The Impact of TFP Growth on Steady-State Unemployment*

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Abstract

Theoretical predictions of the impact of TFP growth on unemployment are ambiguous, and depend on the extent to which new technology is embodied in new jobs. We evaluate a model with embodied and disembodied technology, capitalization, and creative destruction effects. In econometric estimates with a panel of industrial countries we find a large negative impact of TFP growth on unemployment, which implies that embodied technology and creative destruction play no role in the steady-state dynamics of unemployment. Capitalization effects explain some of the estimated impact but a part remains unexplained.

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1 Introduction

The simultaneous slowdown of productivity growth and rise in unemployment in industrial countries in the second half of the 1970s has led many economists to believe that there is a close connection between the two. Several authors have presented econometric estimates that show a strong negative impact of productivity growth on unemployment.[2] But theoretical models have been less successful in explaining why faster productivity growth should be associated with lower unemployment. Two approaches have been followed in the literature. The first approach focuses on the supply of labor and claims that faster productivity growth increases supply. Ball and Moffitt (2002) assume that workers adjust to changes in productivity growth with a long lag, so when productivity growth changes the ratio of wages to productivity gets distorted, causing employment effects. Phelps (1994) assumes that the supply of labor depends on the ratio of income from human capital to income from nonhuman capital, and productivity growth influences nonhuman capital with a long lag. Both these explanations rationalize a negative impact of productivity growth on unemployment but one that should eventually reverse.

The second approach focuses on the influence of productivity growth on the demand for labor. When new technology arrives a firm may be able to upgrade an existing job and keep the same worker, or it may have to destroy the job and fire the worker. In the former case faster productivity growth implies higher demand for labor and permanently lower unemployment because of "capitalization" effects (Pissarides 2000). These effects are essentially due to the fact that the cost of job creation is paid up-front and recovered from the revenues over the life of the job. With faster growth future revenues are discounted at a lower rate but costs are sunk and so are unaffected. If the

[2] The discussion of the connections between productivity growth and employment goes back at least to Bruno and Sachs (1985), who looked at the experience of the 1970s. For more recent empirical (time series) studies see Phelps (1994), Blanchard and Wolfers (2000), Fitoussi et al. (2002), Staiger et al. (2002), and Ball and Moffitt (2002).

firm cannot adopt the new technology in its existing jobs faster productivity growth leads to "creative destruction" and more entry into unemployment, implying permanently higher unemployment in the steady state (Aghion and Howitt 1994). In intermediate cases the impact of growth on unemployment is ambiguous, and depends on the extent to which new technology is embodied in new jobs (Mortensen and Pissarides 1998).

This paper evaluates the second class of models. It has two objectives. The first is to develop a quantifiable steady-state growth model with unemployment and exogenous TFP growth and compute the quantitative importance of the capitalization and creative destruction effects. The first finding of the paper comes out of this analysis. It is that at reasonable parameter values a nontrivial negative impact of TFP growth on unemployment is incompatible with embodied technology. The reason is that at the observed aggregate TFP growth rates and job destruction rates, when technology is embodied creative destruction effects have a much bigger quantitative impact on unemployment than capitalization effects. We emphasize that in this paper by embodied technology we mean technology that is embodied in new jobs; it may or may not be embodied in new capital.[3]

The second objective of the paper is to compare the effects of TFP growth on unemployment that are derived from the model with econometric estimates. Because there are no readily usable estimates in the literature, we compute our own estimates from an estimated system of three equations (for employment, wage growth and capital accumulation) that is consistent with our model.[4] Our estimates show a large negative impact of TFP growth on unemployment at the aggregate level. In the United States TFP growth explains the dynamics of trend unemployment. In Europe it explains less but it still explains a large fraction of the observed changes in unemployment. The reduced-form semi-elasticity of aggregate employment with respect to the TFP growth rate (at 6 percent unemployment rate) is about 1.4. The second finding of the paper is related to these estimated effects. It is that at conventional aggregate rates of growth the capitalization effect can explain

[3] For example, a new version of Microsoft Windows that needs a more powerful computer is new technology that is embodied in new capital. But if the worker who worked with the previous version of MS Windows keeps her job and learns how to use the new version the new technology is not embodied in new jobs. In this paper we have nothing to say about technology that is embodied or disembodied in new captal.

[4] The estimated equations are described fully in the Appendix. The data are an annual panel covering 31 years and 15 industrial countries.

some but not necessarily all of the negative impact of productivity growth on unemployment.

Further examination of the links between growth and unemployment in the model and in the estimates reveals that the wage equation and horizon length play important roles in the transmission of the growth effects. In the theoretical model we study the implications of two wage equations, one that shares the rents from jobs in constant proportions, as is common in the Nash wage equations of equilibrium search models, and one that makes wages a fixed fraction of productivity. The implied elasticity of wages with respect to unemployment in the sharing equation is high, about -0.44.[5] In the second equation it is zero, by assumption. In the econometric estimates the elasticity is very low but statistically significant, about -0.04.[6] We show that the model is more successful at explaining the impact of productivity growth on unemployment when wages are modeled as a fixed fraction of productivity, or when the elasticity is matched to the estimated number, than when they are modeled as a fixed sharing rule.[7]

When the unemployment elasticity of wages is zero, the capitalization effect can explain the entire estimated impact of TFP growth on unemployment but only when the firm's horizon when creating jobs is very long, practically infinite. Davis, Haltiwanger and Schuh (1996) and others estimate that on average a job lasts for ten years. If a ten-year horizon when computing the expected present discounted value of profits from job creation, the capitalization effect is still positive but explains about a third of the impact of TFP growth on unemployment.

[5] This elasticity is computed from the Nash sharing rule when the economy is on the Beveridge curve and the parameters take the values used in the quantitative application of the model.

[6] This estimate is related to the unemployment elasticity of the "wage curve". Blanchflower and Oswald (1994) find that it is -0.1 in a large number of samples, an estimate confirmed more recently by Sanz-de-Galdeano and Turunen (2005) for European countries (who estimate it at -0.14).The wage-curve estimates are usually obtained from single-equation models and large samples of micro data, which may explain the difference with our estimate. Faggio and Nickell (2005) find an average elasticity of -0.04 for the United Kingdom.

[7] Although these conclusions about the behavior of wages seem to reconfirm the recent criticisms of the ability of matching models to match the cyclical behavior of unemployment by Shimer (2005) and Hall (2005), there is an important difference between them. In this paper we examine the impact of the growth rate of productivity on steady-state unemployment. With our wage equations productivity shocks would have no impact on unemployment.

Thus, some problems remain for future research: Do firms create jobs by looking only at short horizons because of high rates of job destruction, or do they apply longer horizons? Why are wages unresponsive to unemployment, and do the mechanisms that explain this lack of response also explain the impact of TFP growth on unemployment that is left unexplained by the capitalization effect? Are these mechanisms related to the temporary but long-lived supply effects emphasized by Phelps (1994) or by Ball and Moffitt (2002)? One robust result of this paper is that the Solow growth model with unemployment is a good framework for future research that might address these issues.

The paper is organized as follows. Section 2 reports summary results of econometric estimates of the impact of TFP growth on employment, wages and capital in a panel of industrial countries. The full set of estimates is given in the Appendix. Section 3 describes and solves the theoretical model. Section 4 calibrates the solution to the experience of the United States and shows that at the aggregate level the model implies that technology is disembodied. It also calculates how much of the estimated impact of TFP growth on unemployment can be explained by the capitalization effect. Some final comments and conclusions are collected in section 5.

2 Empirical evidence

Although the empirical studies cited in the introduction to this paper usually find a positive impact of productivity growth on employment, they do not compute readily usable elasticities for steady-state effects. We summarize here the results of an econometric estimate of the impact of TFP growth on steady-state employment, obtained from the estimation of a three-equation system described more fully in the Appendix. The three equations are for employment, wages and the capital stock and the exogenous variables are TFP and its growth rate, the real interest rate, the participation rate and institutional variables. The data are annual for the period 1965-1995 for the countries of the European Union (except for Spain and Greece), the United States and Japan. The time series for TFP was constructed from growth-accounting equations for each country in the sample by making use of a smoothed labor share, following the procedure of Harrigan (1997), and it was rescaled to be labor-augmenting.[8] The estimated equations are consistent with the model of this paper but they are also consistent with other models, so they are not a test of this or any other model. The objective is to obtain elasticity estimates that can be used to make inferences about the model. The inferences are all about long-run behavior.

The long-run versions of the estimated equations, omitting variables that are of no interest in this exercise (full details are in the Appendix) are as follows:

$$\begin{aligned}
\ln L &= -.98 \ln w + .45 \ln k + .52 \ln A + 1.23 d \ln A && (1)\\
d \ln w &= .53 d \ln k + .26 d \ln A - .19 (\ln w - .47 \ln k - .53 \ln A + .04 \ln u) && (2)\\
d \ln k &= .5 d \ln A - .05 (\ln k - 2.4 \ln A + 1.4 \ln w) && (3)\\
u &= 1 - \frac{L}{LF} \approx \ln LF - \ln L && (4)
\end{aligned}$$

where L is the ratio of employment to the population of working age, w is the real cost of labor, k is the capital-labor ratio, A is TFP, u is the unemployment rate and LF is the participation rate. The only exogenous variables reported in the equations are TFP and the participation rate. All variables are indexed by country and year, with 15 countries and 31 years in the sample.

Under the assumption of a constant participation rate and a constant rate of TFP growth, denoted by a, a steady-state solution to equations (1)-(4) exists and is characterized by constant employment rate, constant unemployment rate, wages growing at rate a and capital-labor ratio growing at rate a. This paper is about this steady state. On this steady state, the semi-elasticity of employment with respect to the TFP growth rate, conditional on the real cost of labor is 1.23. The more interesting reduced form semi-elasticity depends on the unemployment rate. It is computed from (1), (2) and (4) and satisfies

$$\frac{1}{L}\frac{\partial L}{\partial a} = \frac{2.33}{1 + .039/u}. \qquad (5)$$

At $u = .06$, the sample mean of the unemployment rate, it is 1.41, and at $u = .08$, which is more characteristic of the European economies in the later part of the sample, it is 1.57.

[8] We also calculated TFP growth from estimated production functions with time and country dummies with virtually identical results.

Table 1: Actual and predicted unemployment rate, productivity slowdown

Period	mean TFP growth (%)		mean rate of unemployment (%)		predicted rate of unemployment (%)	
	US	EU	US	EU	US	EU
1960-73	1.90	3.95	4.96	2.26	-	-
1974-92	0.80	1.79	6.82	6.60	6.60	5.10

The estimated equation system fits the data well, so the exogenous variables included in the estimates capture well the dynamics of the unemployment rate, wages and the capital stock. But how much is the contribution of TFP growth to this explanation? To answer this question we report the results of a simulation exercise with the estimated model. Figure 1 shows the unemployment rate obtained from the model when we allow TFP growth to take its actual values but keep constant at their initial values all the other exogenous variables. Overall, the figure indicates that TFP growth explains a significant portion of unemployment in the economies of the United States and Europe. It explains well the trend changes in unemployment in the United States. Panel (a) shows three unemployment series, the actual unemployment rate, the univariate trend unemployment rate constructed by Staiger, Stock and Watson (2002) and our simulated series. The simulated series tracks the trend series well, with a correlation coefficient of 0.87. But in the European Union, TFP growth explains a lower fraction of the overall change in the unemployment rate. Although the slowdown in TFP growth in the 1970s explains some of the rise in unemployment up to the mid 1980s, TFP growth fails to account for the dynamics of unemployment in the 1990s.[9]

We report a second experiment with the estimated model, which we will use later to evaluate the quantitative importance of the capitalization effect. We calculate the response of the endogenous variables to a once-for-all fall in the rate of growth of TFP, but instead of assuming an arbitrary change in the rate of growth of TFP, we simulate a productivity slowdown that corresponds roughly to the slowdown observed after 1973. Table 1 shows the average TFP growth rate prior to 1973 and the average growth rate up to 1992, before growth picked up again. We initially fix TFP growth at its pre-

[9] A similar conclusion was reached by Hatton (2006) for Britain in his single-equation historical estimate. He found that the productivity slowdown of the 1970s explains about a quarter of the rise in unemployment over the same period.

1973 mean value and choose the values of the other exogenous variables such that the economy is on a steady state with the capital-labor ratio and wage rate growing at the same rate as the mean TFP rate shown in the Table. The unemployment rate on this steady state is constant at the mean rate shown in the Table for 1960-73. The last row of the Table shows the sample means for 1974-92 and the new steady-state unemployment rates predicted by the estimates when the rate of TFP growth is reduced in 1974 and held indefinitely at the lower mean rate shown in the Table, until a new steady state is reached.[10]

Table 1 shows that our estimates get close to attributing the full rise in US unemployment after 1973 to the productivity slowdown, in contrast to Europe, where our prediction falls short by about 1.5 percentage points. The change in the unemployment rate for each unit change in the growth rate is -1.49 for the United States and -1.31 for the European Union. This ratio is close to the semi-elasticity of employment with respect to the growth rate in (5). The differences in the values calculated from (5) and the values calculated from Table 1 are due mainly to the different unemployment values in the two samples.

The conclusion reached from the econometric estimates is that the impact of TFP growth on unemployment is substantial, both in terms of the estimated elasticities and in terms of the contribution of TFP growth to the explanation of the evolution of the unemployment rate in the last thirty years. Can a matching model of unemployment match these estimated impacts? This is the question that we turn next, focusing on the estimates for the United States.

3 Theory

We model employment by deriving steady-state rules for job creation and job destruction for the representative firm. The key to the derivation of growth effects is to assume that job creation requires some investment on the part of the firm, which may be a set-up cost or a hiring cost. Both firm and worker will want such jobs to last and so they care about the way that the marginal

[10] There are long estimated lags for all the endogenous variables. Wage growth covers half the distance to the new steady state in 3 years, capital growth in 7 years and unemployment in 5 years. Of course, in the new steady state wage growth and capital growth are down to the mean TFP growth rate for 1974-92.

product and wage rate evolve over time.

As in Mortensen and Pissarides (1998), the impact of TFP growth on job creation and job destruction depends on whether new technology can be introduced into ongoing jobs, or whether it needs to be embodied in new job creation. Unlike the Mortensen-Pissarides model, however, here we explicitly introduce a Cobb-Douglas technology and the capital stock as a choice variable, we consider the implications of more than one wage rule, and we model the embodiment or disembodiment of technology in a way that can be quantified and matched to the data. The simple way in which the model can be matched to the data and yield conclusions about the quantitative importance of embodied technology and capitalization effects in the evolution of employment is the main innovation of the theoretical model in this paper.

We assume that there are two types of technology. One, denoted by A_1, can be applied in existing jobs as well as new ones, as in the Solow model of disembodied technological progress. The other, denoted by A_2, can only be used by new jobs, an idea attributed by Aghion and Howitt (1994) to Schumpeter. We let the rate of growth of A_1 be λa and the rate of growth of A_2 be $(1-\lambda)a$, with $0 \leq \lambda \leq 1$, so the total rate of growth of technology is a. Both λ and a are parameters. The parameter λ measures the extent to which technology is disembodied. If $\lambda = 0$ we have the extreme "Schumpeterian" model of embodied technology but if $\lambda = 1$ all technology is disembodied. The parameter a is the growth rate of TFP in the steady state and is observable. The parameter λ is unobservable by the econometrician but an approximate value for it may be inferred from our empirical estimates.

Both technologies are labor augmenting and the production function is Cobb-Douglas. The firm creates new jobs on the technological frontier, adopting the most advanced technology of both types. But because existing jobs cannot benefit from embodied technological progress, jobs move off the frontier soon after creation. We denote output per worker by $f(.,.)$. The first argument of $f(.,.)$ denotes the creation time of the job (its vintage) and the second the valuation (current) time. At time τ, output per worker in new jobs is

$$f(\tau,\tau) = A_1(\tau)^{1-\alpha} A_2(\tau)^{1-\alpha} k(\tau,\tau)^{\alpha}, \tag{6}$$

where $k(\tau,\tau)$ is the capital-labor ratio in new jobs at τ. But in jobs of vintage τ output per worker at time $t > \tau$ is

$$f(\tau,t) = A_1(t)^{1-\alpha} A_2(\tau)^{1-\alpha} k(\tau,t)^{\alpha}, \tag{7}$$

where in general $k(\tau, t) \neq k(t, t)$. Note that in (7) the disembodied technology A_1 is updated but the embodied technology A_2 is not.

When the firm creates a job it keeps it either until an exogenous process destroys it, an event that takes place at rate s, or until it destroys the job itself because of obsolesce, which takes place T periods after creation.[11] There is a perfect rental market for capital and in order to focus on employment we assume that there are no capital adjustment costs. Capital depreciates at rate δ . When the job is destroyed the employee is dismissed at zero cost.

The value of the typical job consists of two parts, the value of its capital stock and a value $V(.,.) \geq 0$, which is due to the frictions and the quasi-rents that characterize employment. The value of a job created at time 0 and lasting until T satisfies the Bellman equation, for $t \in [0, T]$,

$$\begin{aligned} r(V(0,t) + k(0,t)) &= f(0,t) - \delta k(0,t) - w(0,t) - sV(0,t) + \dot{V}(0,t) \quad (8) \\ V(0,T) &= 0. \end{aligned}$$

All variables have been defined except for r, the exogenous rental rate of capital, and $w(0, t)$, the wage rate at t in a job of vintage 0. The interpretation of this equation is the one that has become familiar from search theory. The firm hires capital stock $k(0, t)$ and makes net (super-normal) profit $V(0, t)$, which it loses when the job is destroyed.

The firm's controls at time 0 are (a) whether or not to create a job worth $V(0, 0)$; and if it creates it, (b) when to terminate it, and (c) the path of $k(0, t)$ for $t \in [0, T]$. The wage rate is also a control variable but we assume that it is jointly determined by the firm and the worker after a bargain. We take each of these decisions in turn, starting with capital.

Capital accumulation

Maximization of (8) with respect to $k(0, t)$ yields the condition

$$k(0,t) = A_1(t)A_2(0)(\alpha/(r+\delta))^{1/(1-\alpha)} \qquad t \in [0,T]. \qquad (9)$$

[11] A second endogenous job destruction process could be introduced along the lines of Mortensen and Pissarides (1994), with the firm's productivity being subject to idiosyncratic shocks. This generalization would increase both the complexity and richness of the model, but it is an unnecessary complication for the purposes in hand.

When $t = 0$, this expression refers to new jobs. The path of the capital-labor ratio in pre-existing and new jobs follows immediately:

$$k(0,t) = e^{\lambda at}k(0,0) \tag{10}$$
$$k(t,t) = e^{at}k(0,0). \tag{11}$$

New jobs are technologically more advanced than old jobs and also have more capital than old jobs.

With (9)-(11) it is possible to derive some useful expressions for output and labor's marginal product. From (6) and (7) we find that the evolution of output per worker in the typical job also satisfies expressions similar to (10) and (11). From (7) and (9) labor's marginal product is

$$\phi(\tau,t) \equiv f(\tau,t) - (r+\delta)k(\tau,t). \tag{12}$$

Clearly, given (10) and (11),

$$\phi(0,t) = e^{\lambda at}\phi(0,0), \tag{13}$$
$$\phi(t,t) = e^{at}\phi(0,0). \tag{14}$$

It follows from these expressions that when technology on the frontier grows at rate a, output, the capital stock and labor's marginal product in existing jobs grow at the lower rate λa. They jump up to the technological frontier when the job is destroyed and a new one created in its place.

Because of (9), the solution to (14) is

$$\phi(t,t) = A_1(t)A_2(t)(1-\alpha)\left(\frac{\alpha}{r+\delta}\right)^{\frac{\alpha}{1-\alpha}} \qquad \forall t. \tag{15}$$

We introduce for future reference the notation

$$\phi \equiv (1-\alpha)\left(\frac{\alpha}{r+\delta}\right)^{\frac{\alpha}{1-\alpha}}. \tag{16}$$

It denotes a base value for the marginal product of labor when the capital stock is optimized.

Wages

The wage equation plays a key role in the transmission of the effects of growth to employment. We showed that the marginal product of labor in existing jobs grows at the rate λa. We now show that because of competition from new jobs, workers' reservation wages grow at faster rate, and so eventually jobs become unprofitable.

In order to determine wages we derive first the worker's reservation wage and her payoffs from holding a job. The derivation follows standard search and matching theory (Pissarides, 2000, chapter 1). In unemployment the worker enjoys payoff $U(t)$, given by

$$rU(t) = b(t) + m(\theta)(W(t,t) - U(t)) + \dot{U}(t). \tag{17}$$

In general, when a variable is changing in the steady state we make the dependence on time explicit, but when it is constant we do not, although it would be changing out of steady state. In (17) $b(t)$ is unemployment income, $\theta \geq 0$ is a measure of market tightness, $m(\theta)$ is the rate at which new job offers arrive to unemployed workers and $W(t,t)$ is the present discounted value of lifetime earnings when a new job is accepted at time t. We assume $m'(\theta) > 0$, $m(0) = 0$ and $m(\theta) \to \infty$ as $\theta \to \infty$. We also assume no search on the job and that $b(t)$ grows at the rate a, the average rate of growth of productivity in the economy as a whole. This assumption is needed for the existence of a steady state and could be supported by making unemployment income proportional to mean wages. It is, however, easier and as general to write,

$$b(t) = A_1(t)A_2(t)b, \tag{18}$$

where $b \in [0, \phi)$ is a parameter. The restriction that b is strictly below ϕ is required to ensure that market production is preferable to unemployment.

The present discounted value of earnings in a job of vintage τ satisfies the Bellman equation, for $t \in [\tau, \tau + T]$,

$$\begin{aligned} rW(\tau,t) &= w(\tau,t) + s(U(t) - W(\tau,t)) + \dot{W}(\tau,t) \\ W(\tau,\tau+T) &= U(\tau+T). \end{aligned} \tag{19}$$

The worker accepts a job at t iff $W(t,t) \geq U(t)$. We follow convention and define the reservation wage as the minimum wage that a job can pay for ever and still be acceptable. We show later that wages in new jobs grow at rate a, so $W(t,t)$ and $U(t)$ also grow at rate a. Let $\omega(t)$ be the wage paid by an imaginary reservation job offered at t and suppose that it grows at rate a. With discount rate r the present discounted value of earnings in the reservation job at t are $\omega(t)/(r-a)$, giving the reservation wage $\omega(t) = (r-a)U(t)$.

We study the implications of two wage equations. In the first we follow the search and matching literature and assume that wages in each job share the quasi-rents that the job creates. In this case job destruction is privately efficient, in the sense that there are no transfer payments between firm and worker that can make continuation of the match preferable to destruction. The firm's rents are the solution to (8), $V(\tau, t)$, and the worker's rents are the difference $W(\tau, t) - U(t)$. We assume the sharing rule

$$W(\tau, t) - U(t) = \frac{\beta}{1-\beta} V(\tau, t), \tag{20}$$

where $\beta \in [0, 1)$ is the share of labor. This sharing rule is usually known in the literature as the Nash sharing rule. This equation gives a high exposure of wages to outside market conditions, through a direct dependence of wages on the reservation wage (see below). In our second wage equation we insulate the wage contract from outside conditions but retain the property that job destruction is privately efficient. We assume that wages are either a constant fraction γ of own productivity or equal to the reservation wage, whichever is largest:[12]

$$w(\tau, t) = \max(\gamma\phi(\tau, t), \omega(t)) \quad \gamma \in (0, 1). \tag{21}$$

Standard manipulations with (20) yield[13]

$$w(\tau, t) = (1-\beta)b(t) + \beta m(\theta)V(t, t) + \beta\phi(\tau, t). \tag{22}$$

For this wage equation it is also straightforward to show, by substitution from (20) into (17) that

$$\omega(t) = b(t) + \frac{\beta}{1-\beta} m(\theta)V(t, t). \tag{23}$$

Unemployment income $b(t)$ grows at rate a by assumption and it follows immediately from (8), (23) and (22) that both $V(t, t)$ and $w(t, t)$ also grow

[12] The question of how much influence reservation wages should exert on bargained wages is a controversial one when the threat to quit wage negotiations to look for another job is not a credible one. See Binmore et al. (1986) for the bargaining theory and Hall and Milgrom (2005) for a recent application to search and matching.

[13] Make use of (20) to substitute $W(t, t) - U(t)$ out of (17). Subtract the resulting equation from (19) and use the result to substitute $W(\tau, t) - U(t)$ out of (20). Finally, use (8) to substitute $V(\tau, t)$ out of (20) and collect terms, noting that (20) also holds in the time derivatives because of the assumption of continuous renegotiation.

at rate a. Therefore, we can write the wage equation as the weighted average of the reservation wage and marginal product, with labor's share acting as weight. The reservation wage is the "outside" component and grows at rate a, and marginal product is the "inside" component and grows at rate λa. For a job created at time 0 the wage equation is

$$w(0,t) = (1-\beta)\omega(0)e^{at} + \beta\phi(0,0)e^{\lambda at}. \tag{24}$$

It contrasts sharply with our alternative wage equation, (21), in that (21) does not allow any influence from outside market conditions unless wages are equal to reservation wages.

Given (14) it now follows that wages in new jobs grow at rate a whichever wage method is used:

$$w(t,t) = e^{at}w(0,0). \tag{25}$$

Equations (24) and (25) contrast with (10)-(11) and (13)-(14). In new jobs wages, the capital stock and technology grow at rate a. In existing jobs technology and the capital stock grow at lower rate λa but wages grow at a faster rate because of their dependence on reservation wages, which lies between a and λa. With the second wage equation in (21), however, wages in existing jobs grow either at the lower rate λa or at a, depending on the size of the parameter γ.

Job creation and job destruction

The differential rates of growth of labor's marginal product and reservation wages drive the results on employment. We integrate (8) to arrive at the present discounted value of profit from a job of vintage 0:

$$V(0,0) = \int_0^T e^{-(r+s)t} \left(\phi\left(0,t\right) - w\left(0,t\right)\right) dt. \tag{26}$$

Making use of (13) and working first with the Nash wage equation in (24), we re-write (26) as

$$V(0,0) = (1-\beta)\int_0^T e^{-(r+s)t}\left(e^{\lambda at}\phi(0,0) - e^{at}\omega(0)\right) dt. \tag{27}$$

We simplify the notation by noting that because of (15), (23) and (18), $V(0,0), \phi(0,0)$ and $\omega(0)$ are all proportional to the level of aggregate technology, $A_1(0)A_2(0)$. Therefore we can omit the time notation and write (27) as

$$V = (1-\beta) \int_0^T e^{-(r+s)t} \left(e^{\lambda a t} \phi - e^{at} \omega \right) dt, \tag{28}$$

where ϕ was defined in (16) and

$$\omega = b + \frac{\beta}{1-\beta} m(\theta) V. \tag{29}$$

The firm chooses the obsolescence date T to maximize the job's value. Differentiation of (28) with respect to T gives:

$$T = \frac{\ln \phi - \ln \omega}{(1-\lambda)a}. \tag{30}$$

This says that a job is destroyed when the reservation wage becomes equal to the worker's marginal product. Wages then become equal to reservation wages as well, and the job is no longer viable, as reservation wages continue to grow faster than the marginal product of labor.

Results are similar with the wage equation (21). If γ is sufficiently small that the wage rate is equal to the reservation wage throughout the life of the job, equation (28) holds as before but with $\beta = 0$, so the decision rule in (30) is unaltered. But in this case (17) and (19) yield $\omega(t) = b(t)$, so the model works throughout like the sharing-rule model with $\beta = 0$. This case, however, is not as interesting as the one that satisfies $\gamma\phi(\tau, t) > \omega(t)$ for at least some t, because it does not allow the wage rate to depend on anything other than the worker's income during unemployment. Since $\phi(\tau, t)$ grows less fast than $\omega(t)$, if the inequality $\gamma\phi(\tau, t) > \omega(t)$ is satisfied for some t it is also satisfied for $t' < t$, and if it is not satisfied for some $\tilde{t}$ it is also not satisfied for $\tilde{t}' > \tilde{t}$. Let therefore t^* be the unique t at which $\gamma\phi(\tau, t^*) = \omega(t^*)$. At this t^* marginal product exceeds the reservation wage rate (because $\gamma < 1$) so the job is still profitable. But for $t > t^*$ the wage rate is equal to the reservation wage and so grows at rate a; the marginal product is still growing at rate λa, so eventually a time comes when the reservation wage and marginal product are equal and the job is destroyed. That time is clearly the same T that satisfies (30), except that the value taken by ω in equilibrium is not generally the same as the one taken under the sharing rule.

More formally, the value of the job with the wage equation in (21) is

$$V = (1-\gamma) \int_0^{t^*} e^{-(r+s)t} \left(e^{\lambda a t} \phi \right) dt + \int_{t^*}^T e^{-(r+s)t} \left(e^{\lambda a t} \phi - e^{at} \omega \right) dt, \tag{31}$$

which replaces (28), the equation for the value of the job with the sharing rule. Maximization of this value with respect to T yields the same condition as before, (30).

Figure 2 illustrates the firm's optimal obsolescence policy with either wage equation. The horizontal axis shows time and the vertical axis measures the log of the marginal product of labor and wages. The broken line shows the path of marginal product if the job were to stay on the technological frontier, which grows at rate a. The continuous parallel line below it shows the reservation wage, which also grows at rate a. A new job is created on the frontier at time 0 but the marginal product of labor in it grows at the lower rate λa, shown by the flatter continuous line. Eventually, the marginal product hits the reservation wage line and the job is destroyed. The firm then (or another firm) creates another job in its place, with marginal product on the frontier.

If wages are given by the sharing rule, the wage rate paid by the firm is a weighted average of the reservation wage and the marginal product. So wages start off at a point on the vertical axis between the two lines shown in the figure, and rise monotonically until they meet the point of intersection of the marginal product line and the reservation wage line. If wages are given by the second equation, (21), they also start at a point between the two lines on the vertical axis, but they rise parallel to the marginal product line until they meet the reservation wage line. They then follow the reservation wage line up to time T.

It follows from figure 2 and (30) that whatever the wage rule, if all technology is of the Solow disembodied type, $\lambda = 1$, marginal product in figure 2 remains on the frontier and the firm will never want to destroy a job through obsolescence. Job destruction in this case takes place only because of the exogenous separation process, and for aggregate employment L aggregate job destruction is sL, independent of growth. But if $\lambda < 1$ faster growth (which makes all lines in figure 2 steeper) leads to more job destruction, as by differentiation of (30), $\partial T/\partial a < 0$. But this effect is partial because the reservation wage also depends on the growth rate. Aggregate job destruction in this case has two components, one again given by sL and the other given by all the surviving jobs of age T, which become obsolete.

Given the analytical similarity between the two wage rules we avoid repetition and focus on the sharing rule to close the model, by deriving the labor-market equilibrium. But we show in the next section that quantitatively which wage equation is used makes a lot of difference to the results, because of the bigger insulation of the second equation from labor market conditions. We return to this issue later.

To derive the equilibrium effect of growth on the sharing equilibrium we integrate (28) to obtain:

$$V = (1-\beta)\left(\frac{1-e^{-(r+s-\lambda a)T}}{r+s-\lambda a}\phi - \frac{1-e^{-(r+s-a)T}}{r+s-a}\omega\right). \tag{32}$$

For convenience, we introduce a new symbol for the coefficients inside the brackets:

$$y(\lambda a) \equiv \frac{1-e^{-(r+s-\lambda a)T}}{r+s-\lambda a}, \qquad \lambda \in [0,1], \tag{33}$$

so the returns from a new job, (32), simplify to:

$$V = (1-\beta)(y(\lambda a)\phi - y(a)\omega). \tag{34}$$

By differentiation,

$$y'(\lambda a) > 0, \qquad y''(\lambda a) < 0. \tag{35}$$

In order to derive now the influence of the growth rate on job creation and close the model, suppose that jobs are created at some cost, and that the cost increases in the number of jobs created at any moment in time. A number of alternative arguments can be used to justify this assumption. We follow the search and matching literature, which assumes that at the level of the firm the cost of creating one more job is constant but marginal costs are increasing at the aggregate level because of congestion effects (see Pissarides, 2000). Let our measure of tightness, θ, be the ratio of the aggregate measure of firms' search intensities (e.g., the total number of advertised vacant jobs), to the number of unemployed workers. Then given the rate of arrival of jobs to workers, $m(\theta)$, the rate of arrival of workers to jobs is $m(\theta)/\theta$. Consistency requires that this rate decrease in θ, which is satisfied when the elasticity of $m(\theta)$ is a number between zero and one. We denote this elasticity by $\eta \in (0,1)$ (which is not necessarily a constant).

We now assume that the cost of creating one more job in period t is a flow cost $A_1(t)A_2(t)c$ for the duration of the firm's search effort. The proportionality of the cost to technology is an innocuous simplification (but of course that the cost should be increasing at rate a is necessary for the existence of a steady state). Letting $V^0(t)$ denote the present value of search for the firm (equivalently, the value of creating one more vacant job), the following Bellman equation is satisfied:

$$rV^0(t) = -A_1(t)A_2(t)c + \frac{m(\theta)}{\theta}(V(t,t) - V^0(t)) + \dot{V}^0(t). \tag{36}$$

Under free entry into search, $V^0(t) = \dot{V}^0(t) = 0$, and so each new job has to yield positive profit, which is used to pay for the expected recruitment costs. In period $t = 0$ the job creation condition is:

$$V(0,0) = A_1(0)A_2(0)\frac{c\theta}{m(\theta)}, \tag{37}$$

or equivalently,

$$V = \frac{c\theta}{m(\theta)}. \tag{38}$$

We are now in a position to describe the determination of the optimal destruction time T and the equilibrium market tightness θ. Conditions (23), (18) and (38) are common to all firms and workers and can be used to yield the following equilibrium relation between ω and θ:

$$\omega = b + \frac{\beta}{1-\beta}c\theta. \tag{39}$$

Substitution of V from (34) into (38) gives a second equilibrium relation between ω and θ :

$$(1-\beta)(y(\lambda a)\phi - y(a)\omega) = \frac{c\theta}{m(\theta)}. \tag{40}$$

Because (40) satisfies the envelope property with respect to T, in the neighborhood of equilibrium it gives a downward-sloping relation between ω and θ.[14] But (39) gives a linear upward-sloping relationship, so (40) and (39) are uniquely solved for the pair ω, θ for any value of T that maximizes V. Given this solution for ω, (30) gives the optimal T. Job creation at time t in this economy is given by $x(t) = \tilde{u}(t)m(\theta)$, where $\tilde{u}(t)$ is the predetermined number of unemployed workers and $m(\theta)$ is the matching rate for each worker.

[14] Outside the neighborhood of steady-state equilibrium the relation between the job creation condition and θ may not be monotonic. See Postel-Vinay (2002) for a demonstration in a related model.

In order to obtain the effect of TFP growth on job creation, for given unemployment, we differentiate (40) with respect to a to obtain:

$$\left(\frac{c\beta y(a)}{1-\beta}+\frac{c(1-\eta)}{m(\theta)}\right)\frac{\partial\theta}{\partial a}=(1-\beta)\left(\lambda y'(\lambda a)\phi-y'(a)\omega\right) \tag{41}$$

where, as already defined, $\eta\in(0,1)$ is the elasticity of $m(\theta)$. The coefficient on $\partial\theta/\partial a$ is positive but the right-hand side can be either positive or negative. By (35), the right-hand side is monotonically rising in λ, at $\lambda=0$ it is negative and at $\lambda=1$ it is positive. Therefore, there is a unique λ, call it λ^*, such that at values of $\lambda<\lambda^*$ faster growth reduces market tightness and at values of $\lambda>\lambda^*$ it increases it. At $\lambda=\lambda^*$ growth has no effect on θ.[15]

Aggregation

We now aggregate the representative firm's equilibrium conditions to derive the economy's steady-state paths. We characterize it for the sharing wage equation, the one for the alternative rule following immediately. Aggregate steady-state equilibrium is defined by a path for the average capital-labor ratio (derived from the optimality conditions (9), (10) and (11)), a path for the average wage rate (derived from (24) and (25)) and a stationary ratio of employment to population (derived from (40) and (30)). The exogenous variables are TFP, population and the real cost of capital.

We discuss aggregation informally, with the help of figure 2. Because of our Cobb-Douglas assumptions, the path shown for $\phi(.,.)$ in figure 2 is a displacement of the path of the capital stock (9) and of the one for output per worker, (7), for each job. In the steady state a job is created in period 0, it is destroyed and another one created in its place in period T, which is destroyed and another one created in period $2T$ and so on. Then, the capital stock, output and labor's marginal product from 0 to T, from T to $2T$, and so on grow *on average* at rate a, the slope of the broken line in figure 2, although growth for each individual job is not smooth. It is slow at first and then jumpy at the time of replacement. But if new jobs in the economy as a whole are created continually with the same frequency, which

[15]Note that if λ is small and faster growth reduces job creation, the general equilibrium effect of a on T may reverse because of the dependence of ω on θ. In a market with poor outside opportunities existing jobs become more valuable and workers hold on to them longer, by accepting lower wages. However, the quantitative analysis finds no evidence for such effects.

is an assumption that is required for a steady state, the aggregate capital stock, output and marginal product will grow smoothly at rate a. Finally, again with reference to figure 2, since the two components of the average wage rate, $\phi(.,.)$ and $\omega(.)$ both grow at rate a between 0 and T, the average wage rate also grows at rate a.

Employment in the representative firm evolves on average according to the difference between job creation and job destruction. At time t this is

$$\dot{L}(t) = x(t) - e^{-sT} x(t-T) - sL(t), \tag{42}$$

where $x(t)$ is job creation, and $\exp(-sT)$ is the fraction of jobs of vintage $t-T$ that survive to T, and so become obsolete. In the steady state $\dot{L}(t)$ is equal to the rate of growth of the population of working age, which we assume to be exogenous and equal to n. $x(t)$ is given by $\tilde{u}(t)m(\theta)$ and so it grows at n, because in the steady state the number of unemployed workers $\tilde{u}(t)$ grows at n, whereas θ and T are the solutions to (30) and (40) and they are stationary. Steady-state unemployment is the difference between the exogenous labor force and steady-state employment. Steady-state employment is derived from (42) and satisfies,

$$nL(t) = (LF(t) - L(t))m(\theta) - e^{-(n+s)T}(LF(t) - L(t))m(\theta) - sL(t), \tag{43}$$

where $LF(t)$ is the exogenous labor force. Solving for $L(t)$, we obtain:

$$L(t) = \frac{\left(1 - e^{-(n+s)T}\right) m(\theta)}{\left(1 - e^{-(n+s)T}\right) m(\theta) + n + s} LF(t). \tag{44}$$

The steady-state rate of unemployment is denoted by u. It is defined as the ratio of unemployment to the labor force, $\tilde{u}(t)/LF(t)$:

$$u = \left(1 - \frac{L(t)}{LF(t)}\right) = \frac{n+s}{\left(1 - e^{-(n+s)T}\right) m(\theta) + n + s}. \tag{45}$$

Note that the solutions to T and θ are independent of the level of technology but its rate of growth influences employment because it influences both T and θ.

4 Quantitative analysis

The key result of the model is that TFP growth increases job destruction but it may increase or decrease job creation at given unemployment rate, depending on the value taken by the parameter λ. This general analytical result holds for both wage equations that we introduced in the preceding section. The first task of the quantitative analysis is to compute the ranges of λ that imply a positive or a negative impact of TFP growth on job creation and unemployment for the sharing wage equation. From this and our econometric estimates we will then be able to make inferences about the fraction of technology that is embodied in new jobs. The second task of the quantitative analysis is to calculate the total impact of TFP growth on unemployment that can be explained by the model for each wage equation.

The equations that give the steady-state solutions in the sharing rule case for the three unknowns, T, θ and u, are (30), (40) and (45). By differentiation of the three equations with respect to a it is straightforward to show that a necessary condition for a negative impact of TFP growth on unemployment is that TFP growth should have a positive impact on job creation; i.e., that $\partial\theta/\partial a > 0$.

We showed in connection to (41) that there is a unique λ^*, defined by

$$\lambda^* y'(\lambda^* a)\phi - y'(a)\omega = 0, \tag{46}$$

at which $\partial\theta/\partial a = 0$. At lower values of λ, $\partial\theta/\partial a < 0$ and at higher values $\partial\theta/\partial a > 0$. So, if $\lambda \in [0, \lambda^*]$ job destruction increases and job creation is constant or falls in a, and the impact of a on u is positive. If $\lambda \in (\lambda^*, 1)$ the impact of a on u can be either positive or negative depending on the strength of the creative destruction and capitalization effects. But if $\lambda = 1$ there is no creative destruction effect ($T = \infty$) and so the impact of a on u is negative. A necessary restriction on λ implied by the empirical evidence is therefore $\lambda > \lambda^*$, and given the strength of the effect estimated, the gap between the underlying λ and λ^* is likely to be substantial.

In order to compute λ^* we make use of (46) and the following additional equations, which give the steady-state solutions of the model (all of which were derived in section 3)

$$y(\lambda^* a) = \frac{1 - e^{-(r+s-\lambda^* a)T}}{r + s - \lambda^* a} \tag{47}$$

$$y(a) = \frac{1 - e^{-(r+s-a)T}}{r + s - a} \tag{48}$$

$$T = \frac{\ln\phi - \ln\omega}{(1 - \lambda^*)a} \tag{49}$$

$$\omega = b + \frac{\beta}{1-\beta} c\theta \tag{50}$$

$$(1-\beta)(y(\lambda^* a)\phi - y(a)\omega) = \frac{c\theta}{m(\theta)}. \tag{51}$$

The unknowns are $\lambda^*, y(\lambda^* a), y(a), T, \omega$, and θ. The matching flow is assumed to be constant-elasticity, which is found to be a reasonable specification in empirical studies (Petrongolo and Pissarides 2001):

$$m(\theta) = m_0 \theta^\eta. \tag{52}$$

The period of analysis is a year. We give either standard values to the parameters or sample means (shown in Table 2) except for two which are not directly observable, s and m_0. We calibrate them to the job destruction rate and the steady-state unemployment rate respectively.

The real rate of interest is 4 percent per annum. The value of unemployment income is set at 0.3ϕ, which in equilibrium gives a ratio of unemployment income to wages of about 0.31, which is the sample mean for the United States. The hiring cost is taken from Hamermesh (1993), who estimates it on average to be one month's wages. We set it at $c = 0.1\phi$ (wages in this economy turn out to be about 97 percent of the marginal product of labor). The average recruitment cost in the model is $c\theta/m(\theta)$, which depends on the unknown θ, but it turns out that c is not important in the calibration of λ^* (or of anything other than the absolute value of θ, which is not an interesting variable in the quantitative exercise). The value of ϕ need not be specified because the level of productivity does not influence the steady state. The values for β and η are the ones commonly used in quantitative analyses of search equilibrium models. $\eta = 0.5$ is close to the mid range of estimated values in several countries (Petrongolo and Pissarides 2001). The value for TFP growth is its sample mean for the United States. We calibrate to US values because they are the ones that are least contaminated by policy on employment protection and other institutions that are not in the model. However, calibrating to European values gives very similar results. It turns out that the interesting unknown, λ^*, and the impact of a on u are robust to fairly large ranges of the parameters, with some exceptions discussed below.

In order to obtain s we calibrate to data on job destruction rates. According to Davis, Haltiwanger and Schuh (1996) the average job destruction rate in US manufacturing is 0.1 (and close to the average job destruction rate in several other countries, see their Tables 2.1 and 2.2), which implies that

Table 2: Baseline Parameter Values

r	0.04	β	0.50
b	0.30ϕ	η	0.50
c	0.10ϕ	a	0.02

on average, when a firm creates a job it expects to keep it for ten years. In our model the mean duration of jobs is given by $(1-\exp(-sT))/s$, so we treat s as an unknown and introduce the equation,

$$\frac{1-e^{-sT}}{s} = 10. \tag{53}$$

Finally, the parameter m_0 is calibrated from the steady-state equation for unemployment. In our sample the mean unemployment rate in the United States is 6 percent. We treat m_0 as another unknown and introduce the equation

$$\frac{n+s}{\left(1-e^{-(n+s)T}\right)m_0\theta^{0.5}+n+s} = 0.06. \tag{54}$$

The value given to n turns out to be unimportant. In the model we identified it with the net rate of growth of the labor force but more generally it is the average annual rate of entry into the unemployment pool from outside the labor force. We set it equal to 0.1, which implies that the flow into unemployment from outside the labor force is approximately the same as the flow from employment.

Is technology embodied?

The solutions for all unknowns are given in Table 3. The critical value for λ turns out to be 0.96. At this value $\partial\theta/\partial a = 0$, so the impact of TFP growth on employment predicted by the model is still negative if there is a creative destruction effect. However, the calculated T is 67.5 years, which is equivalent to having no creative destruction effect. With average job durations of 10 years, by the time productivity growth makes a job obsolete (after 67.5 years) the job is certain to have ended for other reasons (only a fraction 0.001 of jobs reach age 67.5).[16]

[16] The other solution values are reasonable and need not be discussed, except for some comments about θ, the ratio of recruitment effort to search effort. Although it is usually

Table 3: Model Solutions

λ^*	0.96	θ	6.52	$y(\lambda^* a)$	8.28
T	67.5	ω	0.94ϕ	$y(a)$	8.34
s	0.10	m_0	1.23	w	0.97

The computed value for λ^* turns out to be robust virtually to all reasonable parameter variations. Table 4 reports some results. The column headed "job dur" replaces the expected duration of a job by the expected duration of a job tenure, which during our sample was 4.2 years. The relevant job duration to use in this model is the one that is covered by the initial creation cost, so if the main component of creation costs is one that has to be repaid every time the worker on the job is replaced, the 4.2-year duration is more appropriate than the 10-year expected duration in the baseline.[17] The other parameter variations are self-explanatory and reported for illustration of the robustness of our baseline results. The only parameter change that appears to make a nontrivial difference to the value of λ^* is the change in the share of labor from 0.5 to 0.1. But even such a big change requires a λ^* of 0.83.

The reason for this robust behavior is that in this model at realistic parameter values obsolescence is a very powerful influence on both job creation and unemployment. In contrast, the capitalization effect turns out to be a weak influence. Obsolescence reduces the useful life of the job and so weakens the impact of discounting on the profit stream. So it weakens the capitalization effect, which works through discounting, and simultaneously increases the flow of workers into the unemployment pool. Our calibrations show that in order to get a positive net impact of TFP on job creation, the model

interpreted as the ratio of vacancies to unemployment (in which case the number 6.52 would be unreasonable) we did not give it this interpretation. We used the steady-state unemployment rate to infer it. It implies that on average the duration of unemployment in the United States is between 3 and 4 months, which is reasonable. It also implies that the average recruitment cost per employee is 0.206ϕ, or about 20 percent of annual wages. This is higher than Hamermesh's estimate, but changing the parameter c in the computations by a factor of 2, which changes the recruitment cost, has no influence on the solutions for λ^* or T and s. It affects only the solution for θ.

[17] Similarly, if the job position is not destroyed for good when it is "destroyed" in the sense of Davis, Haltiwanger and Schuh (1996), the horizon should be longer. See footnote 20 below.

Table 4: Model Solutions at Different Parameter Values

	bench mark	job dur 4.2	β 0.1	β 0.8	b 0.1ϕ	b 0.6ϕ	a 0.05	a 0.10
λ^*	0.96	0.94	0.83	0.97	0.94	0.98	0.97	0.96
T	67.5	59.2	71.1	67.1	67.9	67.1	37.6	15.3

requires that technology be disembodied.

To see more formally why the capitalization effect is too weak to offset the creative destruction effect when technology is embodied consider equation (46). The capitalization effect is due to the difference in the slopes of the present discounted value terms $y'(\lambda a)$ and $y'(a)$. But any difference between these two terms is due to the difference in the discount rates $r + s - a$ and $r + s - \lambda a$. With relatively large values for $r + s$ (0.14 in the benchmark case) and small a (0.02 in the benchmark) the difference between the discount factors cannot be large, whatever the value of λ. In other words, even job durations of 10 years are too short for growth of 2 percent to make much difference to the firm's discounted profits. For a large difference between the two terms in (46), which would make the capitalization effect more powerful, we require either much lower values for $r + s$ or much higher values for a. But at very high values of a the creative destruction effect becomes even more powerful, so the values of λ required to make job creation neutral with respect to a are higher still. The only factor that could increase the effectiveness of the capitalization effect is a lower $r + s$, i.e., much longer expected job durations.

At the low values of a commonly observed at the aggregate level, empirically non-trivial creative destruction requires a large fraction of embodied technology. For example, if half the technology is embodied ($\lambda = 0.5$), the model yields $T = 18$ and $s = 0.073$, so about 27 percent of jobs survive to age T and are made obsolete. But in this case the impact of growth on employment is strongly negative, so it contradicts the empirical evidence. Obsolescence needs to affect a much lower fraction of jobs if TFP growth is to have a positive impact on job creation, at least for rates of TFP growth up to about 5-6 percent (see Table 4). Interestingly, however, once TFP growth exceeds rates of 5-6 percent, a positive impact of TFP growth on job creation is consistent with more obsolescence. For example, at 5 percent growth 2.6 percent of jobs survive to obsolescence at the computed value of λ^*, whereas at 10 percent growth 40 percent of jobs survive. Such rates of growth, however, are unrealistic at the aggregate level, although they may characterize individual sectors during periods of high expansion.

The numerical analysis with the sharing rule wage equation leads to the conclusion that at the low rates of TFP growth and the high rates of job destruction rates observed at the aggregate level, creative destruction is a much more powerful influence on job creation than is the capitalization effect. For TFP growth to have a positive impact on employment as in the econometric estimates, technology needs to be entirely disembodied. Given our discussion of the reasons for the high λ^*, it is not surprising to find that our second wage equation has very similar implications about embodied technology. Although the capitalization effect is stronger with the second wage equation, we show below that it is still too weak to reverse a creative destruction effect and still have the large positive impact on job creation that is required by the econometric estimates. We do not report the computations for the optimal λ^* with the second wage equation to avoid repetition.

Capitalization effects

The maximum positive impact that TFP growth can have on job creation in the model takes place when all technology is disembodied, when only the capitalization effect operates. We investigate here the quantitative importance of the capitalization effect with the two wage equations, with a view to discovering if the mechanisms of the model are strong enough to match the econometric estimates.

When all technology is disembodied $\lambda = 1$ and the equations giving the model solutions for the sharing wage equation are

$$\frac{(1-\beta)(\phi-\omega)}{r+s-a} = \frac{c\theta}{m(\theta)} \tag{55}$$

$$\omega = b + \frac{\beta}{1-\beta}c\theta \tag{56}$$

$$u = \frac{n+s}{m(\theta)+n+s}. \tag{57}$$

The unknowns are θ, ω and u. We use the same parameters as before, given in Table 2, whereas now (53) gives $s = 0.1$. Rather than use an arbitrary change in TFP growth to compute the capitalization effect we calibrate to the observed productivity slowdown after 1973, shown in Table 1. We use the initial unemployment rate for the US economy in the Table, 4.96, to compute m_0. We then ask whether a fall in the TFP growth rate from 1.9 to 0.8 percent is capable of producing a capitalization effect that is strong enough to raise unemployment in the steady state to the value predicted by the econometric estimates, 6.6 percent.

Our computations show that with the sharing wage equation the impact of the fall in the TFP growth rate is too small to explain the estimated rise in unemployment. At the parameter values in Table 2 unemployment rises by a tiny amount, to 4.98. Although different parameter values give slightly different values, none of them gets close to explaining a nontrivial fraction of the estimated impact of the productivity slowdown.

With our second wage equation in (21), and when wages strictly exceed the reservation wage, the steady-state equations collapse to two:

$$\frac{(1-\gamma)\phi}{r+s-a} = \frac{c\theta}{m(\theta)} \tag{58}$$

and (57). In this case, if the initial unemployment rate at some growth rate $\bar{a}$ is denoted $\bar{u}$, the unemployment rate at a new growth rate a is

$$u = \frac{1}{1 + \frac{1-\bar{u}}{\bar{u}} \frac{r+s-\bar{a}}{r+s-a}}. \tag{59}$$

So, if at the initial equilibrium $\bar{a} = .019$ and $\bar{u} = .0496$, the new $a = .008$ gives $u = .0539$, so the capitalization effect explains about 0.43 of the estimated rise of 1.64 percent.

Another way of showing the model's implications for the impact of TFP is to compute the growth elasticities. Differentiation of (57) with respect to a gives,

$$\frac{\partial u}{\partial a} = -u(1-u)\eta \frac{\partial \theta}{\partial a} \frac{1}{\theta}. \tag{60}$$

In the econometric estimates we found that approximately a unit change in a causes a -1.5 change in u, so at the mid point for unemployment, 5.78 percent, and $\eta = 0.5$, we require from the model $(\partial\theta/\partial a)/\theta \approx 55$.

The zero-profit equation (55) or (58) can be rearranged to yield, for any wage w,

$$\phi - w = (r+s-a)cm_0\theta^{1-\eta}. \tag{61}$$

By differentiation

$$\frac{\partial \theta}{\partial a}\frac{1}{\theta} = \frac{\frac{1}{r+s-a}}{1-\eta+\frac{w}{\phi-w}\frac{\partial w}{\partial \theta}\frac{\theta}{w}}. \tag{62}$$

At the benchmark values and solutions for the sharing equation,

$$\frac{\partial w}{\partial \theta}\frac{\theta}{w} = \frac{\beta c\theta}{(1-\beta)b+\beta\phi+\beta c\theta} = 0.33, \tag{63}$$

and $w = 0.97\phi$, so (62) at the midpoint of the growth rates in Table 1 gives

$$\frac{\partial \theta}{\partial a}\frac{1}{\theta} = 0.75. \tag{64}$$

With the second wage equation, $\partial w/\partial \theta = 0$, so

$$\frac{\partial \theta}{\partial a}\frac{1}{\theta} = \frac{1}{(1-\eta)(r+s-a)} = 16.7. \tag{65}$$

Thus, the sharing equation fails to show a significant impact of growth on job creation, whereas the second wage equation can account for about one third of the required elasticity.

In the estimated wage equation the unemployment elasticity of wages is -0.04, which, using (57) yields approximately,[18]

$$\frac{\partial w}{\partial \theta}\frac{\theta}{w} = 0.02. \tag{66}$$

Making use of this elasticity in (62) we obtain

$$\frac{\partial \theta}{\partial a}\frac{1}{\theta} = 6.34, \tag{67}$$

which again is well short of the elasticity needed to account for the full estimated impact of TFP growth on unemployment.

The sensitivity of the wage rate to the tightness of the market works against the capitalization effect, mainly because at reasonable hiring costs

[18] The estimate was obtained by holding constant capital, technology and employment, so it is not strictly an estimate for the elasticity in (62), which is a steady-state one. We use it here as an illustration of the impact of plausible elasticities. The unemployment elasticity reported in the introduction, -0.44, was obtained from the Nash sharing condition by holding employment constant, so it is comparable to the estimated one of -0.04.

wages are too close to the marginal product of labor and the ratio $w/(\phi - w)$ is a big number. The sharing rule wage equation exhibits excess sensitivity to tightness, as frequently pointed out (see in particular Shimer 2005 and Hall 2005), but this does not appear to be the main problem here, because even at the estimated elasticity of 0.02 the impact of TFP growth on tightness is very small.[19]

An inspection of either (59) or (62) shows that a bigger problem with the capitalization effect is the one that we encountered earlier in connection with the relative strengths of the capitalization and creative destruction effects, the relative size of a and $r+s$. Since the discount rate is $r+s-a$, for changes in a to have a big impact on it the model requires either large changes in a or small values for $r+s$. For example, in order to match exactly the estimated impact of TFP growth on unemployment with our second wage equation we require

$$\frac{r+s-\bar{a}}{r+s-a} = 0.738. \tag{68}$$

This ratio could be achieved at the benchmark $r+s = 0.14$ if the fall in the TFP growth rate is 3.66 percentage points. Alternatively, if the fall in the TFP growth rate is the observed 1.1 percentage points, the capitalization effect is strong enough to match the rise in unemployment if $r+s = 0.05$. The latter requirement essentially amounts to assuming that when creating a new job firms use an infinite horizon to discount future revenues, because a discount rate of 5 percent is only marginally above conventionally-used interest rates.[20]

[19] Recall that in this model wages are proportional to productivity and so shocks to productivity would have no impact at all on the unemployment rate, the issue addressed by Shimer and Hall.

[20] One way of reducing the effective discount rate, suggested by a referee, is to assume that although a job may be "destroyed" on average after ten years in the sense of Davis, Haltiwanger and Schuh (1996), the position is not necessarily closed down but brought back into use at a later date. For example, capital may stand idle for a while. In this case the expected life of the job for discounting purposes will be the life of the position, not the job. In the absence of more information on this we cannot give a number to s to match it, but if, say, we double the expected life of a position to 20 years, the fall in the TFP growth rate that we have been modeling explains a rise in unemployment of about 0.72 percentage points instead of the calculated 0.43 percentage points with $s = 0.1$.

5 Conclusions

We argued that although in theory the effect of faster TFP growth on steady state unemployment can be either positive or negative, empirically the effect is strongly negative. We estimated the impact of the TFP growth rate on unemployment for a panel of industrial countries and used our estimates to evaluate a perfect foresight model of job creation and job destruction with embodied and disembodied technology. The impact of TFP growth on employment in the model is derived from the responses of firms to changes in their implicit discount rates (the "capitalization" effect) and to obsolescence (the "creative destruction" effect). The net effect depends critically on the fraction of new technology that is embodied in new jobs. The first finding of the paper is that consistency between the empirical evidence and the model requires totally disembodied technology. "Creative destruction" appears to play no part in the steady-state unemployment dynamics of the countries in our sample and the Solow growth model augmented by an unemployment equation is an appropriate framework for the study of unemployment dynamics.[21]

A second finding is that with entirely disembodied technology, the capitalization effect of faster growth is quantitatively sufficiently strong to explain alone the full impact of TFP growth on unemployment when two other conditions are satisfied. First, wages need to be insulated from labor market conditions, in particular the vacancy-unemployment ratio, and second the firm needs to discount the revenues from new jobs over an infinite horizon. If the wage rate responds to market tightness as in the Nash sharing rule, or if firms discount future profits by taking into account the observed job destruction rates the capitalization effect is weakened.

We focused on the perfect-foresight responses of firms to technological change but our model is not inconsistent with other explanations. For example, there could be additional forces at work contributing to a positive relation between productivity growth and employment, beyond the capitalization effect. Such forces could be related to the labor supply forces identified by

[21]It should be reiterated that our test is for technology embodied in new jobs, not in new capital, and it is consistent with any fraction of embodiment in new capital. For example, Hornstein, Krusell and Violante (2002) claim that a model with a large fraction of embodied technology can explain some labor market facts. Our respective claims are not inconsistent with each other because we test for embodiment in new jobs whereas they test for embodiment in new capital.

Phelps (1994), Hoon and Phelps (1997) and Ball and Moffitt (2002), which, although temporary, imply long lags in the effect of growth on employment. More work is needed in linking the demand-side factors modeled here and the supply-side factors modeled by others. The estimated impact of TFP growth on unemployment at the aggregate level, which in the United States appears to explain the entire trend changes in unemployment, is sufficiently large to warrant more work, both theoretical and empirical.

Appendix : Estimation results and data sources

The estimated equations are reported in Tables 5-7. The data are annual for the period 1965-1995 for the countries of the European Union (except for Spain and Greece), the United States and Japan.[22] Our data come mainly from the online OECD database with some adjustments. The institutional variables (union density, benefit replacement ratio, benefit duration and tax wedge) are from Nickell et al. (2001) and they are available for the period 1960-1995, which is the reason that the sample ends in 1995. The definitions of variables and detailed sources are given at the end of this Appendix.

The equations are estimated by three-stage least squares. In each equation we include country fixed effects, and one time dummy for each year in the sample, to remove common employment trends and cycles. We also include country-specific dummies for German unification by interacting the fixed effect for Germany with the time dummies for the post-unification years, 1991-95. The inclusion of lagged dependent variables can lead to finite sample biases with the within-group estimator but with a sample of 31 years this is not likely to be a problem (see Nickell 1981). The asymptotic unbiasedness of the coefficients requires the absence of serial correlation in the errors, which we test and cannot reject. Finally, with lags of the dependent variables included, when coefficients differ across countries pooling across groups can give inconsistent estimates (Pesaran and Smith 1995). We test for differences in the coefficients across the sample by using a poolability test described by

[22] The European Union countries in the sample are: Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Norway, Portugal, Sweden and the United Kingdom. Greece was excluded because some of the institutional variables were missing and Spain because the fast rise in unemployment in the 1980s and the introduction of temporary contracts in 1984 make it an outlier for reasons unrelated to productivity growth.

Baltagi (1995).[23] The restrictions on the slopes cannot be rejected at conventional levels ($\chi^2_L(126) = 25.89$, $\chi^2_w(180) = 176.69$ and $\chi^2_k(126) = 41.36$).

The steady-state version of our model satisfies two restrictions that we impose on the estimated equations. First, the rates of growth of wages and the capital-labor ratio in the steady state are both equal to the average rate of growth of TFP:

$$\frac{\dot{k}}{k} = \frac{\dot{w}}{w} = a. \tag{69}$$

Second, changes in the capital stock and TFP do not affect steady-state employment:

$$\frac{\partial L}{\partial k} + \frac{\partial L}{\partial w}\frac{\partial w}{\partial k} = 0, \tag{70}$$

$$\frac{\partial L}{\partial A} + \frac{\partial L}{\partial w}\frac{\partial w}{\partial A} = 0. \tag{71}$$

The test for the four restrictions is $\chi^2(4) = 9.60$, which cannot reject them at the 5% level.

The estimated employment equation is derived from (42). The variables influencing job creation are derived from a log-linearized version of (40), under the assumption that job creation costs are exogenous and unobservable. These variables are the contemporaneous level of marginal product, the wage rate, the interest rate and the expected rates of growth of marginal product and the wage rate. Marginal product is proxied by its arguments, the level of TFP and the level of the capital-labor ratio, and the expected rates of growth of marginal product and the wage rate are proxied by the rate of TFP growth. Job destruction is derived from (30). It depends on the same variables as job creation, making it impossible to identify them separately from a single employment equation.

In the short run we allow the capital stock and TFP to have different effects on employment (e.g. because the costs of adjustment in capital are different from the technology implementation lags) but in the long run their effects are restricted by (70)-(71). Any differences in the adjustment lags in job creation and job destruction should also imply different short-run and long-run effects of TFP. Supposing that job destruction reacts faster than

[23] The poolability test is a generalized Chow test extended to the case of N linear regressions, which tests for the common slopes of the regressors. The test statistic is asymptotically distributed as $\chi(q)$ under the null. See Baltagi (1995, 48-54).

Table 5: The employment equation

Dependent variable $\ln(L/P)_{it}$	
Independent Variables	
$\ln(L/P)_{it-1}$	1.180
	(27.12)
$\ln(L/P)_{it-2}$	-0.263
	(-6.30)
$\ln w_{it-1}$	-0.057
	(-4.46)
$\ln(K/P)^{*}_{it}$	0.027
	(3.37)
$\ln A_{it}$	0.030
	(3.34)
$d\ln A_{it}$	-0.084
	(-3.69)
$d\ln A_{it-1}$	0.160
	(7.63)
r_{it}	-0.074
	(-2.70)
Year dummies (31 years)	*yes*
Fixed effects (15 countries)	*yes*
Serial Correlation	0.57
p-value	0.28
Heteroskedasticity	16.38
p-value	0.29
Obs.	462

Notes for Tables 5-7. The estimation method is three stage least squares. Numbers in brackets below the coefficients are t-statistics. $(L/P)_{it}$ is the ratio of employment to population of working age in country i in year t, (K/P) is the ratio of the capital stock to the population of working age, A is measured TFP progress, w is the real wage rate, and r the real interest rate. Serial Correlation is an LM test (Baltagi 1995) distributed N(0,1) under the null (H_0 : no autocorrelation). Heteroskedasticity is a groupwise LM test, distributed $\chi^2(N-1)$ under the null (given $\upsilon_{it} = c_i + \lambda_t + \epsilon_{it}$, $H_0 : \epsilon_{it}$ is homoskedastic). **Instrumented variables:* the instruments used are all the exogenous variables in the three regressions and lags of the endogenous variables.

Table 6: The wage equation

Dependent variable $d \ln w_{it}$	
Independent Variables	
$d \ln w_{it-1}$	0.058
	(1.46)
$d \ln(K/LF)^*_{it}$	0.503
	(4.24)
$d \ln A_{it}$	0.241
	(5.89)
$\ln w_{it-1}$	-0.177
	(-6.65)
$\ln(K/LF)_{it-1}$	0.083
	(4.84)
$\ln A_{it-1}$	0.094
	(5.45)
$\ln u^*_{it}$	-0.010
	(-2.31)
$BD_{it} * \ln u^*_{it}$	0.006
	(2.88)
$union_{it}$	0.043
	(2.10)
$dtax_{it}$	-0.055
	(-0.84)
rer_{it}	-0.020
	(-1.30)
$d^2 \ln p_{it}$	-0.203
	(-3.55)
Year dummies (31 years)	*yes*
Fixed effects (15 countries)	*yes*
Serial Correlation	1.21
p-value	0.11
Heteroskedasticity	16.40
p-value	0.29
Obs.	462

Notes. See notes to Table 5. All variables have been defined except: LF is the labor force, u the unemployment rate, BD the maximum duration of benefit entitlement, *union* the fraction of workers belonging to a union (union density), *rer* the benefit replacement ratio, *tax* the tax wedge and p the price level.

Table 7: The investment equation

Dependent variable $d\ln K_{it}$	
Independent Variables	
$d\ln K_{it-1}$	0.963
	(21.72)
$d\ln K_{it-2}$	-0.141
	(-3.20)
r_{it}	-0.036
	(-2.70)
$\ln w_{it}^*$	-0.012
	(-1.83)
$\ln A_{it}$	0.021
	(5.12)
$d\ln A_{it}$	0.064
	(5.88)
$d\ln A_{it-1}$	0.026
	(2.37)
$\ln(K/P)_{it-1}$	-0.009
	(-2.29)
$d\ln(D/K)_{it}$	-0.005
	(-2.08)
Year dummies (31 years)	*yes*
Fixed effects (15 countries)	*yes*
Serial Correlation	0.38
p-value	0.35
Heteroskedasticity	18.46
p-value	0.19
Obs.	462

Notes. See notes to Table 5. All variables have been defined except for D, which is the level of government debt.

job creation to shocks, as usually found in the data,[24] we should expect the impact effect of productivity growth on employment to be negative, and either remain negative or turn positive in the medium to long run, when job creation has had time to adjust. In the estimated regression we find the effect to be negative in the first year but turn positive in the second.

The level of employment and the capital stock were deflated by the population of working age. This normalization gave statistically better results than the one that deflates the capital stock by the employment level, but it is isomorphic to it. The terms of the employment equation can be rearranged to yield

$$\begin{aligned}\ln(L/P)_t &= 1.21\ln(L/P)_{t-1} - 0.27\ln(L/P)_{t-2} - 0.059\ln w_{t-1} - 0.076r_t \\ &\quad +0.027\ln k_t + 0.031\ln A_t - 0.086d\ln A_t + 0.16d\ln A_{t-1}, \quad (72)\end{aligned}$$

where, as in the theoretical model, k_t is the ratio of capital to employment.

The estimated wage equation is the aggregation of (22) with adjustment lags to pick up short-run dynamics. We estimate an error-correction equation in wage growth and impose the restriction that real wages in the steady state grow at the rate of TFP growth. We also include the first difference in the inflation rate as an additional cyclical variable to pick up temporary deviations from the steady-state path. The unemployment income $b(t)$ is represented by two parameters of the unemployment insurance system, the ratio of compensation to mean wages and the duration of entitlement. However, the only parameter of the unemployment compensation system that we found statistically significant is the duration of benefit entitlement - the restraining influence of unemployment on wages in countries that have long durations is reduced. We tested for taxes but did not find that they increased wage costs. The parameter β stands for the share of labor in the wage bargain and it is postulated that countries with stronger unions extract a bigger share.

The capital stock in the wage equation is divided by the labor force instead of the level of employment to avoid the introduction of cyclical noise but of course since $\ln L - \ln LF = \ln(1-u) \approx -u$, the estimated equation is approximately equivalent to an equation that has the ratio of capital to employment and three lags of the unemployment rate as independent variables.

Similarly, because of the cyclicality of employment, estimating an investment equation by dividing the capital stock by employment does not give

[24] The standard reference is Davies, Haltiwanger and Schuh (1996). In some European countries, however, job creation sometimes reacts faster than job destruction because of firing restrictions. See Boeri (1996).

reliable results and introduces identification problems vis-a-vis the employment equation. We deal with this problem by replacing employment by the real wage and estimate an error-correction equation for the capital stock. The long-run value of the capital stock to which the equation converges is (11), with the capital stock proportional to TFP and the factor of proportionality depending on the cost of capital and the cost of labor. For the cost of capital we use the real interest rate but we also include a variable for government debt, on the assumption that more government involvement in capital markets makes it more difficult for private business to acquire funds.[25]

The data sources are as follows:

L Total employment, persons employed (*source*: OECD National Accounts).

P Working age population (*source*: OECD National Accounts).

LF Labor force (*source*: OECD National Accounts).

w Real labor cost: $w = \left(\frac{WSSE}{def_{GDP}}\right)/(L - L_{self})$, where WSSE is the compensation of employees at current price and national currencies (*source*: OECD Economic Outlook), def_{GDP} is the GDP deflator, base year 1990 (*source*: OECD National Accounts), L is total employment and L_{self} is the total number of self- employed (*source*: OECD National Accounts).

K Real capital stock. The calculation of the capital stock is made according to the Perpetual Inventory Method: $K = (1-\delta)K_{-1} + \left(\frac{I^n}{def_{INV}}\right)_{-1}$, where I^n is the gross fixed capital formation at current prices and national currencies (*source*: OECD National Accounts) and def_{INV} is

[25] The estimated growth effects are unaffected by the inclusion of the government debt variable in the investment equation and the change in the inflation rate in the wage equation but statistically the overall fit of the equations improves because of the removal of cyclical noise. We also experimented by including other cyclical measures as independent variables, to make sure that the estimated coefficients on TFP are not dominated by cyclical effects. The other measures included the cyclical component of GDP and the deviation of hours of work from trend, for the countries with hours data. None of them influenced the estimated coefficient on TFP or its rate of growth, so we omitted them from the preferred specification.

the gross fixed capital formation price index, base year 1990 (*source*: OECD National Accounts) and the depreciation rate, δ, is assumed constant and equal to 8 percent, which is consistent with OECD estimates (Machin and Van Reenen 1998). Initial capital stock is calculated as: $K_0 = \frac{I_0}{g+\delta}$, where g is the average annual growth of investment expenditure and I_0 is investment expenditure in the first year for which data on investment expenditure are available.

A Total factor productivity (TFP). This is computed using the following formula: $d\ln A = \frac{1}{1-\overline{\alpha}}[d\ln Y - \overline{\alpha} d\ln K - (1-\overline{\alpha}) d\ln L]$, where Y is gross domestic output at constant price and national currencies (*source*: OECD National Accounts), K is capital stock as defined above, L is total employment as defined above, $(1-\overline{\alpha})$ is a smoothed share of labor following the procedure described in Harrigan (1997).[26] Labor share is defined as $(1-\alpha) = \frac{wL}{Y}$. In order to make our measure of total factor productivity comparable across countries, we convert both Y and K to US dollars using the GDP and gross fixed capital formation Purchasing Power Parities (for 1990) respectively (*source*: OECD National Accounts).

r Real long term interest rate deflated by the 3-year expected inflation rate: $r = i - E(d\ln p_{+1})$, where i is the long term nominal interest rate (*source*: OECD Economic Outlook). $E(d\ln p_{+1})$ are fitted values from the regression $d\ln p = \gamma_1 d\ln p_{-1} + \gamma_2 d\ln p_{-2} + \gamma_3 d\ln p_{-3} + \nu$, where $d\ln p$ is the inflation rate based on the consumer price index p (*source*: OECD National Accounts) and the coefficients on the right side are restricted to sum to one, indicating inflation neutrality in the long run (see Cristini 1999).

u Unemployment rate: $u = 1 - \frac{L}{LF}$, where L is the total employment and LF is the total labour force (see above for definitions and data

[26] Correcting for changes in hours of work would have restricted the sample too much because of the unavailability of data. However, when we repeated the estimation for the sub-sample of countries that have data for hours and capital utilization, correcting TFP for changes in these, we found that the estimated effects of growth on employment were very close to the ones that we report in this paper.

sources).

union Net union density defined as the percentage of employees who are union members (*source:* Nickell et al. 2001).

tax Tax wedge calculated as the sum of the employment tax rate, the direct tax rate and the indirect tax rate (*source:* Nickell et al. 2001).

rer Benefit replacement ratio defined as the ratio of unemployment benefits to wages for a number of representative types (*source:* Nickell et al. 2001, constructed from OECD data sources).

BD Benefit duration defined as a weighted average of benefits received during the second, third, fourth and fifth year of unemployment divided by the benefits in the first year of unemployment (*source:* Nickell et al. 2001, constructed form OECD data sources).

p Consumer price index , base year 1990 (OECD, Main Economic Indicators).

D Gross government debt (*source*: OECD Economic Outlook and for UK IMF International Financial Statistics) divided by the GDP deflator. For missing values before 1970, debt is calculated using the formula: $D - D_{-1} = DF$, where DF is the government deficit (*source*: IMF International Financial Statistics).

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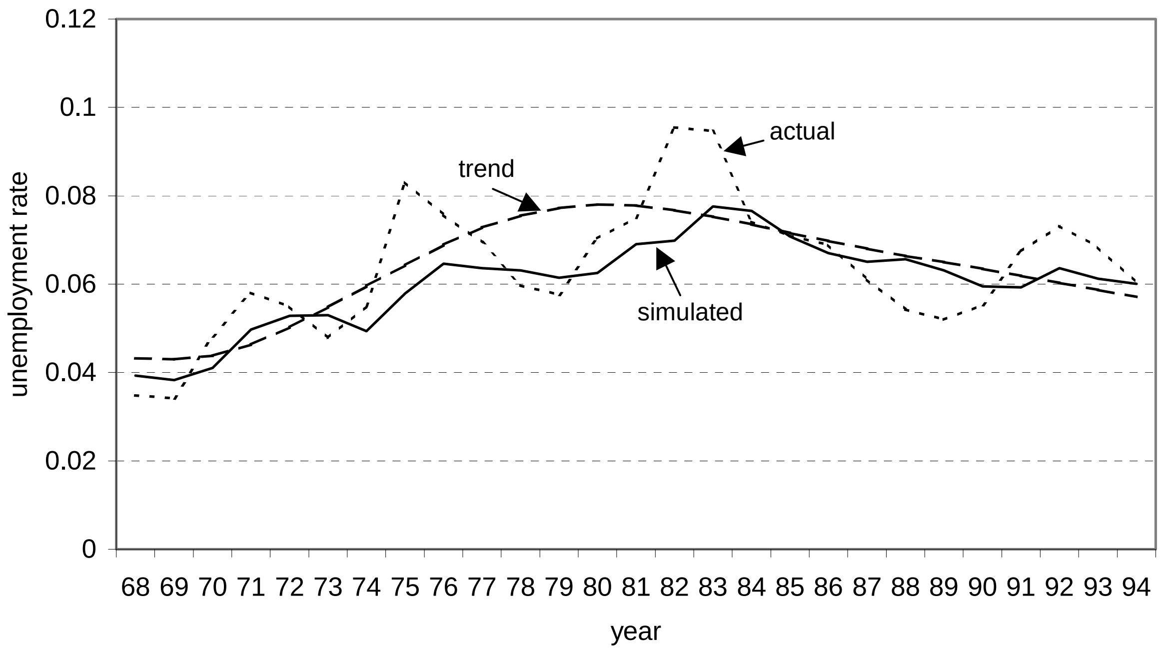
Figure 1

The predicted unemployment rate when TFP takes actual values and other exogenous variables held constant compared with the actual unemployment rate

(a) United States



(b) European Union

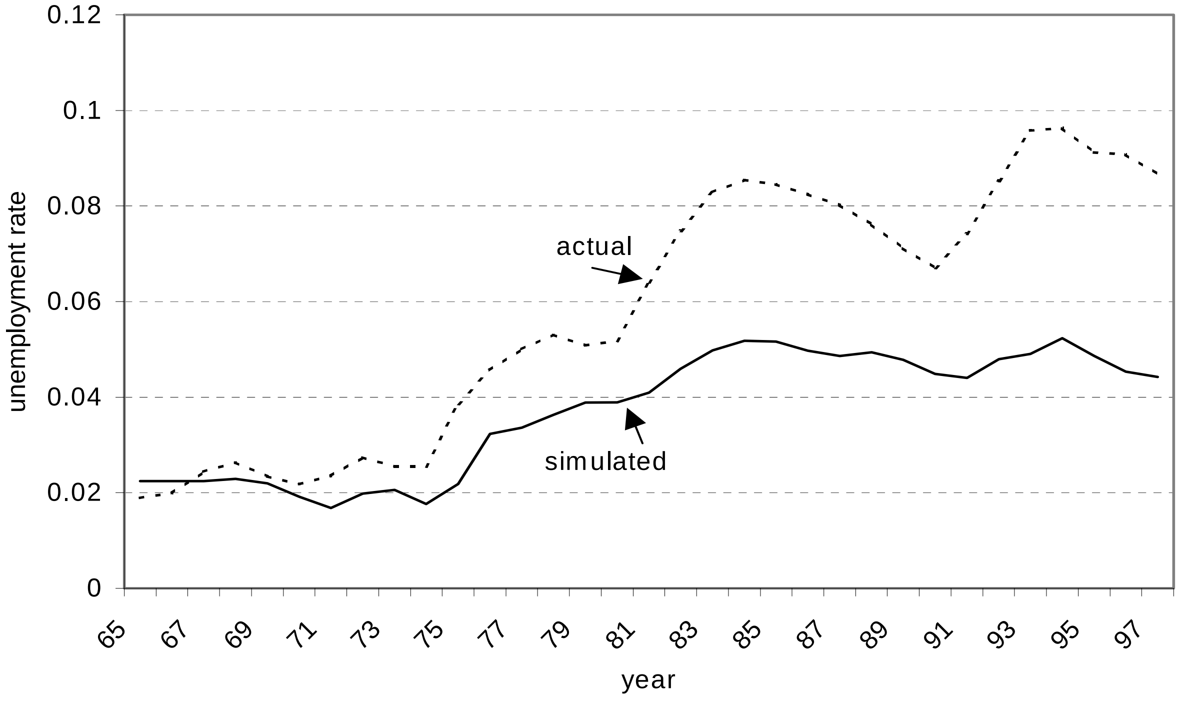


Figure 2
Expected returns and costs from job creation