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Abstract

We argue that the New-Keynesian Phillips Curve literature has failed to deliver a convincing measure of "fundamental inflation". We start from a careful modeling of optimal price setting allowing for non-unitary factor substitution, non-neutral technical change and time-varying factor utilization rates. This ensures the resulting real marginal cost measures match volatility reductions and level changes witnessed in many US time series. The cost measure comprises conventional counter-cyclical cost elements plus pro-cyclical (and co-varying) utilization rates. Although pro-cyclical elements dominate, real marginal costs are becoming less cyclical over time. Incorporating this richer driving variable produces more plausible price-stickiness estimates than otherwise and suggests a more balanced weight of backward and forward-looking inflation expectations than commonly found. Our results challenge existing views of inflation determinants and have important implications for modeling inflation in New-Keynesian models.

JEL Classification: E20, E30.

Keywords: Inflation, Real Marginal Costs, Production Function, Labor Share, Cyclicality, Utilization, Intensive Labor, Overtime Premia.

Non-technical Summary

The New Keynesian Phillips Curve (NKPC) has become the dominant paradigm for analyzing inflation dynamics. Primarily, the specification models inflation as a function of its expectation and some real activity driving variable. NKPCs have been widely estimated and their merits much debated.

Many such debates, though, have focused more on dynamic and expectations issues than on how to treat the driving variable. Indeed, it appears stubbornly difficult to pin down the driving variable. A common observation is that typical Phillips-curve "slopes" (from which measures of price stickiness can be uncovered) have been curiously flat (contrary to microeconomic evidence suggesting frequent price adjustments). A second criticism is that observed reductions in inflation volatility do not appear to be matched by that in candidate driving variables.

We argue that these problems arise because conventional measures of the driving variable (or real marginal costs) are flawed. We propose a theoretically well-founded alternative, and reassess the empirical performance of NKPCs. Admittedly, real marginal costs - as implied by the New Keynesian theory - are difficult to measure. An early approach was to use the deviation of output from a HP filter or a linear/quadratic trend. However, often these non-structural measures entered with the "wrong" (negative) sign. Alternatively, several authors argued in favor of proxying real marginal costs by average real unit labor costs.

Under the special case of a (unitary substitution elasticity) Cobb Douglas production function, real marginal costs reduce to the labor share. The disadvantage of using the labor share is largely three fold: (i) labor share is counter-cyclical which in turn implies that the markup of (sticky) prices over marginal costs is pro-cyclical (by contrast, theory suggests output increases not driven by technological improvements tend to raise nominal marginal costs more than prices and thus that mark-ups should be counter-cyclical); (ii) reflecting its Cobb-Douglas origins, it is underpinned by a unitary elasticity of factor substitution and thus excludes any identifiable role for technical change; and (iii) its use as a measure of real marginal costs implies that either the number of workers or their utilization rate can be adjusted costlessly at a fixed wage rate.

Over business-cycle frequencies, however, *all* of those features appear highly restrictive. Against this background, we attempt a more careful treatment of the driving variable(s). In their landmark overview Rotemberg and Woodford (1999) reviewed means to improve the measurement of real marginal costs, e.g., non Cobb Douglas production, overtime pay, labor adjustment costs, labor hoarding, variable capital utilization and overhead labor. Our paper can be viewed as empirically taking up many of those issues (all but the last in fact) in a unified framework. Moreover, we regard the matter of the cyclicality of real aggregate marginal costs as an empirical matter. As regards the choice of production technology, we estimate both Cobb Douglas and the more general constant elasticity of substitution (CES) form to capture potential output. Further, we do so in "normalized" form and estimate production and technology relationships in a system with cross-equation restrictions with the factor demands.

It turns out that the CES production variant not only empirically dominates Cobb Douglas, it also *does* capture the celebrated volatility reduction in the US economy from the early 1990s. Using CES forms opens up the possibility for non-neutral technical change. Indeed, there appears little obvious reason to suppose that over business-cycle frequencies, technical change will be neutral or mimic balanced growth. The acceleration in US labor productivity and TFP during the second half of the 1990s underpins the need for a careful treatment.

Since Solow (1957), we have also known of the need to disentangle technical change from factor utilization rates. We do so by making flexible, though economically interpretable, parametric assumptions for both. We assume that growth in factor-augmenting technical change is non-constant but smoothly evolving. In so doing, we find that the boom in TFP growth in the 1990s was underpinned by aggressive labor augmenting and declining capital augmentation. This reflected an essentially fully-employed economy and thus - following the insights of the "directed technical change" literature - the necessity to bias innovations towards the scare factor. Notwithstanding, we demonstrate that whether real marginal costs measures are Cobb Douglas or CES based, they remain counter-cyclical. They are, in short, potentially partial measures of firms' real marginal costs.

We rationalize such cyclical short comings as reflecting omitted variations in factor utilization. Regarding employment, we argue that the existence of extensive labor adjustment costs leads to a phenomenon we label "Effective Hours". Effective Hours captures firms' familiar costs increases from overtime labor. But it also captures the inability (or reduced ability) of firms to cut labor costs if utilized labor falls below the norm, essentially reflecting labor hoarding. Likewise, costs related to capital utilization are assumed convex. Moreover, we demonstrate that both factor utilization rates closely co-move. Accordingly, we arrive at a measure of real marginal costs comprising a composite of (*counter-cyclical*) real marginal costs excluding utilization, plus (*pro-cyclical*) utilization costs. The overall cyclicality of this measure depends on how the data weights them. On US aggregate data, when our cost measure is inserted into NKPCs as the driving variable (relative to more standard definitions), price stickiness becomes more consistent with micro studies, the slope of the Phillips curve accordingly strengthens markedly, and that the weight on forward-looking expectations decreases.

1 Introduction

The New Keynesian Phillips Curve (NKPC) has become a popular means of analyzing inflation. Primarily, the specification models inflation as a function of its expectation and – like *all* Phillips Curves – some real-activity driving variable. NKPCs have been widely estimated (e.g., Roberts (1995), Galí and Gertler (1999) for seminal contributions) and their merits and alternatives much debated (Batini (2009), Fuhrer (1997, 2006), Mankiw and Reis (2002), Rudd and Whelan (2007), Rotemberg (2007)).

The literature has, however, mostly focused on dynamic and expectations issues rather than on how to treat the driving variable. This may reflect how difficult that has proved. A common observation, for instance, is that typical Phillips-curve "slopes" – which capture price stickiness – have been curiously flat (contrary to micro evidence suggesting more frequent price adjustments). Another, is that recent reductions in US inflation (and other time series) do not appear to be matched by that in candidate driving variables, e.g. Fuhrer (2006, 2011).

An inappropriate driving variable represents a source of mis-specification. Its use may distort our understanding of the persistence, pressures and sources of inflation. This has policy consequences: a policy maker who views the slope as flat may operate very differently compared to one believing it steep. Indeed, at the extreme if modeled inflation is assumed to be uncoupled from the real economy, indeterminacy would be the implication (i.e., inflation expectations cannot be anchored).

Against this background, our contribution is two fold:

1. We develop a more complete specification of the driving variable (real marginal costs). We allow for non-unitary factor substitution and non-neutral technical change and disentangle technical progress from (co-varying) factor utilization rates.

2. We then ask: how costly and misleading is the use of a mis-specified driving variable? Does it affect NKPC estimates of inflation persistence and stickiness? Would a "better" measure challenge our views on the business-cycle properties of real marginal costs?

In their landmark overview, Rotemberg and Woodford (1999) reviewed means to improve the measurement of real marginal costs, e.g., non Cobb Douglas production technology, overtime pay, labor adjustment costs, labor hoarding, variable capital utilization and overhead labor. Our paper can be viewed as empirically taking up many of those issues (all but the last in fact) in a common framework.

As regards the choice of production technology (from which we initially build real cost measures), we estimate Cobb Douglas (CD) and the more general constant elasticity of substitution (CES) form. We make three deviations from normal practice. First, following the seminal work of La Grandville (1989) and Klump and de La Grandville (2000), we do so in "normalized" form.[1]

[1]Normalization implies representing production in consistent indexed number form. Without it, production-function parameters can be shown to have no economic interpretation since they are dependent on the normalization points and the elasticity of substitution. This significantly undermines estimation and comparative static exercises, e.g. León-Ledesma et al. (2010a,b), Klump and Saam (2008).

Second, following Klump et al. (2007), we estimate production and technology relationships as a system with cross-equation restrictions. Third, we model technical progress as time-varying and "factor augmenting". These various features bring the estimated production-technology relations markedly closer to the data.

The difference that production-function choices make is striking; we find that the CES variant not only empirically dominates CD,[2] its derived marginal costs also – contrary to popular wisdom – capture the celebrated volatility reduction in the US economy over recent decades.

Moreover, CES admits the possibility for non-neutral technical change (i.e., rather than purely Harrod or Hicks-neutral forms). As Acemoglu (2009) (Ch. 15) comments, over business-cycle frequencies there is little obvious reason to believe that technical change will be neutral or mimic balanced growth. Furthermore, the acceleration in US labor productivity and TFP growth during the 1990s (Basu et al. (2001), Jorgenson (2001)) underpins the need for a careful treatment. We make the identifying assumption that growth in factor-augmenting technical change is non-constant but smoothly evolving. In doing so, we find an intriguing result that the boom in TFP growth in the 1990s was underpinned by increasing labor augmentation and declining capital augmentation. This pattern appears consistent with the insights of the "directed technical change" literature (Acemoglu (2002)).

Thus, our measure of real marginal costs addresses level and volatility changes observed in productivity measures. Notwithstanding, however well real marginal costs measures are derived, they remain incomplete since they assume hired inputs are always in full use. We instead attach convex costs to changes in factor utilization rates that introduce the conventionally omitted dependency of marginal costs on factor utilization. Since Solow (1957), we have known of the need to disentangle technical change from factor utilization rates. Given their latent nature, we do so by making flexible, though economically interpretable, parametric assumptions.

Regarding employment, building on Trejo (1991), Bils (1987) and Hart (2004), we argue that the existence of extensive labor adjustment costs leads to a phenomenon we label "Effective Hours". By this we mean that labor costs should capture not only straight-time wages and overtime costs[3] but also labor hoarding. Likewise, costs related to capital utilization are assumed to be convex. In line with Basu et al. (2001), we also show that utilization rates co-move.

We thus arrive at a "full" real marginal cost measure comprising a composite of real marginal costs excluding utilization, plus utilization costs. The net cyclicality of real marginal costs is then an empirical matter: if demand shocks dominate we might expect the driving variable (respectively, the mark-up) to be net pro-cyclical (counter-cyclical), and vice-versa for supply shocks. The more likely outcome, though, is the coexistence of *both* types of shocks which

[2]See also Chirinko (2008), León-Ledesma et al. (2010b). Jones (2003) argues that factor income shares exhibit such protracted swings and trends in many countries as to be inconsistent with CD (see also Blanchard (1997), McAdam and Willman (2011)).

[3]The share of private US industry jobs with overtime provisions is around 80%, and higher in some occupational groups (machinery operation; transport; administrative services), Barkume (2007). Overtime is defined by the Code of Federal Regulations as payments when hours worked exceed that required by the employee's contract or extra payments associated with special workdays: weekends, holidays.

necessitates and justifies modeling different production and cost margins.

When our preferred cost measure is inserted into NKPCs as the driving variable (relative to more standard definitions), price stickiness becomes more consistent with micro studies (implying aggregate fixed prices lasting around 2-3 quarters). The Phillips-curve slope strengthens markedly, and the weight on backward and forward-looking expectations become balanced. These results are robust to whether we use GMM or more recently-developed moment conditions inference methods. We also find that the cyclicality of real marginal costs (and its components) have been declining over time.

Regarding, other contributions, Gagnon and Khan (2005) and Gwin and VanHoose (2008) found that different measures of real marginal costs (respectively, CES production and overall industry-based cost measures), had little effect on NKPC estimates. However, in neither of those papers was there any discussion of appropriate cyclicality properties of real marginal cost measures, the incorporation of technical progress, factor utilization rates, or volatility mappings between the driving and explanatory variable. Mazumder (2009), by contrast, using US manufacturing data incorporates labor utilization into real marginal cost (albeit fitting a truncated polynomial), but finds a negative Phillips curve slope coefficient. Madeira (2011) performs an exercise with aggregate US data using employment frictions in a New Keynesian model, and finds – like us – a much closer fit to actual micro price stickiness estimates than standard NKPC estimations. Nekarda and Ramey (2010) examine mark-up cyclicality on US disaggregate data, although they focus less on full-capacity output specifications, volatility mappings and utilization co-movements, as here.

The paper proceeds as follows. Section 2 defines typical measures of marginal costs. It argues that such measures are typically counter cyclical, reflecting pro-cyclical labor productivity and are incomplete because they do not account for factor utilization rates. In section 3, we define economically plausible choices for factor utilization. Next, we define the firm's profit maximization problem. Utilization rates are then shown to be naturally co-varying. Given this, we define the optimal frictionless price-setting rule incorporating "conventional" and "augmented" real marginal costs (the latter accounting for factor utilization). Section 5 restates the NKPC framework. Section 6 defines our US macro data sources and transformations. Section 7 shows how we parameterize our production-technology system and implement non-constant growth in technical change. This system is estimated in section 8, and the level and volatility characteristics of technology and marginal costs are examined in section 9. Section 10 shows our NKPC estimates incorporating our preferred driving variable (note results are displayed one-by-one so that the contribution of "conventional" marginal costs – and then in empirical combination with other measures based on factor utilization– can be assessed). Section 11 plots our preferred measure of real marginal costs and discusses their cyclical properties. Finally, we conclude.

2 What Measures Real Marginal Costs?

Admittedly, real marginal costs – as implied by the New Keynesian theory – are difficult to measure. An early approach was to use the deviation of output from a HP filter or a linear/quadratic trend. However, often these non-structural measures entered with the "wrong" (negative) sign. Alternatively, Galí and Gertler (1999) argued in favor of proxying real marginal costs by average real unit labor costs. Under the special case of a (unitary substitution elasticity) CD production function, real marginal costs reduce to the labor share.

The advantage of using the labor share is that it is observable, simple[4] and tended to yield the "correct" slope sign (albeit not always significant or quantitatively important). The disadvantage is largely three fold:

1. Labor share is counter-cyclical which implies that the markup of (sticky) prices over marginal costs is pro-cyclical (by contrast, theory suggests output increases not driven by technological improvements tend to raise nominal marginal costs more than prices: Röger (1995), Hall (1998), Rotemberg and Woodford (1999), i.e., mark-ups should be counter-cyclical);

2. Reflecting its Cobb-Douglas origins, the labor share based real marginal cost measure is underpinned by an (empirically ill-founded) unitary elasticity of factor substitution and thus excludes any identifiable role for technical change;

3. The use of the labor share as a measure of real marginal costs implies that either the number of workers or their utilization rate can be adjusted costlessly at a fixed wage rate.

Over business-cycle frequencies *all* of these features (unitary substitution; indeterminate technical progress; zero adjustment costs; fully utilized factors) appear restrictive and counter factual.

Accordingly, let us proceed by assuming a relatively unrestricted form for output, Y_t, namely the factor-augmenting, CES production function, where capital and labor inputs are denoted by K_t and N_t and their respective technical changes by Γ_t^K and Γ_t^N,

$$Y_t = F\left(\Gamma_t^K K_t, \Gamma_t^N N_t\right) = \left[\alpha\left(\Gamma_t^K K_t\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(\Gamma_t^N N_t\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \quad (1)$$

The elasticity of substitution between capital and labor is given by the percentage change in factor proportions due to a change in the marginal products along an isoquant, $\sigma \in [0, \infty] = \frac{d\log(K/N)}{d\log(F_N/F_K)}$. If $\sigma = 1$ the CES function reduces to Cobb-Douglas, $Y_t = A_t K_t^{\alpha} N_t^{1-\alpha}$, where $A_t = \left(\Gamma_t^K\right)^{\alpha}\left(\Gamma_t^N\right)^{1-\alpha}$ is the technology level (i.e., the Solow residual), and to Leontief if $\sigma = 0$.

Production function (1) implies the following for the marginal productivity of labor (F_N)

[4] It does not, for instance, even require explicit production function estimation and also tends to allow researchers to abstract from capital accumulation.

given non-unit and unit elasticities respectively,

$$F_{N_t} = (1-\alpha)\,(\frac{Y_t}{N_t})^{\frac{1}{\sigma}}\left(\Gamma_t^N\right)^{\frac{\sigma-1}{\sigma}} \tag{2}$$

$$F_{N_t|\sigma=1} = (1-\alpha)\,\frac{Y_t}{N_t} \tag{2a}$$

The marginal product, however, can also be expressed as,

$$F_{N_t} = (1-\alpha)\,\Gamma_t^N\left[\alpha\left(\frac{\Gamma_t^K K_t}{\Gamma_t^N N_t}\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\right]^{\frac{1}{\sigma-1}} \tag{3}$$

$$F_{N_t|\sigma=1} = (1-\alpha)\,A_t\left(\frac{K_t}{N_t}\right)^{\alpha} \tag{3a}$$

Concentrating on forms (2) and (2a), real marginal costs, MC^r, are then,

$$MC_t^r = \frac{w_t}{F_{N_t}} = \frac{1}{(1-\alpha)}w_t(\frac{N_t}{Y_t})^{\frac{1}{\sigma}}\left(\Gamma_t^N\right)^{\frac{1-\sigma}{\sigma}} \tag{4}$$

$$MC_{t|\sigma=1}^r = \frac{w_t}{F_{N_t}} = \frac{1}{(1-\alpha)}w_t\frac{N_t}{Y_t} \tag{4a}$$

where w_t denotes the real wage. Equation (4a) reveals the proportionality between CD real marginal costs and the labor income share.

Equations (2) and (3) respectively express F_N in terms of labor productivity, and capital intensity and technical change. The size of the substitution elasticity affects only the impact with which these channels are transmitted into marginal productivity/marginal costs. Therefore for the illustrative nature of this section we concentrate on the simpler CD case.

A well-known implication of CD is that labor productivity, capital intensity and the real wage rate should have a common trend that equals the trend component of the Solow-residual in power $(1-\alpha)^{-1}$. Therefore, the trend deviations of these three variables (as well as the labor share) should be stationary. Further, theory tells us that labor productivity and capital intensity decrease as a response to positive demand (or preference) shocks. Therefore, one would expect both labor productivity and capital intensity to be counter cyclical and – unless the real wage (counter-intuitively) were strongly counter-cyclical – the labor share to be pro-cyclical.

However, **Figure 1,** where factors are measured in terms of heads and installed capital stock, suggests the opposite. It plots the US labor share, real wage, labor productivity and capital intensity as deviations from their estimated common trend against the NBER reference dates.[5] The stationarity requirement of the data are, at most, weakly fulfilled (which itself casts doubt on the CD form). Regarding cyclical properties, the top-panel shows that the labor share, instead of being pro-cyclical, is counter-cyclical. Since the real wage is largely a-cyclical (the middle-panel) the counter cyclicality of the labor share mainly reflects the pro-cyclicality of the average labor productivity (bottom panel). The bottom panel presents capital intensity which is almost the mirror image of labor productivity. Therefore, on the basis of (2a) and (3a) the

[5] We estimated all three variables in a cross-equations system on a common cubic trend, with free constants.

pro-cyclical component in the Solow residual must dominate labor productivity to compensate counter-cyclical capital intensity.

– Figure 1 Here –

There are two possible explanations for a pro-cyclical Solow residual and labor productivity.[6] The first is that changes in technical progress explain not only the trend development of the Solow residual but its cyclical variation too. But this leaves no role for demand shocks in business cycles and, therefore, appears implausible. The empirical evidence supports this interpretation (of implausibility).[7]

The second explanation is that inputs are systematically mis-measured reflecting the omission of unobserved variations in factor utilization rates. To illustrate, although observed labor productivity is pro-cyclical, the opposite may be true when controlling for variation in the labor utilization rate. The Solow residual can then be decomposed as $A_t = \left(\Gamma_t^K \kappa_t\right)^{\alpha} \left(\Gamma_t^N h_t\right)^{1-\alpha} = \Gamma_t \kappa_t^{\alpha} h_t^{1-\alpha}$, where Γ_t denotes non-cyclical (trend) technical progress; $\kappa_t \in [0,1]$ and $h_t \geq 0$ denote the respective utilization rates of capital and labor. Define $\mathbb{H}_t = h_t N_t$ and $\mathbb{K}_t = \kappa_t K_t$, as *effective labor* and *effective capital*, respectively. Corresponding to these definitions we have,

$$F_{\mathbb{H}} = (1-\alpha)\frac{Y_t}{h_t N_t} \tag{5}$$

$$F_{\mathbb{H}} = (1-\alpha)\left(\Gamma_t^K\right)^{\alpha}\left(\Gamma_t^N\right)^{1-\alpha}\left(\frac{\kappa_t K_t}{h_t N_t}\right)^{\alpha} \tag{5a}$$

Now although the observed average productivity per employee is pro-cyclical, the right-hand side of (5) can be counter-cyclical if labor utilization is sufficiently pro-cyclical. In line with that, (5a) now also suggests that the true marginal product of labor is *pro*-cyclical unless variation in the capital utilization rate strongly dominates labor utilization. This cyclically-adjusted marginal product of labor also implies that the definition of real marginal costs and its proportionality to the labor share need no longer hold.

Hence, there are at least <u>two</u> reasons to doubt that the labor share properly measures real marginal costs. First, the validity of the underlying CD assumption is doubtful. Second, paid labor and the installed capital stock need not be continuously at full use.

3 Varying factor utilization rates

The prerequisite for variation in factor utilization rates is that a firm cannot costlessly change its factor composition. Without adjustment costs, inputs would be used at constant maximal intensity. Adjustment costs are not, however, a sufficient condition for varying factor utilization

[6] A third possibility is increasing returns to scale. However, e.g., Basu and Kimball (1997) and Basu et al. (2006) found no significant evidence for this explanation.

[7] Basu et al. (2006) estimated the contribution of factor utilization to the Solow residual and found that the 'purified' TFP followed a random walk with no serial correlation in the residual, implying practically a-cyclical TFP.

rates; variation in utilization must be coupled with convex costs. This creates a short-run trade-off between changes in hired or installed inputs and the intensities at which they are used.

3.1 Labor Utilization

Typically, around two-thirds of the variation in total hired hours originates from employment; the rest from changes in hours per worker, e.g., Hart (2004). The relatively small proportion of the variation of paid hours per worker reflects the fact that labor contracts are typically framed in terms of "normal" working hours. Therefore, it is difficult for firms to reduce hired hours per worker below that norm and often impossible to increase them above without increasing marginal costs. Under these conditions it may be optimal for firms to allow the *intensity* at which hired labor is utilized to vary in response to shocks. Hired hours may therefore underestimate the true variation of the utilized labor input over the cycle.

Like the indivisible labor literature (e.g., Kinoshita (1987), Trejo (1991), Rogerson (1988)), we assume contracts are defined in terms of fixed (or normal) working hours per employee, i.e. in terms of the "straight-time" wage rate. Hours per employee in excess of normal hours may attract a premium. This is standard. However, we also assume employers have locally limited possibilities to decrease paid hours (and costs) when de facto worked hours fall below normal ones.

Total wage costs per employee can therefore be presented as a convex function of the deviation of the labor utilization rate h_t from normal hours $\overline{h}$.[8] Setting $\overline{h}$ to unity and using a variant of the "fixed-wage" model of Trejo (1991) for overtime pay, the following function gives a local approximation of this relation in the neighborhood of effective hours equalling normal hours,[9]

$$W_t = W\left(\overline{W}_t, h_t, a\right) = \overline{W}_t\left[h_t + \frac{a}{2}\left(h_t - 1\right)^2\right] \tag{6}$$

where W_t is the total nominal wage bill per worker, $\overline{W}_t$ is the nominal straight-time wage rate which each firm takes as given. Parameter $a \geq 0$ measures the degree of convexity of the schedule. When $h_t > \overline{h}$, $\frac{a}{2}\left(h_t - 1\right)^2$ can be interpreted as the non-linear dynamic of overtime costs. When $h_t < \overline{h}$, it relates to non-linear wage costs under labor hoarding. Conditional on the wage-cost schedule, (6), effective hours are completely demand determined.

The linear schedule in **Figure 2** (starting from $h = 1, \overline{W} = 100$) depicts total wage costs if $a = 0$, in other words $h_t > \overline{h}$ generates no overtime pay and no labor hoarding arises when $h_t < \overline{h}$. The greater the curvature, the greater the incentive to adjust effective hours, $\mathbb{H}_t$, by changing the number of employees.[10] However, if hiring/firing costs are zero, all adjustment may be done via this margin and, independently from the size of a, $\mathbb{H}_t = N_t\ \forall t$. Naturally, changes

[8] Whilst the overtime pay schedule of a single worker takes a kinked form, this is not so at a firm level and even less on higher aggregation levels, if there are simultaneously employees working at less than full intensity and those working overtime at full intensity (see the discussion in Bils (1987)).

[9] Shapiro (1986) and Bils (1987) used quite similar overtime premium specifications - but with no allowance for cost changes when $h_t < \overline{h}$.

[10] A similar choice of functional form for labor costs is the Linex function, Varian (1974). However, we found our NKPC estimations were very similar upon using this functional form.

in employee number are associated with non-trivial costs. Hence, there is labor hoarding and the associated likelihood that locally wage costs do not follow the linear schedule as $h_t < \overline{h}$, and overtime costs possibilities as $h_t > \overline{h}$

– Figure 2 Here –

3.2 Capital Utilization

The normal assumption for modeling capital utilization, $\Phi(\kappa)$, is Φ', $\Phi'' > 0$: increases in the capital utilization rate increases costs, at an increasing rate, for some upper bound, i.e., $\lim_{\kappa_t \in [0,1]} \Phi(\kappa) \in (\Phi(0), \infty]$. Although, like the labor utilization rate, we also could parametrically specify the capital utilization rate function,[11] matters can be kept simple by focusing instead on co-variation between utilization rates.

4 The Maximization Problem and Price Setting

Let us first solve the firm's profit maximizing problem in the absence of any frictions in price setting. This allows us to define real marginal costs also capturing the costs resulting from time-varying factor utilization rates. In addition, the first-order conditions of profit maximization gives us the equilibrium system used in estimating the parameters of the production-technology system needed for constructing real marginal costs.

Assume firm i faces demand function $Y_{it} = \left(\frac{P_{it}}{P_t}\right)^{-\varepsilon} Y_t$. Its profit function is

$$\Pi_t = P_t \left\{ \begin{array}{c} Y_{it}^{1-\frac{1}{\varepsilon}} Y_t^{\frac{1}{\varepsilon}} - \frac{W(\overline{W}_t, h_{it})}{P_t} N_{it} - \frac{\overline{W}_t}{P_t} \Omega_N(N_{it}, N_{it-1}) - [K_{it} - (1-\delta) K_{it-1}] \\ -\Phi(\kappa_{it}) K_{it} - \Omega_K(K_{it}, K_{it-1}, K_{it-2}) - (1 + I_{t-1}) \frac{P_{t-1}}{P_t} b_{it-1} + b_{it} \end{array} \right\} \quad (7)$$

where Ω_j refers to an adjustment cost function associated to factor $j = N,\ K$, $\delta \in (0,1)$ is the depreciation rate, I denotes the nominal interest rate, and b_{it} denotes a one-period real corporate bond reflecting the possibility of external finance for the firm. The firm maximizes the discounted sum of profits, subject to its production constraints,

$$\max \mathbb{E}_t \sum_{s=t}^{\infty} \prod_{j=0}^{s-t} R_j \left\{ \Pi_s + P_s \Lambda_{is}^Y \left[F\left(\Gamma_s^K \widetilde{\kappa}_{is} K_{is}, \Gamma_s^N h_{is} N_{is} \right) - Y_{is} \right] \right\} \quad (8)$$

where $\mathbb{E}_t$ is the expectation operator, $\widetilde{\kappa}_{it} = \frac{\kappa_{it}}{\kappa_{ss}}$ (κ_{ss} is the equilibrium utilization rate). The

[11] Muns (2009) reviews the various functional forms used in the literature.

first-order conditions are:

$$Y_i : \Lambda_{it}^Y = \frac{P_{it}}{(1+\mu) P_t} \tag{9}$$

$$\kappa_i : \Lambda_{it}^Y = \frac{\Phi'(\kappa_{it})}{F_{K_i}} \widetilde{\kappa}_{it} \tag{10}$$

$$h_i : \Lambda_{it}^Y = \frac{W_{h_i}}{P_t F_{N_i}} h_{it} \tag{11}$$

$$N_i : \frac{\partial \Omega_N (N_{it}, N_{it-1})}{\partial N_{it}} + \mathbb{E}_t \left\{ R_{t+1} \frac{\overline{W}_{t+1}}{\overline{W}_t} \frac{\partial \Omega_N (N_{it+1}, N_{it})}{\partial N_{it}} \right\} = \frac{P_t}{\overline{W}_t} \Lambda_{it}^Y F_{N_i} - \frac{W(\overline{W}_t, h_{it})}{\overline{W}_t} \tag{12}$$

$$b_i : \mathbb{E}_t R_{t+1} = \frac{1}{1+I_t} \tag{13}$$

$$K_i : \frac{\partial \Omega_K (K_{it}, K_{it-1}, ..)}{\partial K_{it}} + \mathbb{E}_t \left\{ R_{t+1} \frac{P_{t+1}}{P_t} \frac{\partial \Omega_K (K_{it+1}, ..)}{\partial K_{it}} \right\} + \mathbb{E}_t \left\{ R_{t+1} \frac{P_{t+1}}{P_t} R_{t+2} \frac{P_{t+2}}{P_{t+1}} \frac{\Omega_K (K_{it+2}, ..)}{\partial K_{it}} \right\}$$

$$= \frac{P_{it}}{(1+\mu) P_t} F_{K_i} - \left(1 - \mathbb{E}_t \left\{ R_{t+1} \frac{P_{t+1}}{P_t} (1-\delta) \right\} + \Phi(\kappa_{it}) \right) \tag{14}$$

$$\Lambda_i^Y : Y_{it} = F\left(\Gamma_t^K \widetilde{\kappa}_{it} K_{it}, \Gamma_t^N h_{it} N_{it} \right) \tag{15}$$

$1+\mu = \frac{\varepsilon}{\varepsilon - 1}$ represents the equilibrium mark-up of prices over costs, $F_{K_i} = \frac{\partial F}{\partial(\Gamma_s^K \widetilde{\kappa}_{is} K_{is})} \Gamma_t^K \widetilde{\kappa}_{it}$ and $F_{N_i} = \frac{\partial F}{\partial(\Gamma_s^N h_{is} N_{is})} \Gamma_t^N h_{it}$. From (6) we note the derivative $W_{h_i} = \overline{W}_t (1 + a(h_{it} - 1))$.

Conditions (9-11) define the shadow price (or marginal cost) of output. Conditions (10) and (11) further highlight that an optimizing firm would equalize the marginal cost of raising output across all factor margins. Conditions (12) and (14) define dynamic demands for the number of employees and capital, (13) defines the discount factor and (15) retrieves the production function.

4.1 Co-variation of Factor Utilization Rates

Given (13), the inverse of gross real interest rate is,

$$(1+r_t)^{-1} = \mathbb{E}_t \left\{ R_{t+1} \frac{P_{t+1}}{P_t} \right\} = \frac{1 + \mathbb{E}_t \pi_{t+1}}{1 + I_t} \tag{16}$$

where π denotes inflation. Conditions (13) and (14) solve for the real user cost of capital, q,

$$q_{it} = \underbrace{\frac{r_t + \delta}{1 + r_t} + \Phi(\kappa_{ss})}_{q_t^e} + [\Phi(\kappa_{it}) - \Phi(\kappa_{ss})] \tag{17}$$

where q_t^e is the equilibrium component common to all firms.

Equations (9)-(11) imply,

$$\frac{\Phi'(\kappa_{it}) \widetilde{\kappa}_{it}}{F_{K_i}} = \frac{\overline{w_t} [1 + a(h_{it} - 1)] h_{it}}{F_{N_i}} \tag{18}$$

where $\overline{w_t} = \overline{W_t} / P_t$

As regards marginal productivities F_{K_i} and F_{N_i} consider their behavior in equilibrium, i.e.,

$h_{it} = \widetilde{\kappa}_{it} = 1$. Now (12), (14) and (17) imply that $\frac{F_{N_i|h_i=1}}{F_{K_i|\widetilde{\kappa}_i=1}} = \frac{\overline{w_t}}{q_t^e}$ holds in the full-capacity equilibrium and further, with the properties of the homogenous production function, that capital intensities as well the marginal productivities of labor and capital are equal across firms. This leads to an important aggregation property for the full-capacity output utilized later in this paper,

$$Y_t^* = \sum Y_{it}^* = \sum F\left(\Gamma_t^K K_{it},\ \Gamma_t^N N_{it}\right) = F\left(\Gamma_t^K K_t,\ \Gamma_t^N N_t\right) \tag{19}$$

where $K_t = \sum K_{it}$, $N_t = \sum N_{it}$.

With the properties discussed above the CES production function implies,

$$F_{N_i} = F_{N|h=1} h_{it}^{\frac{\sigma-1}{\sigma}} = (1+\mu)\, \overline{w_t} h_{it}^{\frac{\sigma-1}{\sigma}} \tag{20}$$

$$F_{K_i} = F_{K|\widetilde{\kappa}=1} \widetilde{\kappa}_{it}^{\frac{\sigma-1}{\sigma}} = (1+\mu)\, q_t^e \widetilde{\kappa}_{it}^{\frac{\sigma-1}{\sigma}} \tag{21}$$

Inserting (20) and (21) into (18) yields,

$$\widetilde{\kappa}_{it}^{\frac{1}{\sigma}} \Phi'\left(\kappa_{it}\right) = q_t^e \left[1 + a\left(h_{it} - 1\right)\right] h_{it}^{\frac{1}{\sigma}} \tag{22}$$

This defines the relationship between capital and labor utilization rates. A closed-form is obtained after applying the first-order Taylor approximation to $\log\left[\Phi'\left(\kappa_{it}\right)\right] \approx \log\left[\Phi'\left(\kappa_{ss}\right)\right] + \frac{\kappa_{ss}}{\Phi'(\kappa_{ss})} \log \widetilde{\kappa}_{it}$ and to $\left[1 + a\left(h_{it} - 1\right)\right] \approx a \log h_{it}$. Equation (22) then becomes,

$$\log \widetilde{\kappa}_{it} = \rho_{\widetilde{\kappa},h} \log h_{it} \tag{23}$$

where

$$\rho_{\widetilde{\kappa},h}\left(\sigma, a, \kappa_{ss}, \Phi'\right) = \left(\frac{1}{\sigma} + a\right)\left(\frac{1}{\sigma} + \frac{\kappa_{ss}}{\Phi'\left(\kappa_{ss}\right)}\right)^{-1} \tag{24}$$

From (24), it is worth noting that the degree to which factor utilization rates co-move is a function of the wage-curvature parameter as well as the elasticity of substitution – the latter showing that the way utilization rates co-move is not independent of the nature of production.

Although, equation (23) suggests strict proportionality between h and $\widetilde{\kappa}$, this is not necessarily the case because $\rho_{\widetilde{\kappa},h}\left(\cdot\right)$ is conditional on the steady state level of the capital utilization rate κ_{ss} that, in turn, depends on the real interest rate (and monetary policy) regime. To illustrate, take the steady state of (22), which, together with (17), implies,

$$\Phi'\left(\kappa_{ss}\right) - \Phi\left(\kappa_{ss}\right) - \frac{r_t + \delta}{1 + r_t} = 0 \tag{25}$$

then differentiate with respect to r_t:

$$\frac{\partial \kappa_{ss}}{\partial r} = \frac{1}{\left(\Phi'' - \Phi'\right)} \frac{\left(1 - \delta\right)}{\left(1 + r\right)^2} > 0 \Leftrightarrow \Phi'' > \Phi' \tag{26}$$

Thus, an increase in the real interest rate raises equilibrium utilization closer to its technical upper bound if capital utilization costs are sufficiently convex. This, in part, reduces further the need to invest in the more expensive capital stock.

4.2 Labor and Overall Capacity Utilization Rates

Aggregate capital and labor utilization rates are essentially latent variables. Disentangling them without some additional identifying assumptions is problematic. Here we, however, show that we can derive a relationship between the observed capacity utilization rate and individual factor utilization rates.

Let Y_t and Y_t^* denote actual and full-capacity output, respectively,

$$Y_t = F\left(\Gamma_t^K \widetilde{\kappa}_t K_t, \Gamma_t^N h_t N_t\right) \tag{27}$$

$$Y_t^* = F\left(\Gamma_t^K K_t, \quad \Gamma_t^N N_t\right) \tag{28}$$

where, to recall, $\widetilde{\kappa}_t = \kappa_t/\kappa_{ss}$, is the capital utilization rate re-scaled by its equilibrium level κ_{ss}. Hence, $\widetilde{\kappa}_t$ varies in the interval $0 \leq \widetilde{\kappa}_t \leq 1/\kappa_{ss}$ on both sides of unity. Taking a first-order approximation of (27) around $\widetilde{\kappa}_t = h_t = 1$ yields the overall capacity utilization rate, u_t,

$$\underbrace{\log \frac{Y_t}{Y_t^*}}_{u_t\, -\, 1} \approx \underbrace{\frac{\Gamma_t^K K_t}{Y_t^*} \frac{\partial Y_t^*}{\partial\left(\Gamma_t^K K_t\right)}}_{\alpha} \left(\widetilde{\kappa}_t - 1\right) + \underbrace{\frac{\Gamma_t^N N_t}{Y_t^*} \frac{\partial Y_t^*}{\partial\left(\Gamma_t^N N_t\right)}}_{(1-\alpha)} \left(h_t - 1\right) \tag{29}$$

which is given by the (factor-income-share) weighted average of factor utilization rates. Under CD and CES with Harrod neutrality, approximation (29) is exact. The quality of the approximation is also relatively good under factor-augmenting technical progress unless factor income shares contain very strong trends.

Substituting (23) into (29), we further derive a relationship between labor utilization and total capacity utilization,[12]

$$\log h_{it} = \frac{1}{1 + \alpha_0\left(\rho_{\widetilde{\kappa},h} - 1\right)} \log u_{it} \tag{30}$$

[12]Note, if we assume capital utilization is constant, i.e., $\rho_{\widetilde{\kappa},h} = 0$, then labor utilization can be retrieved from $\log h_{it} \approx (1-\alpha_0)^{-1} \log u_{it}$, where $\log(h_{it}) = \log\left\{\frac{F^{-1}\left(Y_t/\Gamma^N,\ \Gamma^K/\Gamma^N K_t\right)}{N_t}\right\} \approx (1-\alpha_0)^{-1} \log \frac{Y_t}{Y_t^*}$.

4.3 Frictionless Price Setting of the Firm

If there is no friction in price setting, equations (9), (11) and (20) imply that the firm's optimal reset price, P_{it}^{f}, can be expressed into two ways:[13]

$$\log P_{it}^{f} = \log(1+\mu) + \underbrace{\underbrace{\log\left[\frac{W\left(\overline{W}_t, h_{it}\right)}{F_{N|h=1}}\right]}_{\text{conventional}} + \underbrace{\log\left[\frac{1+(h_{it}-1)}{1+\frac{a}{2}\left(\frac{h_{it}-1}{h_{it}}\right)^2} h_{it}^{\frac{1}{\sigma}-1}\right]}_{\approx\varphi^h \log h_{it}\ \text{(augmented)}}}_{\text{full } mc_{it}^{n}} \tag{31}$$

$$\log P_{it}^{f} = \log(1+\mu) + \underbrace{\underbrace{\log\left[\frac{W\left(\overline{W}_t, h_{it}\right)}{F_{N|h=1}}\right]}_{\text{conventional}} + \varphi^u \underbrace{\log(u_{it})}_{\text{augmented}}}_{\text{full } mc_{it}^{n}} \tag{32}$$

where $mc_{it}^{n} = \log\left(P_t \cdot MC_{it}^{r}\right)$ and

$$\varphi^h = \frac{1}{\sigma} - 1 + a \tag{33}$$

$$\varphi^u = \frac{\varphi^h}{1+\alpha_0\left(\rho_{\widetilde{\kappa},h}-1\right)} \tag{34}$$

Equations (31) and (32) define what we call the *full* measure of marginal costs. Both comprise a "conventional" measure W/F_N (F_N being derived from a CES or CD production function) and an "augmented" component which captures costs associated to factor utilization (whether it be total capacity utilization, u_t, or labor utilization, h_t). The conventional measure can naturally be retrieved from the full measure by setting φ^h, $\varphi^u = 0$. Moreover, $F(\cdot)$ would typically be assumed to be CD.

Note further that if φ^h or $\varphi^u > 1$, the resulting MC^r will tend to weigh the (pro-cyclical) utilization more than the (counter-cyclical) conventional component; we shall see the importance of this later when discussing and graphing our various results.

4.3.1 Identification

Equations (31) and (32) thus illustrate two ways to define the utilization component of marginal costs: (i) using a definition of labor utilization or (ii) overall utilization. The choice of (i) becomes operational only under the assumption that capital is always fully utilized, $\kappa_{it} = \kappa_{ss} = 1$ and, hence, no co-variation in utilization rates exists, $\rho_{\widetilde{\kappa},h} = 0$.(i.e., variation in capital utilization can be ignored)

Regarding (ii), overall utilization, u_{it}, for a given production-function estimation, is observable. The drawback (see equation (34)) is that the wage cost curvature parameter a and the utilization co-variation, $\rho_{\widetilde{\kappa},h}$, are not mutually identifiable; identification of one requires prior

[13] Proof that the second squared bracket in (31) can be approximated by $\varphi^h \log h_{it}$ is available on request.

information on the other. A common assumption (see King and Rebelo (1999) for a discussion) would appear to be $\rho_{\widetilde{\kappa},h} \geq 1$.[14]

By contrast, since φ^h is estimable directly (with a solved from $\widehat{\varphi^h} - \widehat{\sigma} + 1$) and no identification issue arises. Although this is only because one has already been made: capital is always fully utilized.

4.4 Frictionless Aggregate Price and Full-Capacity Output

Equations (31) and (32) define the optimal frictionless firm-level price setting. However, since we use macro data, we need the aggregate rule. If no idiosyncratic shocks exist, then the utilization rates $h_{it} = h_t$ and $u_{it} = u_t$, the wage rate per worker $W\left(\overline{W}_t, h_{it}\right) = W_t$ and the production shares $s_{it} = Y_{it}/Y_t = Y_{it}^*/Y_t^* = s_{it}^*$. Thus the optimal price P_{it} is common across firms. It is, however, realistic to allow firm-specific, idiosyncratic shocks and, hence, differentiated firm-specific utilization rates. However, we can use the output-share aggregator that results in a good approximation for the aggregate frictionless price level:

$$\log P_t^f = \sum \frac{s_{it}}{\sum s_{it}} \log P_{it} = \log(1+\mu) + \overbrace{\underbrace{\sum \frac{s_{it}}{\sum s_{it}} \log\left(\frac{W\left(\overline{W}_t, h_{it}\right)}{F_{N|h=1}}\right)}_{\log\left(\frac{W_t}{F_{N|h=1}}\right)} + \varphi^u \cdot \underbrace{\sum \frac{s_{it}}{\sum s_{it}} \log\left(\frac{Y_{it}}{Y_{it}^*}\right)}_{\log\left(\frac{Y_t}{Y_t^*}\right)}}^{mc_t^n} \tag{35}$$

We see that the aggregate level equation (35) retains the same functional form as the firm-level rule (32). However before being able to implement (35) we need to know the parameters of the aggregate full-capacity production function (19). For that purpose in the following section we derive the aggregated equilibrium supply system that, as shown by León-Ledesma et al. (2010a), offers an efficient way to estimate the parameters of the factor-augmenting CES production function.

In our empirical application, the CES production function corresponding to full-capacity output, takes the following normalized form, where X_0 etc denotes the value of X_t at a chosen point of sample normalization, $t = t_0$:

$$Y_{it}^* = Y_{i0}\left[\alpha_0\left(\frac{\Gamma_t^K K_{it}}{\Gamma_0^K K_{i0}}\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha_0)\left(\frac{\Gamma_t^N N_{it}}{\Gamma_0^N N_{i0}}\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{36}$$

A useful property of the normalized CES is that unlike in the un-normalized form, e.g. (1), the distribution parameter α_0 has a clear interpretation in the data. It corresponds to the capital income share of total factor income at the point of normalization.

[14] This would imply that capital utilization is less costly to vary, reflecting perhaps a flatter local cost profile.

4.5 A Stationary Equilibrium System

Subtracting the log of aggregate price level P_t from the both sides of (35) yields,

$$\log P_t - \log(1+\mu) - \log\left(\frac{W_t}{F_{N|h_t=1}}\right) = \underbrace{\underbrace{-\log\left(\frac{P_t^f}{P_t}\right)}_{\log[(1+\mu)MC_t^r]} + \varphi^u \log\left(\frac{Y_t}{Y_t^*}\right)}_{\textbf{stationary}} \tag{37}$$

The FOCs (14) and (15), with the discussed production function properties, imply relations,

$$\begin{aligned} F_{K|\widetilde{\kappa}=1} - (1+\mu)\,q_t^e &= \underbrace{F_{K|\widetilde{\kappa}=1}\left(1-\frac{P_{it}}{P_t}\widetilde{\kappa}_{it}^{\frac{\sigma-1}{\sigma}}\right) + (1+\mu)\left(q_{it}-q_t^e\right)}_{\textbf{stationary}} \\ &+ (1+\mu)\underbrace{\left\{\begin{array}{c} \frac{\partial\Omega_K(K_{it},..)}{\partial K_{it}} + \frac{1}{1+r_t}\mathbb{E}_t\frac{\partial\Omega_K(K_{it+1},..)}{\partial K_{it}} \\ + \left(\frac{1}{1+r_t}\right)\mathbb{E}_t\left[\left(\frac{1}{1+r_{t+1}}\right)\frac{\Omega_K(K_{it+2},..)}{\partial K_{it}}\right] \end{array}\right\}}_{\textbf{stationary}} \end{aligned} \tag{38}$$

$$\log Y_t - \log F\left(\Gamma_t^K K_t, \Gamma_t^N N_t\right) = \underbrace{\log\left(\frac{Y_t}{Y_t^*}\right) = u_t - 1}_{\textbf{stationary}} \tag{39}$$

where $F_{K|\widetilde{\kappa}=1} = \alpha_0\left(\frac{Y_0}{K_0}\Gamma_t^K\right)^{\frac{\sigma-1}{\sigma}}\left(\frac{Y_t}{K_t}\right)^{\frac{1}{\sigma}}$ and $F_{N|h=1} = (1-\alpha_0)\left(\frac{Y_0}{N_0}\Gamma_t^N\right)^{\frac{\sigma-1}{\sigma}}\left(\frac{Y_t}{N_t}\right)^{\frac{1}{\sigma}}$.

After the exact functional forms of augmenting technical progress Γ_t^i are defined (see Section 7.1) the left hand sides of (37)-(39) are expressed in terms of observable aggregate level I(1) variables. The right hand sides are not directly observables but have exact economic interpretations and are, by definition, stationary. Hence, using the terminology of the cointegration literature we have the three equation system of long-run equilibrium relationships: i.e., a relationship between observable variables which has, on average, been maintained for a long period.

The estimation of this equilibrium system, i.e. by treating the stationary right hand sides as estimation residuals, allows us to extract consistent – indeed super consistent, Stock (1987) – estimates of the parameters of interest (in our case, technical change dynamics, the substitution elasticity).

4.5.1 Residual Interpretation

It turns out that the residuals in the system above have an important – and, in the literature, overlooked – property. The residual from (39) gives the capacity utilization rate. The residual of (37) is the difference of the markup over full real marginal cost plus $\widehat{\varphi^u}$ times the capacity utilization rate (i.e. the residual of (39)).

Hence, looking back at (32), real marginal costs – except for the exact parameter value φ^u multiplying the capacity utilization rate – are fully determined by these two residuals, and can be consistently substituted into the dynamic NKPC specification presented below. In the NKPC all variables are $I(0)$ series. Hence, in terms of the cointegration literature the estimation the NKPC equation represents the second step of the Engle-Granger two-step approach to estimate a dynamic equation of co-integrated variables (Granger (1983), Engle and Granger (1987)) In turn, estimation of the NKPC allows us to estimate φ^u (alternatively, φ^h), as well as β, θ and ω.

Further, it is interesting to see that, if utilization margins matter for the correct measurement of real marginal costs (i.e., implying $\varphi^h, \varphi^u \neq 0$ ($\varphi^h, \varphi^u > 0$ if $\sigma < 1$)) then the estimation residuals of (37) and (39) must be correlated (positively if $\sigma < 1$). In the special case of frictionless price setting – i.e. $P_t = P_t^f$ and $MC_t^r = (1+\mu)^{-1}$ – this correlation would be perfect. Friction in price setting, via a time-varying markup (i.e., P_t^f/P_t being non constant over time), decreases the correlation between these two residuals.

5 The NKPC

As in Galí and Gertler (1999) and subsequent literature, we assume a Calvo-type price setting framework under imperfect competition, where a fraction θ of firms do not change their prices in any given period.[15] The remaining firms set prices optimally as a mark-up on discounted expected marginal costs. When resetting, firms also take into account that the price may be fixed for many future periods. The NKPC can then be expressed as,

$$\pi_t = \beta \mathbb{E}_t \pi_{t+1} + \lambda \left(mc_t^r + \mu \right) \tag{40}$$

where π_t represents current inflation and $mc_t^r = mc_t^n - p_t$ with mc_t^n as defined by (35). β is a discount factor, θ measures price stickiness (average fixed-price length being $D = \frac{1}{1-\theta}$), $\lambda = \frac{(1-\theta)(1-\theta\beta)}{\theta}$ represents the slope of the Phillips curve. Iterating (40) forward, we see that if mc_t^r is itself a persistent series then the higher is λ the more inflation "inherits" its persistence: $\pi_t = \lambda \sum_{k=0}^{\infty} \beta^k \mathbb{E}_t \left(mc_{t+k}^r + \mu \right)$.

Additionally, it is often assumed that of the $1-\theta$ price-re-setting firms a fraction, $1-\omega$, reset prices optimally with the remaining fraction choosing to set their price according to lagged inflation. This implies a NKPC with an intrinsic expectations component,

$$\pi_t = \underbrace{\frac{\theta\beta}{\phi}}_{\gamma_f} \mathbb{E}_t \pi_{t+1} + \underbrace{\frac{\omega}{\phi}}_{\gamma_b} \pi_{t-1} + \lambda \left(mc_t^r + \mu \right) \tag{41}$$

where $\lambda \mid_{\omega > 0} = \frac{(1-\omega)(1-\theta)(1-\theta\beta)}{\phi}$ and $\phi = \theta + \omega \left[1 - \theta \left(1 - \beta \right) \right]$. The composite parameters γ_f, γ_b and λ capture, respectively, what is termed extrinsic, intrinsic and inherited inflation persistence.

[15] In recent times there have considerable extensions to the NKPC framework: e.g., open-economy variants; time-variation in parameters and inflation trends; sticky-information; non-constant demand elasticities; firm-specificities etc (Batini et al. (2005)and Tsoukis et al. (2011) provide excellent discussions). However, since our contribution is a new measure of the driving variable rather than the underlying dynamic theory, and for benchmarking purposes with the core of the literature, we use the above for our estimations. Using our full driving variable in these newer forms would be a valuable offshoot of our work.

6 Data

We use quarterly series for the US from 1954:1 to 2008:2. Our principal source was the NIPA Tables (National Income and Product Accounts) for production and income. The output series is calculated as Private non-residential Sector Output: i.e., total output minus Indirect Tax Revenues and minus Public-Sector and Housing-Sector Output. After these adjustments, the output concept used is compatible with that of our private, non-residential capital stock series. The output deflator is obtained as a ratio of nominal to constant price output.

Employment is defined as a sum of self-employed persons and the private sector full-time equivalent employees. As this NIPA employment series is annual, total private non-farm employees of the Bureau of Labor Statistics (Table B-1) was used as a quarterly indictor in constructing the quarterly employment series. Labor income is defined as the product of compensation to employees and labor income of self-employed workers. In evaluating the latter, compensation-per-employee is used as a shadow price of labor of self-employed workers as in Blanchard (1997) and Gollin (2002).

Real capital income was calculated as a residual of the value of production excluding the aggregate mark-up and labor income:

$$qK = \frac{Y}{1+\mu} - wN \tag{42}$$

where we assume that mark-up $\mu = 0.10$ in line with several other studies, although results were not sensitive to reasonable variations around that value.

To create quarterly private non-residential capital stock compatible with both the annual index of constant replacement cost capital stock, Herman (2000), and the accumulated NIPA net investment, we first estimated the base value for the capital stock as a ratio:

$$KB = \frac{\sum_{t=0}^{T} \text{Net Investment}}{KI_T \; - \; KI_0} \tag{43}$$

where KI_T and KI_0 refer to the values of the capital stock index at the end and beginning of the sample respectively. The quarterly constant price non-residential private capital stock was then calculated by accumulating (de-cumulating) the base level KB from the midpoint of the sample by using the quarterly NIPA series of non-residential private net investment. This procedure ensures that the constructed quarterly capital stock has the same trend as the annual capital stock index.

7 Empirical Specifications

7.1 Technical Progress: Empirical Specification

In most empirical studies, linear (constant growth) technical progress is assumed. Recent contributions as in Acemoglu (2002) have highlighted the role of induced (or directed) innovations in shaping income distribution and TFP dynamics. In short, though stable factor incomes can only ultimately be achieved if technical progress is asymptotically labor-augmenting, we might also expect *transitional* periods of capital-augmenting technical progress.

Thus, it is not unreasonable to expect *non-constant* growth rates of technical progress. Accordingly, Klump et al. (2007) proposed a specification for Γ_t^j based on the flexible Box-Cox transformation. With normalization this implies $\Gamma_t^j = e^{g_j}$ where $g_j = \frac{\gamma_j t_0}{\lambda_j}\left(\left[\frac{t}{t_0}\right]^{\lambda_j} - 1\right)$, $j = K, N$, with shape parameter λ_j.[16] $\lambda_j = 1$ yields the (textbook) linear specification; $\lambda_j = 0$ a log-linear specification; and $\lambda_j < 0$ a hyperbolic one for technical progress. This family of functions provide a useful, though certainly reduced form, way to capture smoothly-evolving technical progress.

Moreover, given the evidence (e.g., Hansen (2001), Oliner and Sichel (2000)) of a structural break in US labor productivity (and TFP growth) in the 1990s, we allow a break in factor-augmenting technical progress in the early 1990s.[17]

7.2 Production System: Empirical Specification

For completeness, we re-state the system (37-39) in full normalized form,

$$\log\left(\frac{w_t N_t}{Y_t}\right) = \log\left(\frac{1-\alpha_0}{1+\mu}\right) + \frac{1-\sigma}{\sigma}\log\left(\frac{Y_t/Y_0}{N_t/N_0}\right) + \frac{\sigma-1}{\sigma}\left[g_N + \tau\cdot g_{N_1}\right] \tag{44}$$

$$\log\underbrace{\left(\frac{1}{1+\mu} - \frac{w_t N_t}{Y_t}\right)}_{q_t K_t} = \log\left(\frac{\alpha_0}{1+\mu}\right) + \frac{1-\sigma}{\sigma}\log\left(\frac{Y_t/Y_0}{K_t/K_0}\right) + \frac{\sigma-1}{\sigma}\left[g_K + \tau\cdot g_{K_1}\right] \tag{45}$$

$$\log\left(\frac{Y_t}{N_0}\right) = \frac{\sigma}{\sigma-1}\log\left[\begin{array}{r} \alpha_0\left(\frac{K_t}{K_0}e^{\left(g_K+\tau\cdot g_{K_1}\right)}\right)^{\frac{\sigma-1}{\sigma}} \\ +(1-\alpha_0)\left(\frac{N_t}{N_0}e^{\left(g_N+\tau\cdot g_{N_1}\right)}\right)^{\frac{\sigma-1}{\sigma}} \end{array}\right] \tag{46}$$

where $\tau = \begin{cases} 0 & \text{if} \quad t \leq 1992:1 \\ 1 & \quad\text{otherwise} \end{cases}$ and where the normalization point is defined in terms of sample averages (geometric averages for growing variables, except for time, t, and arithmetic ones otherwise). In estimation, we fix the aggregate mark-up parameter μ to 0.1 and α_0 (the capital income share in total factor income) to 0.2.[18] The possibility to predetermine the distribution parameter α_0 is one of the empirical advantages of normalization.

[16] Note we scaled (divided) the original γ_j and time t by the fixed point value t_0. This rescaling allows us to interpret γ_N and γ_K directly as the rates of labor- and capital-augmenting technical change at the fixpoint period t_0. And it is this which is reported in the relevant rows of Table 1.

[17] We dated the break point by optimizing the system log determinant across quarterly break increments from the start until the end of the sample; our detected break point accords very well with those suggested in the literature.

[18] Note, this is the capital income share in terms of factor income; the corresponding GDP-share of capital income is 0.27.

8 Estimation of Production-Technology System

8.1 Estimator Background

We use a Generalized Nonlinear Least Squares (GNLLS) estimator which is equivalent to a non-linear SUR model, allowing for cross-equation error correlation. As shown in the Monte Carlo study of León-Ledesma et al. (2010b), this estimator is able (in contrast to single-equation estimators) to identify unbiasedly both the substitution elasticity and factor augmenting technical progress parameters. Since non-linear estimation can be sensitive to initial parameter conditions we further varied parameters individually and jointly around plausible supports to ensure global results (details available). Standard errors reported are heteroscedasticity and autocorrelation consistent.

8.2 Production-Technology System: Results

Table 1 shows results for system estimation (44-46) for both CES and CD. It reports the substitution elasticity, σ; technical change parameters, γ_N, γ_K; the (fixed point) TFP growth; residual stationarity (ADF-t-test); and the system metric (the Log Determinant). In terms of the system metric, the CES system fits the data better than CD. High negative ADF-statistics are compatible with the stationarity of the residuals as required by cointegration. The correlation of the residuals of equations (44 and 46) are high but well below unity. Recalling section 4.5.1, this high correlation suggests that utilization measures *are* an important determinant of the marginal costs, while the deviation from a unitary correlation corroborates non-trivial price-setting frictions.

– TABLE 1 Here –

A structural break was tested for in both production specifications. The estimated substitution elasticity (at 0.55) is consistent with consensus aggregate values (e.g., Chirinko (2008)). Both production specifications detect a rise in technical progress over time. In the CES case, this break can affect the value of both labor and capital-augmenting technical progress; under CD, we treat technical progress as Harrod Neutral.

Although our specification implies time-varying technical change (graphed below), table 1 shows values at the point of normalization. The 1950s were periods of exceptionally high TFP growth which, coupled with hyperbolic curvature parameters, λ_K and λ_N, implies subsequently strong deceleration well in line with observed US labor productivity and growth patterns. In the early 1990s, we see a renewed acceleration of TFP growth, led (in the CES case) by strong labor-augmenting technical change but declining (in growth terms) capital-augmenting technical change. Next, we graph and interpret these.

9 Real Marginal Costs: Levels and Volatility Characteristics

9.1 Marginal Cost Levels: A Graphical Analysis

Figure 3 shows the Box-Cox technical progress growth rates (and components) for our preferred case. TFP and labor productivity of course feed directly into measures of real marginal costs. The figure demonstrates the deceleration of technical progress in the early 1970s (from the 1950s) and its rapid acceleration in the early 1990s (Fernald (2007) identified similar patterns[19]).

Although the composition of this increase is an empirical finding, it can be rationalized quite intuitively: capital augmentation, though initially dominant, falls continuously through the sample, consistent with the "Acemoglu hypothesis", Acemoglu (2002).[20] Labor augmenting technical change starts to rise and dominate overall TFP growth. This pattern was stable until the early 1990s, when was a widely-observed structural break in TFP growth (led, it is often argued, by Information and Communication Technology improvements and adaptions).

– Figure 3 Here –

This acceleration took the labor-augmenting form with a corresponding TFP acceleration (e.g., Fernald and Ramnath (2004), Oliner and Sichel (2000)) reflecting that – in the medium run – labor availability remained a constraining factor for growth, indicated by low, stable unemployment and stable factor income shares suggesting the profitability of capital saving did not increase over time.

9.2 Marginal Cost Volatilities: A Graphical Analysis

Having examined the *level* of technological improvements, we can now examine volatility. In both CD and CES cases (Figure 4)[21], the components of real marginal costs, which exclude the impacts of labor utilization rate, (as in equation (4)) are stationary with similar business-cycle properties (i.e., both are counter-cyclical). A striking difference is that the CES variant is substantially more volatile. Another – even more striking – difference is that the CES driving variable undergoes a substantial and sustained volatility reduction from the mid-1980s onwards, consistent with observed volatility patterns, e.g., McConnell and Perez-Quiros (2000). But the CD-based measure exhibits no such volatility change.

– Figure 4 Here –

[19]Note, Fernald (2007) also detected a break in the mid-1970s. In our case, this does not require an explicit break in the technical progress functions given the empirically determined curvatures of those functions which display a rapid change in productivity then.

[20]In other words, we witness the co-existence of labor and capital-augmenting technical change but with a tendency for the latter to decline asymptotically. This can be shown to have implications for the income shares of capital and labor depending on the composition of these technical changes and whether production is characterized by gross complements or gross substitutes.

[21]Note the common axis ranges for comparability.

Why? Recalling definitions (4), (31) and (32), taking logs and re-arranging, the difference in second moments between our CES ($\widehat{\sigma} = 0.55$) and CD measures would respectively be (omitting time subscripts):

$$Var\left(mc^r\right) = \begin{cases} Var\left(w - g_N\right) + \underbrace{\left(1/\sigma^2\right)}_{3.31} Var\left(y - n - g_N\right) - \underbrace{\left(2/\sigma\right)}_{3.64} CoVar\left(w - g_N,\ y - n - g_N\right) \\ \\ Var\left(w - g_N\right) + \qquad Var\left(y - n - g_N\right) \quad - 2CoVar\left(w - g_N,\ y - n - g_N\right) \end{cases} \tag{47}$$

where $Var\left(w - g_N\right)$, $Var\left(y - n - g_N\right)$ are the variance of the log deviation of the real wage rate and average labor productivity respectively from labor-augmenting technical change.

We can appreciate better the differences across specifications – *and* across break samples[22] – by looking at **Table 2**: whilst the CD real marginal cost (excluding utilization) measures barely changes, the CES-based variant falls substantially over sub-samples (0.0013→0.0003). Although both specifications have relative variance reductions in $w - g_N$, and $y - n - g_N$, that are quite similar across sub-samples, the substantially higher relative weight given to the latter in the CES measure (i.e., 3.31) ensures that precisely that component which decreased the most attracts the higher weight.[23]

– Table 2 Here –

Finally, **Figure 5** shows that the estimation of the effective hours (or indeed total utilization, not shown) measures across CD and CES production forms differs relatively little. Both witness a large reduction in volatility from the mid-1980s onwards. [24]

– Figure 5 Here –

Thus, the CES-based real marginal cost measure replicates relatively better the observed volatility reduction otherwise witnessed in many US time series. This is an important observation since, by contrast, some discussion suggested that reduction in US inflation volatility in recent years had not been matched by that in candidate driving variables, e.g. Fuhrer (2006, 2011).

10 Phillips Curve Estimations

Tables 3 to 6 present estimations for the NKPC and NKPC with intrinsic persistence for the case where the driving variable is derived from the CES production system (i.e., last column in

[22] We broke the sample consistent with our detected break in technical change; it could equally be done in the early 1980s where the volatility break is usually dated.

[23] Of course, this need not exclude other explanations for the reductions in inflation volatility such as improved monetary policy. Although this aspect – at least to a first approximation – might be expected more relevant to inflation dynamics than the characteristics of the driving variable.

[24] The time-series homogeneity of output gap calculations across different choices of potential function types is also a conclusion of Fisher et al. (1977) and León-Ledesma et al. (2010b).

Table 1), where the driving variable is conventional then our preferred measures.[25] Results are shown for constrained ($\beta = 0.99$) and unconstrained discounting. For robustness, among generalized empirical likelihood (GEL) methods, we estimate using both 2-step GMM and the CUE (continuously updated estimator) forms. CUE estimation has superior large and finite-sample properties and is more efficient (Anatolyev (2005)). Two-step GMM methods, by contrast, can display poor small-sample properties, e.g., Hansen et al. (1996) and are not invariant to the specification of the moment conditions.[26] The instrument set for the regressions are given below the respective tables.

10.1 NKPC Estimations

Here (**Tables 3 and 4**), when conventional real marginal costs are used as the driving variable (the first two column sets), relatively high durations are uncovered (≈ 9 quarters) and accordingly small slope coefficients (0.02). Durations almost halve (≈ 4 periods) when the augmented driving variable is incorporated and slope coefficients essentially triple. This pattern is robust across both estimator types.

– Tables 3 and 4 Here –

If we assume $\rho_{\widetilde{\kappa},h}$ is in the range [0.5, 1, 1.5], and given an average value, $\overline{\varphi^u} \approx 0.95$, in Table 3, this would imply (using (34)) an a value between 0.04-0.22. These are, although positive, admittedly on the low side.

By contrast, under the assumption that capital is always fully utilized (i.e., h_t rather than u_t used as the utilization measure), **Table 4** would suggest a marginally negative (statistically zero) estimate for a.

Further, in the two tables, we see $\overline{\varphi^u}, \overline{\varphi^h < 1}$ which would suggest that full real marginal costs are counter-cyclical.

10.2 NKPC with Intrinsic Persistence

When the conventional driving variable is used (see **tables 5 and 6**), we find an apparently high share of forward-looking price setting, $\gamma_f \approx 0.8$, but relatively modest slope estimates and long fixed price duration estimates. This is a common finding in the literature.[27] When we introduce full marginal costs, a more balanced weighting of backward and forward-looking price setting emerges (around 0.5 each), and duration estimates become more aligned with micro price-setting studies (around 2-3 quarters).

– Tables 5 and 6 Here –

[25] We show the NKPC results only for the CES-generated driving variable because it is the more data-coherent of the two and for reasons of space. Results based on a CD-generated driving variable are available on request.

[26] See Gabriel and Martins (2009) for a valuable discussion of the different GEL estimators.

[27] Galí and Gertler (1999), table 2; Tsoukis et al. (2011).

For $\overline{\varphi^u} \approx 1.5$, as Table 5 suggests, this would imply premium curvature parameters of $a \in [0.54, 0.68, 0.82]$ corresponding to the range $\rho_{\widetilde{\kappa},h} \in [0.5, 1, 1.5]$ which accords more closely with our priors (Trejo (1991), Hart (2004)) regarding broad overtime rates. Table 6, though derived under the extreme assumption of fully utilized capital, implies a quite plausible a estimate (0.3).

11 *Full* Real Marginal Costs: A Graphical Analysis

For our estimated CES case, **Figure 6** plots the conventional measure of CES-based real marginal costs (reproduced from Figure 4) alongside our preferred measure (derived from Table 5 assuming $\overline{\varphi^u} \approx 1.5$). Our preferred measure turns from counter- (when measured conventionally) to pro-cyclical reflecting the dominance of (pro-cyclical) utilization rates. We also observe that the cyclicality properties weaken in the last third of sample, reflecting large variance reductions from especially the conventional component of real marginal costs. For example, observe the many cases (e.g., the recessionary cycles of 1957:3 1958:2, 1973:4 1975:1 and 1981:3 1982:4) where our preferred measure lags the cycle. This highlights the risk of taking a stand on the cyclicality of real marginal costs since they depend on the cyclicality of the two components and their relative sizes and weights.

– Figure 6 Here –

11.1 Time-Varying Cyclicality?

Finally, **Figures 7** shows recursive OLS estimation of each measure of real marginal costs on a constant and the CBO output-gap measure.[28] The full measure is pro-cyclical, but in absolute terms less strongly cyclical than its components. All measures are becoming *less* cyclical overtime.

– Figure 7 Here –

12 Conclusions

How production costs pass through to prices matters for understanding inflation and goes to the heart of policy. Despite this, the literature has tended to focus more on dynamics and expectational issues. Following the lead taken by Rotemberg and Woodford (1999), we constructed richer measures of real marginal costs and reappraised the sensitivity of inflation specifications.

Our analysis suggests the following:

- Conventional real marginal cost measures are incomplete:

[28] The CBO measure is derived from a CD production. But its time-series properties accord well with the NBER reference dates. That CD and CES production function give display similar turning points was discussed in León-Ledesma et al. (2010b) and is substantiated by our earlier Figure 5.

(1) The use of Cobb Douglas (and hence of labor share as the driving variable) is unsuitable given its empirical rejection. Its use also suppresses aspects key to understanding cost margins: non-neutral technical change and non-unitary factor substitutability.

(2) By contrast, CES-based real marginal costs empirically dominates Cobb Douglas, and is able to match the recent volatility reductions witnessed in many US time series.

(3) However, conventional measures of real marginal costs do not account for variations in factor utilization rates.

- To disentangle technical progress from factor utilization, we modeled the latter as a factor-augmenting, smoothly-evolving process. This reveals that technical progress from the mid-1990s onwards took the labor (rather than capital) augmenting form, reflecting an essentially fully-employed economy (and consistent with the insights of the "directed technical change" literature).

- We introduced a parametric form of "effective labor hours" to capture overtime costs increases as well as firms' reduced ability to cut labor costs if utilized labor falls below the norm (reflecting labor hoarding). Allowance was also made for co-variation with capital utilization.

- We extract a real marginal cost measure comprising counter-cyclical real marginal costs excluding utilization, plus pro-cyclical utilization costs. Its net cyclicality is an empirical matter, dependent on the prevalence of demand and supply influences and the data weighting. Moreover, since utilization costs mimic an output gap (the weighting average of factor utilization rates), our "full" measure contributes to the emerging belief that Phillips curve approaches that merge new and old elements are helpful in accounting for inflation (Blanchard and Galí (2007, 2010)).

- In general, mis-specification of the driving variable *is* costly; failure to account for non-unitary factor substitution, non-neutral technical change, and factor utilization rates in driving variable biases upward the contribution of extrinsic inflation persistence. It exaggerates fixed-price contract lengths. Our results thus lend weight to a more balanced perspective on historical, inflation dynamics – see also, for example, Mankiw and Reis (2002), Fuhrer (2011). They can also be better reconciled well with micro measures of price stickiness.

- Real marginal costs have become less cyclical since the early 1980s.

All Phillips curves (new and old) are driven by some measure of real activity. Richer and more plausible specifications for that driving variable contribute to better estimation across the board. The benchmarking of our results with others in the more recent literature – see Gabriel and Martins (2011) for a promising approach in that respect – appears therefore an attractive way to proceed. Incorporation of our driving variable into inflation equations embedded into general equilibrium policy models is another interesting research extension.

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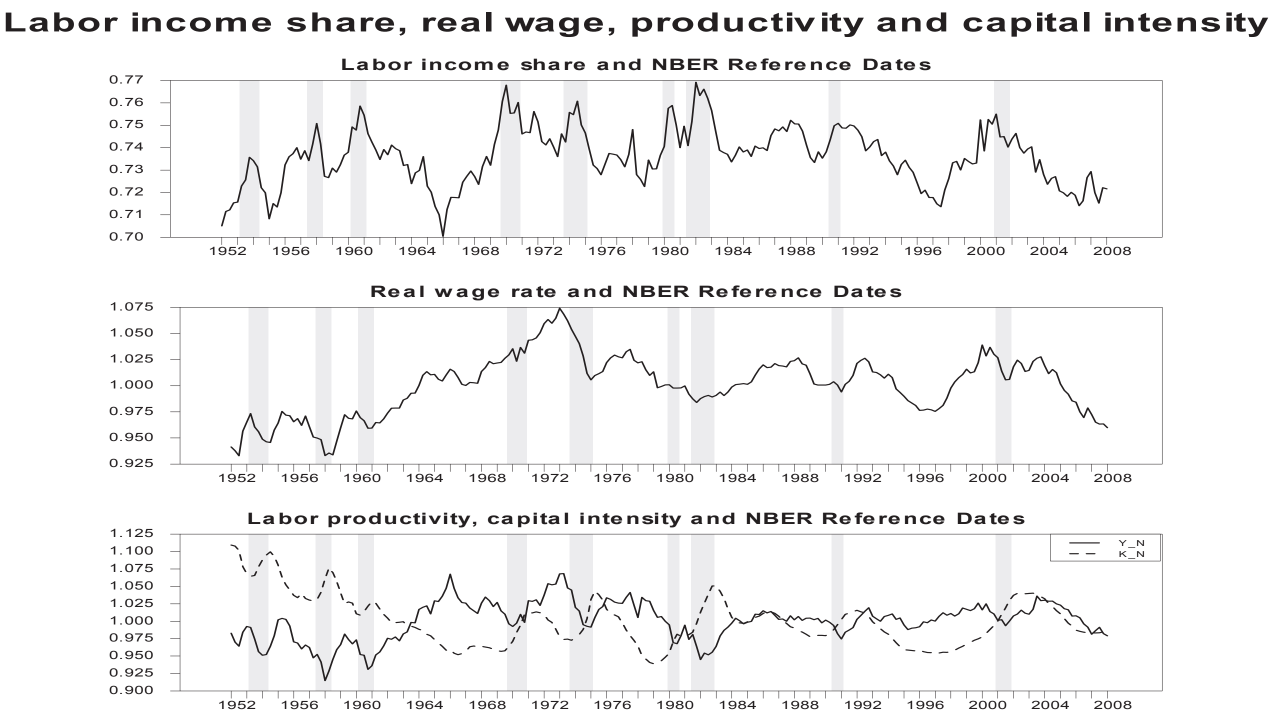
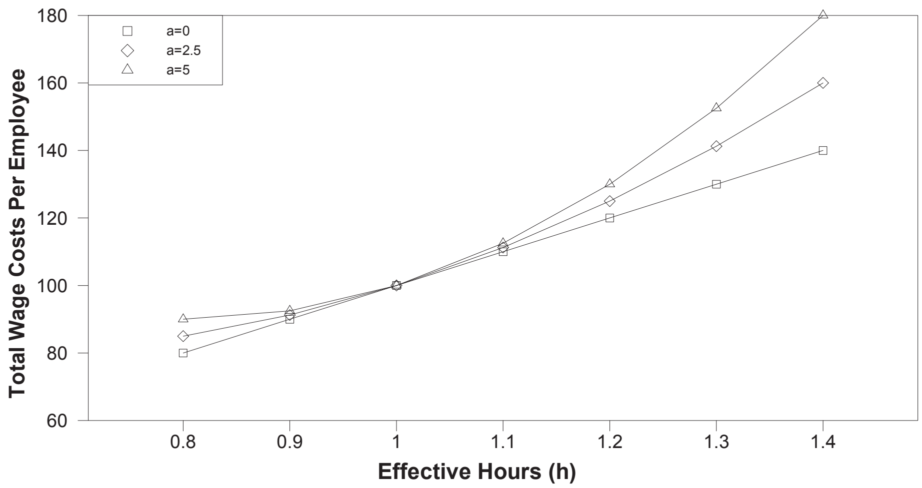
Figure 1: The Cyclicality of Factor Components



Note: Shaded areas represent recessions as identified by the NBER.

Figure 2: Utilization Rates under Effective Hours

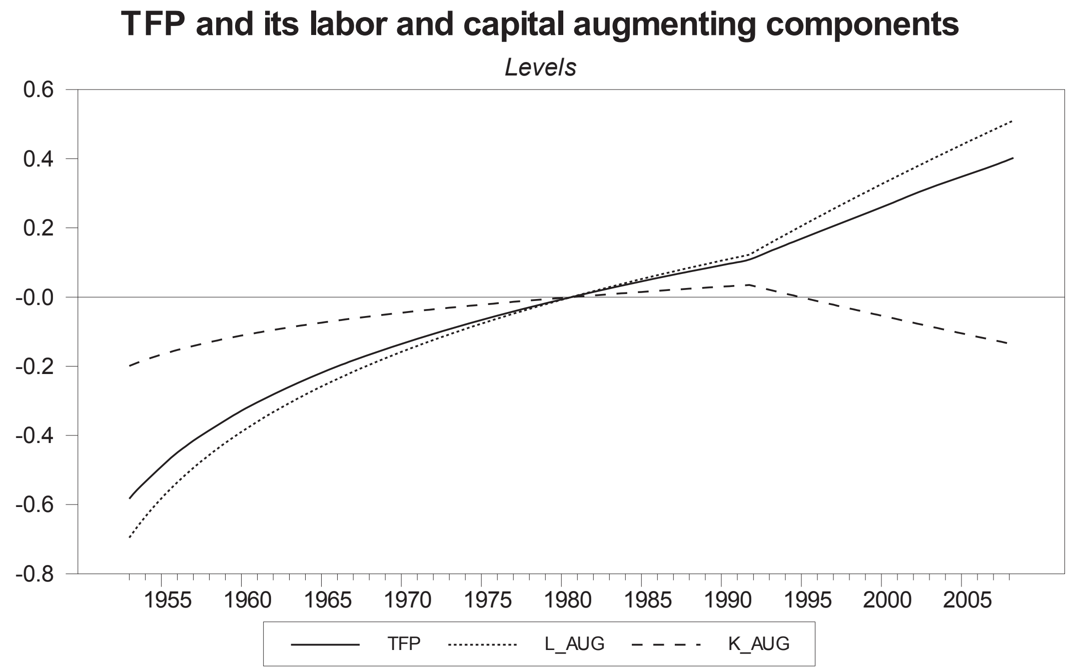


Note: This figure plots total wage cost relating to the function,

$$W_t = \overline{W}_t\left[h_t + \frac{a}{2}\left(h_t - 1\right)^2\right]$$

starting from $\overline{W} = 100, h_t = \overline{h} = 1$, for different a values and different h values.

Figure 3: TFP Growth

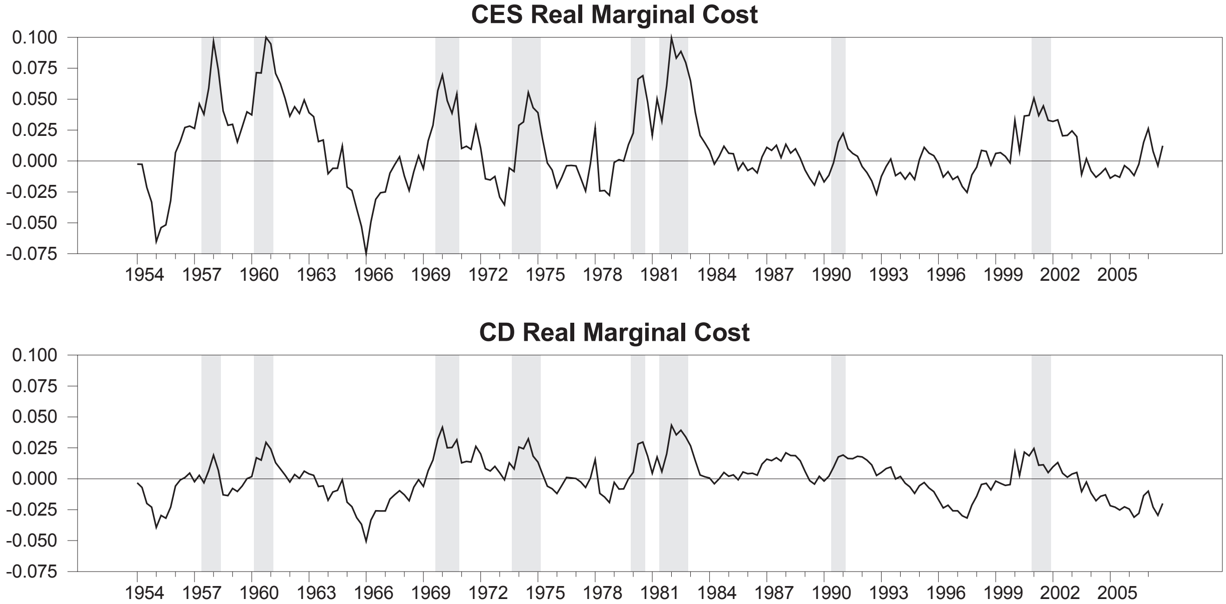


Note: This figure plots the estimated dynamics from the estimated Box-Cox functions,

$$g_j = \frac{\gamma_j t_0}{\lambda_j}\left(\left[\frac{t}{t_0}\right]^{\lambda_j} - 1\right), j = K, N$$

At $t = t_0$, $g_j = 0$ as seen above.

Figure 4: Log Real Marginal Costs (excluding utilization): CES and CD



Note: Shaded areas represent recessions as identified by the NBER.

Figure 5: Effective Hours Real Marginal Costs: CES and CD

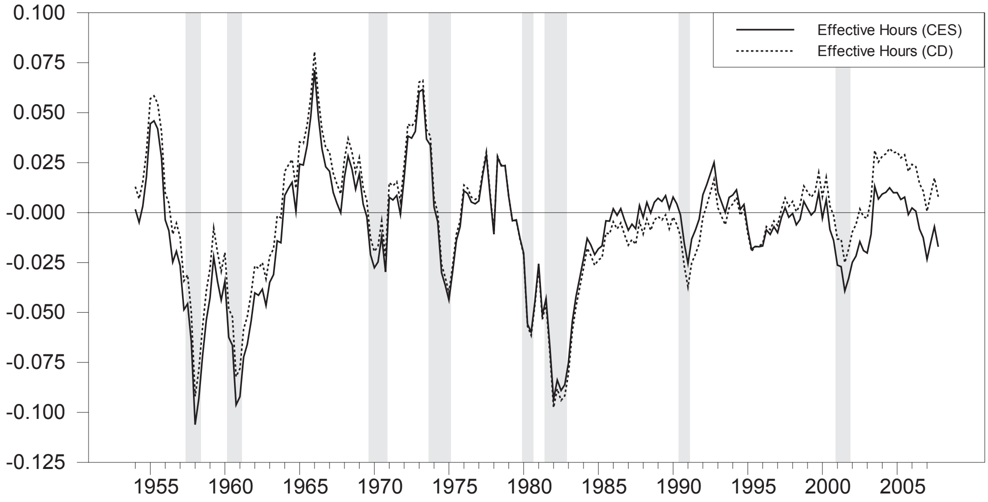
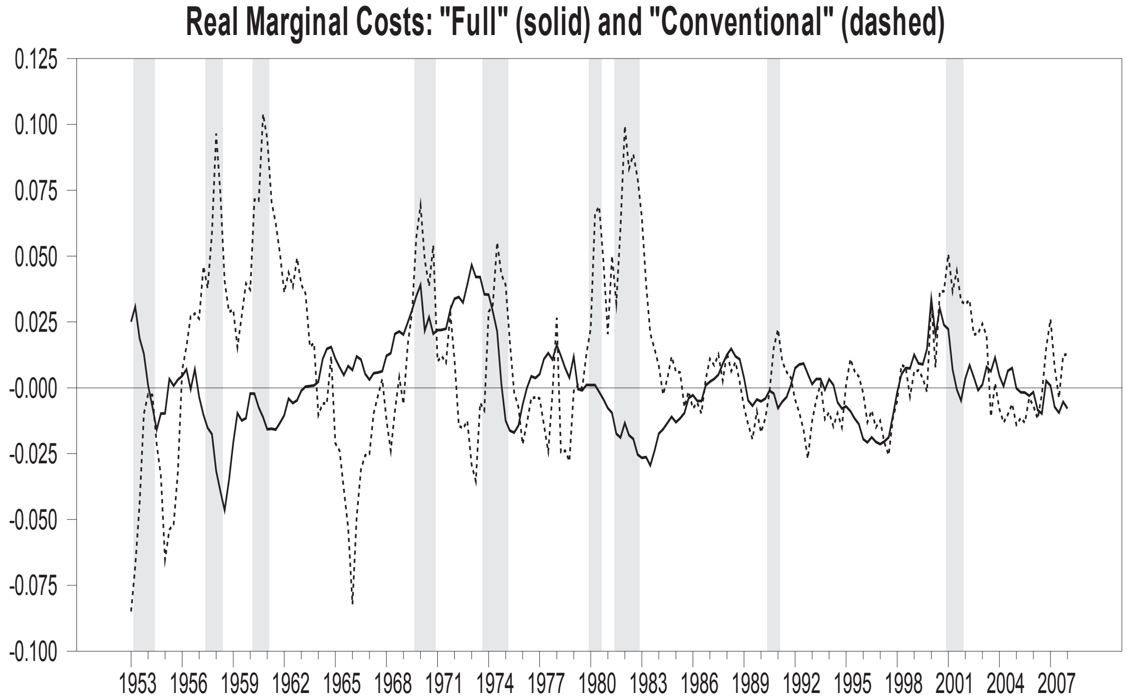


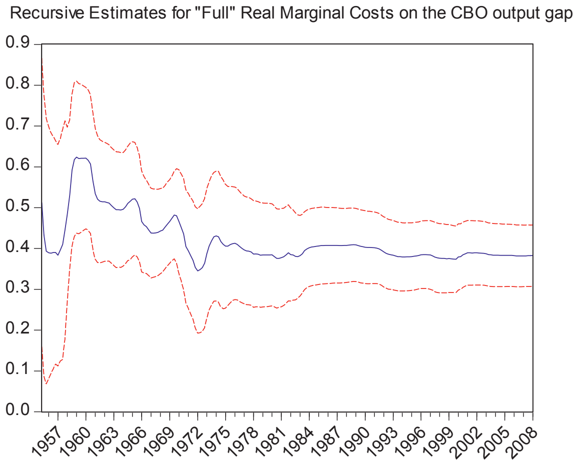
Figure 6: Real Marginal Costs and NBER dates



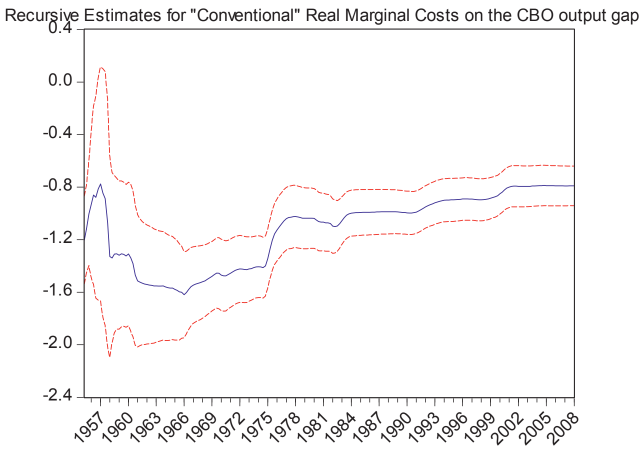
Notes: Shaded areas represent recessions as identified by the NBER. This figure plots the full an conventional measures of real marginal cost taken from equation (32) for the CES production function an assuming $\overline{\varphi}^{u} = 1.5$ (consistent with Table 5) in the derivation of the full measure.

Figure 7: Recursive Estimates

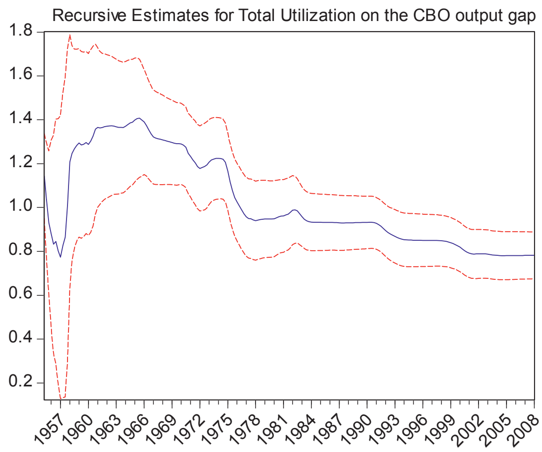
(a)



(b)



(c)



Note: These figures show the parameters of recursive OLS estimates from regressing the "full", conventional and utilization-based components of real marginal on a constant and the CBO output gap measure.

Table 1: Production-Technology System Estimates

	CD	CES
ξ^*	1.035 (0.005)	1.034 (0.002)
γ_N	0.014 (0.001)	0.013 (0.000)
γ_{N1}	0.009 (0.004)	0.016 (0.001)
γ_K	–	0.004 (0.000)
γ_{K1}	–	-0.014 (0.001)
σ	1.000 (–)	0.548 (0.001)
TFP**	0.011	0.012
ADF_N	-3.919	-4.416
ADF_K	-4.000	-4.306
ADF_Y	-4.153	-4.253
Log. Det	-26.335	-26.733

Note: Estimation of Production-Technology System (38) – (40)
***:** The nonlinearity of the CES function implies that the sample average of production need not exactly coincide with the level of production implied by the production function with sample averages of the right hand variables. Following Klump et al. (2007), we introduce an additional parameter, ξ. Hence, we define $Y_0 = \xi\overline{Y}, K_0 = \overline{K}, N_0 = \overline{N}$ and $t_0 = t$, where the bar refers to the appropriate type of sample average.
****:** An exact method to calculate the log(TFP) contribution to output is to calculate the log ratio of the estimated production function with and without technical change,

$$\log(TFP) = \frac{\sigma}{\sigma-1}\log\left[\frac{\alpha_0\left(\frac{K_t}{K_0}e^{g_K}\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha_0)\left(\frac{N_t}{N_0}e^{g_N}\right)^{\frac{\sigma-1}{\sigma}}}{\alpha_0\left(\frac{K_t}{K_0}\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha_0)\left(\frac{N_t}{N_0}\right)^{\frac{\sigma-1}{\sigma}}}\right]$$

. We estimated λ_N and λ_K to be around 0.1. Given the smaller sample after the break, we calibrated λ_{N1} and λ_{K1} to be 0.5.

Table 2: Estimated Real Marginal Costs (Conventional) across CES and CD forms

	CES				
	$Var(mc^r)$		$Var(w-g_N)$	$3.31 \cdot Var(y-n-g_N)$	*est. covar.*
1953:1-1991:4	0.001312	=	0.000760	$\underbrace{3.31 \cdot 0.00928}_{=0.003072}$	-0.002520
1992:1-2008:2	0.000332		0.000715	$\underbrace{3.31 \cdot 0.00034}_{=0.001125}$	-0.001520
	CD				
	$Var(mc^r)$		$Var(w-g_N)$	$Var(y-n-g_N)$	*est. covar.*
1953:1-1991:4	0.000289	=	0.000538	0.001073	-0.001322
1992:1-2008:2	0.000222		0.000343	0.000221	-0.000342

Note: This table decomposes real marginal using the decompositions in equation (47), depending on whether production is CES or CD.

Table 3: NKPC Estimates: Capacity utilization

	GMM				CUE			
θ	0.876 (0.013)	0.875 (0.013)	0.786 (0.047)	0.792 (0.045)	0.887 (0.020)	0.891 (0.021)	0799 (0.053)	0.797 (0.055)
β	0.977 (0.010)	0.990	0.962 (0.020)	0.990	0.966 (0.018)	0.990	0.952 (0.024)	0.990
φ^u	-		0.956 (0.094)	0.920 (0.033)	-		0.935 (0.247)	1.002 (0.249)
λ	0.020 (0.004)	0.019 (0.004)	0.067 (0.033)	0.057 (0.027)	0.018 (0.007)	0.014 (0.006)	0.060 (0.034)	0.054 (0.032)
D	8.08 (0.86)	8.01 (0.80)	4.67 (0.65)	4.81 (0.55)	8.86 (1.55	9.20 (1.81)	4.97 (0.859)	4.94 (0.943)
J	[0.872]	[0.880]	[0.910]	[0.872]	[0.893]	[0.737]	[0.988]	[0.853]

Notes:
Estimation of NKPC, equation (40), using conventional then "full" measure of real marginal costs (based on (32)). Instrument set: 3-period lags of inflation, 4-period lags of the hours deviation from normal, 1-period lags of the conventional real marginal cost, 4-period lags of the growth rates of crude oil price, 2-4-period lags of the interest rate spread (the difference of 5-year and 3-month Treasury bond yields) and 3-4 period lags of hourly compensation growth rates.

Notes for all NKPC estimation tables:
Standard errors, with a Newey-West correction, are in parenthesis. Probability-value for the Hansen's J statistic of the over-identifying restrictions is in squared brackets

Table 4: NKPC Estimates: Effective Hours

	GMM				CUE			
θ	0.876 (0.017)	0.875 (0.016)	0.781 (0.054)	0.774 (0.054)	0.887 (0.020)	0.891 (0.021)	0.797 (0.054)	0.779 (0.053)
β	0.977 (0.015)	0.990	0.971 (0.021)	0.990	0.966 (0.018)	0.990	0.963 (0.022)	0.990
φ^h	-		0.781 (0.164)	0.797 (0.154)	-		0.749 (0.197)	0.833 (0.155)
λ	0.020 (0.006)	0.019 (0.0052)	0.068 (0.024)	0.068 (0.025)	0.020 (0.008)	0.014 (0.006)	0.060 (0.023)	0.065 (0.026)
D	8.085 (1.088)	8.014 (1.052)	4.57 (1.13)	4.42 (1.06)	8.86 (1.55)	9.20 (1.81)	4.92 (1.30)	4.53 (1.09)
J	[0.713]	[0.618]	[0.913]	[0.925]	[0.893]	[0.735]	[0.988]	[0.937]

Notes:
Estimation of NKPC, equation (40), using conventional then "full" measure of real marginal costs (based on (31)). See also notes to previous table.

Table 5: NKPC with Intrinsic Persistence Estimates: Capacity utilization

	GMM				CUE			
θ	0.884 (0.019)	0.882 (0.012)	0.621 (0.086)	0.619 (0.119)	0.890 (0.019)	0.890 (0.020)	0.655 (0.145)	0.612 (0.156)
β	0.979 (0.011)	0.990	0.937 (0.090)	0.990	0.966 (0.018)	0.990	0.931 (0.069)	0.990
ω	0.167 (0.185)	0.207 (0.178)	0.763 (0.035)	0.758 (0.078)	0.079 (0.167)	0.074 (0.177)	0.723 (0.158)	0.767 (0.131)
φ^u	-		1.508 (0.134)	1.493 (0.184)	-		1.400 (0.250)	1.482 (0.245)
γ_f	0.826 (0.008)	0.803 (0.002)	0.430 (0.037)	0.446 (0.047)	0.890 (0.024)	0.914 (0.021)	0.454 (0.094)	0.441 (0.074)
γ_b	0.159 (0.149)	0.191 (0.133)	0.563 (0.038)	0.553 (0.069)	0.082 (0.159)	0.077 (0.170)	0.537 (0.115)	0.558 (0.082)
λ	0.012 (0.005)	0.011 (0.004)	0.028 (0.012)	0.026 (0.013)	0.015 (0.008)	0.013 (0.007)	0.028 (0.012)	0.026 (0.018)
D	8.63 (0.98)	8.50 (0.89)	2.64 (0.71)	2.62 (0.67)	9.08 (1.57)	9.09 (1.65)	2.90 (0.960)	2.57 (0.899)
J	[0.955]	[0.962]	[0.972]	[0.979]	[0.897]	[0.933]	[0.998]	[0.986]

Note: Estimation of Hybrid NKPC, equation (41), using conventional then “full” measure of real marginal costs (based on (32)). Instrument set: 3-period lags of inflation, one-period lags of the hours deviation from normal, 1-2-period lags of the conventional real marginal cost, 4-period lags of the growth rates of crude oil price, 2-4-period lags of the interest rate spread (the difference of 5-year and 3-month Treasury bond yields) and 3-4-period lags of hourly compensation growth rates.

Table 6: NKPC with Intrinsic Persistence Estimates: Effective Hours

	GMM				CUE			
θ	0.884 (0.018)	0.882 (0.018)	0.672 (0.150)	0.675 (0.139)	0.890 (0.019)	0.890 (0.020)	0.689 (0.142)	0.665 (0.130)
β	0.979 (0.016)	0.990	0.991 (0.066)	0.990	0.966 (0.023)	0.990	0.977 (0.051)	0.990
ω	0.163 (0.197)	0.203 (0.194)	0.694 (0.192)	0.692 (0.185)	0.078 (0.167)	0.069 (0.178)	0.671 (0.188)	0.701 (0.155)
φ^h	-	-	1.150 (0.231)	1.147 (0.226)	-	-	1.077 (0.229)	1.111 (0.194)
γ_f	0.829 (0.012)	0.806 (0.003)	0.489 (0.051)	0.491 (0.051)	0.891 (0.025)	0.919 (0.069)	0.499 (0.077)	0.484 (0.057)
γ_b	0.156 (0.160)	0.188 (0.145)	0.509 (0.119)	0.508 (0.116)	0.081 (0.159)	0.072 (0.172)	0.498 (0.117)	0.515 (0.081)
λ	0.013 (0.007)	0.0109 (0.006)	0.025 (0.011)	0.025 (0.011)	0.015 (0.008)	0.013 (0.007)	0.025 (0.011)	0.025 (0.011)
D	8.63 (1.342)	8.499 (1.325)	3.05 (1.40)	3.07 (1.31)	9.08 (1.57)	9.09 (1.67)	3.21 (1.46)	2.98 (1.16)
J	[0.938]	[0.887]	[0.959]	[0.981]	[0.987]	[0.933]	[0.997]	[0.995]

Note: Estimation of Hybrid NKPC, equation (41), using conventional then "full" measure of real marginal costs (based on (31)). See notes to previous table.