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Productivity, Aggregate Demand and Unemployment Fluctuations

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Abstract
This paper presents new empirical evidence on the cyclical behavior of US unemployment that poses a challenge to standard search and matching models. The correlation between cyclical unemployment and the cyclical component of labor productivity switched sign at the beginning of the Great Moderation in the mid 80s: from negative it became positive, while standard search models imply a negative correlation. I argue that the inconsistency arises because search models do not allow output to be demand determined in the short run. I present a search model with nominal rigidities that can rationalize the empirical findings, and I document two new facts about the Great Moderation that can account for the large and swift increase in the unemployment-productivity correlation in the mid-80s.

JEL Classifications: J64, E32, E37, E52
Keywords: Unemployment Fluctuations, Labor productivity, Search and matching model, New-Keynesian model

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1 Introduction

What drives unemployment fluctuations at business cycle frequencies? Since the seminal work of Mortensen-Pissarides (1994), a vast literature has focused on labor productivity to explain movements in unemployment.[1] In a Mortensen-Pissarides (MP) search and matching model, an increase in productivity raises the surplus of a match between a firm and a worker, leads firms to post more job vacancies and pulls down the unemployment rate. Shifts in labor demand are caused by changes in productivity, and productivity is seen as the central driving force of unemployment fluctuations.

Given the major role played by productivity, there is surprisingly little empirical evidence on the impact of productivity changes on unemployment. In fact, this paper uncovers new empirical findings that are inconsistent with the standard MP prediction that an increase in productivity leads to lower unemployment. I argue that the inconsistency arises because the MP model does not allow output to be demand determined in the short run, and I present a search model with costly price adjustment that can rationalize the empirical observations.

The first contribution of this paper is empirical. I provide a thorough study of the relationship between unemployment fluctuations and different measures of productivity in the US, and I highlight new empirical facts that posit a challenge to the standard MP model. I find that ρ, the contemporaneous correlation between labor productivity and unemployment displays a large and swift increase in the mid 80s; from negative it became positive during the Great Moderation.[2] Furthermore, I use long run identifying restrictions to decompose labor productivity and unemployment into technology shocks and non-technology shocks. I find that a positive technology shock, identified as the only disturbance with a permanent impact on labor productivity, *increases* unemployment temporarily, whereas a positive non-technology shock (temporarily) increases productivity and *decreases* unemployment.

The standard search model of unemployment is confronted with two problems. First, it predicts that an increase in productivity leads to lower unemployment and implies a negative value for ρ. Second, with only one mechanism through which productivity affects the labor market, it cannot generate two different impulse responses or explain large fluctuations of ρ.

The second contribution of this paper is theoretical. I extend the MP model by introducing nominal frictions so that hiring firms are demand constrained in a New-Keynesian fashion. I also make a crucial distinction between the extensive (number of workers) and the intensive (hours *and* effort) labor margins. In this framework, unemployment fluctuations are the prod-

[1]See, among others, Merz (1995), Andolfatto (1996), den Haan, Ramey and Watson (2000), Shimer (2005a), Hall (2005) and Mortensen and Nagypal (2005).

[2]The so-called "Great Moderation" refers to the dramatic decline in macroeconomic volatility enjoyed by the US economy since the mid 80s. (see, for example, McConnell and Perez-Quiros, 2000)

uct of two disturbances: technology shocks and monetary policy (or aggregate demand) shocks. Positive technology shocks temporarily raise unemployment because with sticky prices, aggregate demand does not adjust immediately to the new productivity level, and firms use less labor. The correlation between unemployment and productivity, ρ, is positive. In contrast, positive aggregate demand disturbances decrease unemployment and increase productivity temporarily, because firms increase labor effort to satisfy demand in the short run. As a result, ρ is negative. In this model, movements in ρ reflect changes in the relative importance (or volatility) of technology and aggregate demand shocks.

The volatility of the non-technology shocks identified with long run restrictions displays a large drop in the early 80s. By interpreting non-technology shocks as aggregate demand shocks in the model, this can explain why ρ increased. Furthermore, it can be argued that a structural change took place in the early 80s. Notably, productivity became less procyclical, i.e. the endogenous component of productivity due to variable capacity utilization of inputs decreased. With a less endogenous response of productivity, the negative impact that aggregate demand shocks have on ρ is diminished. This can also explain why ρ increased. I simulate the impact of the simultaneous structural change and drop in the volatility of aggregate demand shocks, and I find that these two events can quantitatively explain the sign switch of ρ that took place in the mid 80s. A remaining question is why productivity became less procyclical after the mid 80s, and I discuss an explanation emphasizing a change in the behavior of inventories after 1984.[3]

The seminal contributions of Galí (1999) and Basu, Fernald and Kimball (1999) spawned an important empirical literature on the negative effect of technology shocks on total hours worked, but the focus has mostly been on hours and not employment or unemployment. Galí (1999) offered a New-Keynesian explanation, and the present model invokes a similar mechanism to account for an increase in unemployment following a technology shock. A few papers introduce search models of unemployment into New-Keynesian frameworks but to my knowledge, this paper is the first to propose a model emphasizing the interaction between hiring frictions and nominal frictions and capable of rationalizing large movements in ρ. Models in the spirit of Trigari (2004) or Walsh (2004) introduce a separation between firms facing price stickiness (the retail sector) and firms evolving in a MP labor market without nominal rigidities (the wholesale sector). Firms responsible for employment are never demand constrained; adjustments occur through prices, not quantities, and the correlation between productivity and unemployment is counterfactually negative for technology shocks. In Krause and Lubik (2003), hiring firms are demand constrained, but without intensive margin, the model cannot generate any endogenous movement in productivity. Finally, in a recent paper written in parallel to the present one,

[3] See Blanchard and Simon (2001), Kahn, McConnell, and Perez-Quiros (2002) and Ramey and Vine (2004).

Blanchard and Galí (2006) present a model similar in spirit but focus on the consequence of hiring frictions on optimal monetary policy.

The remainder of the paper is organized as follows: Section 2 studies the relationship between labor productivity and unemployment; Section 3 presents a New-Keynesian model with search unemployment; Section 4 describes the equilibrium and dynamics of the model; Section 5 confronts the model with the data; and Section 6 concludes.

2 Empirical Evidence

This section documents empirical findings that pose a challenge to the current search theory of unemployment fluctuations but also guide the formulation of a consistent model. First, I study the joint behavior of productivity and unemployment and show that their contemporaneous correlation ρ changed sign in the mid 80s. Second, I use long run identifying restrictions to decompose labor productivity and unemployment into technology shocks and non-technology shocks. I confront the standard MP model with this evidence and argue that it cannot, as such, account for the behavior of cyclical unemployment in the US. I conclude that a theory of unemployment fluctuations should explicitly consider the interaction of technology and non-technology shocks.

2.1 The ρ puzzle

Figure 1 shows the detrended series for US unemployment and labor productivity (i.e. output per hour) over 1948-2005.[4] Until 1985, the two series seem negatively correlated with unemployment lagging labor productivity. After 1985 however, the correlation becomes positive. This is especially true for 1993 when both unemployment and labor productivity increase sharply but this is apparent throughout the post-1985 period. The magnitude of this sign flip is large: looking at Table 2-1, ρ goes from -0.31 over 1948-1984 to 0.40 over 1985-2005, and both estimates are significant at the 5%-level.[5] To see more sharply this change in the correlation, Figure 2 plots ρ_{10}, the 10-year rolling contemporaneous correlation between unemployment and labor productivity. In about a year's time, the rolling correlation switches swiftly from

[4] The data are taken from the U.S. Bureau of Labor Statistics (BLS) and cover the period 1948:Q1 through 2005:Q4. Labor productivity is measured as real average output per hour in the non-farm business sector and unemployment is the quarterly average of the monthly unemployment rate series constructed by the BLS from the Current Population Survey. All series are expressed as deviations from an HP-filter with smoothing parameter 1600. The conclusions are independent of the smoothing parameter.

[5] Gali and Gambetti (2007), in recent work conducted independently, stress that the correlation of hours with labor productivity experienced a remarkable decline, shifting from values close to zero in the pre-84 period to large negative values after 1984.

negative to positive values. But ρ_{10} also displays large fluctuations throughout the whole period, and before 1984, ρ_{10} deviates sometimes by 50% from its 1948-1984 mean. Although I so far only considered the contemporaneous correlation, a quick look at the unemployment-productivity cross-correlogram before and after 1985 gives the same conclusion. As we can see on Figure 3, the two cross-correlograms look dramatically different. Notably, the correlation between unemployment and labor productivity lagged two-quarters is positive after 1985 but corresponds to the peak negative correlation before 1985.

As a robustness check, I verify that the swift jump of ρ is not the result of a change in the definition of unemployment or the labor force, and in Figure 4 and 5, I plot respectively the 10-year rolling correlation between employment (in millions) and output per hour and the 10-year rolling correlation between vacancies and output per hour.[6] Both display a large jump similar to ρ. Table 2-1 confirms this result as the correlation between productivity and vacancies went from 0.34 over 1951-1984 to -0.18 over 1985-2005.

Finally, I consider an alternative measure of productivity. Chang and Hong (2006) argue that TFP is a more natural measure of technology than output per hour because the latter also reflects changes in input mix as well as improved efficiency. Figure 6 plots the 10-year rolling correlation between unemployment and TFP adjusted for capacity utilization.[7] The correlation is never strongly negative but oscillates between positive and negative values until the mid-80s. However, its evolution resembles the evolution of ρ, and one can observe a similar jump in the mid-80s.

2.2 The impact of technology shocks on unemployment

There is little empirical evidence on the impact of productivity movements on cyclical unemployment. Galí (1999) and Basu, Fernald and Kimball (1999) spawned an important empirical literature on the negative effect of technology shocks on total hours worked but the issue has almost never been studied in the context of unemployment models.[8]

Galí (1999), following the seminal work by Blanchard and Quah (1989), proposed a method to identify technological disturbances. By imposing long run restrictions, it is possible to isolate technology shocks and study their impact on the economy. Technology shocks are identified as the only shocks with a permanent impact on productivity. Using a similar framework, I

[6] The employment series is the number of employed workers (in millions) in the non-farm business sector and is taken from the BLS. The vacancy series is the Conference Board help advertising index. Both series cover 1951:Q1-2005:Q4 and are detrended with an HP-filter with smoothing parameter 1600.

[7] The TFP series is taken from Beaudry and Portier (2006) and covers 1948:Q1 to 2000:Q4.

[8] Two exceptions are Michelacci and Lopez-Salido (2005) and Ravn (2005). Ravn's (2005) impulse responses are likely to be distorted because he does not remove the low-frequency movements in productivity and unemployment that bias the estimates. Michelacci and Lopez-Salido (2005) find impulse responses similar to the present paper but focus on the creative destruction aspect of technological progress.

study the response of unemployment (instead of hours) to a technology shock. Specifically, I am interested in estimating the system

$$\begin{pmatrix} \Delta x_t \\ u_t \end{pmatrix} = C(L) \begin{pmatrix} \varepsilon_t^a \\ \varepsilon_t^m \end{pmatrix} = C(L)\varepsilon_t \tag{1}$$

where x_t is labor productivity defined as output per hours, u_t unemployment, $C(L)$ an invertible matrix polynomial and ε_t the vector of structural orthogonal innovations comprised of ε_t^a technology shocks and ε_t^m non-technology shocks. I use the estimation method of Shapiro and Watson (1988) and Francis and Ramey (2003) to allow for time-varying variance of the structural innovations. The details of the estimation are described in the Appendix.

I use quarterly data taken from the U.S. Bureau of Labor Statistics (BLS) covering the period 1948:Q1 to 2005:Q4. Labor productivity x_t is measured as real average output per hour in the non-farm business sector, and unemployment u_t is the quarterly average of the monthly unemployment rate series constructed by the BLS from the Current Population Survey. Following Fernald (2005), I allow for two breaks in Δx_t, 1973:Q1 and 1997:Q1, and I filter the unemployment series with a quartic trend. Fernald (2005) showed that the presence of a low-frequency correlation between labor productivity growth and unemployment, while unrelated to cyclical phenomena, could significantly distort the estimates of short run responses obtained with long run restrictions.[9]

The first row of Figure 7 displays the impulse response functions of productivity and unemployment following a technology shock. Labor productivity undershoots its new long run level by around 20% and plateaus after about one and a half years. After an initial jump, unemployment displays a hump-shaped positive response that peaks quite rapidly, in about 2 quarters. Quantitatively, a 0.5% rise in productivity is associated with a 0.2 percentage point *increase* in unemployment. The second row of Figure 7 shows the dynamic effects of a non-technology shock. On impact, productivity jumps by 0.6% and reverts to its long run value in one year. Unemployment decreases, reaches a trough after one year, and reverts slowly to its long run value. Quantitatively, a 0.6% increase in productivity is correlated with a 0.2 percentage point *drop* in unemployment.

As a robustness check, I now reproduce this exercise using the TFP series from Beaudry and

[9] At low frequencies, unemployment displays a low-high-low pattern. With high growth in the 60s followed by a slowdown in the 70s and an acceleration in the late 90s, productivity growth displays a similar U-shape trend. To get non-distorted impulse responses, I remove the low-frequency movement in productivity growth and unemployment. An alternative proposed by Fernald (2005) would be to separately analyze subsamples with no breaks in technology growth. In a robustness check, I restrict the sample period to 1973-1997 where there is no clear trend break. Results remain very similar.

Portier (2006) instead of output per hour in (1).[10] Indeed, Chang and Hong (2006) question Gali's (1999) finding that technology shocks decrease total hours worked and attribute it to the use of output per hour as a measure of productivity. They argue that, because output per hour, unlike TFP, is influenced by permanent shifts in input mix (e.g. shocks affecting permanently the capital-labor ratio), Gali (1999) mislabels changes in input mix as technology shocks and does not properly identify the response of total hours worked to technology shocks. My approach is obviously subject to the same criticism, and Figure 8 shows the impulse response functions to technology and non-technology shocks using TFP unadjusted for capacity utilization. Encouragingly, the impulse responses look very similar to the ones using output per hour, and technology shocks increase unemployment temporarily. Using TFP adjusted for capacity utilization, one can observe in Figure 9 that the unemployment responses are unchanged but that, following a non-technology shock, the response of adjusted TFP is much weaker and never significant. Following a technology shock, adjusted TFP jumps immediately to its long run value without any undershooting.

2.3 Confronting the MP model with the data

The standard search model with productivity shocks used in Mortensen-Pissarides (1994), Shimer (2005a) or Hall (2005) is confronted with two problems. First, it predicts a negative value for ρ, as an increase in productivity raises the surplus of a match, leads firms to post more vacancies and pulls down the unemployment rate. However, ρ is positive since the beginning of the Great Moderation, and I find that a positive technology shock increases unemployment in the short run. Using TFP instead of output per hour as a measure of productivity gives an even more puzzling result as the unemployment-TFP correlation is never significantly negative over the whole 1948-2005. Second, the standard MP model cannot account for changes in the sign of ρ because it embeds only one mechanism through which productivity affects the labor market.

I now argue that the interaction of technology and non-technology shocks is key to understand the behavior of ρ.

[10] In another robustness check, I follow Fisher (2006) and estimate a more general specification allowing for two types of technology shocks: neutral technology shocks (N-shocks) and investment specific technology shocks (I-shocks). Both shocks can have a permanent effect on productivity but only I-shocks can affect the price of investment in the long-run. Using a trivariate VAR with the real price of equipment, output per hour and unemployment, I find that the Blanchard-Quah aggregation theorem holds because the responses of productivity and unemployment to I-shocks resemble the responses to non-technology shocks. The results are available upon request.

2.4 Explaining the behavior of ρ

In order to identify the possible factors behind the large movements in the unemployment-productivity correlation, I start by deriving an analytical expression for ρ. Indeed, when Δx_t and u_t are represented by (1), they can be rewritten as

$$\begin{aligned} \Delta x_t &= \sum_{j=0}^{\infty} C_{1j}^{\Delta x} \varepsilon_{t-j}^{a} + \sum_{j=0}^{\infty} C_{2j}^{\Delta x} \varepsilon_{t-j}^{m} \\ u_t &= \sum_{j=0}^{\infty} C_{1j}^{u} \varepsilon_{t-j}^{a} + \sum_{j=0}^{\infty} C_{2j}^{u} \varepsilon_{t-j}^{m} \end{aligned}$$

so that I can write ρ as

$$\rho = \frac{\sigma_a^2 \sum_{j=0}^{\infty} C_{1j}^{x} C_{1j}^{u} + \sigma_m^2 \sum_{j=0}^{\infty} C_{2j}^{x} C_{2j}^{u}}{\sqrt{\sigma_a^2 \sum_{j=0}^{\infty} \left(C_{1j}^{x}\right)^2 + \sigma_m^2 \sum_{j=0}^{\infty} \left(C_{2j}^{x}\right)^2} \sqrt{\sigma_a^2 \sum_{j=0}^{\infty} \left(C_{1j}^{u}\right)^2 + \sigma_m^2 \sum_{j=0}^{\infty} \left(C_{2j}^{u}\right)^2}} \tag{2}$$

where $C_{1j}^{x} = \sum_{i=0}^{j} C_{1i}^{\Delta x}$ and $C_{2j}^{x} = \sum_{i=0}^{j} C_{2i}^{\Delta x}$.

This expression shows that ρ depends on the variances of the two shocks hitting the economy σ_a^2 and σ_m^2 but also on the polynomial coefficients capturing the dynamic responses of unemployment and productivity to these shocks. Hence, in the context of the specification from Section 2.2, there are two (non-exclusive) explanations for a change in the sign of the correlation: (a) a change in the relative importance (or volatility) of technology and non-technology shocks and (b) a structural change in the transmission mechanism of these shocks.

Further, I can use (2) to make an educated guess about the reasons behind the large increase in ρ. Looking at the impulse responses from Section 2.2, I can reasonably assume that, up to a good approximation, $C_{1j}^{x} \geq 0$, $C_{1j}^{u} \geq 0$, $C_{2j}^{x} \geq 0$ and $C_{2j}^{u} \leq 0$, $\forall\, j \geq 0$. Hence, for the unemployment-productivity covariance (the numerator of ρ) to increase dramatically and change sign, at least one of two things must happen: either σ_a^2 increases and/or σ_m^2 decreases, i.e. technology shocks become bigger relative to non-technology shocks, or C_{1j}^{x} and C_{1j}^{u} increase and/or C_{2j}^{x} and C_{2j}^{u} decrease. I explore these two possibilities successively.

2.4.1 A change in the volatility of shocks

Since technology and non-technology shocks generate opposite comovements of unemployment and productivity, ρ will depend on their relative strength. If one type of shock became more "important" than the other, the resulting correlation could theoretically switch between positive and negative values. For example, smaller non-technology shocks or larger technology shocks would increase ρ. Figure 10 shows the 5-year rolling standard deviations of technology and non-technology shocks previously identified. Although the variances of both shocks display a downward trend, it is more pronounced for non-technology shocks with a large drop in the mid 80s.[11] The standard deviation of non-technology shocks decreased by more than 200% while the standard deviation of technology shocks was roughly constant in the mid 80s. Was the sign switch of ρ caused by a large decrease in the volatility of all shocks except for technological shocks? In Figure 11, I plot simultaneously ρ_5, the 5-year rolling correlation between unemployment and labor productivity, and the ratio of the 5-year rolling standard deviation of technology shocks to the 5-year rolling standard deviation of non-technology shocks. The result is striking: the two series look very similar despite different construction methods. Moreover, ρ_5 lags the shock series by about a year, suggesting a causal role for volatility fluctuations and an explanation for the sign flip of ρ.

2.4.2 Structural changes

Significant changes occurred in the early- to mid 80s since the beginning of the Great Moderation: a change in the conduct of monetary policy, a change in inventory management and a change in the regulatory environment.[12] Analyzing the response of total hours worked to technology shocks, Galí, López-Salido and Vallés (2003) and Fisher (2006) split their data sample in two sub-periods and report very different impulse response functions for each sub-period.

To allow for a structural change, I also split the sample in two sub-periods, 1948-1983 and 1984-2005, and Figure 12 shows the impulse responses obtained for each period. The responses differ in two points: (a) technology shocks have a smaller impact on unemployment after 1984, and (b) non-technology shocks have a smaller impact on labor productivity after 1984.

Better monetary policy and the response of unemployment to technology shocks: Galí, López-Salido and Vallés (2003) argue that the Fed's response to technology shocks significantly changed after 1982, and that it tended to over-stabilize output in the pre-Volcker/Greenspan era. Figure 12 confirms this finding with a smaller and less significant response of unemployment after 1984 that can be attributed to an improvement in monetary policy.[13] Looking at

[11] The finding that the volatility of shocks decreased since the mid-80s is not new. Stock and Watson (2002, 2003) argue that smaller shocks may be responsible for half or more of the "great moderation", a decline in the cyclical volatility of output and inflation since 1984.

[12] See, for example, Stock and Watson (2002, 2003).

[13] Gali, Lopez-Salido and Vallés (2003) removed the 1979:Q3-1982:Q2 period from their sample because of the unusual monetary operating procedures that were effective. Since my original impulse response functions were obtained using the whole sample of data, I do not remove that particular period from the sub-sample for ease of comparison.

(2), the improvement in the conduct of monetary policy decreases C^u_{1j} which tends to decrease the unemployment-productivity covariance. However, since the denominator of ρ increases when C^u_{1j} decreases, the improvement in the conduct of monetary policy has an ambiguous effect on ρ. As a result, this structural change does not appear to be the main reason for the large and swift increase in ρ.

A decline in the procyclicality of productivity: As we can see in Figure 12, productivity is less responsive after 1984. Following the same aggregate demand shock, productivity responds almost half as much after 1984 with the response on impact going from 0.82 to 0.44 and becoming non significant at the 10% level after 1984. The responses for unemployment, on the other hand, are comparable. A lower endogenous response of productivity for the same response in unemployment tends to decrease the negative impact that a demand shock has on ρ. Looking at (2), this decline in the procyclicality of measured labor productivity corresponds to a decline in C^x_{2j} which increases ρ as the nominator increases while the denominator decreases.

This evidence indicates that the interaction of technology and non-technology shocks plays an important role in explaining unemployment fluctuations and productivity movements. I interpret non-technology shocks as aggregate demand shocks, and I now present a New-Keynesian model with search unemployment.[14]

3 A New-Keynesian model with search unemployment

To account for the conflicting evidence, I depart from the standard MP framework by allowing output to be demand determined in the short run. Firms need to meet the demand for their product at all time, and to do that, I assume that they can adjust the quantity of inputs used *but also* their level of capacity utilization. In this framework, a positive technology shock may temporarily raise unemployment if aggregate demand does not adjust immediately to the new productivity level (e.g. because of nominal rigidities). When productivity increases faster than aggregate demand, firms need less labor and decrease their level of employment as well as their capacity utilization of labor. In contrast, a positive aggregate demand disturbance decreases unemployment and increases productivity temporarily because firms increase their capacity utilization of inputs in order to satisfy demand in the short run.[15]

[14] An alternative interpretation could ignore aggregate demand altogether and emphasize different types of technology shocks. I defer a discussion of this interpretation to Section 6.

[15] Note that this transmission mechanism is supported by the evidence presented in Section 2. If variations in the degree of capacity utilization of inputs are behind the movements in labor productivity reported in Figure

I now present a general equilibrium model with monopolistic competition in the goods market, hiring frictions in the labor market and nominal price rigidities. I also make a distinction between the extensive (number of workers) and the intensive (hours *and* effort) labor margins. There are three types of agents: households, firms and a monetary authority. In this framework, unemployment fluctuations and productivity movements are the product of two disturbances: technology shocks and monetary policy (i.e. aggregate demand) shocks.

3.1 Households

I consider an economy populated by a continuum of households of measure one. With equilibrium unemployment, ex-ante homogenous workers become heterogeneous in the absence of perfect income insurance because each individual's wealth differs based on his employment history. To avoid distributional issues, I follow Merz (1995) and Andolfatto (1996) in assuming that households are extended families that pool their income and choose per capita consumption and assets holding to maximize their expected lifetime utility. Moreover, I assume that the family employment rate is equal to the aggregate employment rate n_t. In order to generate endogenous productivity, each employed family member supplies hours h_t and effort per hour e_t to the firm. Employed workers receive the wage payment $w_t h_t e_t$ with w_t the wage per efficiency unit, and unemployed workers receive unemployment benefits $b_t = bA_t$ with A_t the aggregate technology index. Unemployment benefits are taken as given by workers and firms. Denoting $g(h_t, e_t)$ the individual disutility from working, the representative family seeks to maximize

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[\ln(C_t) + \lambda_m \ln(\frac{M_t}{P_t}) - n_t g(h_t, e_t) \right]$$

subject to the budget constraint

$$\int_0^1 P_{it} C_{it} di + M_t + B_t = n_t w_t h_t e_t + (1 - n_t) b_t + M_{t-1} + (1 + i_{t-1}) B_{t-1} + \Pi_t + T_t$$

with λ_m a positive constant, M_t nominal money holdings, B_t bonds holdings paying an interest rate i_t, Π_t aggregate profits, T_t transfers from the government and C_t the composite consumption good index defined by

$$C_t = \left(\int_0^1 C_{it}^{\frac{\varepsilon-1}{\varepsilon}} di \right)^{\frac{\varepsilon}{\varepsilon-1}}$$

7, the endogenous response of productivity should vanish when one uses TFP adjusted for capacity utilization. As Figure 9 shows, this is exactly what happens. This result is also interesting in the context of the literature spawned by Gali (1999) on the effect of technology shocks on total hours worked. To my knowledge, it is the first time that Gali's crucial assumption of varying capacity utilization receives direct empirical support.

where C_{it} is the quantity of good $i \in [0,1]$ consumed in period t and P_{it} is the price of variety i. $\varepsilon > 1$ is the elasticity of substitution among consumption goods. The aggregate price level is defined as $P_t = \left(\int_0^1 P_{it}^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}$. The disutility from supplying hours of work h_t and effort per hour e_t is the sum of the disutilities of the members who are employed. The individual period disutility of labor takes the form:

$$g(h_t, e_t) = \frac{\lambda_h}{1+\sigma_h} h_t^{1+\sigma_h} + h_t \frac{\lambda_e}{1+\sigma_e} e_t^{1+\sigma_e}$$

where $\lambda_h,\ \lambda_e,\ \sigma_h$ and σ_e are positive constants.[16] The last term reflects disutility from exerting effort with the marginal disutility of effort per hour rising with the number of hours. An infinite value for σ_e generates the standard case with inelastic effort.

3.2 Firms and the labor market

Each differentiated good is produced by a monopolistically competitive firm using labor as the only input. There is a continuum of large firms distributed on the unit interval. At date t, each firm i hires n_{it} workers to produce a quantity

$$y_{it} = A_t n_{it} L_{it}^{\alpha} \tag{3}$$

where A_t is an aggregate technology index, L_{it} the effective labor input supplied by each worker and $0 < \alpha < 1$.[17] I define effective labor input as a function of hours h_{it} and effort per hour e_{it}:

$$L_{it} = h_{it} e_{it}. \tag{4}$$

Total effective labor input can be adjusted through three channels: the extensive margin n_{it}, and the two intensive margins: hours h_{it} and effort per hour e_{it}. The latter affects output per hour, i.e. labor productivity. Being a monopolistic producer, the firm faces a downward sloping demand curve $y_{it}^d = (\frac{P_{it}}{P_t})^{-\varepsilon} Y_t$ and chooses its price P_{it} to maximize its value function given the aggregate price level P_t and aggregate output Y_t. When changing their price, firms face quadratic adjustment costs $\frac{\nu}{2}\left(\frac{P_{i,t}}{P_{i,t-1}} - \pi^*\right)$ with ν a positive constant and π^* the steady-state level of inflation.[18]

[16] Bils and Cho (1994) use a similar disutility of working to introduce cyclical fluctuations in effective hours.

[17] The model does not explicitly consider capital for tractability reasons but (3) can be rationalized by assuming a constant capital-worker ratio and a standard Cobb-Douglas production function $y_{it} = A_t \left(nL_{it}\right)^{\alpha} K_{it}^{1-\alpha}$.

[18] A more common approach in New-Keynesian models is the assumption of Calvo-type price setting in which firms can only reset their price at random dates. However, the fact that a fraction of randomly selected firms cannot reset its price each period introduces heterogeneity amongst firms. This complicates greatly the

In a search and matching model of the labor market, workers cannot be hired instantaneously and must be hired from the unemployment pool through a costly and time-consuming job creation process. Firms post vacancies at a unitary cost, $c_t = cA_t$, and unemployed workers search for jobs. Vacancies are matched to searching workers at a rate that depends on the number of searchers on each side of the market. I assume that the matching function takes the usual Cobb-Douglas form so that the flow m_t of successful matches within period t is given by

$$m_t = m_0 u_t^{\sigma} v_t^{1-\sigma}$$

where m_0 is a positive constant, $\sigma \in (0,1)$, u_t denotes the number of unemployed and $v_t{=}\int_0^1 v_{it} di$ the total number of vacancies posted by all firms. Accordingly, the probability of a vacancy being filled in the next period is $q(\theta_t) \equiv m(u_t, v_t)/v_t = m_0 \theta^{-\sigma}$ where $\theta_t \equiv \frac{v_t}{u_t}$ is the labor market tightness. Similarly, the probability for an unemployed to find a job is $m(u_t, v_t)/u_t = m_0 \theta_t^{1-\sigma}$. Matches are destroyed at an exogenous rate λ.

Because of hiring frictions, a match formed at t will only start producing at $t+1$, i.e. n_{it} the employment of firm i at date t is a state variable.[19] For a firm posting v_{it} vacancies at date t, the law of motion for its employment is given by

$$n_{it+1} = (1-\lambda) n_{it} + q(\theta_t) v_{i,t}.$$

Finally, firm i's cost function, ζ_{it}, is the sum of wage payments to employees and vacancy posting costs

$$\zeta_{it} = n_{it} h_{it} e_{it} w_{it} + c_t v_{it}.$$

3.3 Hours/effort decision and procyclical productivity

When a firm and a worker meet, they must decide on the allocation of hours and effort to satisfy demand. I assume that both parties negotiate the hours/effort decision by choosing the optimal allocation. More precisely, they solve

$$\min_{h_{it}, e_{it}} \frac{\lambda_h}{1+\sigma_h} h_{it}^{1+\sigma_h} + h_{it} \frac{\lambda_e}{1+\sigma_e} e_{it}^{1+\sigma_e} \tag{5}$$

integration of price setting decisions, wage bargainings and hiring decisions. In the Appendix, I present the model with Calvo-type price setting, and I show that its implications are similar to the one with costly price adjustment. Apart from the behavior of the equilibrium real wage, both models imply the same first-order conditions and the same New-Keynesian Phillips curve.

[19] The reader might question this assumption given that the average life of a vacancy is less than one month in the US. However, adding a fully operational worker to the production chain involves not only filling up the vacancy but also training. The firm could certainly not increase its production immediately, should it rely only on the extensive margin. Treating employment as a state variable is a way to model this rigidity.

subject to satisfying demand $A_t n_{it} h_{it}^{\alpha} e_{it}^{\alpha} = y_{it}^d$ at date t. The firm and the worker choose hours and effort per hour to satisfy demand at the lowest utility cost for the worker.

The first-order conditions imply that effort per hour is a function of total hours

$$e_{it} = e_0 h_{it}^{\frac{\sigma_h}{1+\sigma_e}} \tag{6}$$

where $e_0 = \left(\frac{1+\sigma_e}{\sigma_e}\frac{\lambda_h}{\lambda_e}\right)^{\frac{1}{1+\sigma_e}}$ is a positive constant. Thus, changes in hours can proxy for changes in effort, and I can write a reduced-form relationship between output and hours:

$$y_{it} = y_0 A_t n_{it} h_{it}^{\varphi}$$

with $y_0 = e_0^{\alpha}$ and $\varphi = \alpha\left(1 + \frac{\sigma_h}{1+\sigma_e}\right)$.

For $\varphi > 1$, the production function displays short run increasing returns to hours. In times of higher demand, firms respond by increasing hours and effort, which increases output per hour, i.e. measured labor productivity. This condition is critical to generate the procyclical response of measured productivity to aggregate demand shocks. It holds with sufficiently high marginal product of efficient hour (high α) or high effort elasticity with respect to hours (high $\frac{\sigma_h}{1+\sigma_e}$), and from now on, I assume that the model's parameters ensure $\varphi > 1$.

With short run increasing returns to hours but constant returns to employment, one may wonder why a demand constrained firm would ever want to hire an extra worker. However, rewriting the firm's cost function with (6), we can see that the cost of extra hours and effort increases even faster than output since $\zeta_{it} = w_{it}.e_0 h_{it}^{1+\frac{\sigma_h}{1+\sigma_e}} n_{it} + c_t v_{it}$ and $1 + \frac{\sigma_h}{1+\sigma_e} > \varphi = \alpha\left(1 + \frac{\sigma_h}{1+\sigma_e}\right)$. For a given level of employment, the cost of satisfying demand y_{it}^d with the intensive margin is given by

$$\zeta_{it} = w_{it}\left(\frac{y_{it}^d}{A_t}\right)^{\psi} n_{it}^{1-\psi} + c_t v_{it}$$

where $\psi = \frac{1}{\alpha} > 1$. Hence, absent hiring frictions, the firm would actually rather hire an extra worker than use the intensive margin because the cost of longer hours and higher effort increases faster than output. But because employment is a state variable and is costly to adjust, the firm must also rely on the intensive margin to satisfy demand. This property of the model captures the fact that the intensive margin is more flexible than the extensive one, but that this flexibility comes at a higher cost. Although it is easier to increase the workload of an employee than to hire and train a new one, overtime hours are more expensive than regular ones.

3.4 Wage bill setting

The discussion has so far left the wage unspecified. In the standard MP model, each firm-worker pair bargains over the rent of the match and the outcome maximizes the weighted product of the parties' surpluses. Here, I depart from the match-specific wage inherent to search models and assume instead that firms take the market wage as given so that $w_{it} = w_t$.[20] How is this market wage determined? Denoting $J(w_t)$ the value of a matched worker to the firm and $W(w_t)$ and $U(w_t)$ the value for a worker of being respectively employed and unemployed, any wage satisfying $W(w_t) - U(w_t) > 0$ and $J(w_t) > 0$ (i.e. within the bargaining set) can be an equilibrium. I assume that the equilibrium real wage is determined by Nash-bargaining between a representative firm and a representative worker.

If γ is the bargaining power of the worker, the Nash-bargained wage of the representative match takes the form

$$w_t^{nb} h_{it} e_{it} = \gamma \left(\frac{P_{it}}{P_t} \frac{y_{it}}{n_{it}} + c_t \theta_t \right) + (1-\gamma) \left(b_t + g_0 y_t h_{it}^{1+\sigma_h} \right) \tag{7}$$

with $g_0 = \frac{\lambda_h}{1+\sigma_h} + \frac{\lambda_e}{1+\sigma_e} e_0^{1+\sigma_e}$.

3.5 The firm's problem

Given the market wage and aggregate price level, firm i will choose a sequence of price $\{P_{it}\}$ and vacancies $\{v_{it}\}$ to maximize the expected present discounted value of future profits subject to the demand constraint, the hours/effort choice and the law of motion for employment. Formally, the firm maximizes its value

$$E_t \sum_j \beta^j \frac{u'(C_{t+j})}{u'(C_t)} \left[\frac{P_{i,t+j}}{P_{t+j}} y_{i,t+j}^d - n_{i,t+j} h_{i,t+j} e_{i,t+j} w_t - c A_t v_{i,t+j} - \frac{\nu}{2} \left(\frac{P_{i,t+j}}{P_{i,t+j-1}} - \pi^* \right)^2 Y_t \right]$$

subject to the hours/effort decision

$$e_{it} = e_0 h_{it}^{\frac{\sigma_h}{1+\sigma_e}}$$

the demand constraint

$$y_{it}^d = A_t n_{it} h_{it}^{\varphi} = (\frac{P_{i,t}}{P_t})^{-\varepsilon} Y_t$$

[20] In the benchmark MP search model with Nash bargaining, market wage and match-specific wage coincide. This happens because a constant marginal rate of substitution between consumption and labor is assumed. As a result a single firm can never influence the wage and takes it as given. On the other hand, with non-linear preferences, firms' hiring decisions depend on the wage as well as their hours/effort level which itself influences the Nash bargained wage. This additional channel complicates the analysis and I shut it down by assuming that firms take the wage as given.

and the law of motion for employment

$$n_{it+1} = (1-\lambda) n_{it} + q(\theta_t) v_{it}.$$

The optimal vacancy posting condition takes the form

$$\frac{c_t}{q(\theta_t)} = E_t \beta_{t+1} \left[\chi_{it+1} + \frac{c_{t+1}}{q(\theta_{t+1})}(1-\lambda) \right] \tag{8}$$

where $\beta_{t+1} = \beta \frac{u'(C_{t+1})}{u'(C_t)}$ is the stochastic discount factor, and χ_{it}, the shadow value of a marginal worker, can be written as

$$\chi_{it} = -\frac{\partial \zeta_{it}}{\partial n_{it}} = (\psi - 1)\, w_t h_{it} e_{it} = (\psi - 1)\, w_t \left(\frac{y_{it}^d}{A_t n_{it}} \right)^{\psi}.$$

Since $\frac{1}{q(\theta_t)}$ is the expected duration of a vacancy, equation (8) has an intuitive interpretation: each firm posts vacancies until the expected cost of hiring a worker $\frac{A_t c}{q(\theta_t)}$ equals the expected discounted future benefits $\left\{\chi_{it+j}\right\}_{j=1}^{\infty}$ from an extra worker. Because the firm is demand constrained, the flow value of a marginal worker is not his contribution to revenue but his reduction of the firm's wage bill. The first term of χ_{it+1}, $\psi w_{t+1} h_{it+1} e_{it+1}$, represents the next-period savings due to the decrease in hours and effort achieved with an extra worker, while the second term $-w_{t+1} h_{it+1} e_{it+1}$ is the wage payment going to that extra worker. Because $\psi > 1$, $\chi_{it+1} > 0$ and the marginal worker always reduces the cost of satisfying a given level of demand.[21] Similarly to Woodford's (2004) New-Keynesian model with endogenous capital, the marginal contribution of an additional worker is to reduce the wage bill through substitution of one input for another. Here, the intensive and the extensive margins are two different inputs. The former is flexible but costly, while the latter takes time and resources to adjust. The firm chooses the combination of labor margins that minimizes the cost of supplying the required amount of output.

Turning to the optimal price setting rule, a firm resetting its price at date t will satisfy the first-order condition:

$$(1-\varepsilon)\frac{y_{it}}{P_t} - \varepsilon \frac{y_{it}}{P_{it}} s_{it} - \nu \frac{y_t}{P_{it-1}} \left(\frac{P_{it}}{P_{it-1}} - \pi^* \right) = E_t \beta_{t+1} \nu y_{t+1} \left(\pi_{t+1} - \pi^* \right) \frac{P_{it+1}}{P_{it}^2} \tag{9}$$

[21] Note that $\psi > 1$ is a necessary condition to ensure the existence of an equilibrium with non-zero employment. For a sufficiently low level of employment, the (positive) value of a marginal worker becomes higher than the cost of a vacancy and firms start hiring.

where the firm's real marginal cost s_{it} is given by

$$s_{it} = \frac{\partial \zeta_{it}}{\partial y_{it}} = \psi \frac{w_t}{A_t} \left(\frac{y_{it}^d}{A_t n_{it}} \right)^{\psi - 1} \tag{10}$$

With $\psi > 1$, the real marginal cost increases with demand but decreases with the employment level. As a result, firms can lower the impact of shocks on their real marginal cost and optimal price by adjusting their extensive margin n_{it}. Inflation will be less responsive to shocks than in a standard New-Keynesian model without unemployment but will display more persistence. This inertia arises not only because unemployment is itself a slow moving variable but also because the firm's real marginal cost is decreasing in its own employment. Following an increase in demand, the value of a marginal worker goes up and leads the firm to increase its level of employment. But this decreases future real marginal cost and leads the firm to post lower prices, which itself increases demand and output next period. This in turn leads to a future rise in employment, and, as the process goes on, the response to a demand shock will die out more slowly than in the standard New-Keynesian case.

Finally, since firms are homogenous, in equilibrium $P_{it} = P_t$ and $y_{it} = y_t$ so that I can drop the i index and rewrite (9) as the standard price-setting condition for New-Keynesian models with quadratic price adjustment

$$1 - \nu \pi_t (\pi_t - \pi) + E_t \beta_{t+1} \nu \frac{y_{t+1}}{y_t} (\pi_{t+1} - \pi^*) \pi_{t+1} = \varepsilon (1 - s_t) \tag{11}$$

In steady state, when inflation $\pi_t = \pi^*$, (11) collapses to $s_t = \frac{\varepsilon - 1}{\varepsilon}$ the inverse of the mark-up $\mu = \frac{\varepsilon}{\varepsilon - 1}$.

3.6 Technological progress and the central bank

In order to be consistent with the long run identifying assumption made in Section 2, the technology index series should be non-stationary with a unit root originating in technological innovations. Hence, I assume that technology is comprised of a deterministic and a stochastic component: $A_t = A_t^* \tilde{A}_t$ with $\frac{A_t^*}{A_{t-1}^*} = e^a$ and $\tilde{A}_t = e^{a_t}$ with $a_t = a_{t-1} + \varepsilon_t^a$. ε_t^a is a technology shock with a permanent impact on productivity.

Consistent with a growing economy and zero inflation in "steady-state", the quantity of money M^s evolves according to $M_t = M_t^* \tilde{M}_t$ with $\frac{M_t^*}{M_{t-1}^*} = e^a$ and $\tilde{M}_t = e^{m_t}$ with $\Delta m_t = \rho_m \Delta m_{t-1} + \varepsilon_t^m + \tau^{cb} \varepsilon_t^a$, $\rho_m \in [0, 1]$. I interpret ε_t^m as a demand shock. With $\tau^{cb} \neq 0$, the monetary authority is assumed to respond in a systematic fashion to a technology shock.[22]

[22] The reader may wonder why I do not use a Taylor rule $i_t = \phi_\pi \pi_t + \phi_y (y_t - y_t^{flex})$ with $y_t - y_t^{flex}$ the

As in Gali (1999), the degree of monetary accommodation plays a key role as it determines the response of unemployment to technology shocks. Following a positive technology shock, if monetary policy is not too accommodating ($\tau^{cb} < 1$), the price level has to decrease sufficiently in order to bring aggregate demand in line with the new productivity level. But with costly price adjustment this may be too expensive, and aggregate demand is sticky in the short run. Being more productive, each firm meets its demand by using less labor, and unemployment will increase.

3.7 Closing the model

Since firms are homogenous, in equilibrium $n_{it} = n_t$, $P_{it} = P_t$ and $y_{it} = y_t$ so that I can drop the i index from all the equations. As a result, total employment evolves according to $n_{t+1} = (1-\lambda)n_t + v_t q(\theta_t)$. The labor force being normalized to one, the number of unemployed workers is $u_t = 1 - n_{t.}$ Finally, assuming that vacancy posting costs are distributed to the aggregate households, $C_t = Y_t$ in equilibrium.

4 Equilibrium and dynamics

I now present and study the equations governing the behavior of the model economy. First, I characterize the long run equilibrium (or steady-state) of the model economy. Second, I argue that the model needs a degree of real wage rigidity for it to be consistent with the predictions of the standard MP model. Then, I present the log-linearized equations governing the model around the (zero-inflation) long-run equilibrium. Finally, because some equations are difficult to interpret, in the last subsection, I make a number of simplifying assumptions that allow me to derive closed-form solutions and study the properties of the model.

4.1 Long-run equilibrium of the model economy

In this non-stationary economy, I rescale the non-stationary variables with the technology index A_t. Absent nominal rigidities, money is neutral and the only disturbances of interest are technology shocks. Since vacancy posting costs and unemployment benefits are proportional to

"New-Keynesian" output gap defined as the deviation from y_t^{flex}, the ouput under flexible prices. However, as Gali and Rabanal (2004) point out, this ouput gap is difficult to observe for the policy maker. In fact, the Taylor rule originally proposed by Taylor (1993) is $i_t = \phi_\pi \pi_t + \phi_y(y_t - \bar{y}_t)$ in which the central bank responds to the output gap defined as the deviation from some trend $\bar{y}_t$. However, it is not clear how one should model this trend, and I keep the model relatively simple with a money growth rule. In addition, these two different Taylor rules have very different implications in terms of stabilization of output. In response to technology shocks, the first rule implies an accomodating policy whereas the second rule implies the opposite. With a money growth rule, I can let the data decide whether the central bank in fact accomodates, or not, technology shocks.

the technology index, it is easy to see from (7) that the Nash-bargaining wage is proportional to A_t. As a result, I can write $w_t^{nb} = w^* A_t$ where $w^* A_t$ is the Nash-bargained real wage in the frictionless (zero-inflation) economy. Denoting rescaled variables with lower-case letters, the economy is described by the following system with 6 equations and 6 unknowns θ^*, y^*, h^*, e^*, n^* and w^*:

$$\begin{aligned}
y^* &= \left(\frac{Y_t}{A_t}\right)^* = y_0 n^* h^{*\varphi} \\
e^* &= e_0 (h^*)^{\frac{\sigma_h}{1+\sigma_e}} \\
\frac{c}{q(\theta^*)}(1-\beta(1-\lambda)) &= \beta\chi^* = \beta w^* h^* e^* (\psi - 1) \\
w^* h^* e^* &= \gamma\left(\frac{y^*}{n^*} + c\theta^*\right) + (1-\gamma)\left(b + g_0 y^* h^{*1+\sigma_h}\right) \\
1 &= \mu\psi w^* \frac{h^* e^* n^*}{y^*} \\
n^* &= \frac{\theta^* q(\theta^*)}{\lambda + \theta^* q(\theta^*)}
\end{aligned}$$

where y_0 and e_0 are positive constants defined previously.[23]

The wage being proportional to the level of technology, a technology shock will have no impact on market tightness or the level of unemployment. The equilibrium level of unemployment $1 - n^*$ depends only on constant parameters of the model. This non-stationary equilibrium describes the economy in the long run, when all price and wage variables have adjusted to shocks.

4.2 The need for real wage rigidity

When prices are fully flexible (i.e. costless to adjust), my model reduces to a standard neoclassical MP model. However, with the Nash-bargaining equilibrium wage proportional to technology A_t, a positive technology shock leaves the unemployment rate unchanged because the wage increase absorbs all of the surplus and leaves the firm's profit unchanged. This property is not satisfactory as it is at odds with the search literature that views unemployment fluctuations as originating mainly in labor productivity changes (e.g. Shimer, 2005a).

In order to be consistent with the MP model, I assume that the market wage lags technology so that the firm's surplus increases temporarily following a positive technology shock. A number of explanations has been advanced to motivate the assumption that real wages are rigid and

[23] This system has a unique solution provided that $1-\gamma\mu\psi-\gamma\theta q(\theta^*)(\psi-1)\frac{(1-\beta(1-\lambda))}{\beta} > 0$ and b is a constant fraction of wage payments. These conditions will be verified by the parameters chosen in the calibration.

adjust slowly to technology changes.[24] Without being explicit about the specific source of real wage rigidity, I choose a simple partial adjustment model for $\ln\left(\frac{w_t}{A_t^*}\right)$:[25]

$$\ln\left(\frac{w_t}{A_t^*}\right) = \varpi.\ln\left(\frac{w_t^{nb}}{A_t^*}\right) + (1-\varpi)\ln\left(\frac{w_{t-1}}{A_{t-1}^*}\right) \tag{12}$$

where w_t^{nb} is the long run equilibrium wage defined previously.

4.3 Log-linearized equilibrium dynamics

I now consider the more general case where $\nu \neq 0$. To analyze the behavior of the economy with real wage rigidity and costly price adjustment, I log-linearize around the (zero-inflation) long run equilibrium.

Since firms are homogenous, I can drop the i index from the equations, and by log-linearizing the job posting condition (8), I get

$$\frac{c\sigma}{q(\theta^*)}\hat{\theta}_t = E_t\beta\left[\chi^*\hat{\chi}_{t+1} + \frac{c(1-\lambda)\sigma}{q(\theta^*)}\hat{\theta}_{t+1}\right] + \frac{c}{q(\theta^*)}E_t\left(\hat{y}_t - \hat{y}_{t+1}\right) \tag{13}$$

with the average value of a marginal worker $\hat{\chi}_t$ given by

$$\hat{\chi}_t = \hat{w}_t + \psi(\hat{y}_t - \hat{n}_t) \tag{14}$$

and where $\hat{\theta}_t = \ln\left(\frac{\theta_t}{\theta^*}\right)$, $\hat{n}_t = \ln\left(\frac{n_t}{n^*}\right)$ and $\hat{y}_t = \ln\left(\frac{Y_t/A_t}{y^*}\right)$ are the log-deviations of rescaled variables from their long-run equilibrium values.

Log-linearizing the price setting condition (11) yields the standard New-Keynesian Phillips curve

$$\pi_t = \delta\hat{s}_t + \beta E_t\pi_{t+1} \tag{15}$$

with $\delta = \frac{\varepsilon-1}{\nu}$.The firm's real marginal cost $\hat{s}_t$ given by

$$\hat{s}_t = \hat{w}_t + (\psi-1)\left(\hat{y}_t - \hat{n}_t\right) \tag{16}$$

As I discussed previously, firms' real marginal costs are decreasing in the level of employment, and the interaction of nominal frictions and hiring frictions generates a propagation mechanism absent from New-Keynesian models without hiring frictions.

[24] See Pissarides (1987), Phelps (1994), Ball and Moffitt (2002) or Hall (2005).

[25] Blanchard and Gali (2005) or Cristoffel and Linzert (2005) follow a similar approach to introduce real wage rigidity.

Finally, the law of motion for the wage (12) becomes

$$\hat{w}_t = \varpi.\hat{w}_t^{nb} + (1-\varpi)\hat{w}_{t-1} - (1-\varpi)\varepsilon_t^a \tag{17}$$

with $\hat{w}_t = \ln\left(\frac{w_t^m/A_t}{w^*}\right)$ the log-deviation of the rescaled wage from its long run equilibrium value and $\hat{w}_t^{nb} = \ln\left(\frac{w_t^m/A_t}{w^*}\right)$ the log-linearized Nash-bargaining wage given by

$$\hat{w}_t^{NB} = \gamma c\theta\hat{\theta}_t + \omega_y\hat{y}_t - \omega_n\hat{n}_t$$

with $\omega_y = \frac{1}{(1-(1-\gamma)b_0)w^*h^*e^*}\gamma\frac{y}{n} + (1-\gamma)\frac{2+\sigma_h}{1+\sigma_h}\lambda_h h^{1+\sigma_h}y - (1-(1-\gamma)b_0)\frac{w^*h^*e^*}{\alpha}$
and $\omega_n = \frac{1}{(1-(1-\gamma)b_0)w^*h^*e^*}\left(\gamma\frac{y}{n} + (1-\gamma)\lambda_h h^{1+\sigma_h}y - (1-(1-\gamma)b_0)\frac{w^*h^*e^*}{\alpha}\right)$.

Log-linearizing the first-order conditions for the household and denoting $\hat{m}_t = \ln\left(\frac{M_t/P_tA_t}{(M/P)^*}\right)$ the log-deviation of real rescaled money from its constant value in the zero-inflation equilibrium, I get $\hat{y}_t = E_t\hat{y}_{t+1} - (\hat{\imath}_t - E_t\pi_{t+1})$ and $\hat{m}_t = \hat{y}_t - \eta_i\hat{\imath}_t$ with $\hat{\imath}_t = \ln\left(\frac{1+i_t}{1+i^*}\right)$.

Finally, the log-linearized law of motion for employment can be written

$$\hat{n}_{t+1} = (1-\lambda-\theta q(\theta))\hat{n}_t + \frac{1-n}{n}(1-\sigma).\theta q(\theta)\hat{\theta}_t.$$

4.4 A simpler framework

4.4.1 Three simplifying assumptions

Albeit relatively simple, these equations are difficult to interpret because of the behavior of the real wage. I now make three simplifying assumptions that allow me to study the properties of the model analytically and derive some closed form solutions.[26] First, I assume that the money growth rate exhibits no persistence, i.e. $\rho_m = 0$. This implies a constant nominal interest rate so that $\hat{m}_t = \hat{y}_t$. Second, I assume that firms are risk-neutral. This does not change the main conclusions of the model but makes analytical expressions much simpler as the vacancy posting condition becomes

$$\frac{c\sigma}{q(\theta^*)}\hat{\theta}_t = E_t\beta\left[\chi^*\hat{\chi}_{t+1} + \frac{c(1-\lambda)\sigma}{q(\theta^*)}\hat{\theta}_{t+1}\right]. \tag{18}$$

My last simplification is less innocent: I assume that the flexible wage towards which the equilibrium market wage converges is not the Nash bargained wage anymore but a constant value independent of labor market conditions and simply proportional to technology. More

[26] In addition, they allow me to show analytically that, in the benchmark case without costly price adjustment, my model is consistent with the prediction of the standard MP model that an increase in productivity decreases unemployment: A positive technology shock will decrease unemployment in the short run but as the real market wage ultimately adjusts to any technology level, unemployment converges back to its long run equilibrium level. I leave the proof for the Appendix.

specifically, the market wage w_t converges to $w^* A_t$, the Nash-bargaining outcome of the representative match in a zero-inflation economy, and satisfies the law of motion

$$\ln\left(\frac{w_t}{A_t^*}\right) = \varpi . \ln\left(\frac{w^* A_t}{A_t^*}\right) + (1-\varpi)\ln\left(\frac{w_{t-1}}{A_{t-1}^*}\right) \tag{19}$$

so that the log-linearized law of motion (17) simplifies to

$$\hat{w} = (1-\varpi)\hat{w}_{t-1} - (1-\varpi)\varepsilon_t^a. \tag{20}$$

This contract could just as well be an equilibrium. It will satisfy both parties and will not produce inefficient separation as long as it remains within the bargaining set; i.e. as long as $W_t - U_t > 0$ and $J_t > 0$. And this will be the case for small enough fluctuations around the zero-inflation equilibrium. This market wage will not respond to small aggregate demand disturbances (such as monetary policy shocks) since they have no long-run impact but will converge to the long run equilibrium wage $w^* A_t$ (which does not, by definition, respond to short run demand disturbances).[27] However it will adjust to technological change. Otherwise the bargaining set would eventually be above or below any constant wage and that wage could no longer be an equilibrium. In addition, this real wage specification has the merit of being consistent with the empirical evidence from Edge, Laubach and Williams (2003) who show that the real wage responds progressively to technology shocks but is virtually insensitive to monetary policy shocks.

This last simplification is very similar in spirit to Hall's (2005) wage norm. Hall assumes that productivity is the product of two components, a slow moving trend and a mean-reverting process, but that the wage norm adjusts only to the trend component. Here this follows from the existence of two different disturbances: demand shocks (with a temporary impact on productivity) and technology shocks (with a permanent impact). The market wage, or wage norm, adjusts to permanent but not to temporary changes in productivity.

4.4.2 Towards a traditional Phillips curve

Standard New-Keynesian models abstract from labor market imperfections and unemployment. As a result, they are ill equipped to study any relationship linking unemployment to inflation. Thanks to the previous simplifying assumptions, I now show that a search model with costly price adjustment can deliver a traditional Phillips curve linking inflation to unemployment.

Combining the job posing condition (14) and (16), we can express $\hat{\chi}_t$ as a function of $\hat{s}_t$

[27] The insensitivity of the market wage to monetary policy shocks can be justified by assuming a cost to wage negotiations that is not worth incurring for small and transitory disturbances.

and $\hat{w}_t$

$$\hat{\chi}_t = \frac{\psi}{\psi - 1}\hat{s}_t - \frac{1}{\psi - 1}\hat{w}_t \tag{21}$$

With costly price adjustment, there is a positive comovement between the flow value of a marginal worker and the firm's real marginal cost. Since the former drives unemployment fluctuations and the latter inflation, a relation between inflation and unemployment emerges.

In fact, with a little algebra left for the Appendix, I can rewrite the New-Keynesian Phillips curve as

$$\pi_t = \delta\hat{s}_t + \kappa_\theta\delta\hat{\theta}_t + \tilde{\kappa}_w\delta\hat{w}_t \tag{22}$$

where $\kappa_\theta = \frac{c\sigma(1-\alpha)}{\beta\chi q(\theta)} > 0$ and $\tilde{\kappa}_w = \frac{\alpha\beta(1-\varpi)}{(1-\beta(1-\varpi))} \geq 0$.

Inflation can now be expressed as a function of current variables only. Notably, it depends on current real marginal cost *and* current labor market tightness. Higher labor market tightness raises the cost of hiring and reduces the firm's future desired employment. But with a lower level of future employment, future marginal costs are higher. The firm anticipates this and raises its price. Hence, inflation is positively related to labor market tightness. Inflation depends also on the market wage through $\tilde{\kappa}_w$. $\tilde{\kappa}_w$ captures the impact of real wage rigidities on future marginal costs and thus inflation. Without real wage rigidity ($\tilde{\kappa}_w = 0$), the wage immediately adjusts to any technology movement and has no impact on future marginal costs and inflation. With real wage rigidity ($\tilde{\kappa}_w > 0$), the wage lags technology and has an impact on future marginal costs.

Finally, using the log-linearized first-order conditions for the household and the fact that labor market tightness is related to unemployment through the law of motion for employment, I can rewrite the New-Keynesian Phillips curve (22) as a standard Phillips curve linking inflation to unemployment

$$\pi_t = -\kappa_{\Delta u}\Delta\hat{u}_{t+1} - \kappa_u\hat{u}_t + \kappa_m\varepsilon_t^m - \kappa_a(\tau^{cb})\varepsilon_t^a + \kappa_w\hat{w}_{t-1} + \kappa_m\hat{m}_{t-1} \tag{23}$$

with $\kappa_{\Delta u}$, κ_u, κ_w, and κ_m some positive constants, $\kappa_a(\tau^{cb}) = \kappa_w - \delta\frac{(\psi-1)(\tau^{cb}-1)}{1+\delta(\psi-1)}$, $\hat{u}_t$ the deviation of the unemployment rate from its long run value and $\hat{m}_t = \ln\left(\frac{M_t/P_tA_t}{(M/P)^*}\right)$, the log-deviation of real rescaled money from its constant value in the zero-inflation equilibrium.[28] κ_w has a similar interpretation as $\tilde{\kappa}_w$ but it captures the impact of real wage rigidities on current *and* future real marginal costs: $\kappa_w = 0$ when real wages adjust immediately to technology changes, and $\kappa_w > 0$ otherwise.

This equation is the main theoretical result of this New-Keynesian model with hiring frictions and calls for a couple of remarks. First, despite the negative contemporaneous relation

[28] See the Appendix for details of the derivation.

between inflation and unemployment, this Phillips curve is New-Keynesian. Inflation expectations are still forward-looking, but the sum of expected future real marginal costs can be written as a function of current unemployment and change in unemployment.

Second, as first emphasized by Blanchard and Galí (2005, 2006), the combination of real wage rigidity and price stickiness creates a trade-off between inflation and unemployment absent in the New-Keynesian Phillips curve. The term $-\varepsilon_t^a$ in (23) may remind the reader of the cost-push term *added* to New-Keynesian models to restore the inflation-unemployment trade-off.

Starting from an equilibrium with no inflation and constant unemployment ($\forall\ j < t$, $\varepsilon_j^a = \varepsilon_j^m = 0$ so that $\hat{u}_t = 0$, $\hat{m}_{t-1} = 0$ and $\hat{w}_{t-1} = 0$), let us consider the impact of an unexpected negative technology shock $\varepsilon_t^a < 0$. At date t, the Phillips curve can be written $\pi_t = -\kappa_{\Delta u}\hat{u}_{t+1} + \kappa_m \varepsilon_t^m - \kappa_a(\tau^{cb})\varepsilon_t^a$. The responses of inflation and unemployment depend on the central bank reaction τ^{cb} and the degree of real wage rigidity. With flexible wages ($\kappa_w = 0$), the central bank can keep inflation constant ($\pi_t = 0$) by accommodating the technology shock with $\tau^{cb} = 1$ so that $\kappa_a(\tau^{cb}) = 0$. With $\hat{m}_t = (\tau^{cb} - 1)\varepsilon_t^a = 0$, real money balances (i.e. aggregate demand) are unchanged, and unemployment stays constant as well. With rigid wages however, $\kappa_w > 0$ and the firm's real marginal costs are higher at date t and in future dates, as it takes time for the market wage to adjust. To offset this increase in current and future marginal costs, the central bank needs to overaccommodate the shock by setting $\kappa_a(\tau^{cb}) = 0$, i.e. $\tau^{cb} = 1 + \frac{(1+\tilde{\kappa}_w)(1-\varpi)}{(\psi-1)} > 1$. But this decreases the real money supply since $\hat{m}_t = (\tau^{cb} - 1)\varepsilon_t^a < 0$ and leads to a contraction in demand that will increase future unemployment. Hence, the central bank faces a trade-off between inflation and unemployment.

5 Confronting the model with the data

In this section, I study whether a calibrated version of the model can account for the impulse responses to technology and non-technology shocks, as well as quantitatively explain the sign flip of ρ.

5.1 Calibration

First, I discuss the calibration of the parameters of the model. Consistent with the data used in Section 2, I assume a quarterly frequency for the model. I set the quarterly discount factor β to 0.99. I assume that the markup of prices over marginal costs is on average 10 percent. This amounts to setting ε equal to 11. To pick a value for the price adjustment cost parameter ν and the Phillips curve coefficient δ, I exploit the mapping between my model with costly price adjustment and the model with Calvo type price setting described in the Appendix.

Both models imply the same linearized New-Keynesian Phillips curve but in the latter, δ is determined by the frequency of price adjustment. When, as consistent with recent micro estimates (Bils and Klenow, 2004), firms reset their price every 2 quarters, δ takes the value 0.10, so I choose $\nu = 100$ to match δ. I set the growth rate of technology (and money supply) to $a = 0.5\%$ a quarter so that the economy is growing by 2% on average each year. I use a money growth autocorrelation parameter ρ_m of 0.6, in line with the first autocorrelations of M1 and M2 growth in the US. Turning to the labor market, I set the matching function elasticity to $\sigma = 0.4$ as measured by Blanchard and Diamond (1994). The scale parameter of the matching functions m_0 is chosen such that, as reported in den Haan, Ramey and Watson (2000), a firm fills a vacancy with probability $q(\theta) = 0.7$ and a worker finds a job with probability $\theta q(\theta) = 0.45$.[29] Following Shimer (2005a), the separation rate is 10% so jobs last for about 2.5 years on average. Unemployment benefits are paid a constant fraction of the long-run equilibrium wage, and the income replacement ratio is set to 40% of mean income so that $b = 0.4w^*h^*e^*$. By setting the returns to efficient labor α to 0.64, I fix ψ, the elasticity of the firm's cost function with respect to demand, to 1.56. I set the degree of real wage rigidity ϖ to 0.75, implying an average duration of real wages of one year. Pencavel (1986) reports micro estimates of hours per week elasticity between 0 and 0.5, and I choose a mid-range value of 0.2 with $\sigma_h = 5$. The last two variables to specify are σ_e, i.e. $\varphi = \alpha\left(1 + \frac{\sigma_h}{1+\sigma_e}\right)$ the short run scale parameter of the production function, and τ^{cb} the degree of monetary policy accommodation. As in Altig, Christiano, Eichenbaum and Linde (2005), I choose them by fitting the simulated impulse responses to the empirical ones. The estimated $\varphi = 1.30$ is consistent with Basu and Kimball's (1997) evidence that φ ranges from 1.1 to 1.4. With an estimated τ^{cb} of -0.43, the central bank contracts the money supply when technology increases. A negative value for τ^{cb} is relatively surprising given that central banks should accommodate technology shocks, not contract the money supply. But this is not implausible given the difficulty central banks have in estimating the relevant output gap. As Galí and Rabanal (2005) argue, the Taylor rule originally proposed by Taylor (1993) was $i_t = \phi_\pi \pi_t + \phi_y y_t$ in which the central bank responds to the output gap (i.e. deviation from trend), not the real marginal cost, difficult to observe for the policy maker. Positive technology shocks may have been misinterpreted as a deviation from trend that should be avoided to keep inflation at bay, leading the central bank to pursue a contractionary policy.[30]

[29] Shimer (2005b) reports a higher value $\theta q(\theta) = 0.6$ but the main results do not rely on this particular choice of calibration.

[30] Indeed, Orphanides (2002) claims that the Great Inflation of the 1970's "could be attributed to [...] an adverse shift in the natural rate of unemployment that could not have been expected to be correctly assessed for some time."

5.2 Impulse response functions

The dotted lines in Figure 13 and 14 show the simulated impulse response functions of productivity, unemployment, output and inflation to a technology and a monetary policy shock alongside the empirical impulse responses reported in Section 2.

Following a positive technology shock, real money balances (i.e. aggregate demand) do not increase as much as productivity because prices are costly to adjust and because the central bank does not fully accommodate the shock. As a result, aggregate demand is sticky in the short run. Being more productive, firms initially meet their demand by decreasing hours and effort since employment is a state variable. Measured labor productivity (i.e. output per hour) undershoots its new long run level because of short run increasing returns to hours. With shorter hours and lower effort, the value of a marginal worker (i.e. the reduction in labor costs achieved with an extra worker) goes down, firms post fewer vacancies, and unemployment increases. As prices adjust to the new productivity level, both labor margins return to their long run values.

Following a positive monetary policy shock, firms need to increase their labor input in order to satisfy demand. Again, since they must first rely on the intensive margin, measured labor productivity initially increases as hours and effort increase. With higher hours and effort, the value of a marginal worker goes up, firms post more vacancies and unemployment goes down. As prices adjust to the new money supply level, both labor margins return slowly to their long run values.

Apart from a slight departure from the 95% confidence interval for the unemployment response, the model is remarkably successful at matching the empirical responses. Moreover, the model output response to a technology shock is similar to the empirical response reported by Galí (1999).

5.3 The sign switch of ρ

In Section 2, I argue that two events could be responsible for the large increase in ρ in the mid-80s: (a) a decline in the relative importance (or volatility) of non-technology shocks versus technology shocks, and (b) a structural change in the transmission mechanism of shocks. In this subsection, I test whether they can quantitatively explain the magnitude of the change in ρ.

5.3.1 Changes in the volatility of shocks

In Section 2, I document a large drop in the volatility of non-technology shocks relative to technology shocks and present some evidence suggesting that changes in the relative size of technology and non-technology shocks drive fluctuations in ρ. To explore whether the volatility movements around 1980 are quantitatively large enough to explain the sign flip of ρ, I use my calibrated model to simulate the impact of a drop in the volatility of aggregate demand shocks on the correlation between productivity and unemployment. I generate unemployment and productivity series using technology and monetary innovations with standard deviations following step functions that mimic the volatility movements that occurred around 1980. Figure 10 depicts the step functions used in the simulation. The validity of this approach is subject to the correct identification and separation of technology and non-technology shocks. There is reassuring evidence (see Galí and Rabanal (2004)) that technology shocks are correctly identified by long run restrictions but, since I emphasize the role played by aggregate demand shocks, I also look at the Romer and Romer (2004) monetary shocks. Those shocks are identified with a different method, but we can see in Figure 15 that, notwithstanding the large volatility increase in the late 70s, their volatility in 1975 is twice as high as that in 1990, a volatility drop similar to the one used in the simulation.

I simulate 50 years of data for unemployment and productivity. After filtering the (non-stationary) productivity series, I can calculate $\hat{\rho}_{10}$, the simulated 10-year rolling correlation between simulated productivity and unemployment. I repeat this exercise 5000 times to obtain the empirical distribution of $\hat{\rho}_{10}$. As shown in Figure 16, $\hat{\rho}_{10}$ increases by around 0.3 and explain less than 50% of the total increase in $\tilde{\rho}_{10}$. In addition, $\tilde{\rho}_{10}$ overestimates $\tilde{\rho}_{10}$ until 1980 and underestimates $\tilde{\rho}_{10}$ afterwards lying only marginally inside the 95% confidence interval.[31] If a drop in aggregate demand volatility seems to be part of the story, something else contributed to the sign switch in the mid 80s.

5.3.2 Structural changes

In Section 2, I argue that two structural changes could be responsible for the large movement in ρ in the mid-80s: (a) the central bank became more accommodating after 1984, and (b) a decline in the procyclicality of measured labor productivity declined after 1984. In my model, a decrease in the procyclicality of productivity appears as a decrease in φ, the short run returns to hours. Explicitly modeling a decrease in φ is beyond the scope of the model but it would still be interesting to test if the decrease in the procyclicality of productivity is enough to account for the sign flip of ρ. I estimate the value of φ and τ^{cb} for each sub-sample, and I find that φ decreased from 1.6 to 1.05 between 1948-1983 and 1984-2005, while τ^{cb} increased from -0.6 to -0.2.

[31] Since the model implies no response of unemployment on impact (employment is a state variable), I define $\hat{\rho} \equiv corr(\hat{U}_{t+1}, \frac{\hat{y}_t}{\hat{h}_t})$. To be consistent, I compare $\hat{\rho}$ to $\tilde{\rho} \equiv corr(U_{t+1}, \frac{y_t}{h_t})$ instead of $\rho \equiv corr(U_t, \frac{y_t}{h_t})$. This does not change any of the conclusions since ρ and $\tilde{\rho}$ are very similar up to a vertical translation.

To study the impact of better monetary policy *and* less procyclical productivity on ρ, I proceed as previously and simulate 50 years of data for unemployment and productivity but allowing for different φ and τ^{cb} over the two sub-periods as well as a drop in the volatility of monetary policy shocks. As shown in Figure 17, $\hat{\rho}_{10}$ increases this time from around -0.5 to 0.1, lies comfortably within the 95% confidence interval and does not over overestimate $\tilde{\rho}_{10}$ before the 80s.

A remaining question is why productivity became less procyclical after 1984. A possible answer lies with a change in the behavior of inventories. The covariance between inventory investment and sales switched sign in 1984 and turned from positive to negative. A negative covariance means that inventories are used to smooth production fluctuations. To satisfy demand in the short run, firms use their inventories and do not rely as much on the intensive labor margin. With short run increasing returns to hours, productivity is less procyclical. On the other hand, with a positive covariance, inventory investment increases with sales, and in the short run, firms use their intensive margin to satisfy demand and increase inventories. Productivity is more procyclical. Various explanations have been proposed to explain this change in the covariance. Kahn, McConnell and Perez-Quiros (2002) argue that the late 70s and early 80s were times of dramatic innovations in manufacturing technology and inventory management. This has facilitated using inventories to smooth production. Looking at the automobile industry, Ramey and Vine (2004) propose a different explanation after showing that the serial correlation of sales decreased after 1984. With more transitory shocks, firms can more easily allow for deviations from their desired inventory-sales ratio since they know that deviations will be short-lived. Again, this facilitates the use of inventories to smooth production.

6 Conclusion

By studying the joint behavior of labor productivity and unemployment before and after the beginning of the Great Moderation, I uncover a large and swift increase in the unemployment-productivity correlation that poses a puzzle to search models of unemployment. From negative, the correlation turned positive in the mid 80s, while standard search models imply a negative correlation. Further, using long run restrictions to identify technological innovations, I find that, contrary to what search models imply, a positive technology shock increases unemployment in the short run.

I present a model with hiring frictions, variable effort and costly price adjustment that can rationalize the empirical observations. In this framework, positive technology shocks temporarily raise unemployment because with costly price adjustment, aggregate demand does not increase as much as productivity, and firms use less labor. The correlation between unemployment and productivity, ρ, is positive. On the other hand, positive aggregate demand disturbances decrease unemployment and increase productivity temporarily because firms increase workers' effort to satisfy demand in the short run. As a result, ρ is negative. I document two new facts about the Great Moderation that can account for the large and swift increase in ρ in the mid 80s: (a) an increase in the size of technology shocks relative to other shocks, and (b) a decline in the procyclicality of measured productivity since the mid 80s. Thanks to a calibrated version of the model, I simulate the impact of these two events and find that they quantitatively explain the sign switch of ρ. I suspect that the decrease in the procyclicality of labor productivity after 1984 is linked to a change in inventory management after 1984 but a precise examination would require a theoretical integration of capacity utilization decisions (such as workers' effort) *and* inventory decisions, and I leave this task for future research.

Appendix:

Estimation of technology and non-technology shocks

I am interested in estimating the system

$$\begin{pmatrix} \Delta x_t \\ u_t \end{pmatrix} = C(L) \begin{pmatrix} \varepsilon_t^a \\ \varepsilon_t^d \end{pmatrix} = C(L)\varepsilon_t \tag{24}$$

where x_t is labor productivity defined as output per hours, u_t unemployment, $C(L)$ an invertible matrix polynomial and ε_t the vector of structural orthogonal innovations comprised of ε_t^a technology shocks and ε_t^d non-technology shocks. I use the estimation method of Shapiro and Watson (1988) and Francis and Ramey (2003) to allow for time-varying variance of the structural innovations.

Without loss of generality, (24) can be written

$$\begin{aligned} \Delta x_t &= \sum_{j=1}^{p} \beta_{xx,j} \Delta x_{t-j} + \sum_{j=0}^{p} \tilde{\beta}_{xu,j} u_{t-j} + \varepsilon_t^a \\ u_t &= \sum_{j=1}^{p} \beta_{uu,j} u_{t-j} + \sum_{j=1}^{p} \beta_{ux,j} \Delta x_{t-j} + \alpha \varepsilon_t^a + \varepsilon_t^m \end{aligned}$$

As discussed in Shapiro and Watson (1988), imposing the long run restriction that only technology shocks have a permanent effect on x_t is equivalent to restricting the variable u_t to enter the first equation in differences. Consequently, the system reduces to

$$\Delta x_t = \sum_{j=1}^{p} \beta_{xx,j} \Delta x_{t-j} + \sum_{j=0}^{p-1} \beta_{xu,j} \Delta u_{t-j} + \varepsilon_t^a \tag{25}$$

$$u_t = \sum_{j=1}^{p} \beta_{uu,j} u_{t-j} + \sum_{j=1}^{p} \beta_{ux,j} \Delta x_{t-j} + \alpha \varepsilon_t^a + \varepsilon_t^m \tag{26}$$

Since Δu_{t-j} is correlated with ε_t^a, equation (25) must be estimated with instrumental variables. I use lags 1 to $p = 4$ of Δx_t and u_t as instruments. The residual from this IV regression is the estimated technology shock $\hat{\varepsilon}_t^a$. The second equation can be identified by OLS but using $\hat{\varepsilon}_t^a$ in place of ε_t^a. Finally to allow for time-varying variance of the structural innovations (or more generally heteroskedasticity), I follow Francis and Ramey (2003) and estimate both equations jointly using GMM. That way, I can estimate the variance-covariance matrix of the estimates and generate the standard error bands for the impulse response functions. The error bands are derived by generating random vectors from a multivariate normal distribution with mean equal to the coefficient estimates and variance-covariance matrix equal to the estimated one, and then calculating the impulse response functions.

Rewriting the New-Keynesian Phillips curve as a classic Phillips curve

I want to rewrite the New-Keynesian Phillips curve (15) as a function of current variables only. Iterating (15) forward and replacing real marginal cost with (21), I can express inflation as a function of current marginal cost, future expected values of a marginal worker, and future market wages:

$$\pi_t = \delta \hat{s}_t + \delta E_t \sum_{j=1}^{\infty} \beta^j \hat{s}_{t+j} = \delta \hat{s}_t + \delta \frac{\psi - 1}{\psi} E_t \sum_{j=1}^{\infty} \beta^j \hat{\chi}_{t+j} + \frac{\delta}{\psi} E_t \sum_{j=1}^{\infty} \beta^j \hat{w}_{t+j} \tag{27}$$

Iterating (18) forward and using the approximation $\beta(1-\lambda)e^a = \beta + o(\beta) \simeq \beta$ for λ and a close to zero, I can rewrite the discounted sum of expected future values of a marginal worker as a function of current labor market tightness

$$\begin{aligned} E_t \sum_{j=1}^{\infty} \beta^j \hat{\chi}_{t+j} &\simeq E_t \sum_{j=1}^{N} \beta^j \hat{\chi}_{t+j} \qquad (28) \\ &\simeq E_t \sum_{j=1}^{N} \beta^j \left(e^a(1-\lambda)\right)^{j-1} \hat{\chi}_{t+j} \\ &\simeq E_t \sum_{j=1}^{\infty} \beta^j \left(e^a(1-\lambda)\right)^{j-1} \hat{\chi}_{t+j} = \frac{c\sigma}{\beta \chi q(\theta)} \hat{\theta}_t \end{aligned}$$

since $\beta^N \hat{\chi}_{t+N}$ and $\beta^N \left(e^a(1-\lambda)\right)^{N-1} \hat{\chi}_{t+N}$ become very small for N large enough. Finally, using the law of motion for the market wage (20), I get

$$E_t \sum_{j=1}^{\infty} \beta^j \hat{w}_{t+j} = \frac{\beta(1-\varpi)}{1-\beta(1-\varpi)} \hat{w}_t. \tag{29}$$

Rewriting the New-Keynesian Phillips curve (27) with (28) and (29), I obtain

$$\pi_t = \delta \hat{s}_t + \kappa_\theta \delta \hat{\theta}_t + \tilde{\kappa}_w \delta \hat{w}_t$$

where $\kappa_\theta = \frac{c\sigma(1-\alpha)}{\beta \chi q(\theta)} > 0$ and $\tilde{\kappa}_w = \frac{\alpha\beta(1-\varpi)}{(1-\beta(1-\varpi))} \geq 0$.

Log-linearizing the first-order conditions for the household and denoting $\hat{m}_t = \ln\left(\frac{M_t/P_t A_t}{(M/P)^*}\right)$ the log-deviation of real rescaled money from its constant value in the zero-inflation equilibrium, I get $\hat{y}_t = E_t \hat{y}_{t+1} + E_t \pi_{t+1}$ and $\hat{m}_t = \hat{y}_t$.

Finally, the log-linearized law of motion for employment can be written

$$\hat{n}_{t+1} = (1 - \lambda - \theta q(\theta))\hat{n}_t + \frac{1-n}{n}(1-\sigma).\theta q(\theta)\hat{\theta}_t. \tag{30}$$

Combining the firm's first order-conditions with the household's conditions and using the law of motion for employment, I can rewrite the New-Keynesian Phillips curve (22) as a standard Phillips curve linking inflation to unemployment. Denoting $\hat{u}_t = u_t - u^*$ deviations of the unemployment rate from its long run value, labor market tightness can be related to the unemployment rate using the approximation $\hat{u}_t = -\hat{n}_t$ and the employment dynamics equation (30)

$$\hat{\theta}_t = \frac{-n}{(1-n)(1-\sigma)\theta q(\theta)} \left[\Delta \hat{u}_{t+1} + (\lambda + \theta q(\theta))\, \hat{u}_t\right]$$

so that with (16), I obtain the Phillips curve relation

$$\pi_t = -\kappa_{\Delta u} \Delta \hat{u}_{t+1} - \kappa_u \hat{u}_t + \kappa_m \varepsilon_t^m - \left(\kappa_w - \delta \frac{(\psi-1)(\tau^{cb}-1)}{1+\delta(\psi-1)}\right) \varepsilon_t^a + \kappa_w \hat{w}_{t-1} + \kappa_m \hat{m}_{t-1}$$

with $\kappa_{\Delta u} = \delta \frac{\kappa_\theta n \frac{\sigma}{(1-\beta)}}{(1+\delta(\psi-1))(1-n)(1-\sigma)\theta q(\theta)} > 0$, $\kappa_u = \delta\left(\frac{\kappa_{\Delta u}}{\delta}(\lambda + \theta q(\theta)) + \psi - 1\right) > 0$, $\kappa_w = \delta \frac{(1+\tilde{\kappa}_w)(1-\varpi)}{1+\delta(\psi-1)} > 0$, and $\kappa_m = \frac{\delta(\psi-1)}{1+\delta(\psi-1)} > 0$.

An equivalent model with Calvo price setting

In this section, I describe a model similar to the one presented on Section 3 but with the assumption of Calvo price setting instead of costly price adjustment. Specifically, firms can only reset their price (at no cost) at random dates, and each period a fraction ν of randomly selected firms cannot reset its price.

I now show that such a model delivers similar first-order conditions as well as the same log-linearized New-Keynesian Phillips curve. However, a complication arises because Calvo price setting introduces heterogeneity amongst firms. Indeed, with Calvo-type price stickiness, the Nash-bargaining match-specific wage paid to each worker becomes firm-specific, and the worker's opportunity cost of accepting a job depends on the pricing decisions of all other firms. This complicates greatly the determination of the equilibrium wage and the rest of the analysis, and this is the main reason why I preferred the assumption of costly price adjustment to Calvo price setting in the workhorse model.

However, recall that firms take the wage as given when making their price or hiring decisions. As a result, apart from the determination of the wage, the first-order conditions remain similar with the household's problem unchanged and the firm's problem only slightly modified. Given the market wage and aggregate price level, firm i will choose a sequence of price $\{P_{it}\}$

and vacancies $\{v_{it}\}$ to maximize the expected present discounted value of future profits subject to the demand constraint, the Calvo price setting rule, the hours/effort choice and the law of motion for employment. Formally, the firm maximizes its value

$$E_t \sum_j \beta^j \left[\frac{P_{i,t+j}}{P_{t+j}} y^d_{i,t+j} - n_{i,t+j} h_{i,t+j} e_{i,t+j} w_t - cA_t v_{i,t+j} \right]$$

subject to the hours/effort decision

$$e_{it} = e_0 h_{it}^{\frac{\sigma_h}{1+\sigma_e}}$$

the demand constraint

$$y^d_{it} = A_t n_{it} h^{\varphi}_{it} = (\frac{P_{i,t}}{P_t})^{-\varepsilon} Y_t$$

and the law of motion for employment

$$n_{it+1} = (1-\lambda) n_{it} + q(\theta_t) v_{it}.$$

The job posting condition is unchanged and takes the form

$$\frac{c_t}{q(\theta_t)} = E_t \beta_{t+1} \left[\chi_{it+1} + \frac{c_{t+1}}{q(\theta_{t+1})} (1-\lambda) \right] \tag{31}$$

where χ_{it}, the shadow value of a marginal worker, can be written as

$$\chi_{it} = -\frac{\partial \zeta_{it}}{\partial n_{it}} = (\psi - 1) \, w_t h_{it} e_{it} = (\psi - 1) \, w_t \left(\frac{y^d_{it}}{A_t n_{it}} \right)^{\psi}.$$

However, with Calvo-type price setting, firms can only reset their price at random dates and each period a fraction ν of randomly selected firms cannot reset its price. As a result, the optimal price setting rule is different, and a firm resetting its price at date t will satisfy the standard Calvo price setting condition:

$$E_t \sum_{j=0}^{\infty} \nu^j \beta_j \left[\frac{P^*_{it}}{P_{t+j}} - \mu s_{it+j} \right] Y_{t+j} P^{\varepsilon}_{t+j} = 0 \tag{32}$$

where the optimal mark-up is $\mu = \frac{\varepsilon}{\varepsilon - 1}$ and the firm's real marginal cost

$$s_{it} = \frac{\partial \zeta_{it}}{\partial y_{it}} = \psi \frac{w_t}{A_t} \left(\frac{y^d_{it}}{A_t n_{it}} \right)^{\psi - 1}$$

The firm will choose a price P^*_{it} that is, in expected terms, a constant mark-up μ over its real marginal cost for the expected lifetime of the price.

To derive the New-Keynesian Phillips curve, I log-linearize around the zero inflation equilibrium. However, because of firms' ex-post heterogeneity, the derivation is not as straightforward, and I follow Woodford's (2004) similar treatment of endogenous capital in a New-Keynesian model with Calvo price rigidity. In my case, employment is the state variable and plays the role of capital in Woodford's model. I start by log-linearizing the first-order conditions (31) and (32) around the zero-inflation equilibrium. For any $t > 0$, the vacancy posting condition becomes

$$\frac{c\sigma}{q(\theta^*)}\hat{\theta}_t = E_t\beta\left[\chi^*\hat{\chi}_{it+1} + \frac{c(1-\lambda)\sigma}{q(\theta^*)}\hat{\theta}_{t+1}\right] + \frac{c}{q(\theta^*)}E_t\left(\hat{y}_t - \hat{y}_{t+1}\right) \tag{33}$$

with the value of a marginal worker $\hat{\chi}_{it}$ given by

$$\hat{\chi}_{it+1} = \hat{w}^n_{t+1} + \psi(\hat{y}_{it+1} - \hat{n}_{it+1})$$

and the price-setting condition becomes

$$\sum_{k=0}^{\infty}(\nu\beta)^k\hat{E}^i_t\left[\tilde{p}_{it+k} - \hat{s}_{it+k}\right] = 0 \tag{34}$$

with

$$\hat{s}_{it+k} = \hat{w}^n_{t+k} + (\psi - 1)\left(\hat{y}_{it+k} - \hat{n}_{it+k}\right). \tag{35}$$

The notation $\hat{E}^i_t$ denotes an expectation conditional on the state of the world at date t but integrating only over future states in which firm i has not reset its price since period t. $\tilde{p}_{it} \equiv \log\left(\frac{P_{it}}{P_t}\right)$ is the firm's relative price.
Denoting log prices by lower-case letters and p^*_{it} the optimal (log) price for firm i at t, the demand curve for firm i at date $t+1$ can be written $\hat{y}_{it+1} = \hat{y}_{t+1} - \varepsilon(p_{it} - p_{t+1})$ if it cannot reset its price at $t+1$ and $\hat{y}_{it+1} = \hat{y}_{t+1} - \varepsilon(p^*_{it+1} - p_{t+1})$ if it can reset its price.
Averaging across all firms, I get

$$\begin{aligned}\int_0^1 \hat{y}_{it+1}di &= \hat{y}_{t+1} - \varepsilon\left[\nu(\int_0^1 p_{it}di - p_{t+1}) + (1-\nu)(\int_0^1 p^*_{it+1}di - p_{t+1})\right] \\ &= \hat{y}_{t+1} - \varepsilon\left[\nu(p_t - p_{t+1}) + (1-\nu)(p^*_{t+1} - p_{t+1})\right] \end{aligned} \tag{36}$$

where $p^*_{t+1} = \int_0^1 p^*_{it+1}di$ is the average price chosen by all price setters at date $t+1$.

With Calvo price-setting, I can write

$$p_{t+1} = \left((1-\nu)p_{t+1}^{*1-\varepsilon} + \nu p_t^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}$$

or

$$1 = (1-\nu)\left(\frac{p_{t+1}^*}{p_{t+1}}\right)^{1-\varepsilon} + \nu\left(\frac{p_t}{p_{t+1}}\right)^{1-\varepsilon}.$$

Log-linearizing around the zero-inflation equilibrium gives $-\nu(p_{t+1}-p_t) = (1-\nu)(p_{t+1}^* - p_{t+1})$ and combining with (36) gives $\int_0^1 \hat{y}_{it+1}di = \hat{y}_{t+1}$. Further, $\int_0^1 \hat{n}_{it}di = \hat{n}_t$.

Averaging (35) across all firms. I get $\hat{s}_{t+k} = \hat{w}_{t+k}^m + (\psi - 1)(\hat{y}_{t+k} - \hat{n}_{t+k})$ so that I can rewrite the real marginal cost as

$$\hat{s}_{it} = \hat{s}_t + \frac{1-\alpha}{\alpha}(-\varepsilon\tilde{p}_{it} - \tilde{n}_{it}) \tag{37}$$

where $\tilde{n}_{it} = n_{it} - n_t$ is the relative employment of firm i.

Using that $\hat{E}_t^i \tilde{p}_{it+k} = p_{it} - E_t p_{t+k}$ and (37) in (35) yields

$$\left(1+\varepsilon\frac{1-\alpha}{\alpha}\right)p_{it}^* = (1-\nu\beta)\sum_{k=0}^{\infty}(\nu\beta)^k \hat{E}_t^i\left[\hat{s}_{t+k} + \left(1+\varepsilon\frac{1-\alpha}{\alpha}\right)p_{t+k} - \frac{1-\alpha}{\alpha}\tilde{n}_{it+k}\right] \tag{38}$$

Averaging the shadow value of a marginal worker gives

$$\hat{\chi}_t = \hat{w}_t^n + \psi(\hat{y}_t - \hat{n}_t)$$

so that by subtracting (33) from its average, I get

$$\begin{aligned}
\tilde{n}_{it+1} &= E_t(\hat{y}_{it+1} - \hat{y}_{t+1}) \\
&= -\varepsilon E_t\left[\nu(p_{it} - p_{t+1}) + (1-\nu)(p_{it+1}^* - p_{t+1}\right] \\
&= -\varepsilon\nu\tilde{p}_{it} - \varepsilon(1-\nu)(p_{it+1}^* - p_{t+1}^*)
\end{aligned} \tag{39}$$

since $p_{t+1} = \nu p_t + (1-\nu)p_{t+1}^*$.

The firm's pricing decision depends on its employment level and the economy's aggregate state. But to a first order, the log-linearized equations are linear so that the difference between p_{it}^* and p_t^*, the average price chosen by all price setters, is independent from the economy's aggregate state and depends only on the relative level of employment $n_{it} - n_t = \tilde{n}_{it}$. So as in Woodford (2004), I guess that the firm's pricing decision takes the form

$$p_{it}^* - p_t^* = -\epsilon\tilde{n}_{it} \tag{40}$$

with ϵ a constant to be determined. Hence, (33) becomes

$$\tilde{n}_{it+1} = \frac{-\varepsilon\nu}{1-\varepsilon(1-\nu)\epsilon}\tilde{p}_{it} = -f(\epsilon)\tilde{p}_{it}$$

Since this was shown for any $t > 0$, I also get $\tilde{n}_{it+k} = -f(\epsilon)\tilde{p}_{it+k-1}$, $\forall k > 0$ so that I can rewrite (38) as

$$\phi p_{it}^{*} = (1-\nu\beta)\sum_{k=0}^{\infty}(\nu\beta)^{k}\hat{E}_{t}^{i}\left[\hat{s}_{t+k} + \phi p_{t+k}\right] - (1-\nu\beta)\frac{1-\alpha}{\alpha}\tilde{n}_{it} \tag{41}$$

with $\phi = \left(1 + \varepsilon\frac{1-\alpha}{\alpha} - \nu\beta\frac{1-\alpha}{\alpha}f(\epsilon)\right)$.

Subtracting (41) from its average, I obtain

$$\phi(p_{it}^{*} - p_{t}^{*}) = -(1-\nu\beta)\frac{1-\alpha}{\alpha}\tilde{n}_{it}. \tag{42}$$

This equation is of the conjectured form (40) if and only if ϵ satisfies

$$\epsilon = \frac{(1-\nu\beta)\frac{1-\alpha}{\alpha}}{1+\varepsilon\frac{1-\alpha}{\alpha} - \nu\beta\frac{1-\alpha}{\alpha}f(\epsilon)}. \tag{43}$$

Finally, averaging (41) and using $\pi_t = \frac{1-\nu}{\nu}(p_t^{*} - p_t)$, I obtain the New-Keynesian Phillips curve

$$\pi_t = \delta.\hat{s}_t + \beta E_t \pi_{t+1}$$

with $\delta = \frac{(1-\nu)(1-\nu\beta)}{\nu\phi}$.

Hence, a model with a Calvo price setting mechanism is described by the same log-linearized first-order conditions as a model with costly price adjustment, and the determination and behavior of the real wage (or wages if heterogenous firms pay different wages) is the only difference.

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Table 1. Correlation Estimates

	1948-1984	1985-2005
$\rho_{U,Y/H}$	-0.31**	0.40**
	(0.11)	(0.20)
$\rho_{V,Y/H}$	0.34**	-0.18
	(0.14)	(0.17)

Note: Table 1 reports estimates of the correlation between unemployment and labor productivity over 1948:Q1-1984:Q4 and 1985:Q1-2005:Q4, and between vacancies and labor productivity over 1951:Q1-1984:Q4 and 1985:Q1-2005:Q4. All series are detrended with an HP-filter with smoothing parameter 1600. Standard-errors are shown in parentheses. Significance is indicated by one asterisk (10-percent level) or two asterisks (5-percent level).

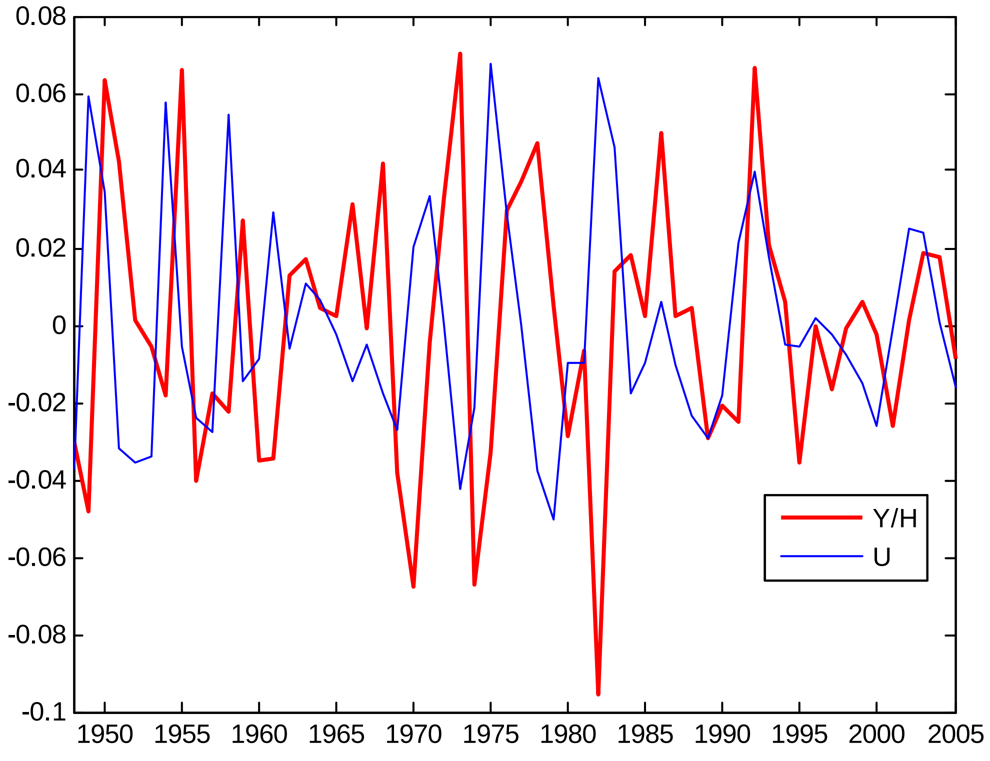

Figure 1: Unemployment and labor productivity (output per hour) over 1948-2005. The quarterly series are detrended with an HP-filter λ=1600 and annualized for clarity of exposition.

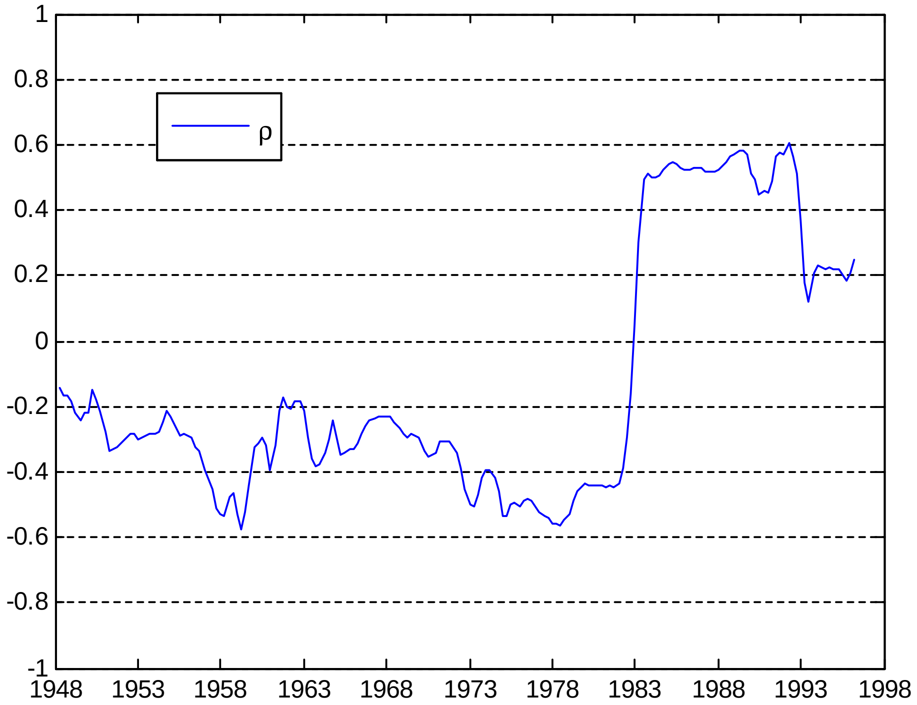

Figure 2: 10-year rolling correlation (unemployment,output per hour) over 1948-2005.

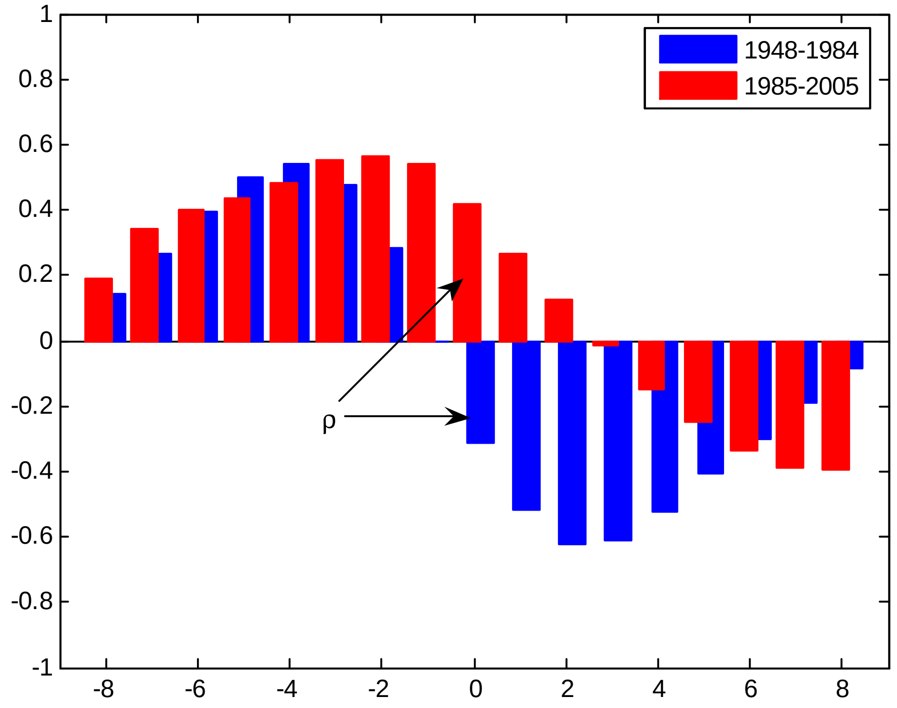

Figure 3: Empirical Cross-Correlogram of Output per Hour and Unemployment over 1948-1984 (background) and 1985-2005 (foreground).

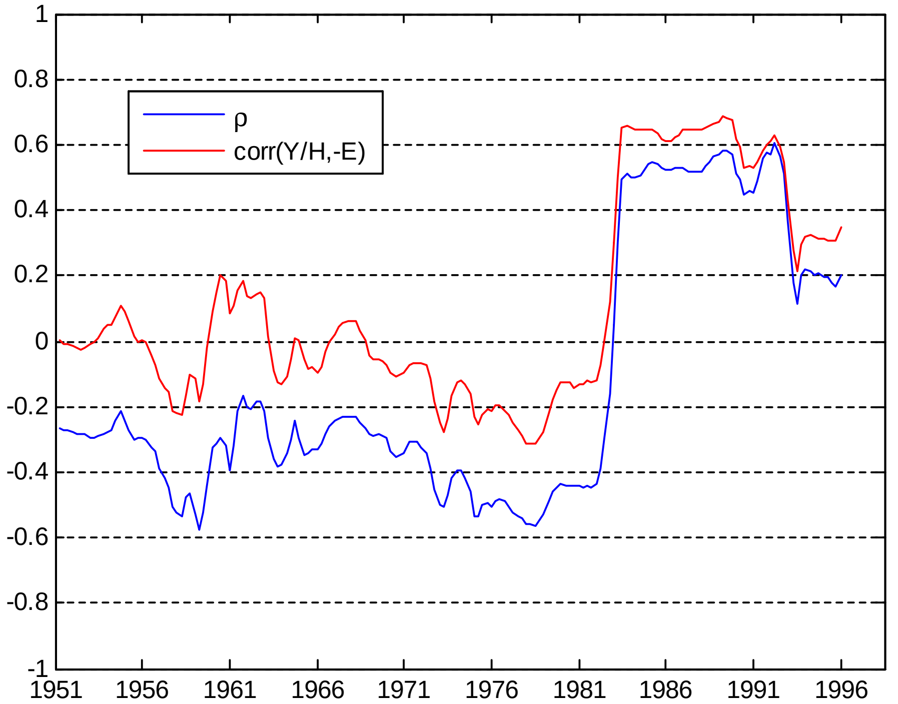

Figure 4: ρ and the10-year rolling correlation (employment,output per hour) over 1951-2005. Employment is measure in millions of workers and is detrended with an HP-filter ($\lambda = 1600$).

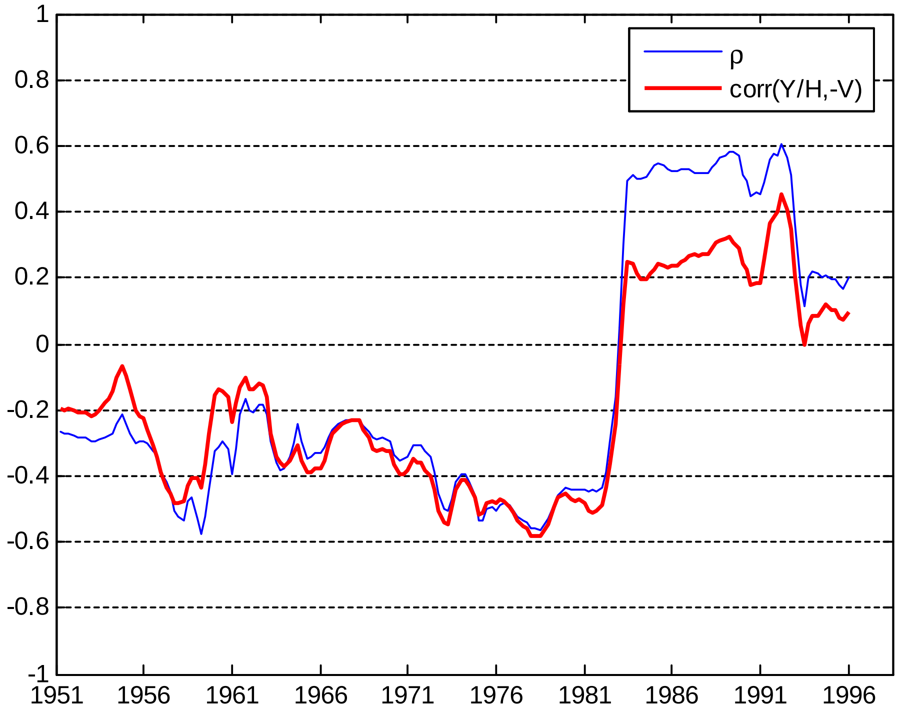

Figure 5: ρ and the 10-year rolling correlation (vacancies,output per hour) over 1951-2005.

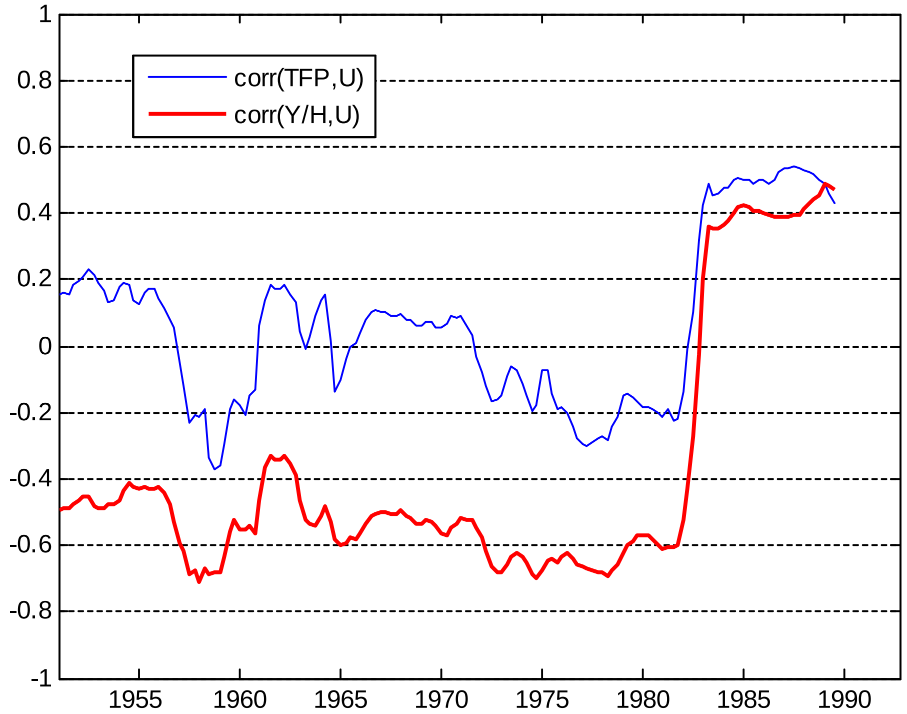

Figure 6: ρ and the10-year rolling correlation (unemployment,TFP) over 1948-2000. TFP is adjusted for capacity utilization and taken from Beaudry and Portier (2006).

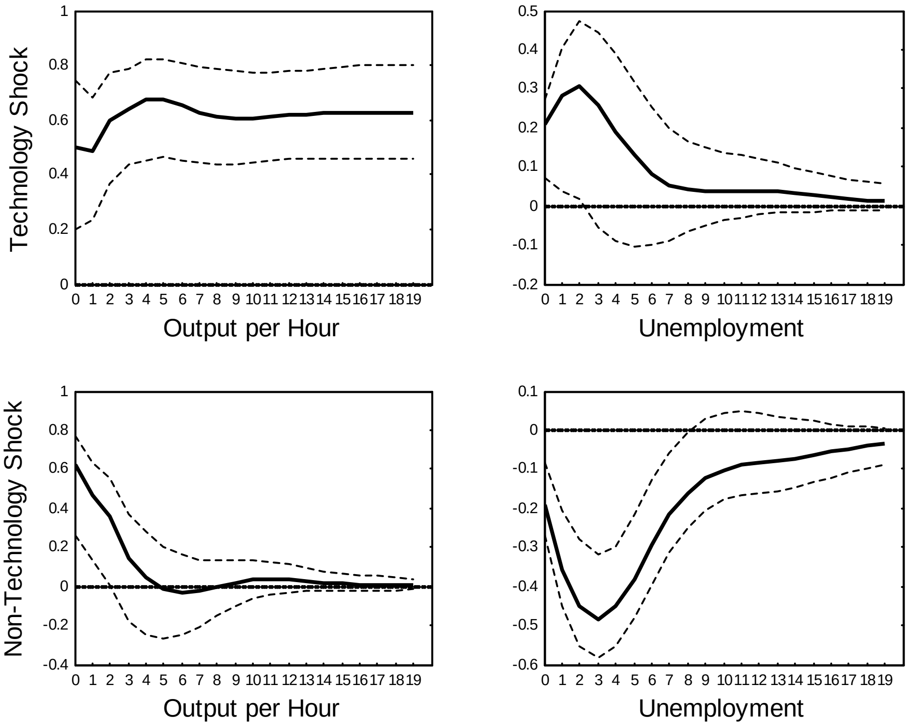

Figure 7: Impulse response functions to technology and non-technology shocks. Dashed lines represent the 95% confidence interval.

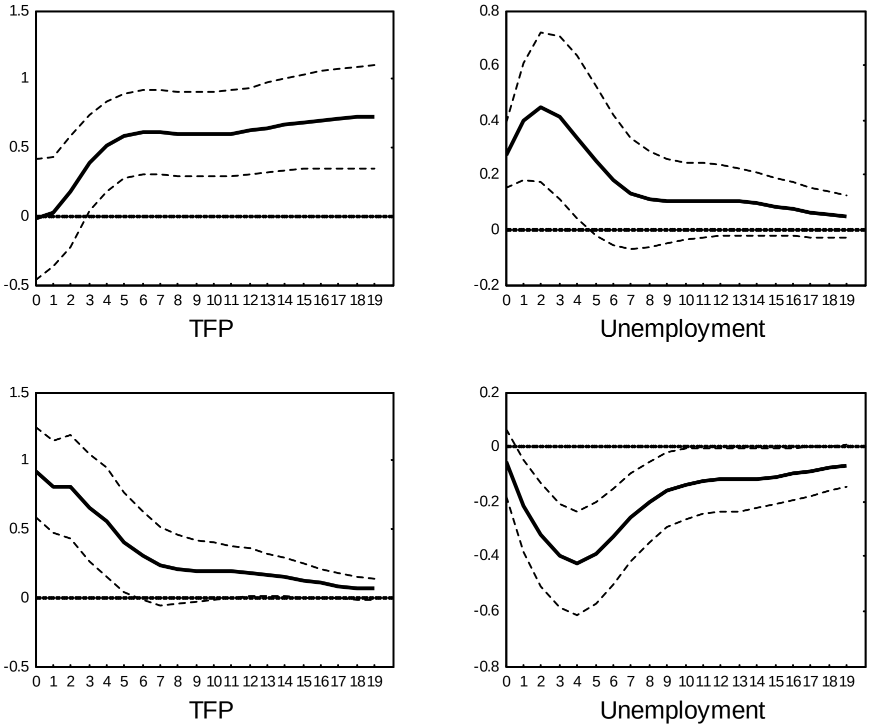

Figure 8: Impulse response functions to technology and non-technology shocks. Productivity is measured with TFP unadjusted for capacity utilization. Dashed lines represent the 95% confidence interval.

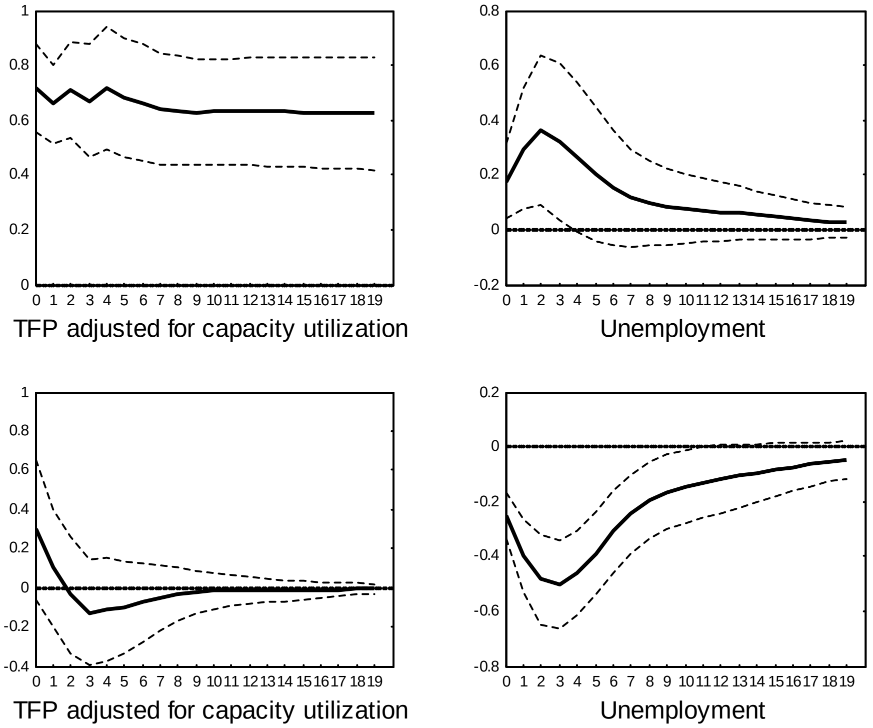

Figure 9: Impulse response functions to technology and non-technology shocks. Productivity is measured with TFP adjusted for capacity utilization. Dashed lines represent the 95% confidence interval.

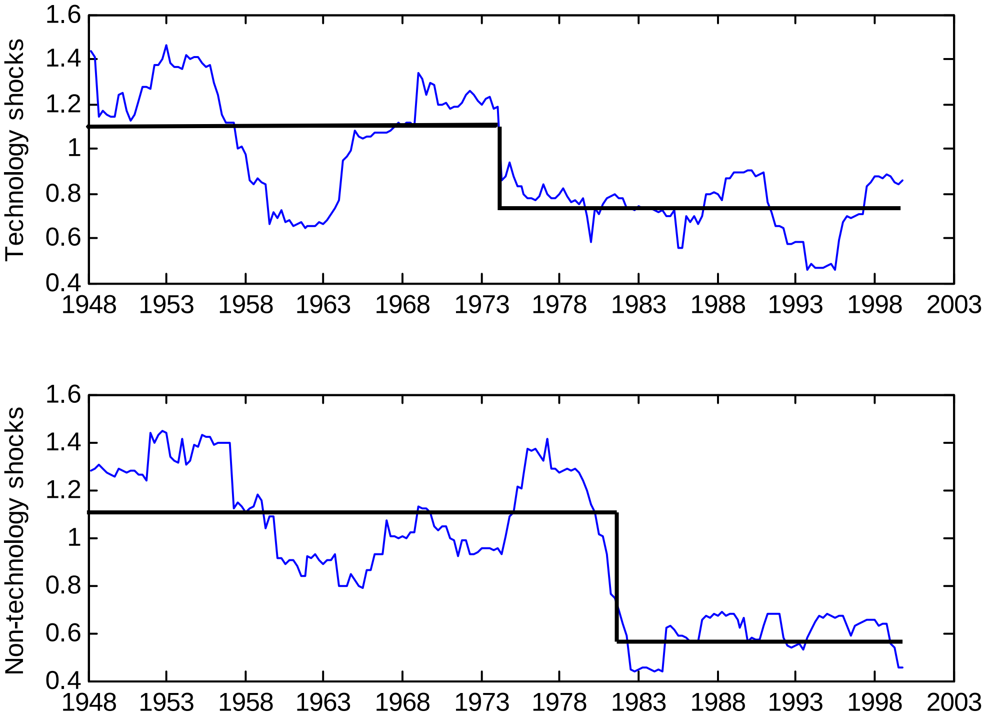

Figure 10: 5-year rolling standard-deviation of technology and non-technology shocks and step functions approximating the standard deviations. Both standard deviations are normalized to one for ease of comparison, 1948-2005.

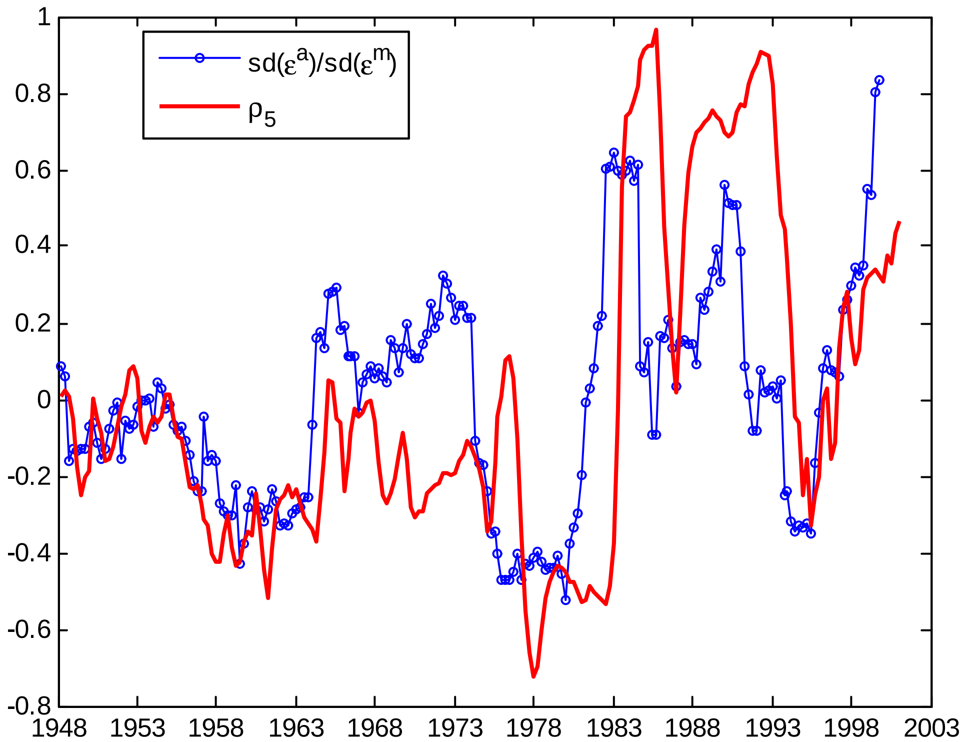

Figure 11: 5-year rolling correlation (unemployment,output per hour) and ratio of the 5-year rolling standard deviation of technology shocks to the 5-year rolling standard deviation of non-technology shocks. Deviations from the mean, 1948-2005.

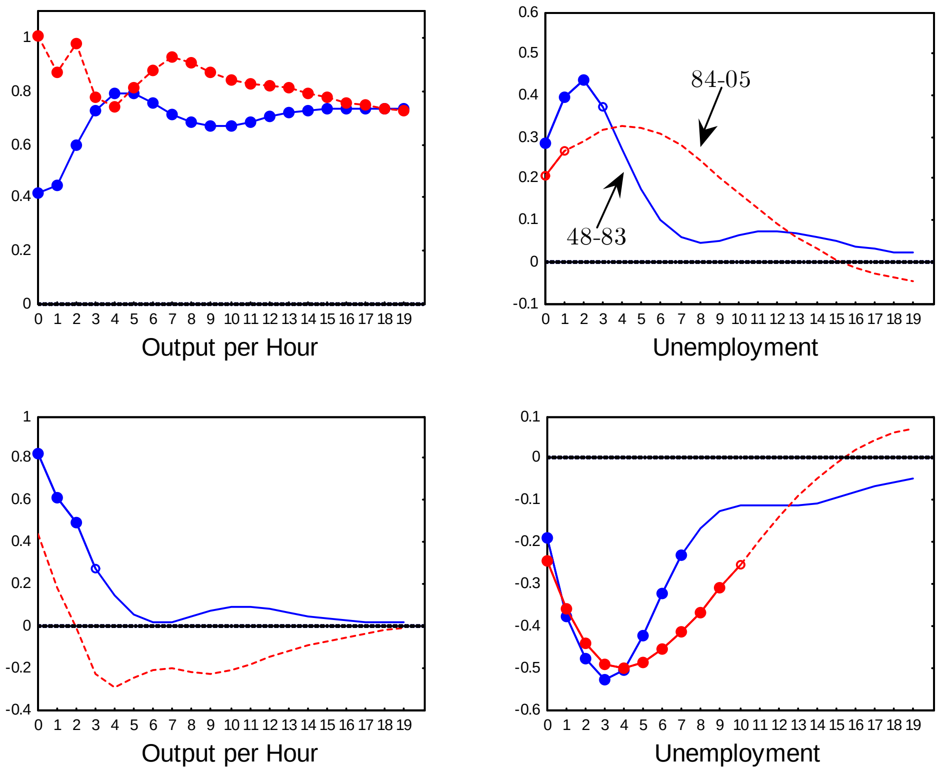

Figure 12: Impulse response functions to technology and non-technology shocks. Solid lines show estimates for 1948-1983 and dashed lines for 1984-2005. Solid circles indicate that the response is significant at the 5% level and open circles at the 10% level.

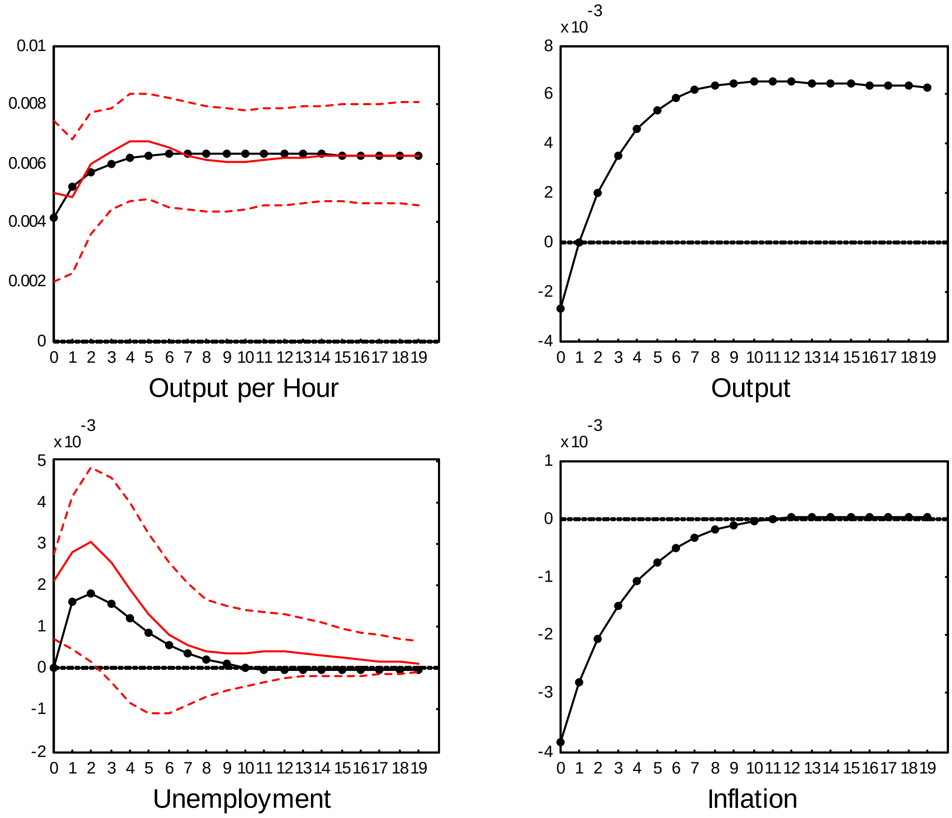

Figure 13: Model (dotted line) and Empirical (plain line) impulse response functions to a technology shock. Dashed lines represent the 95% confidence interval.

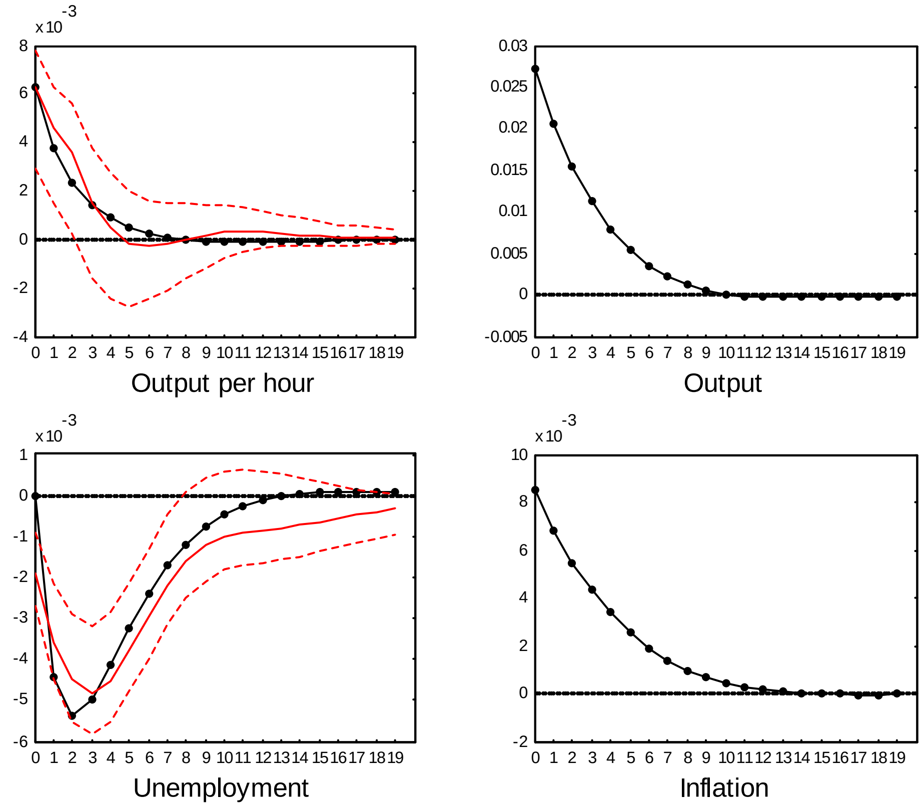

Figure 14: Model (dotted line) and Empirical (plain line) impulse response functions to a non-technology shock. Dashed lines represent the 95% confidence interval.

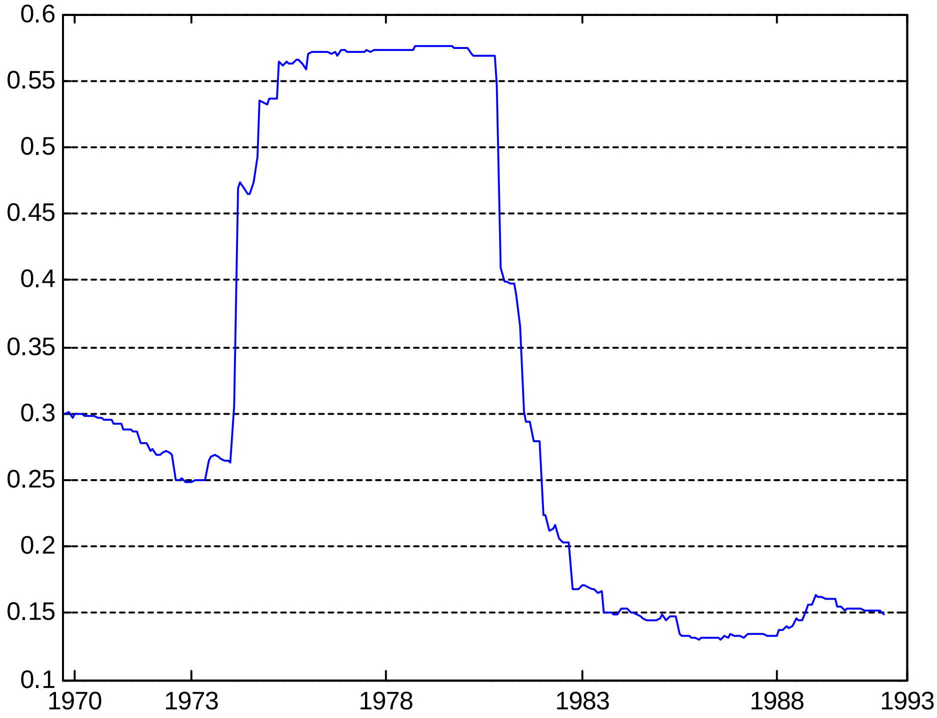

Figure 15: 5-year rolling standard-deviation of Romer and Romer monetary shocks. 1969:Q1-1996:Q4.

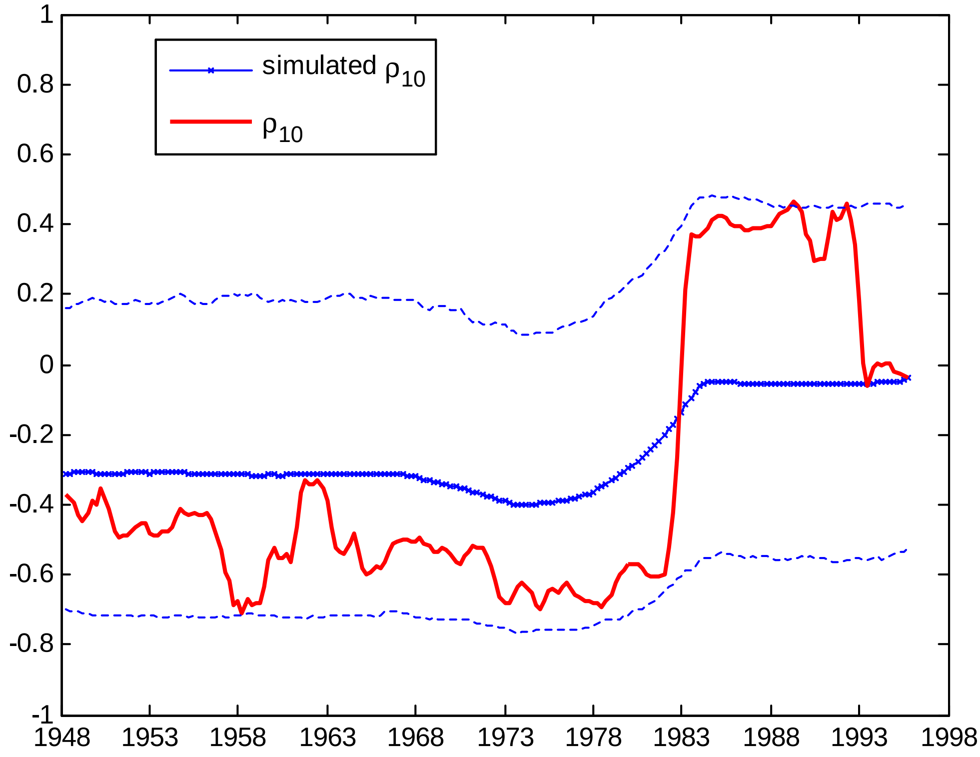

Figure 16: Simulation of ρ with volatility drop after 1984. (dashed lines represent the 95% confidence interval)

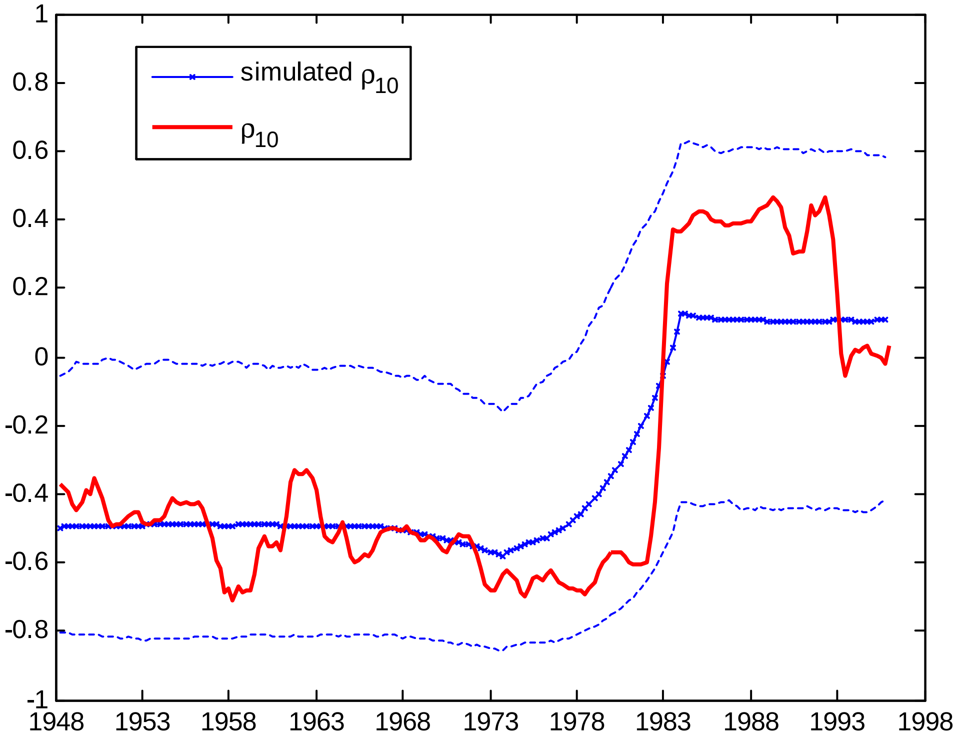

Figure 17: Simulation of ρ with volatility drop *and* structural change after 1984. (dashed lines represent the 95% confidence interval)

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