The Cleansing Effect of Recessions

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We investigate industry response to cyclical variations in demand. Production units that embody the newest process and product innovations are continuously being created, and outdated units are being destroyed. Although outdated units are the most likely to turn unprofitable and be scrapped in a recession, they can be "insulated" from the fall in demand by a reduction in creation. The structure of adjustment costs plays a determinant role in the responsiveness of those two margins. The calibrated model matches the relative volatilities of the observed manufacturing job creation and destruction series, and their asymmetries over the cycle. (*JEL* E00, L00, J00)

This paper investigates the response of industries to cyclical variations in demand in the framework of a vintage model of "creative destruction."[1] Our premise is that the continuous process of creation and destruction of production units that results from product and process innovation is essential for understanding not only growth, but also business cycles.[2] This idea goes back at least to Joseph A. Schumpeter (1939, 1942), although we do not go so far as to adopt his view that the process of creative destruction is itself a major *source* of economic fluctuations (as in Andrei Shleifer [1986]). Our emphasis here is on variations in demand as a source of economic fluctuations, and on the way a continuously renovating productive structure responds to them.

A stark example of this effect of demand on industry structure has been recently documented by Timothy F. Bresnahan and Daniel M. G. Raff (1991, 1992) in their study of the effect of the Great Depression

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[1]In independent work, Dale Mortensen and Christopher Pissarides (1991, 1992) study issues similar to the ones considered in this paper in the context of a search model of unemployment.

[2]For an analysis of creative destruction in Leif Johansen's (1959) vintage model of embodied technical progress, see Robert M. Solow (1960), Edmund S. Phelps (1963), Eytan Sheshinski (1967), and references therein. For two recent models of growth through creative destruction, see Gene R. Grossman and Elhanan Helpman (1991) and Philippe Aghion and Peter Howitt (1992).

For recent analyses of the empirical significance of creative destruction for growth, see Eric J. Bartelsman and Phoebus J. Dhrymes (1991), Martin N. Baily et al. (1992), and Charles R. Hulten (1992). Using price-based estimates of embodied technical change, Hulten (1992) argues that as much as 20 percent of the change in total factor productivity can be directly associated with capital embodiment. Bartelsman and Dhrymes (1991) and Baily et al. (1992) use plant-level data to decompose improvements in aggregate productivity into a component due to resource allocation from relatively inefficient to relatively efficient plants, and another due to improvements in technology purely at the plant level. Both studies find that a major part of technical progress arises from factor reallocation, a fact consistent with the view of an economy subject to ongoing creative destruction. Compounded over the period 1972–1987 for a sample of 22 industries, the results in Baily et al. (1992) indicate that aggregate growth is made up of 6.7 percent due to reallocation and 3.5 percent due to plant-level technical progress (results for "all industries except 3573" in their table 1, p. 207).

on the American motor vehicles industry. Using Census panel data, they find that the large contraction in automotive production was the occasion for a permanent structural change in the industry. At the beginning of the Depression, the diffusion of mass-production techniques in manufacturing had only been partial, and a substantial segment of the industry was still based on skilled craftsmanship. Plant shutdown, which accounted for a third of the decline in industry employment during the Depression, was concentrated in smaller, less productive craft-production plants, while plants that had adopted the mass-production system had a competitive advantage that made them more likely to survive. The result was a true shakeout or "cleansing" of the productive structure, as most plant shutdowns were permanent. Interestingly, creation was still taking place alongside this massive destruction process, with a sizable number of new plants entering even in the depths of the Depression.[3]

In general, industries undergoing continuous creative destruction can accommodate variations in demand in two ways: they can vary either the rate at which production units that embody new techniques are created or the rate at which outdated units are destroyed. The central question becomes: along which of these two margins will business cycles be accommodated?

Since a representative-firm economy is unsuited to answer this question, we address it in the context of a simple theoretical model of creative destruction with heterogeneous technologies.[4] Production units embody the most advanced techniques available at the time of their creation. Creation costs slow down the process of technology adoption and lead to the coexistence of production units of different vintages. This decouples the two margins and permits a meaningful analysis of the issue at hand.

The interaction of two margins can challenge one's intuition. We isolate two effects. Old production units, having an inferior technology, can more easily turn unprofitable and be scrapped in a recession than new ones. However, units in place may not experience the full fall in demand if it is accommodated by a reduction in the creation rate. We investigate the extent to which this "insulating" effect of creation will operate and reduce the responsiveness of destruction to demand. The structure of adjustment costs turns out to play a determinant role in the extent to which insulation will take place. When adjustment costs are linear, we show that insulation is complete, and the industry responds *exclusively* on its creation margin. As the motive for smoothing the creation process over time becomes more important, insulation becomes more limited, and the destruction margin becomes more responsive.

What is the empirical evidence on the cyclical responsiveness of creation and destruction? We next turn to the U.S. evidence on gross job creation and destruction collected by Olivier J. Blanchard and Peter A. Diamond (1990) and Steven Davis and John Haltiwanger (1990, 1992). As emphasized by Blanchard and Diamond, the simultaneous high observed rates of job creation and destruction in narrowly defined sectors lend plausibility to the view of an economy subject to ongoing creative destruction. This view is further confirmed by the strong persistence of job destruction at the plant level documented by Davis and Haltiwanger (1990). We analyze Davis and Haltiwanger's (1990, 1992) data on manufacturing job flows in light of our model. The evidence is that job destruction is much more cyclically responsive than job creation. Thus, the insulating effect of creation seems very imperfect. According to our model, this is due to the structure of creation costs that gives a motive for smoothing the creation process. Interestingly, the data exhibit features that provide a natural experiment to test this explanation. Noting that business cycles are highly asymmetric, with recessions shorter but much sharper than expansions, our model would predict that those asymmetries would be smoothed out in the

[3] In the 1929–1931 period, industry 1408 saw 13 new plant entries and 60 exits. During 1931–1933, those numbers were 9 and 45.

[4] A steady-state variant of this model has been used by Boyan Jovanovic and Saul Lach (1989) to study technology diffusion.

creation process. The evidence confirms this prediction: creation is roughly symmetric around its mean, while destruction is highly asymmetric.

The view that emerges from interpreting the greater cyclicality of job destruction along creative-destruction lines is one of recessions as times of "cleansing," when outdated or relatively unprofitable techniques and products are pruned out of the productive system—an idea that was popular among pre-Keynesian "liquidationist" theorists like Hayek or Schumpeter (see J. Bradford De Long, 1990), but *need not* be taken to imply, as those authors did, that recessions are "desirable" events.

In Section I, we lay out our basic vintage model of creative destruction and characterize its steady state. Section II introduces demand fluctuations into the model, and asks which of the creation or destruction margins will respond to them. Section III interprets the data on manufacturing job flows in terms of our model and ends with a calibration exercise in which the model's theoretical response to the observed path of manufacturing activity is calculated and compared to the actual response.

I. A Vintage Model of Creative Destruction

In this section, we present the basic features of the model of creative destruction that is used throughout the paper. The first subsection describes the basic statistics of the model; Subsection B turns to market equilibrium conditions; and Subsection C characterizes the model's steady state.

A. *Production Units: Distribution and Flows*

We model an industry experiencing exogenous technical progress. New production units that capture the most advanced techniques are continuously being created, and outdated ones are being destroyed. Because the creation process is costly, production units with different productivities coexist.

More specifically, labor and capital combine in fixed proportions to form *production units*. A production unit created at time t_0 embodies the leading technology at t_0, and produces the same constant flow $A(t_0)$ of output throughout its lifetime. Technical progress makes the productivity $A(t)$ of the leading technology at time t grow at an exogenous rate $\gamma > 0$.

Although we interpret the creation process as one of technology adoption, it could also be interpreted as one of product innovation. In this case, there is a continuum of perfectly substitutable products that yield different utilities. A production unit created at t_0 will be producing a unit flow of the most advanced product in existence at t_0, which yields utility $A(t_0)$.

Since production units that were created at different times (and thus have different productivities) may coexist, we must keep track of their age distribution. Let

$$f(a,t) \qquad 0 \le a \le \bar{a}(t)$$

denote the cross-section density of production units aged a at time t, where $\bar{a}(t)$ is the age of the oldest unit *in operation* at time t.[5] The boundary $f(0,t)$ is given by the rate at which new units are created, and the age $\bar{a}(t)$ at which units become obsolete is determined by the destruction process. Our assumptions will be such that $f(a,t)$ and $\bar{a}(t)$ are continuous functions.

The density $f(a,t)$ can be aggregated to obtain the total number (or "mass") of production units at any time t:

$$N(t) = \int_0^{\bar{a}(t)} f(a,t)\, da.$$

Because of fixed proportions, $N(t)$ is a measure of both the industry's employment and its capital stock in operation. Industry output is given by

$$(1) \qquad Q(t) = \int_0^{\bar{a}(t)} A(t-a) f(a,t)\, da.$$

We now turn to the flows that determine the evolution of the density $f(a,t)$. Production units are subject to an exogenous de-

[5] Of course the use of the word "density" is an abuse of terminology.

preciation (or failure) rate $\delta > 0$ and to the endogenous process of creative destruction. Since, as we describe below, the latter turns out to affect $f(a,t)$ only at its boundaries, we know that at any time t the number of units that have survived for a years is given by

$$(2) \quad f(a,t) = f(0,t-a)e^{-\delta a} \qquad 0 < a \leq \bar{a}(t).$$

Measures of production unit flows can be obtained by differentiating $N(t)$ over time, taking (2) into account:[6]

$$\dot{N}(t) = f(0,t) - \left\{ f(\bar{a}(t),t)\left[1-\dot{\bar{a}}(t)\right] + \delta N(t) \right\}.$$

The first term $f(0,t)$ measures the rate of creation of production units, and the second measures the rate of destruction. When normalized by $N(t)$, they are denoted by CC(t) and DD(t), respectively. The rate of destruction has three components: $f(\bar{a}(t),t)$ units will be destroyed because they have reached the obsolescence age $\bar{a}$; $-f(\bar{a}(t),t)\dot{\bar{a}}(t)$ are destroyed because $\bar{a}$ changes over time; and $\delta N(t)$ units depreciate. With some abuse of terminology, we call the sum of the first two components "endogenous destruction." Our assumptions are such that endogenous creation and destruction are always positive, that is, $f(0,t) > 0$ and $\dot{\bar{a}}(t) < 1$, for all t.

Finally, it will be useful to have an expression for the change in output as a function of the above flows:[7]

$$(1') \quad \dot{Q}(t) = A(t)f(0,t) - \left\{ A(t-\bar{a}(t))f(\bar{a}(t),t) \times \left[1-\dot{\bar{a}}(t)\right] + \delta Q(t) \right\}.$$

B. *Market Equilibrium*

We now turn to supply and demand conditions in this model, and to the economics of creative destruction. We model a perfectly competitive industry in partial equilibrium. Because our main argument does not depend on the presence or absence of uncertainty, we assume perfect foresight.

Supply is determined by free entry and perfect competition. There is a cost c of creating a new production unit:[8]

$$c = c(f(0,t)) \qquad c(\cdot) > 0, c'(\cdot) \geq 0.$$

Here, c is allowed to depend on the creation rate $f(0,t)$ to capture the possibility that, for the industry as a whole, fast creation may be costly, and adjustment may not take place instantaneously. This can be due to different reasons. It can arise from a concave production function in the sector producing the industry's capital stock, or from standard convex capital installation and labor training costs.[9] Industry-wide convexity could also have been derived from a nondegenerate distribution of linear individual adjustment costs across potential entrants (see e.g., Peter Diamond, 1993).

As long as creation is taking place, free entry equates a unit's creation cost to the present discounted value of profits over its lifetime. More formally, set the operating cost of a production unit—including wages —to 1 by choosing it as a numeraire, and let $P(t)$ denote the price of a unit of output. The profits generated at time t by a produc-

[6]The derivation involves the partial differential equation $f_t + f_a + \delta f = 0$, $0 < a < \bar{a}(t)$, which follows directly from (2) and corresponds to the basic McKendrick-von Foerster equation in population dynamics (see R. M. Nisbet and W. S. C. Gurney, 1982).

[7]Differentiate (1) using

$$\partial A(t-a)/\partial t = -\partial A(t-a)/\partial a.$$

[8]An alternative specification is $c = c(f(0,t)/N(t))$. Normalizing the creation rate by $N(t)$ may be more appealing because it makes the model scale-free. But it complicates things by introducing an additional benefit of creating a production unit, equal to the reduction in future creation costs due to the increase in $N(t)$. We choose the simpler specification to avoid this added complexity.

[9]In this case, because we did not choose the scale-free specification mentioned in footnote 8, we would need to assume a fixed number (normalized to 1) of symmetric, perfectly competitive firms to derive a marginal adjustment cost of the form $c = c(f(0,t))$.

tion unit of age a are

$$\pi(a,t) = P(t)A(t-a) - 1.$$

Now let $T(t)$ measure the maximum lifetime of a unit created at t, which by perfect foresight satisfies

$$\bar{a}[t + T(t)] = T(t). \tag{3}$$

At any time t, the free-entry condition is

$$c(f(0,t)) = \int_t^{t+T(t)} \pi(s-t,t) e^{-(r+\delta)(s-t)} ds \tag{4}$$

where $r > 0$ is the exogenously given instantaneous interest rate.

To see what determines exit note that, assuming $P(t)$ is continuous, whenever a unit is being destroyed it must be the case that the profits it generates have reached zero. Since such a unit must be the oldest in operation at that time, $\bar{a}(t)$ must satisfy

$$P(t)A(t - \bar{a}(t)) = 1. \tag{5}$$

This condition relates the price $P(t)$ to $\bar{a}(t)$. From this it is simple to see that the continuity of $\bar{a}(t)$ implies the continuity of $P(t)$, and that $P(t)$ must be decreasing if there is endogenous destruction ($\dot{\bar{a}}(t) < 1$).[10] Since we restrict our attention to cases in which the latter is always taking place, it follows that $P(t)$ is always decreasing and that production units will be destroyed the *first* time their profits hit zero.

The demand side of the model is quite simple. We assume a unit-elastic demand function, and take total spending $\bar{D}(t)$ on the industry's output to be an exogenous and continuous function of time:

$$P(t)Q(t) = \bar{D}(t). \tag{6}$$

An equilibrium in this industry is a path $\{f(0,t), \bar{a}(t), T(t), P(t), Q(t)\}_{t \geq 0}$ that satisfies equations (1)–(6), summarized below, for all $t \geq 0$, given an initial density $f(a,0)$, $a > 0$, of production units:

$$Q(t) = \int_0^{\bar{a}(t)} A(t-a) f(a,t)\, da \tag{1}$$

$$f(a,t) = f(0,t-a)e^{-\delta a} \qquad 0 < a \leq \bar{a}(t) \tag{2}$$

$$\bar{a}(t + T(t)) = T(t) \tag{3}$$

$$c(f(0,t)) = \int_t^{t+T(t)} [P(s)A(t) - 1] e^{-(r+\delta)(s-t)} ds \tag{4}$$

$$P(t)A(t - \bar{a}(t)) = 1 \tag{5}$$

$$P(t)Q(t) = \bar{D}(t). \tag{6}$$

Since the paths of $T(t)$, $P(t)$, and $Q(t)$ are immediately determined from the path $\{f(0,t), \bar{a}(t)\}$ by equations (1)–(3) and (5), we will focus on the latter path as a sufficient description of equilibrium.

Note that, instead of using the free-entry and free-exit conditions, equations (4) and (5) could alternatively have been derived as the first-order conditions for maximization of a number of perfectly competitive firms that hold the production units in this industry. This highlights the efficiency of the resulting equilibrium outcome, and its compatibility with different institutional arrangements. It can also be used to establish the existence and uniqueness of equilibrium.[11]

C. *Steady State*

Before we turn to the response of our industry to demand fluctuations, it is instructive to characterize its steady-state (or balanced-growth) equilibrium, assuming that demand is a constant $\bar{D}^*$ over time.

[10] To see this, differentiate (5):

$$\dot{P}(t) = -\gamma[1 - \dot{\bar{a}}(t)]P(t).$$

[11] See Hugo Hopenhayn (1990) for a general discussion of existence and uniqueness of a dynamic industry equilibrium in the presence of heterogeneity and creation costs.

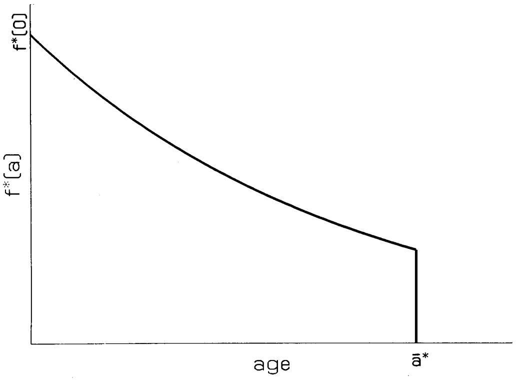

FIGURE 1. STEADY-STATE CROSS-SECTIONAL DENSITY

In steady state, the lifetime of production units is constant: $T(t)=\bar{a}(t)=\bar{a}^*$, for all t; their age distribution is time-invariant: $f(a,t)=f^*(a)$, for all t; and by (5) the price $P(t)$ must be decreasing at constant rate γ. Equation (2) implies that the distribution of production units in steady state is the truncated exponential distribution illustrated in Figure 1:

$$f^*(a)=f^*(0)e^{-\delta a} \qquad 0<a\le\bar{a}^*.$$

The creation rate and destruction age $(f^*(0),\bar{a}^*)$ are jointly determined from free-entry and market-equilibrium conditions (4) and (6) in steady state. Using (1) and (5), we get

$$(7)\qquad c(f^*(0))=\frac{e^{\gamma\bar{a}^*}-e^{-(r+\delta)\bar{a}^*}}{\gamma+r+\delta}-\frac{1-e^{-(r+\delta)\bar{a}^*}}{r+\delta}.$$

$$(8)\qquad f(0)=\frac{(\gamma+\delta)\bar{D}^*}{e^{\gamma\bar{a}^*}-e^{-\delta\bar{a}^*}}.$$

For future use, creation normalized by N, which is equal to $f^*(0)(1-e^{-\delta\bar{a}^*})/\delta$, is given in steady state by

$$(9)\qquad \mathrm{CC}^*=\frac{\delta}{1-e^{-\delta\bar{a}^*}}.$$

The special case when the creation cost is a constant c, independent of the creation rate, will be examined closely in what follows. In this case system (7)–(8) is recursive. We can first solve (7) for the steady-state efficient lifetime $\bar{a}^*$ that balances the benefits and costs of updating technology, independently of demand and the rate of creation.[12] Then we can obtain $f^*(0)$ from (8), given $\bar{a}^*$ and the level of demand $\bar{D}^*$.

II. Business Cycles

We now turn to the response of the creative-destruction process modeled above to cyclical fluctuations in demand. From a pure accounting point of view, our industry has two margins along which it can accommodate a fall in demand $\bar{D}(t)$. As can be seen from (1′), it can either reduce the rate of creation $f(0,t)$ or increase the rate of endogenous destruction $f(\bar{a}(t),t)[1-\dot{\bar{a}}(t)]$, which amounts to reducing the age $\bar{a}(t)$ at which units are destroyed [since $f(\bar{a}(t),t)$ is given at t]. The issue is which of these two margins, $f(0,t)$ or $\bar{a}(t)$, will respond to demand fluctuations, and to what extent?

The problem's difficulty comes from the interaction between two margins. For a given creation rate, a fall in demand will cause the most outdated units to turn unprofitable and be scrapped. But if the recession is partly accommodated by a fall in the creation rate, units in place may not suffer its full impact. We argue that the extent to which creation will thus "insulate" existing units from variations in demand depends on the costs of fast creation in the industry, that is, on $c'(f(0,t))$. The insulating effect of creation will be more complete, the smaller is $c'(f(0,t))$. In the extreme case where $c'(f(0,t))=0$ and adjustment takes place instantaneously, creation will

[12]The effect of different parameters on $\bar{a}^*$ is quite intuitive in this case: $\bar{a}^*$ decreases with γ, since faster technical progress raises the opportunity cost of delaying renovation; it increases with c so as to give more time to recoup higher creation costs; and it increases with r and δ, because they lead to heavier discounting of future profits and make it more difficult to recover creation costs in a short time.

$$(10)\quad f(0,t)=\frac{\dot{\bar{D}}(t)+\delta\bar{D}(t)+P(t)A(t-\bar{a}(t))f(\bar{a}(t),t)\left[1-\dot{\bar{a}}(t)\right]-\dot{P}(t)Q(t)}{P(t)A(t)}$$

fully accommodate demand fluctuations, and destruction will not respond. We start by examining this special case to clarify the insulation mechanism in our model, and then look at what happens more generally when insulation is incomplete.

A. *The "Insulation" Effect: An Extreme Case*

The insulating effect of creation can be best understood in the extreme case where the cost of creation c is a constant, independent of the rate $f(0,t)$ at which it is taking place. In this case adjustment is instantaneous, and as long as the nonnegativity constraint on $f(0,t)$ is not binding, the insulation effect is complete. Demand fluctuations are accommodated *exclusively* on the creation margin, and destruction does not respond.[13] To see why, note that there is a very simple way to solve equilibrium conditions (1)–(6) when $c(f(0,t))$ is constant. As we saw in the analysis of the steady state, the system of equations is recursive in this case. We can first solve for $\bar{a}(t)$, using the free-entry condition (4) together with (3) and (5). Given that these equations do not depend on the path of $\bar{D}(t)$ and $f(0,t)$, they can be solved independently. But since this is exactly what we did in the analysis of steady state when c was constant, the solution is the same constant lifetime $\bar{a}^*$ we obtained there, and accordingly a price $P(t)$ falling at constant rate γ.

Given this, we can then solve for the creation rate $f(0,t)$ to satisfy market equilibrium condition (6), using (1) and (2). In other words, the creation rate adjusts continuously to accommodate demand and, from (1′), is given by equation (10), above, which we assume yields a nonnegative $f(0,t)$.[14] In the resulting equilibrium, demand fluctuations are fully accommodated by adjustments at the creation margin $f(0,t)$, while $\bar{a}(t)$ remains constant at the destruction margin. The creation process neutralizes the effect of demand fluctuations on the price $P(t)$, thus fully "insulating" existing units from changes in demand. $P(t)$ falls at a constant rate γ that reflects the rate of technical progress, providing the right signal for production units to operate for the constant lifetime $\bar{a}^*$.

Note that the above analysis does not imply that the destruction rate will be constant in equilibrium, but only that it does not respond to demand through variations in the age $\bar{a}(t)$ at which units are destroyed. Variations in the destruction rate reflect an "echo" effect of the history of demand on the number $f(\bar{a}^*,t)$ of units that reach the age of obsolescence $\bar{a}^*$.

It is clear from the above proof that, in the case of constant creation cost, the full-insulation result is robust to any modification of the model that preserves the independence of (3)–(5) from $\{\bar{D}(t)\}$ and $\{f(0,t)\}$. In particular, it does not hinge on certainty, on perfect competition, or on the degree of industry-wide returns to scale. Perfect foresight is not necessary because, as long as it is known that the nonnegativity constraint on $f(0,t)$ will never be binding, implementing equilibrium behavior does not

[13]The insulation effect is *not* due to asymmetric adjustment costs on the creation and destruction margins. Insulation would still be complete if we were to add linear destruction costs, since doing so is equivalent to adding the present value of those costs to the cost of creation.

[14]By replacing equation (6) in (10) and noticing that $f(\bar{a}(t),t)\geq 0$ for all t, one may show that a *sufficient* condition for positive entry in the full insulation case is:

$$\dot{\bar{D}}(t)/\bar{D}(t)>-(\delta+\gamma).$$

Since creation cannot be negative, a fall in demand larger than $\delta+\gamma$ may break insulation, for any further fall in demand beyond the point of zero creation must be accommodated on the destruction side.

require expectations of future demand. Fully accommodating demand on the creation side only requires knowledge of *current* conditions. Perfect competition is not necessary either, since a monopolist's first-order conditions would only add a markup to equations (4) and (5) and preserve the recursive structure of system (1)–(6).[15]

Robustness with respect to industry-wide returns to scale is also straightforward but will be discussed in some detail for future reference. Assume the simple case where short-run increasing or decreasing returns are due to an industry-wide externality. More specifically, suppose that the output at t of a production unit of age a is $q(t)^{\beta}A(t-a)$, where $q(t)\equiv Q(t)/A(t)$ is aggregate output detrended by the leading technology and is taken as given by firms. In this case, it is simple to see that equilibrium conditions (1)–(6) remain unchanged if we substitute $\tilde{Q}(t)\equiv Q(t)/q(t)^{\beta}$ and $\tilde{P}(t)\equiv P(t)q(t)^{\beta}$ for $Q(t)$ and $P(t)$, respectively. We can then apply the same argument as before on the transformed system to prove that $\bar{a}(t)$ is constant in equilibrium.

B. *Creation and Destruction over the Cycle*

The full-insulation effect in the previous section was primarily due to the special case of constant creation costs. In reality, the industry may not be able to create all the necessary production units instantaneously in response to a rise in demand. In this section we show that if $c'(f(0,t))$ is positive, insulation will only be partial, and destruction will also respond to demand fluctuations.

Once we allow c to depend on $f(0,t)$, system (1)–(6) loses its analytic tractability and must be solved numerically. The solution method we devised is described in the Appendix: we turn (1)–(6) into a system of time-varying delay differential equations in $(f(0,t),\bar{a}(t))$ (see H. Gorecki et al., 1989), develop a "multiple-shooting" method for finding an equilibrium solution for given *arbitrary* values for the path $T(t)$, and then use an iterative procedure to converge to the right expectations for this path. For all numerical solutions we use the simple linear functional form

$$(11)\quad c(f(0,t))=c_0+c_1f(0,t)\qquad c_0,c_1>0.$$

To show the way both creation and destruction respond to demand, we generated a sinusoidal demand $\bar{D}(t)=1+0.07\sin(t)$ and solved for the resulting periodic equilibrium.[16] Figure 2 depicts the response of the normalized creation and destruction rates (CC and DD) to the change in demand, $\bar{D}(t)$. It is clear that the insulation effect is imperfect, and a fall in demand is accommodated partly by a fall in the creation rate and partly by a rise in the destruction rate.

With increasing creation costs, the industry will smooth the creation process, since it is costly to accommodate demand fluctuations fully with variations in $f(0,t)$. Reducing the rate of technology adoption to a near standstill in a recession may require firms to catch up at prohibitively expensive rates in the ensuing expansion. Thus creation will not fully insulate existing units, and part of the contraction will have to take place at the destruction margin.[17] From a purely formal point of view, destruction responds to demand because equations (3)–(5) are no longer independent of the path of $f(0,t)$ and demand.

III. Application to Job-Flow Data

In this section we explore the broad consistency of our model with U.S. data on

[15]In this case, the elasticity of demand would have to be greater than 1 for the monopolist's problem to be well defined.

[16]We set $r=0.065$, $\delta=0.15$, $\gamma=0.028$, $c_0=0.3$, and $c_1=1.0$. The cost parameters are entirely arbitrary at this stage. Later we calibrate them using U.S. manufacturing data on job flows.

[17]Had we introduced uncertainty in our model, a very similar effect would have emerged from a "time to build" feature of the creation process. In this case, unexpected changes in demand cannot be accommodated instantaneously on the creation margin and will therefore lead to a response on the destruction margin.

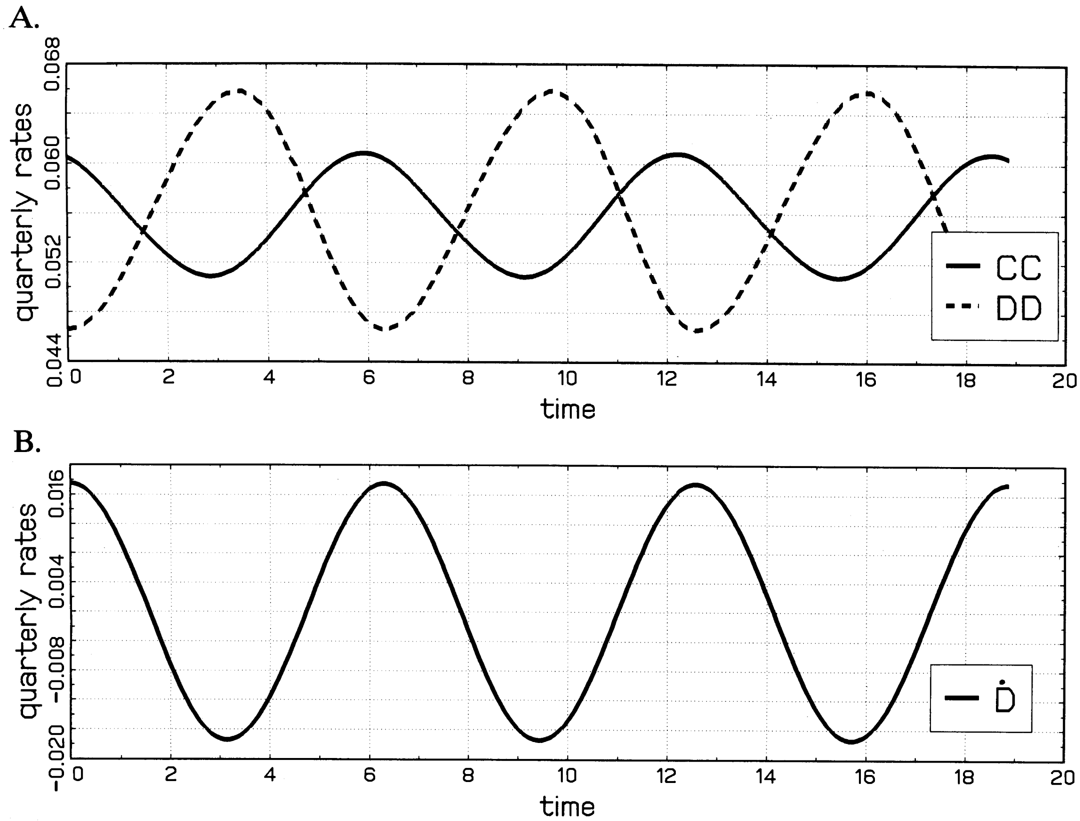

FIGURE 2. A) CREATION AND DESTRUCTION ($c_0 = 0.3$, $c_1 = 1.0$); B) CHANGE IN DEMAND (SYMMETRIC)

gross job flows. Although this is not meant to be a thorough investigation of labor markets, we find the match of nontrivial aspects of the job flow data a success for such a stylized model.

A. *A Look at the Data*

Production units in our model combine labor and capital in fixed proportions to produce output. One could therefore think of each unit as creating a job in the industry and use job-flow data to measure production unit flows.

Data on job creation and destruction that correspond roughly to our theoretical CC and DD series have been constructed by Davis and Haltiwanger (1990, 1992) and by Blanchard and Diamond (1990) using different sources. We focus on the data of Davis and Haltiwanger, who draw on the Longitudinal Research Database to construct quarterly series for U.S. manufacturing plants for the period 1972:2–1986:4.[18,19]

Since our model analyzes the response of job flows to demand fluctuations, we examine the corresponding relationship in the data. We use output $Q(t)$ to pin down demand empirically and take the growth rate

[18]Blanchard and Diamond's (1990) series are monthly and cover both manufacturing (for the period 1972–1981) and the economy as a whole (1968–1986). They are based on employment-flow data, from the Bureau of Labor Statistics for the manufacturing series and from the Current Population Survey for the economy-wide series.

[19]Because we lack within-plant measures of gross flows, there is an issue of whether the Davis-Haltiwanger series give us a useful measure of total gross job flows. One indication that they do is that they have major features in common with the Blanchard-Diamond series which are collected from workers rather than plants.

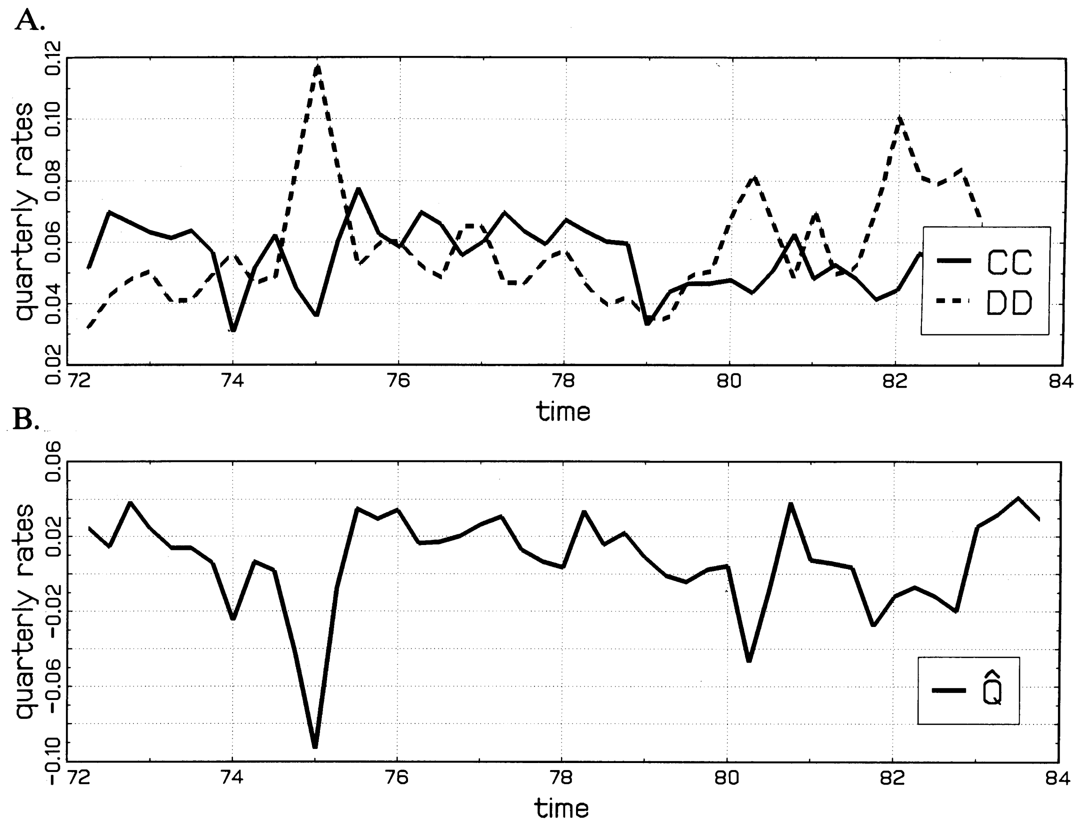

FIGURE 3. A) JOB CREATION AND DESTRUCTION IN U.S. MANUFACTURING; B) INDEX OF INDUSTRIAL PRODUCTION (RATE OF GROWTH)

of the index of industrial production as a measure of output growth.[20] Figure 3 depicts job creation, job destruction, and output growth for the manufacturing sector. The relation between these series is analyzed in Table 1 using two-digit SIC data. Regressions are run by constraining all coefficients to be equal across sectors, except for a constant.[21]

The first block ($\hat{Q}$) in Table 1 presents results from the regression of sectoral rates of job creation and job destruction on leads and lags of the corresponding rates of growth of the indexes of industrial production. The first result that arises is that the rate of job destruction is more responsive to changes in sectoral activity than is the rate of job creation (the sums of coefficients are -0.384 and 0.218, respectively). This can be seen directly from Figure 3 and is one of

[20] In our basic model $Q(t)$ is a smoothed [by the movements in $P(t)$] version of exogenous demand $\overline{D}(t)$. The degree of smoothing depends on the elasticity of demand, which, for simplicity, we assume to be 1 in the model. Interestingly, $Q(t)$ can be as volatile as $\overline{D}(t)$ [and $P(t)$ completely rigid] in the external-economies version of the model briefly discussed in Section II-A. Similarly, in our basic partial-equilibrium analysis we have assumed a constant consumption wage. However, allowing for a procyclical consumption wage, as would probably be the case in general equilibrium if shocks are correlated across industries, would dampen the effect of demand shocks but would not alter the basic qualitative features of our analysis.

[21] We also ran the regressions using aggregate manufacturing instead of sectoral industrial production on the right-hand side. The results were virtually unchanged.

TABLE 1—JOB CREATION AND DESTRUCTION RESPONSE TO OUTPUT GROWTH

		Creation		Destruction	
Regressor	Timing	Coefficient	Standard deviation	Coefficient	Standard deviation
$\hat{Q}$	2 leads	0.029	0.006	0.030	0.010
	1 lead	0.065	0.007	−0.068	0.010
	contemporaneous	0.108	0.007	−0.185	0.010
	1 lag	0.013	0.007	−0.103	0.010
	2 lags	0.003	0.006	−0.058	0.010
	Sum:	0.218	0.013	−0.384	0.017
$\hat{Q}^+$	2 leads	0.052	0.012	0.012	0.016
	1 lead	0.102	0.012	0.002	0.016
	contemporaneous	0.131	0.012	−0.065	0.016
	1 lag	0.059	0.012	−0.025	0.016
	2 lags	0.055	0.012	−0.008	0.016
	Sum:	0.399	0.026	−0.066	0.023
$\hat{Q}^-$	2 leads	0.002	0.010	0.006	0.014
	1 lead	0.022	0.011	−0.149	0.014
	contemporaneous	0.093	0.012	−0.293	0.015
	1 lag	−0.012	0.012	−0.139	0.015
	2 lags	−0.021	0.012	−0.059	0.015
	Sum:	0.084	0.020	−0.634	0.024

Notes: The table shows the response of job creation and job destruction to changes in the growth rate of the index of industrial production for each sector ($\hat{Q}$), and to the latter split into values above and below its mean ($\hat{Q}^+$ and $\hat{Q}^-$, respectively). The data are quarterly observations for the two-digit SIC manufacturing industries, for the period 1972:2–1986:4. The coefficients are constrained to be equal across all sectors, except for a constant (not shown).

the key findings of Davis and Haltiwanger (1990, 1992) and Blanchard and Diamond (1990). In terms of our model, the insulating effect of job creation seems far from complete. As can be seen in the simulated example in Figure 2, our model can easily match the fact that destruction is more responsive than creation.[22]

This kind of behavior can be generated in our model by costly speed of adjustment $c'(f(0,t)) > 0$. In fact, as our calibration exercise below shows, only a small elasticity of creation costs (around 0.2) is needed to explain the facts. In any case, the data exhibit features that provide a natural experiment to test this mechanism. Observed business cycles are highly asymmetric, with recessions shorter but much sharper than expansions. In this context, our model predicts that those asymmetries would be smoothed out in the creation process.

The evidence is summarized in the second and third blocks in Table 1, which split the regressors between periods in which the rates of growth of sectoral output are above their mean ($\hat{Q}^+$) and periods in which they are below it ($\hat{Q}^-$). Looking first at job creation, we find that it is more responsive to expansions in sectoral activity than to contractions (the sum of coefficients for $\hat{Q}^+$ and $\hat{Q}^-$ are 0.399 and 0.084, respectively). Going back to Figure 3, this corresponds to

[22] Davis and Haltiwanger (1992) show that the large variance of job destruction relative to that of job creation is mostly the result of the behavior of old, large, multi-unit establishments. Young, small, single-unit establishments exhibit the opposite pattern; that is, job creation is more volatile than job destruction. Our model is silent with respect to the size and multi-unit dimensions, given that its perfectly competitive linear setting makes no predictions about the division of production into firms and plants. However, it can easily rationalize the age-dependence of the relative volatility of job creation and destruction, since presumably older plants have a relatively large fraction of the outdated production units that our model predicts exhibit cyclical destruction, while young plants have mostly new production units.

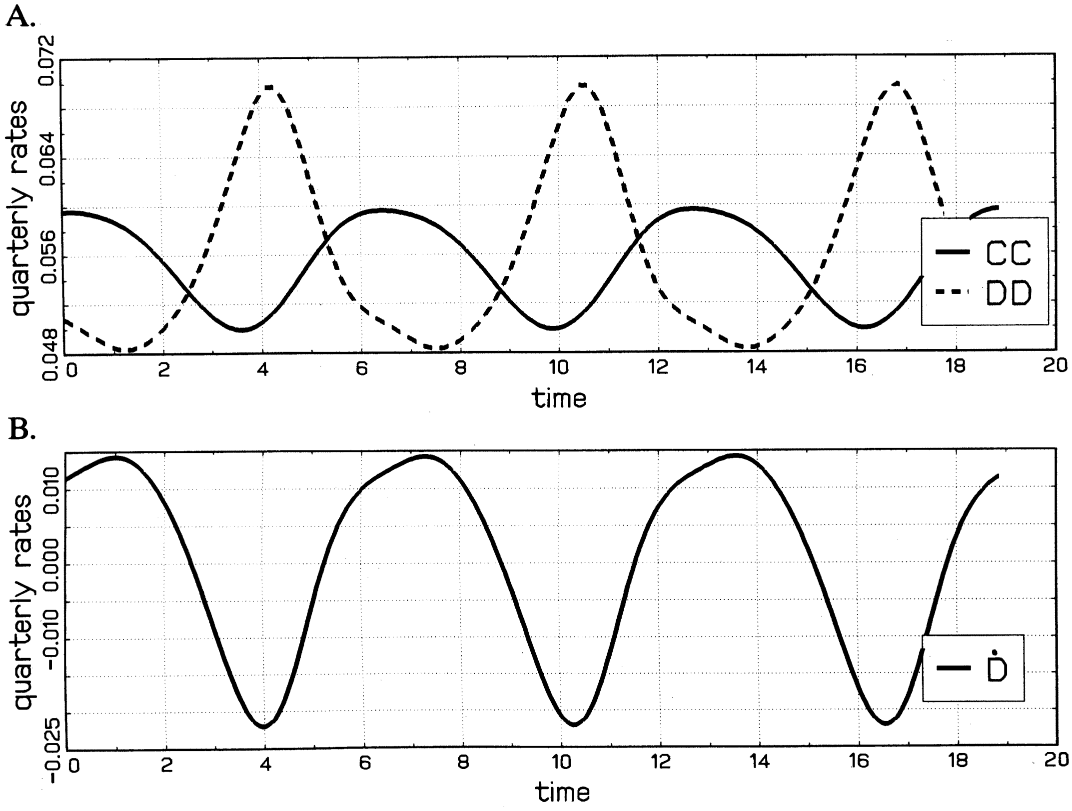

FIGURE 4. A) CREATION AND DESTRUCTION ($c_0 = 0.3$, $c_1 = 1.0$); B) CHANGE IN DEMAND (ASYMMETRIC)

the fact that job creation is roughly symmetric around its mean, while output growth is highly asymmetric, with recessions that are shorter-lived but much sharper than expansions. It is not surprising, then, that our regression yields an asymmetric response of job creation to expansions and recessions.

If we turn to job destruction, we find quite the opposite effect, with a sum of coefficients that is substantially larger in absolute value for recessions than it is for expansions (-0.634 vs. -0.066). Asymmetries in output are thus not only preserved in the response of job destruction (which would hold if the sum of coefficients were symmetric), but are actually amplified.

The fact that asymmetries in demand are smoothed out in the response of job creation and amplified in the response of destruction matches our model's predictions well. To show this, we simulated a periodic equilibrium with the *asymmetric* process for demand $\dot{\bar{D}}$ depicted in Figure 4.[23] It is clear that the creation process is roughly symmetric, while destruction is highly asymmetric. Firms use predictions of future demand in trying to smooth job creation; thus, the asymmetries in demand are smoothed out by the averaging of demand over the unit's lifetime. On the other hand, destruction depends only on current conditions; thus asymmetries are reflected directly on it. Moreover, if creation declines only mildly in response to a sharp contraction, the equilibrium price falls more sharply, which induces

[23]This process was generated with the equation $\dot{\bar{D}}(t) = 0.05[\cos(t) + \sin(t)] - 0.016\,\sin(2t) - 0.003\cos(3t)$. The initial level is set to $\bar{D}(0) = 1$, and model parameters are set to $r = 0.065$, $\delta = 0.15$, $\gamma = 0.028$, $c_0 = 0.3$, and $c_1 = 1.0$.

additional destruction. This is the reason why destruction not only preserves, but *amplifies* the asymmetries in demand; it must "make up" for the symmetry in creation.

B. *Calibration Exercise*

We now present the results of an exercise based on aggregate manufacturing series that provides a synthesis for the previous discussion. We calibrate the model and use it to generate the equilibrium job creation and destruction series that are consistent in theory with the observed path of employment. In other words, we use the model to split observed net changes in employment into their gross creation and destruction components. We then repeat the exercise using the observed path of output and compute the creation and destruction series that are consistent in theory with the path of demand implied by observed output movements. In both cases, the model-generated series are compared with actual observations.

Solving for an equilibrium requires an initial age distribution of jobs, and expectations of what demand would be after the end of the sample period. We handle this problem by solving for a *periodic* equilibrium, with a period equal to the sample period. The model's response was simulated for the period 1972:2–1983:4 using the method described in the Appendix.[24]

The parameter values we used to calibrate the model are summarized in Table 2. We chose a yearly interest rate $r = 6.5$ percent and a depreciation/failure rate $\delta = 15$ percent. To choose the rate of technical progress γ, we approximated trend values by averages over the sample. Since there was very little growth in manufacturing employment over the sample period (and one can easily show the direct link between demand and employment growth), we attributed all of the average growth rate of output to technical progress and set $\gamma =$ 2.8 percent.

TABLE 2—CALIBRATED PARAMETERS

Variable	Symbol	Value
Interest rate	r	0.065
Depreciation rate	δ	0.150
Rate of technical progress	γ	0.028
Adjustment cost parameters	c_0	0.403
	c_1	0.500

While our results are not very sensitive to the above parameters, they strongly depend on the parameters c_0 and c_1 of the adjustment-cost function (11). These parameters were chosen as follows. First $\bar{a}^*$ was calibrated based on equation (9), which relates the steady-state lifetime of jobs to job turnover CC*. Using the average value of CC over the sample for CC*, we find that $\bar{a}^* = 7.42$ years. This, together with the parameter values above, allows us to calculate from (7) the present discounted value of profits a production unit can generate in steady-state. By the free-entry condition, this must be equal to the steady-state creation cost, and it is found to be $c^* = 0.525$ (equivalent to a half year's operating costs for the production unit). This leaves us with only one free adjustment-cost parameter, since c_0 and c_1 are related in steady state to c^* by (11):

$$c^* = c_0 + c_1 f^*(0)$$

where $f^*(0)$ is given by equation (8). We searched for the value of c_1 that minimizes the weighted sum of squared residuals of the creation and destruction series and found a value of 0.5.[25] This corresponds to a relatively small elasticity for the creation

[24]Although the Davis and Haltiwanger (1990, 1992) job-flow series extend to 1986:4, we chose a shorter period for three reasons. (i) Numerical problems get worse as the simulation period gets longer. (ii) Because we are solving for a periodic equilibrium, we need demand to be roughly at the same level at the beginning and at the end of the period. (iii) Our model has little to say about the behavior of job destruction in 1985–1986, which exhibits two sharp peaks that are not associated with much action on the demand side.

[25]We used the inverse of the covariance matrix of creation and destruction as a weighting matrix. Our grid evaluated the model at values of c_1 0.1 units apart. We calibrated c_1 using the employment-driven simulations, which gave us higher values of c_1 than the demand-driven simulations. The qualitative conclusions are unaffected by our choice, however.

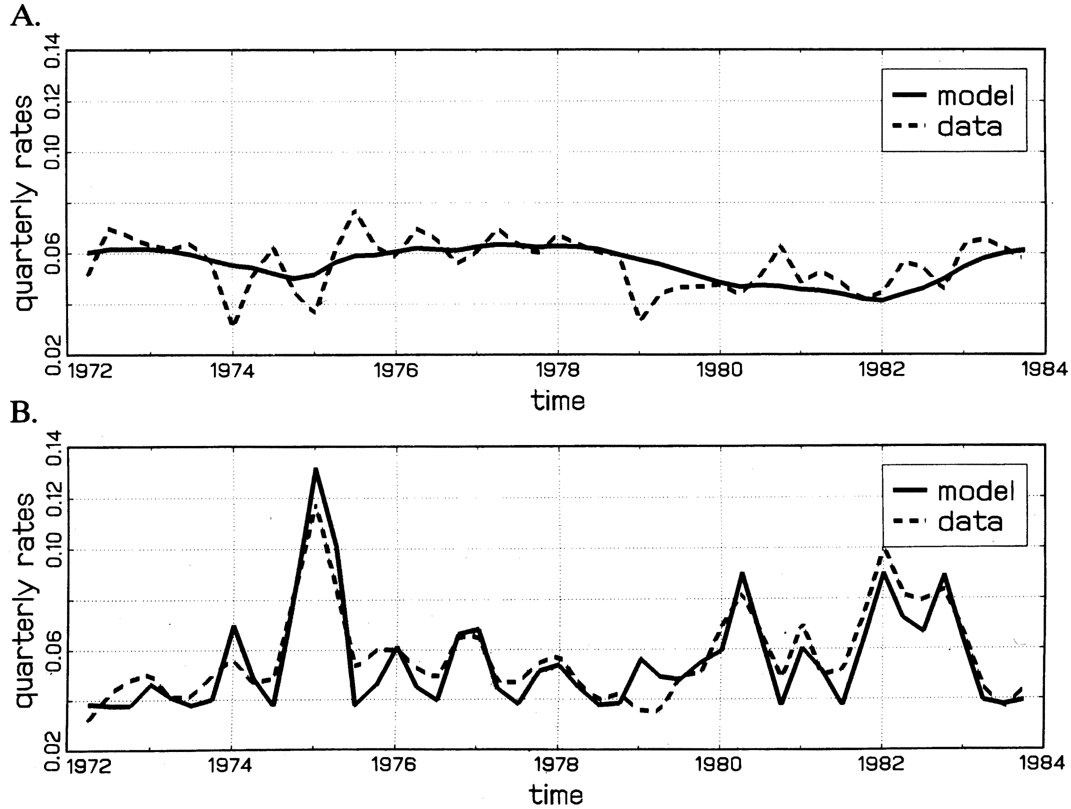

FIGURE 5. A) EMPLOYMENT-DRIVEN JOB CREATION ($c_0 = 0.403$, $c_1 = 0.500$); B) EMPLOYMENT-DRIVEN JOB DESTRUCTION ($c_0 = 0.403$, $c_1 = 0.500$)

cost function, which reflects the fact that, although the insulation mechanism breaks down easily, creation has enough volatility in the data so costs of fast creation cannot be too large.

An issue we faced in the output-driven simulation concerned the observed procyclicality of average labor productivity, which our basic model is not designed to explain. To capture this, we introduced an output externality along the lines discussed in Section II-B and set the externality parameter β equal to 0.18 (as estimated by Caballero and Richard K. Lyons [1992]). Note, however, that our particular interpretation of procyclical productivity is not crucial here, since all it does is dampen the output fluctuations used to drive the simulation by a factor of β. The employment-driven simulation is unaffected.

The results of the employment-driven and output-driven simulations are given and compared to the data in Figures 5 and 6.[26] Job creation appears too smooth compared to the data, which is at least partly due to the absence of uncertainty in our model. In general, however, the model can clearly account for the relative volatility of job creation and destruction, and for the greater symmetry of the former compared to the latter.

[26]Note that the output-driven simulation cannot be expected to capture seasonal movements in observed job flows (which are not seasonally adjusted) because the driving process, industrial production, is seasonally adjusted.

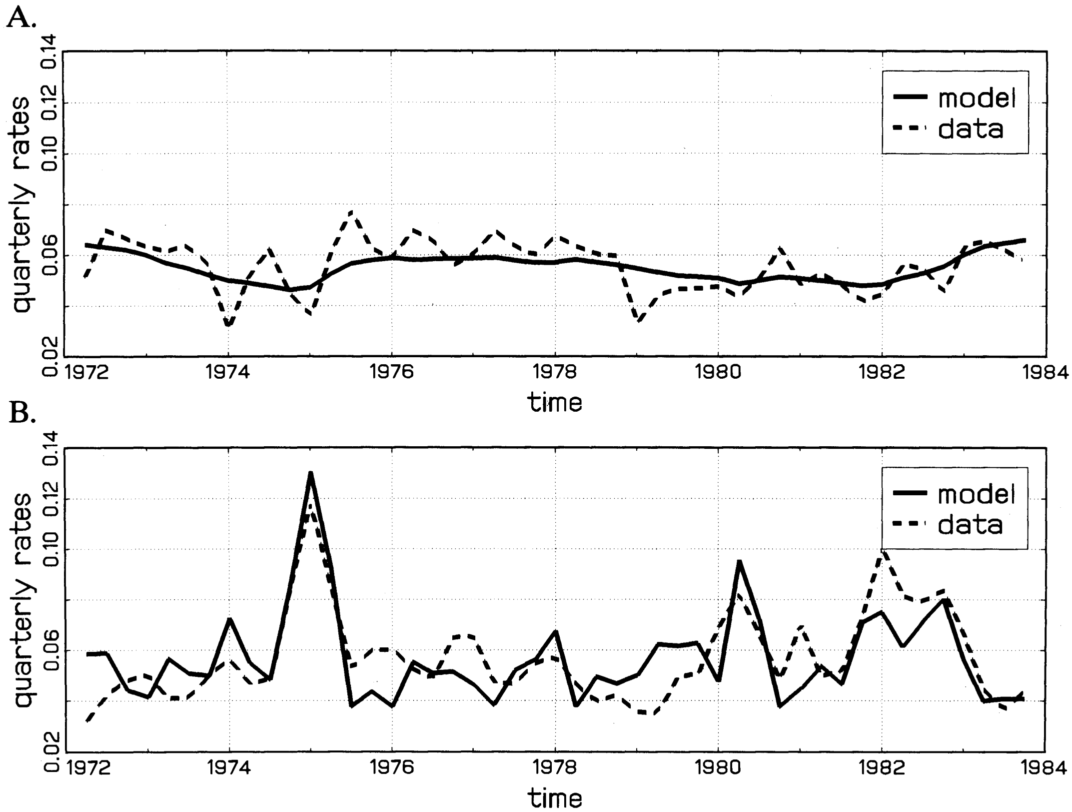

FIGURE 6. A) OUTPUT-DRIVEN JOB CREATION ($c_0 = 0.403$, $c_1 = 0.500$); B) OUTPUT-DRIVEN JOB DESTRUCTION ($c_0 = 0.403$, $c_1 = 0.500$)

IV. Concluding Remarks

This paper has examined industry response to demand fluctuations in a vintage model of creative destruction, where the response can take place along two possible margins. We have argued that responses to demand fluctuations on the creation margin have an "insulating" effect on existing production units, reducing the sensitivity of the destruction side. The extent to which this happens depends on the structure of creation costs. Empirically, the model seems to provide a good basis for interpreting the data of Davis and Haltiwanger (1990, 1992) on gross job flows.

The central features in our analysis are heterogeneity across production units and their turnover. Although they arise quite naturally in the context of creative destruction, these features can also appear in other environments. Hopenhayn and Richard Rogerson (1991) and Caballero (1992) provide examples of models in which two margins arise because of idiosyncratic productivity or demand shocks.[27]

Several extensions can be introduced without modifying the basic results of the paper. For example, there is evidence that new plants tend to have larger failure rates, which can be easily accommodated in our

[27]A meaningful treatment of two margins of adjustment requires heterogeneous production units. In our paper, this arises because of embodied technical progress ($\gamma > 0$) coupled with creation costs. In the absence of technical progress ($\gamma = 0$) all production units would be identical, and the two margins would not generally be active simultaneously, unless we introduce another source of heterogeneity, such as idiosyncratic shocks.

model by making the exogenous failure rate a decreasing function $\delta(a)$ of a. Furthermore, not all surviving production units in a given cohort turn out to be equally productive, which amounts to specifying a productivity function $A(t,z)$, where z is an index of productivity within a cohort with some distribution $g(z)$. Finally, it is also reasonable to allow for a learning curve; that is, the productivity of a production unit created at time t_0 can depend on its age, $A(t_0, a)$, with $0 < A_a(\cdot,\cdot) < \gamma A(\cdot,\cdot)$.

In terms of our model, the fact that job destruction is much more responsive than creation to the business cycle leads to the view that recessions are a time of "cleansing," when outdated or unprofitable techniques and products are pruned out of the productive system. A related, but distinct idea is the "pit-stop" view of recessions, according to which recessions are times when productivity-improving activities are undertaken because of their temporarily low opportunity costs (see e.g., Davis and Haltiwanger, 1990; Aghion and Gilles Saint-Paul, 1991; Jordi Galí and Hammour, 1991; Robert Hall, 1991).

One objection to the view that recessions are times of cleansing is that it implies countercyclical productivity, while average labor productivity is in fact procyclical. However, one can show that this effect on productivity is likely to be small and may be dwarfed by other factors (labor hoarding, externalities, etc.) that make measured productivity procyclical.[28,29] An appropriate empirical investigation into the cleansing effect must look at the *dynamic* response of productivity to business cycles. There, the evidence has been debated. Although William T. Dickens (1982) argues that recessions leave permanent productivity scars, the more recent paper by Galí and Hammour (1991) finds evidence that recessions improve productivity over the medium–long term.

Finally, one should be careful to distinguish the positive view that recessions are times of cleansing, from the normative view that recessions are therefore "desirable" events. This paper addresses only the positive side of the question, while the normative side is analyzed in Caballero and Hammour (1994).

Appendix

This appendix describes our method for computing the equilibrium path of the model given by equations (1)–(6), given a periodic path for demand. Let $\phi(t) \equiv f(0,t)$. Differentiating (4) and (6) with respect to time, taking (1), (2), and (5) into account, yields

$$\text{(A1)}\quad \dot{\bar{a}}(t) = 1 + \frac{\dot{\bar{D}}(t) + \delta\bar{D}(t) - e^{\gamma\bar{a}(t)}\phi(t)}{\gamma\bar{D}(t) + \phi(t-\bar{a}(t))e^{-\delta\bar{a}(t)}}$$

$$\text{(A2)}\quad \dot{\phi}(t) = \frac{1}{c_1}\left((r+\delta+\gamma)[c_0 + c_1\phi(t)] - (e^{\gamma\bar{a}(t)} - 1) + \gamma\frac{1-e^{-(r+\delta)T(t)}}{r+\delta}\right)$$

[28]Starting from steady state and using calibrated values for model parameters ($\delta = 0.15$, $\gamma = 0.028$, $\bar{a}^* = 7.4$ years), the effect of destroying 10 percent of the jobs in an industry at the low-productivity margin is a 1.1-percent improvement in average labor productivity. It will be even smaller relative to trend if accompanied by a fall in the creation rate.

[29]This idea finds strong support in Bresnahan and Raff's (1991) study of the motor-vehicles industry during the Great Depression. Although average labor productivity fell during the Depression, they found that "output per worker in the industry did not decline nearly so much as output per worker at a typical continuing plant from 1929 to 1933. Because the exiting plants were low in labor productivity and because their numbers were large in the aggregate, they account for this large composition effect" (p. 330).

This phenomenon is documented for a broader set of industries in the Baily et al. (1992) study mentioned in footnote 2, which decomposes productivity growth into a part that takes place at the plant level and a part due to resource reallocation across plants. For the three periods 1972–1977, 1977–1982, and 1982–1987, the plant-level components were 2.80 percent, −6.08 percent, and 7.16 percent, while the reallocation components were 1.83 percent, 2.90 percent, and 1.82 percent (results for "all industries except 3573," in Baily et al.'s table 1 [p. 207]). Thus, the cyclical contraction in *aggregate* productivity that took place in the middle of the period was smaller than the contraction that took place at the typical plant. This difference was due to the positive reallocation component of productivity growth, which was in fact larger than in the first and last periods.

where $\{T(t)\}$ is related to $\{\bar{a}(t)\}$ through equation (3):

$$\text{(A3)} \qquad \bar{a}(t+T(t)) = T(t).$$

The differential system (A1)–(A3) has several interesting but complex features. First, equation (A1) for $\dot{\bar{a}}(t)$ includes the second variable $\phi(t-\bar{a}(t))$ delayed. Second, this delay is not only flexible, but depends on $\bar{a}(t)$. Third, equation (A2) for $\dot{\phi}(t)$ includes $T(t)$, which by (A3) is a flexible lead that depends on the function $\bar{a}(\cdot)$.

In order to solve this system, we limit ourselves to the case of a periodic driving force $\bar{D}(t)$, with period R. Our algorithm calculates at each iteration i a one-period path $X_i \equiv \{\phi_i(t), \bar{a}_i(t)\}_{0 \leq t < R}$ of creation and destruction, *given* a history of past creation $H_i \equiv \{\phi_i(t)\}_{t<0}$ and expected lifetimes $E_i \equiv \{T_i(t)\}_{0 \leq t}$. With the given history and expectations, system (A1)–(A2) can be solved forward for any initial values for $(\phi(0), \bar{a}(0))$. Using a multiple-shooting procedure, X_i is chosen to be a "periodic" solution for (A1)–(A2), in the sense that

$$(\phi_i(0), \bar{a}_i(0)) = (\phi_i(R), \bar{a}_i(R)).$$

The algorithm proceeds as follows:

Initialization.—Set $i=1$ and the initial history H_1 and expectations E_1 to arbitrary values (e.g., their steady-state values for an average level of demand $\bar{D}^*$).

Iteration i.—Generate the one-period solution X_i, given H_i and E_i. If $i>1$ and $|X_i - X_{i-1}|$ is less than some small ε, the procedure has converged. Use X_i as the equilibrium solution and terminate the algorithm. Otherwise, calculate H_{i+1} and E_{i+1} for the next iteration by extending the "periodic" function X_i to the whole real time interval. H_{i+1} is set equal to the resulting periodic history of $\phi(t)$, and E_{i+1} is obtained from the periodic expectation of $\bar{a}(t)$ using equation (A3). Once this is done, increment i and repeat the iteration.

We ran the two theoretical simulations in Figures 2 and 4 using this method. The employment- and output-driven simulations in Figures 5 and 6 were run with the same method, except that equation (A1) was modified so that we can take output and employment as given, rather than demand.

For the employment-driven simulation, equation (A1) was modified as follows. Since the path of $N(t)$ is taken as given, we rewrite (A1) in terms of employment. Recalling the expression

$$\dot{N}(t) = f(0,t) - \{f(\bar{a}(t),t)[1-\dot{\bar{a}}(t)] + \delta N(t)\}$$

derived in Section I-A, we get

$$\text{(A1}'\text{)} \quad \dot{\bar{a}}(t) = 1 + \frac{\dot{\bar{N}}(t) + \delta\bar{N}(t) - \phi(t)}{\phi(t-\bar{a}(t))e^{-\delta\bar{a}(t)}}.$$

We replace (A1) by (A1′) and use the solution method described above.

As for the output-driven simulation, recall that we introduced an externality β along the lines described in Section II-A. In this case equilibrium conditions (1)–(6) only hold if we substitute $\tilde{Q}(t) \equiv Q(t)/q(t)^{\beta}$ and $\tilde{P}(t) \equiv P(t)q(t)^{\beta}$ for $Q(t)$ and $P(t)$, respectively, where $q(t) \equiv Q(t)/A(t)$. In other words, by (5), we need to dampen observed output fluctuations $\hat{Q}(t)$ (where a "hat" designates a growth rate) by a factor of β and use

$$\hat{\tilde{Q}}(t) = \hat{Q}(t) - \beta[\hat{Q}(t) - \gamma].$$

With this in mind, we rewrite (A1) in terms of "dampened" output. The latter is related to demand through equations (5) and (6):

$$\bar{D}(t) = \tilde{Q}(t)e^{-\gamma[t-\bar{a}(t)]}$$

where units were chosen so that $A(0)=1$. Replacing for $\bar{D}(t)$ and $\dot{\bar{D}}(t)$ in (A1) and rearranging, we get

$$\text{(A1}''\text{)} \quad \dot{\bar{a}}(t) = 1 + \frac{\left[\dot{\tilde{Q}}(t) + \delta\tilde{Q}(t)\right]e^{-\gamma t} - \phi(t)}{\phi(t-\bar{a}(t))} \times e^{(\gamma+\delta)\bar{a}(t)}.$$

We replace (A1) by (A1″) and solve.

Note that to run these simulations in continuous time, we need a continuous path for $N(t)$ and $Q(t)$, whereas the observed path is discrete. To handle this problem, we regress the growth rates of these two series on as many $\sin(i\omega t)$ and $\cos(i\omega t)$ terms, $i = 1, 2, \ldots,$ as we have degrees of freedom, where $\omega \equiv 2\pi / R$. We use the resulting continuous and periodic representation to run the simulations.

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