capital goods of all productivity types in complete markets. At the beginning of each period, each consumer owns two types of assets, a portfolio of the economy's operational plants and another of construction projects at various stages of completion. Consumers sell the operational plants and their labor services to the production firms. Production firms only exist for one period. They produce the aggregate good with the technology described above. After production, the firms decide which of the surviving plants to keep intact and which to salvage for their scrap value. Then the firms sell their stock of the aggregate good, consisting of what they produced and recovered as scrap, to the consumers and the construction firms. The aggregate good is the numeraire, and its spot price always equals one. It is perishable, so the consumer must consume her purchases within the current period. The construction firms also exist for only one period. They purchase the aggregate good from the production firm and plants under construction from the consumer. They turn the oldest construction projects into new plants and advance the younger projects towards completion. At the end of the period, firms in both the production sector and the construction sector liquidate, selling their plants and construction projects to the consumers. Between periods, the operational plants receive their productivity innovations.

This market structure, as opposed to one in which consumers rent capital goods to firms every period, naturally prices the economy's capital assets.[8] The technology available to firms in both sectors obeys constant returns to scale. Therefore, firms earn zero profits in equilibrium.

3.4 The Firm's Problem

Given the prices of all plants and the wage rate, the representative production manager hires labor and trades plants to maximize its profits. The wage rate in period t is w_t, the price of a plant with productivity level v_t at the beginning of the period is $q_t^0(v_t)$, and the analogous price at the end of the period is $q^1(v_t)$. The representative firm chooses the number and types of plants to purchase at the beginning of the period, which plants to close at the end of the period, and the plants' employment to maximize current profits. The envelope theorem allows this problem to be broken into two steps. First consider the problem of maximizing the firm's output given its capital and labor inputs. This is the labor allocation problem. Solow (1960) showed that this problem has a simple analytical solution. Let $k\left(v_t\right)$ be the number of plants with productivity v_t the firm purchases and let $n\left(v_t\right)$ be the labor allocated to one plant of type v_t. Define the firm's *effective capital stock* to be

$$\bar{k} = \int_{-\infty}^{\infty} e^{v_t} k(v_t) dv_t.$$

The effective capital stock is the sum of the number of plants of each type, weighted by their productivity level. The solution to the labor allocation problem is

$$n(v_t) = ne^{v_t}/\bar{k}.$$

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[8] **Additional markets in state contingent claims on capital assets and the aggregate good could be added at the expense of considerable extra notation, but spot market prices for physical assets would not change.**

A plant's labor input is proportional to its productivity. Substituting this into the firm's production function yields

$$y = \bar{k}^{1-\alpha} n^{\alpha}.$$

A Cobb-Douglas production function in labor and *effective* capital represents the aggregate production possibilities.

In light of this aggregation result, it is clear that the firm's optimal employment will be characterized by the familiar first order condition.

$$w_t = \alpha \left(\frac{\bar{k}}{n} \right)^{1-\alpha}$$

The firm's plant retirement decision is also easy to characterize. If asset prices equal discounted expected dividend streams, they will be increasing in v_t. A plant's scrap value is invariant to its productivity, so the representative firm will choose to scrap only those plants below a threshold, $\underline{v}_t$. Those plants with productivity levels above the threshold will remain in production. The scrap value of a plant with productivity level $\underline{v}_t$ equals its market value as a productive plant.

$$\eta = q_t^1(\underline{v}_t)$$

This threshold scrap rule is similar to those found in Hopenhayn(1992) and Jovanovic(1982). Finally, the plant purchase and sale decisions of the firm must be characterized by a zero profit condition.

$$q_t^0(v_t) = (1-\alpha) \left(\frac{\bar{k}}{n} \right)^{-\alpha} e^{v_t} + 1\{v_t < \underline{v}_t\}\eta + 1\{v_t \geq \underline{v}_t\} q_t^1(v_t)$$

The indicator function, $1\{\cdot\}$, equals one if its argument is true and zero otherwise. This equation constrains an asset's beginning of period price to equal the dividends it returns plus its value at the end of the period. If the asset is scrapped, this value equals that of the scrap capital. Otherwise, it equals its sale price.

The profit maximization problem facing the construction firms is trivial. A construction firm which buys one unit of the aggregate good can produce a construction project one period old. The price of such a construction project is $q_t^{1i}(1)$. The zero profit condition associated with this transaction is

$$1 = q_t^{1i}(1)$$

Similarly, a firm purchasing a construction project j periods old at the beginning of the period for $q_t^{0i}(j)$ can sell it at the end of the period for $q_t^{1i}(j+1)$. For no profit opportunity to exist, these prices must be equal.

$$q_t^{0i}(j) = q_t^{1i}(j+1) \quad j = 1 \ldots T^i - 1$$

3.5 Market Clearing and Equilibrium

The utility maximization problem of a consumer is straightforward, so a detailed discussion of it is omitted in the interest of brevity. Each consumer maximizes her expected utility by choosing state contingent sequences of consumption, labor, and asset holdings taking wages, asset prices, and her initial asset holdings as given. In a competitive equilibrium the firms' and consumers' problems are connected through the imposition of market clearing conditions. In general no analytical expression exists for the economy's competitive equilibrium, but its approximate computation is feasible. The first and second welfare theorems apply to the model economy, so the problem of computing a competitive equilibrium can be conveniently recast as solving a social planning problem. The solution to this problem is a set of decision rules expressing the social planner's choice variables as functions of the current state.

Eliminating all sources of non-stationarity is the first step in solving the problem. First note that the center of the distribution $K(v_t)$ will continually shift to the right as z_t grows. The aggregate production function is Cobb-Douglas in capital and labor, so the capital augmenting technological change can be expressed in labor augmenting form. Therefore, the economy satisfies the balanced growth restrictions of King, Plosser, and Rebelo(1988). As in that work, scaling all of the social planner's choice variables but hours worked by the level of labor augmenting technology yields a social planning problem for an equivalent economy which is stationary.

To find an approximate solution to this stationary social planning problem, replace its first order necessary conditions with log-linear approximations around its steady state. Because the capital stock is a function rather than a scalar, these approximate first order conditions are *functional* equations. Quadrature approximations, the evaluation of which only requires the function's values at a finite number of points, replace the functional equations.[9] This approximation produces a finite dimensional linear dynamical system. Although its dimension is much greater than that of a standard problem, its solutions can be found by applying standard linear algebraic techniques. The approximate system of equations possesses a continuum of solutions. The unique one which also satisfies the social planning problem's transversality condition is an approximate solution to the scaled economy's social planning problem. Rescaling the solution by the level of labor augmenting technology yields the desired approximate solution to the original problem. A computational appendix to this paper, available upon request, describes this solution strategy in greater detail.

4. The Model's Behavior

This section addresses the ability of a parameterized version of the model to re-

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[9] See Press, Teukolsky, Vetterling, and Flannery (1992) for an explanation of quadrature approximation of integrals.

produce the empirical relationships of entry and exit with the business cycle and productivity growth. As in Kydland and Prescott(1982), the model's parameter values match features of the model's steady state growth path with average quantities of the U.S. economy. Some of the model's parameters are familiar from previous quantitative work using the stochastic one-sector growth model, so the analogous values are used here.

4.1 Parameter Values and Steady State

Two parameters characterize the consumer's preferences, β, the consumer's rate of time preference, and κ, her constant marginal utility of leisure. Along the steady state growth path, β equals the inverse of the risk free gross interest rate. This is set to equal a 3% annual rate, so that $\beta = 1.03^{-\frac{1}{4}}$. The marginal utility of leisure is set so that 0.26 of the consumer's time endowment is spent at work. Because the model's labor and product markets are competitive, the elasticity of output with respect to labor input, α, equals labor's share of output. Accordingly, this is set equal to 2/3, labor's average share in the U.S. economy. The model's steady state growth rate of output equals $\frac{1-\alpha}{\alpha}\mu_z$. Given a value for α, μ_z is chosen to match this with the average growth rate of the U.S. economy between 1972 and 1988, 0.34% per quarter.

The remaining parameters govern plant level dynamics. As such, they have no direct analogues in the first moments of the U.S. data. In principle, values for these parameters can be measured directly from microeconomic data on establishments; but such an exercise is impractical. Although the parsimonious model of plant level dynamics lends itself to theoretical tractability, it abstracts from several important features of establishments' environments. First, the lumpy nature of individual plants' job creation and destruction decisions suggests that they face employment adjustment costs, as in Campbell and Fisher(1996). In this model, a plant's employment can be costlessly adjusted at will. Second, disturbances to plants' productivity levels have transitory as well as permanent components. In this model, all shocks permanently influence productivity. Third, investment in capital equipment does occur over a plant's lifetime, although infrequently.[10]

With these qualifications in mind, the parameters describing the plants' environment were set using an alternative strategy. First, consider, σ, the standard deviation of plants' productivity innovations. In the absence of evidence regarding the magnitude of permanent innovations to plants' productivities, the model's equilibrium was computed using a range of values for this parameter from 0.01 to 0.05. For the sake of brevity, this section only reports the results with $\sigma = 0.03$. The cyclical behavior of entry and exit is robust to the choice of this parameter. Next, the time to deliver, T^i, was set to five quarters. This is about the horizon over which exit leads entry.

Two of the model's remaining parameters, the scrap value of old plants, η, and the standard deviation of entrants' productivity distribution, σ_e, are set to match exit rates from the model and the U.S. economies. It is clear that raising the scrap value increases the return to closing an unproductive plant and thereby induces more exit. How the entrants' productivity distribution determines exit rates is less obvious. Two features of the plant level productivity process make σ_e an important determinant of exit. First, embodied technological progress implies that each cohort of new entrants will be more productive than the previous cohort. Second, plants with the same productivity level but different birth dates are identical. With nothing to offset them, these features will imply that older plants exit more frequently than new entrants. In the U.S. economy, new plants are more

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[10] See Doms and Dunne (1994) for a summary of the investment behavior of U.S. manufacturing plants.

Parameter	**Value**
β	$1.03^{-\frac{1}{4}}$
μ_z	0.66%
α	2/3
σ	3%
σ_e	25%
η	0.85
σ_z	0.55%
T^i	5
N_0	0.26

Table 2: Baseline Parameter Values

likely to exit than their older counterparts. The average exit rate for plants less than one year old is 1.64%, compared to 0.83% for all plants. The addition of substantial idiosyncratic uncertainty surrounding a plant's initial draw of v_t can remedy this problem. If σ_e is much larger than σ, then the probability of a new entrant falling below the exit threshold will be higher than that of an incumbent plant with $v_t = z_t$ doing so. Accordingly, η and σ_e were chosen to match the model's steady state overall exit rate and that for young plants with the average exit rates in the U.S. economy.

The final parameter to be determined is the standard deviation of the innovation to embodied technological progress, σ_z. Because no direct observations of z_t are available with which to measure σ_z, this parameter was chosen so that the standard deviation of the exit rate in the model economy equals that in the data, about 0.26%. With this value, the model then tells us the amount of output and productivity variation attributable to embodied technology shocks under the assumption that such shocks cause all fluctuations in the exit rate. When $\sigma = 0.03$ and η and σ_e are chosen as described above, $\sigma_z = 0.58\%$. Table 2 summarizes the set of baseline parameter values used below.

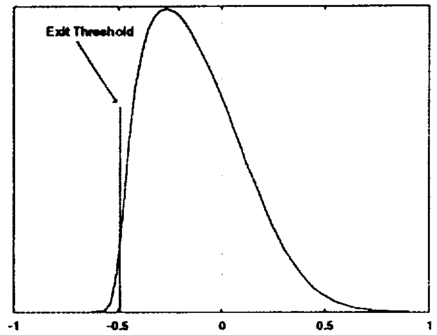

Figure 7: Steady State Distribution of $v_t - z_t$

With the baseline parameter values, the impact of irreversibility and ongoing productivity uncertainty on the exit decision is evident. Figure 7 graphs the distribution of productivity across all plants and the exit threshold in the model's steady state. When an incumbent's productivity is 15% lower than the leading edge, it provides the same expected capital services as would the average entrant produced from scrapping the old plant and investing the proceeds. Yet exit does not occur until a plant is 49% less productive than an average entrant. The idiosyncratic uncertainty has driven a considerable wedge between the plant's material scrap value and the exit threshold. Although a plant's productivity may be low today, the option to operate it tomorrow if its fortunes improve is valuable. Accounting for this option value causes a considerable, although rational, delay in exit.

4.2 Responses to Embodied Technology Shocks

To summarize the model's stochastic behavior, figures 8, 9, and 10 graph the response of its key aggregate variables to a one percent improvement in embodied technology. Figure 8 graphs the response of the entry and exit rates. The exit

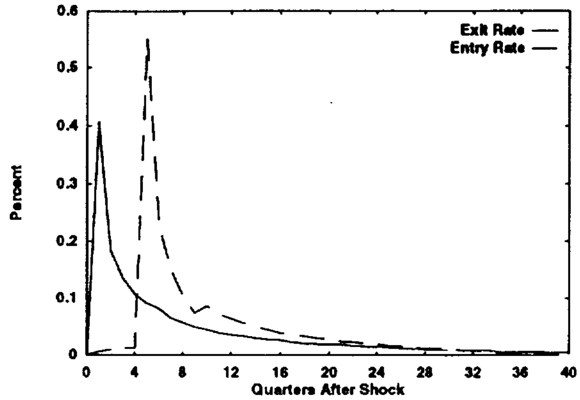

Figure 8: Responses of Entry and Exit

threshold rises 1.09% following a 1% increase in z_t. It then slowly falls towards its new long-run level 1% higher than before the shock. The jump in the exit threshold causes the following quarter's exit rate to increase by 0.41%. This is a sizeable increase relative to the exit rate's steady state value, 0.83%. The impact of the technology shock on the exit rate is persistent: The exit rate is 0.14% higher three quarters after the shock. The entry rate mimics the exit rate, but with a lag due to the time to deliver investment technology. Five quarters following the improvement, the entry rate jumps 0.55%. This jump is persistent, being 0.10% above its steady state value after eight quarters.

Figures 9 and 10 graph the impulse response functions for employment, the effective capital stock, output, and measured total factor productivity. Because the aggregate production function is Cobb-Douglas in labor and effective capital, conventionally measured total factor productivity should equal zero if the correct measure of capital input, $\overline{K}_t$, is used. The measure reported in figure 10 is computed using a perpetual inventory capital measure, $\widehat{K}_t$. This measure is

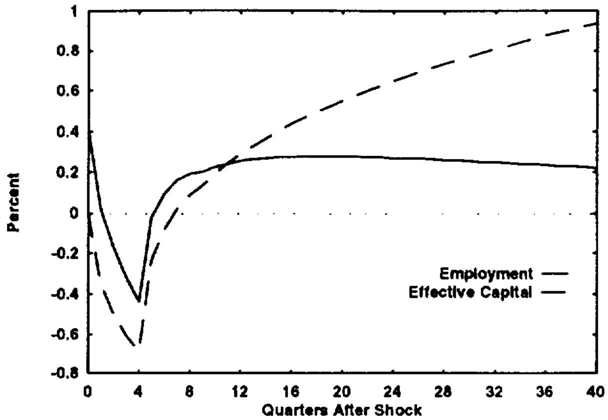

Figure 9: Responses of Employment and Effective Capital

constructed to satisfy the difference equation

$$\widehat{K}_t = (1-\widehat{\delta})\widehat{K}_{t-1} + \widehat{I}_t.$$

The measured depreciation rate, $\widehat{\delta}$, is set equal to the fraction of capital lost to exit each quarter, about 0.002. Net investment $\widehat{I}_t$ is defined to equal new construction projects begun minus scrap capital returned from exiting plants.

Because the technology shock increases the productivity of new plants, it decreases the price of investment goods relative to consumption. As in Barro and King(1984) and Greenwood, Hercowitz, and Huffman(1988), if the substitution effect of the relative price change outweighs the income effect the consumer will delay gratification by consuming less and working more to increase her investment in physical capital. In the model, the substitution effect dominates, so employment increases, about 0.4% in the period of the shock. Thereafter it declines for four quarters, then rises following the entry of the new plants. The increase in exit causes the effective capital stock to decline. The magnitude is slight at first, but as better plants exit, the impact becomes more severe. After four quarters,

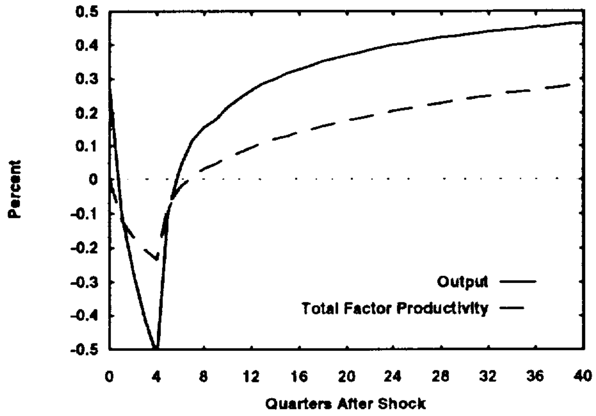

Figure 10: Responses of Output and TFP

the effective capital stock declines 0.7%. It begins to rise when the first wave of entrants becomes operational. Thereafter, it steadily climbs towards its new steady state value as both the quantity and quality of plants increase. By construction, the perpetual inventory capital stock measure is smooth, so measured TFP mimics the response of the effective capital stock. The immediate increase in employment following the shock causes output to expand. Thereafter, it falls as both hours worked and capital input decline. Output rises again when the first entrants join the economy's effective capital stock.

Labor and capital are complements in a Cobb-Douglas production function, so the increase in hours worked and the decrease in the effective capital stock imply that the rental rate for capital services increases immediately following an improvement in the leading edge technology. The immediate returns to remaining in production increase, yet so does exit. The solution to this paradox lies in exit's irreversibility. Once made, the decision to exit cannot be reversed. Furthermore, each plant experiences ongoing uncertainty about its future productivity. These

Variable	Mean	Std. Dev.	U.S. Mean	U.S. Std. Dev.
Entry Rate	1.87%	0.35%	0.62% (0.04%)	0.23% (0.04%)
Exit Rate	0.88%	0.26%	0.83% (0.06%)	0.26% (0.04%)
ΔGDP	0.34%	0.39%	0.34% (0.18%)	1.14% (0.14%)
ΔTFP	0.22%	0.12%	0.09% (0.08%)	0.84% (0.07%)

Table 3: Summary Statistics

two factors imply that a rational manager may leave an unproductive plant active while waiting to see if its productivity improves. If not for that possibility, the marginal plant would have exited long ago. An improvement in z_t lowers the price of capital goods relative to consumption in the long run. This lowers the probability that, if left in place, a plant's value will ever surpass its scrap value. The option to remain in production becomes less valuable, so the plant exits.

4.3 Observable Implications

The timing of the exit and entry decisions and their impact on output and productivity, determined by the endogenous option value considerations and by the exogenous time-to-deliver entry technology, produce correlations of exit with output and productivity growth which mimic those from the U.S. economy. Table 3 reports the mean and standard deviation for the output and total factor productivity growth rates and the entry and exit rates from the model economy and analogous statistics from the U.S. economy.[11] All of the statistics from the U.S. economy are measured using data from the same sample period as the entry and exit series. Beside each U.S. statistic is its asymptotic standard error.

By construction, the exit rate's mean and standard deviation are similar in the model and U.S. economies. The mean entry rate in the model economy is

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[11] The average exit rate for the model is sigificantly different from the steady state exit rate because it is calculated as a ratio of levels. Its expected value is $x_0 \exp\left(\frac{\sigma_x^2}{2}\sum_{i=0}^{\infty} c_i^2\right)$, where c_i is the i'th moving average coefficient of the exit rate's logarythm.

much larger than in the U.S. economy, 1.87% versus 0.62%. The intuition for this is simple: In the model employment is increasing in productivity, and only the least productive plants exit. Entrants are more productive than exiters on average, and there are more of them. Therefore, entrants' employment must be larger than exiters'. The exact opposite is true in the U.S. economy. Of course, the model abstracts from learning about new technologies through production, as documented by Irwin and Klenow(1994), and therefore may overstate the average size of new entrants.

The shocks to the leading edge technology induce significant fluctuations in output growth. The standard deviation of output growth in the model economy is 0.39%, slightly more than 1/3 of the analogous statistic from the U.S. economy. As in Burnside and Eichenbaum (1996), the model's fluctuations in TFP growth reflect variable capital utilization. Following a technological improvement, both exit and the construction of new plants surge. This temporarily moves capital resources from the production sector to the construction sector. When they leave, measured TFP falls, and it rises again when they return. Thereafter, it smoothly rises as the new technology diffuses throughout the economy. The standard deviation of total factor productivity growth is 0.12% in the model economy, 1/7 of its value in the U.S. economy.

Figures 11 and 12 plot the dynamic correlations of the entry and exit rates with output growth from the model economy. The entry rate is positively correlated with current and future output growth. The recession immediately following a technology shock generates a large negative correlation with output growth four quarters earlier. The correlations of exit with output growth strongly resemble those estimated with the U.S. data. In particular, exit is strongly positively

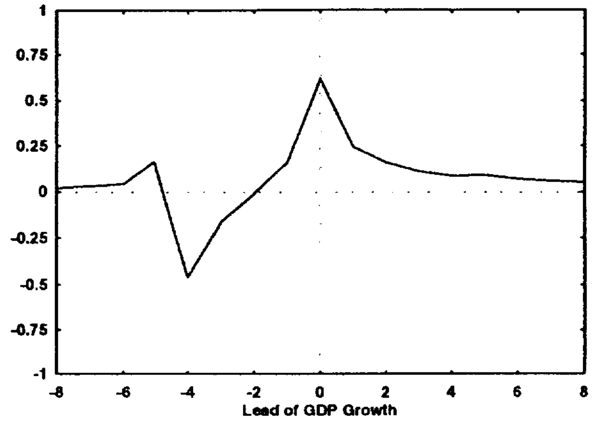

Figure 11: Model's Dynamic Correlations of Entry with GDP Growth

correlated with future output growth. It also has a small positive correlation with output growth one quarter ago. The initial positive labor supply response to a shock generates this correlation. Figure 13 plots the model's dynamic correlations between the exit and entry rates. As the impulse response functions suggest, there is a nearly perfect correlation between the current exit rate and the entry rate four quarters hence.

Figures 14 and 15 plot the model's dynamic correlations of the entry and exit rates with measured TFP growth. Unsuprisingly, entry is positively correlated with current and future TFP growth. As it is with GDP growth, it is negatively correlated with TFP growth four quarters in the past. The exit rate has a very strong positive correlation with future TFP growth. The correlation between exit and TFP growth four quarters hence is 0.76. One important difference with the U.S. economy is in the contemporaneous relationship between exit and TFP. The sample correlation is nearly zero while in the model it is -0.32.

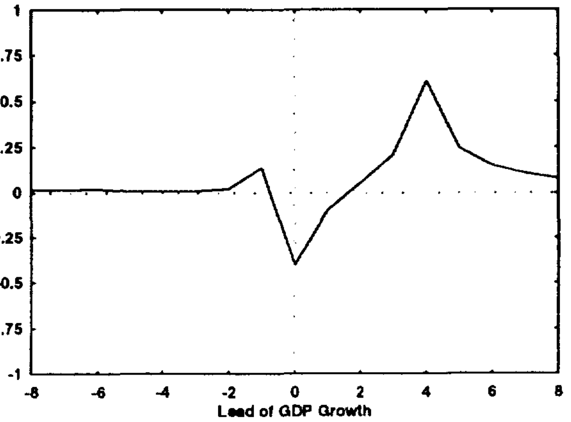

Figure 12: Model's Dynamic Correlations of Exit with GDP Growth

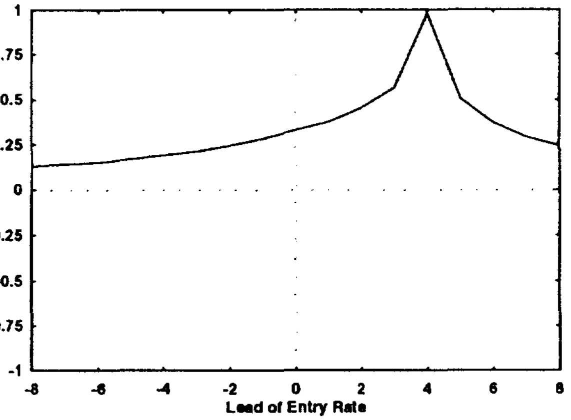

Figure 13: Model's Dynamic Correlations fo Exit Rate with Entry Rate

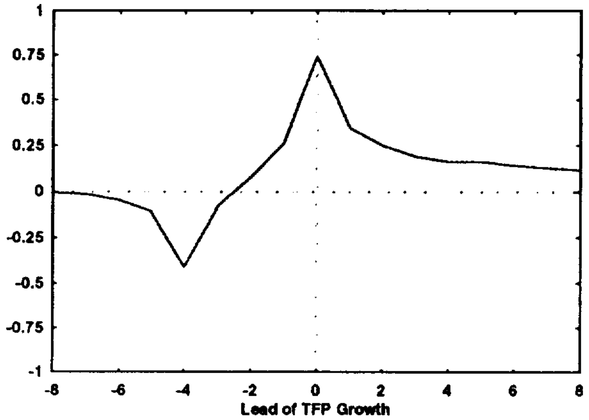

Figure 14: Model Correlations of Entry with TFP Growth

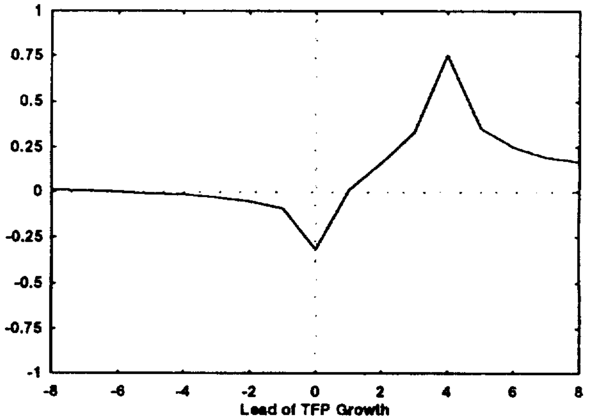

Figure 15: Model Correlations of Exit with TFP Growth

5. Conclusion

Models of endogenous capital obsolescence and replacement have been previously applied to the study of business cycles. Cooper and Haltiwanger(1993) showed that synchronization of annual machine replacement can generate substantial seasonal movements in output and productivity. Greenwood, Hercowitz, and Krusell(1997) showed with a vintage capital model that variation in the rate of embodied technological change can cause significant cyclical fluctuations. The empirical and theoretical results of this paper provide new support for the hypothesis that shocks to the pace of embodied technological progress are a significant source of business cycles. The replacement of old with new machines, as measured by plant entry and exit, exhibits a strong relationship with the business cycle. Increases in the plant exit rate precede output and productivity growth, while increases in the entry rate accompany these. A general equilibrium model in which all technological progress is embodied in entering plants and the pace of such progress is stochastic mimics the cyclical behavior of entry and exit in the U.S. economy.

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