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PRICING, PRODUCTION, AND PERSISTENCE

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Abstract

Though built with increasingly precise microfoundations, modern optimizing sticky price models have displayed a chronic inability to generate large and persistent real responses to monetary shocks, as recently stressed by Chari, Kehoe, and McGrattan [2000]. This is an ironic finding, since Taylor [1980] and other researchers were motivated to study sticky price models in part by the objective of generating large and persistent business fluctuations.

We trace this lack of persistence to a standard view of the cyclical behavior of real marginal cost built into current sticky price macro models. Using a fully articulated general equilibrium model, we show how an alternative view of real marginal cost can lead to substantial persistence. This alternative view is based on three features of the "supply side" of the economy that we believe are realistic: an important role for produced inputs, variable capacity utilization, and labor supply variability through changes in employment. Importantly, these "real flexibilities" work together to dramatically reduce the elasticity of marginal cost with respect to output, from levels much larger than unity in CKM to values much smaller than unity in our analysis. These "real flexibilities" consequently reduce the extent of price adjustments by firms in time-dependent pricing economies and the incentives for paying fixed costs of adjustment in state-dependent pricing economies. The structural features also lead the sticky price model to display volatility and comovement of factor inputs and factor prices that are more closely in line with conventional wisdom about business cycles and various empirical studies of the dynamic effects of monetary shocks.

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1. Introduction

Many macroeconomists believe that price stickiness is necessary for generating persistent real economic responses to shifts in monetary policy. The consequences of monetary shocks and alternative monetary policy rules have therefore been the subject of much recent analysis within models that most frequently employ staggered pricing along the lines of Taylor [1980] or Calvo [1983]. Increasingly, these macroeconomic models are being built under the discipline imposed by solid microeconomic foundations, with the hope that they will better match actual economic behavior and be more suitable for use in normative analysis.[1]

However, as these macroeconomic models have developed better microfoundations, a chronic finding has been that there is little persistence in the response of real economic activity to nominal shocks. Recently, this "persistence problem" has been highlighted by Chari, Kehoe, and McGrattan [2000], henceforth CKM. These authors display the persistence problem in a standard calibration of a general equilibrium model with sticky prices and imperfect competition; they also show that the problem continues to arise under many different parameter settings and with many different model modifications that have been suggested in the literature. While they do not disagree that monetary policy shocks may have persistent effects empirically, CKM [2000] instead claim that microfoundations provide restrictions that eliminate the persistence of fluctuations found in the early nominal rigidity models developed by Taylor and others. In particular, they conclude that "in versions of our model without intertemporal links, staggered price-setting leads to persistent output fluctuations after monetary shocks, but once such links are introduced, output fluctuations are no longer persistent." In essence, the message is that the effect of imposing quantitative general equilibrium discipline on New Keynesian economics is to destroy its empirical promise.

By contrast, we demonstrate that a more realistic general equilibrium macroeconomic model will lead to substantial persistence and otherwise enhance the empirical promise of this class of models. Our counter-argument is based on three key aspects of the production structure that are central to real business cycle analysis. These features are relevant across many industries in most modern economies and involve: (1) a substantial role for produced inputs, (2) significant variability in capacity utilization, and (3) variation in labor supply along an extensive margin. Each of these supply-side features allows for a more elastic response of output to demand without increased marginal cost, so we term these "real flexibilities". While the mechanisms we analyze fall into the broader category of what Ball

[1] Goodfriend and King [1997] describe such models, which blend the New Keynesian mechanisms of imperfect competition and sticky prices with the classical real business cycle model, as the New Neoclassical Synthesis.

and Romer [1990] have labeled real rigidities, the focus of their work (and that of Romer [1993]) is on non-Walrasian labor markets and marginal revenue channels, such as smoothed-off kinked demand curves.[2] Since Ball and Romer paid little attention to model features that increase the elasticity of various factors of production, "real rigidities" has become mainly identified with such channels. So, we employ the phrase "real flexibilities" to stress that we are studying production-side mechanisms making output adjustment more flexible.[3]

Incorporating these supply-side features into a fully articulated quantitative general equilibrium model leads to a substantial reduction in the sensitivity of marginal cost to demand-induced variations in aggregate output. That is: smaller variations in marginal cost lead firms to make smaller price adjustments or to adjust less frequently or both, which diminishes the sensitivity of the price level to changes in aggregate demand. In turn, the increased sluggishness of the price level leads to increased persistence of output.

In addition to producing persistent real effects of monetary shocks, our model economy also has other implications that make them more consistent with general features of cyclical activity as well as the estimated effects of monetary policy disturbances. First, with elastic labor supply, there are small changes in real wages over the business cycle in our model as in a variety of empirical studies.[4] Second, dating back to at least Burns and Mitchell [1946], students of business cycles have noted that the movements in output and labor input are approximately proportionate at both the industry and aggregate level. Third, in many industries materials input is a large fraction of gross output, which varies cyclically in a manner that is also roughly proportionate to gross output and value-added. Fourth, when measures of varying capacity utilization are constructed, these measures display substantial cyclical variability, at least as great as that of labor.[5] Fifth, in most industries, the bulk of business cycle variations in total man-hours are accounted for by changes in employment rather than in hours-per-worker.

Without real flexibilities, our model would have great difficulty accounting for the above-mentioned features of the data. For example, without variable capacity utilization and holding productivity fixed, the standard aggregate model implies that output will change

[2] In subsequent work, Dotsey and King [2004], we investigate the persistence generating effects of smoothed off kinked-demand curves as well as firm specific labor.

[3] We thus agree with the sentiments expressed in Woodford [2003] that the term nominal rigidities is unfortunate, especially with respect to the model features that we stress

[4] For example, Christiano, Eichenbaum, and Evans [2005], henceforth referred to as CEE, report that, in response to monetary shocks, the level of of real economic activity varies over twice as much as the real wage.

[5] Further, as indicated by CEE, these measure also display substantial volatility in response to a monetary policy shock.

roughly two-thirds as much as labor input. Without real flexibilities, our model would also suggest implausibly large variations in factor prices, notably in wages, relative to the output response. In studying the effects of real flexibilities, our work is related Kimball's [1995] analysis of mechanisms for reducing the responsiveness of marginal cost to output, and explorations of the role of intermediate inputs by Basu [1995], Bergin and Feenstra [2000], and Huang and Liu [2001]. Like these authors, we find that materials inputs contribute to making marginal cost less responsive to output, thus resulting in price adjustments less aggressive in the face of increases in nominal aggregate demand. Hence, both increased factor supply elasticities and the inclusion of materials inputs each separately increase persistence, but we also find mutually reinforcing effects on persistence.

Although our models generate substantial persistence, they also generate some puzzling predictions. Substantial expected inflation arises because the monetary shocks studied are ones that raise the long-run path of the price-level and because the price level only adjusts gradually. As a result, nominal interest rates rise in response to positive monetary injections, which is a recurrent result for optimizing sticky price models. Some have argued that this interest rate response, by itself, is a fatal deficiency of this class of models since monetary expansions are widely taken to lower rather than raise the nominal interest rate. However, we suspect this implication can be overturned by incorporating a more realistic specification of monetary policy without overturning the central result that monetary policy shocks lead to persistent changes in economic activity.

The organization of the paper is as follows. Section 2 discusses the implications that the production structure has for the cyclical behavior of real marginal cost. It contrasts the implications of two views: the standard perspective that the elasticity of real marginal cost with respect to output is quite high, as imbedded in CKM [2000], and of our production structure, which makes it quite small. Section 3 provides an overview of our fully articulated macroeconomic model, which is then used to evaluate the general equilibrium dynamics in response to monetary disturbances. Section 4 shows how the persistence of output depends on structural features of this economy. Section 5 is a conclusion.

2. Marginal cost and the supply side

The cyclical behavior of real marginal cost plays a central role in modern business cycle models with imperfect competition and sticky prices. In turn, the supply side of the model economy governs how the cyclical behavior of real marginal cost is related to the level of output. The supply side also governs the cyclical comovement of factors of production and relative prices. In this section, we highlight two alternative visions of supply-side determinants of real marginal cost and factor variability: one that is standard in the literature and our alternative vision that stresses materials inputs, variable capacity utilization, and variable labor supply on the extensive margin. In subsequent sections below, we then build this supply side into a fully articulated macroeconomic model.

2.1. The standard view of marginal cost and output

The standard view of the link between marginal cost and output derives from a simple production function combined with a labor supply schedule.[6] In particular, with a constant returns-to-scale production function and economy-wide competitive factor markets,

$$\log(y_t/y) = \alpha \log(n_t/n) + (1-\alpha)\log(k_t/k)$$

where α is labor's cost share in output, y_t is output, n_t is labor input, and k_t is the stock of capital as well as the relevant measure of capital input (a variable without a time subscript indicates a steady state value). Further, with constant returns to scale, real marginal cost is related to input prices according to

$$\log(\psi_t/\psi) = \alpha \log(w_t/w) + (1-\alpha)\log(q_t/q)$$

where w_t is the real wage rate and q_t is the rental price of capital.

The preceding two equations have two important implications for the observed characteristics of economic fluctuations mentioned in the introduction.

Output and labor. Because capital input adjusts only slowly to shocks, standard models are inconsistent with the observed cyclical behavior of output and labor input, which is roughly proportionate, since they predict that labor will be much more volatile. For example, with $\alpha = 2/3$, a 1 percent increase in output requires a 1.5 percent increase in labor input.

Marginal cost and output. Standard models imply that real marginal cost will be highly sensitive to demand-induced variations in output because these models imply that factor prices are highly sensitive to output. To develop these factor price implications, it is convenient to use a Cobb-Douglas production function, so $\log(q_t/q) - \log(w_t/w) = \log(n_t/n) - \log(k_t/k)$. With aggregate capital fixed in any given period and for convenience normalized to its steady state value, its rental price is thus related to output according to $\log(q_t/q) = \log(w_t/w) + \frac{1}{\alpha}\log(y_t)$. Assuming that there is a labor supply schedule of the form,

$$\log(n_t/n) = \zeta_w \log(w_t/w) - \zeta_y \log(y_t/y),$$

[6] The standard analysis of the cyclical behavior of real marginal cost is based on a Cobb-Douglas production function and is described by Bils [1987]. It has been built into general equilibrium sticky price models of the Calvo sort by King and Wolman [1996] and Yun [1996] and forms the reference case for Chari et al. [2000].

labor market equilibrium will require that $\log(w_t/w) = \frac{1+\alpha\zeta_y}{\alpha\zeta_w}\log(y_t/y)$.[7] Hence, in the standard model, the behavior of real marginal cost is

$$\log(\psi_t/\psi) = \{[\frac{(1-\alpha)}{\alpha}] + [\frac{1/\alpha + \zeta_y}{\zeta_w}]\} \log(y_t/y) = \phi \log(y_t/y).$$

This expression highlights two influences on the elasticity of real marginal cost with respect to output, which we denote ϕ. The first bracketed term reflects the increase in the rental rate on capital. Additional labor is required to produce additional output: more labor increases the marginal product of capital, thus raising its rental price proportionately in the Cobb-Douglas case. Given that the cost share of capital is $(1-\alpha)$, the overall effect is $[\frac{(1-\alpha)}{\alpha}] = \frac{1}{2}$ if labor's share is $\alpha = 2/3$. The second bracketed term involves wage adjustments, which are influenced by the labor supply elasticity ζ_w; the effect of output on labor supply ζ_y; and the slope of the effective demand for labor.[8] For example, if $\zeta_y = \zeta_w = 1$, then the second bracketed expression is 5/2 implying a value of $\phi = 3$ under the traditional view. Thus, marginal cost responds highly elastically to output, and it is largely these features that preclude persistence in standard models.

CKM report that economies with capital formation display less persistence. To highlight why this occurs, it is convenient to let the labor supply elasticity become infinite, so that ϕ takes on its minimum value of $[\frac{(1-\alpha)}{\alpha}]$. Increasing the role of capital, a fixed factor, therefore increases the elasticity of marginal cost with respect to output. While capital formation also affects other aspects of the model, it is this feature of capital that mainly contributes to reduced persistence.[9]

2.2. An alternative view based on real flexibilities

A quite different view of the links between marginal cost, inputs, and output is embedded in our models, which feature: (i) elastic factor supply; (ii) materials inputs and (iii) small

[7] While we work with a labor supply schedule here, we note that Dotsey et al. [1999] assume that there is no aggregate variation in capital and that there is a representative consumer with a utility function $\frac{1}{1-\sigma}c^{1-\sigma} - \frac{\chi}{1+\gamma}(1-l)^{1+\gamma}$. This preference specification gives rise to the labor supply schedule in the text, under some assumptions that are worth highlighting. Initially, assume that consumption and output move together with $log(c_t/c) = \tau \log(y_t/y)$. Then, it follows that the labor supply schedule would take the form in the text with $\zeta_w = 1/\gamma$ and $\zeta_y = \sigma * \tau$.

[8] As in the general disequilibrium literature of the late 1970s, the labor demand that is relevant in the current discussion is given by the requirement that a given level of output be produced. The prior discussion indicates that labor demand may therefore be written as $\log(n_t/n) = (1/\alpha)\log(y_t/y)$. Thus, the slope is $1/\alpha$, which is the first term in the numerator of the second bracketed expression.

[9] Continuing the discussion of footnote 7, Dotsey et al. [1999] study a reference case in which $\zeta_y = 1$ and values of ζ_w between ∞ and .2. They find small output and not very persistent output effects.

incentives for firms to substitute between inputs.

Factor supply: Specifically, we make two sets of assumption about factor supply that differ from the standard view. First, we assume that capital services are variable, with the quantity of capital services given by $k_t^s = z_t k_t$, where the utilization rate is z_t. As explained in more detail below, our models specify that a higher rate of utilization involves higher marginal depreciation costs. Efficient utilization is therefore an increasing function of the rental rate, as in

$$\log(q_t/q) = \xi \log(z_t/z) \tag{2.1}$$

where ξ is an inverse supply elasticity. Second, we assume there is variation in both hours per worker (h_t) and the number of employed individuals (e_t), with the total quantity of man-hours being given by $n_t = h_t e_t$. Consistent with much empirical work on business cycles, we assume that the employment rate responds substantially over the cycle, making the supply of elasticity for total hours much larger than the supply elasticity of hours per worker. The larger labor supply elasticity we use accords with analyses of the effect of wages on labor supply by Mulligan [1998] and by Imai and Keane [2004].

Intermediate inputs with limited factor substitution: A final goods firm in our economy has a production function for gross output of the nested constant returns-to-scale form ((2.2) and (2.3)), where gross output y_t^g is a function of a materials input aggregate (to be discussed further below) in the amount x_t and another aggregate y_t, which we will interpret as the firm's value-added. The value-added input is a function of labor input (in man-hours n_t) and capital services input (in amount k_t^s).

$$y_t^g = g(x_t, y_t) \tag{2.2}$$

$$y_t = f(n_t, k_t^s) \tag{2.3}$$

For illustrative purposes in this section, we will assume that both g and f are essentially fixed proportions implying that intermediate inputs, gross output, and net output move one-for-one together, and that net output, labor and capital utilization also move together in a one-for-one manner.

Even though our production functions are assumed to have low elasticities of substitution, there are first-order approximations to the levels of gross and net output that generalize those of the standard model.

$$\begin{aligned} \log(y_t^g/y^g) &= s_x \log(x_t/x) + (1 - s_x)\log(y_t/y) \\ \log(y_t/y) &= \alpha \log(n_t/n) + (1 - \alpha)[\log(z_t/z) + \log(k_t/k)], \end{aligned}$$

where s_x is the share of intermediate inputs in gross output and α is labor's share in net output (value added). One key implication is that even with the capital stock held fixed, demand-induced changes in net output can now be accommodated in ways other than via labor adjustment.

Further, the loglinear equation governing the relationship between marginal cost and factor prices is

$$\begin{aligned}\log(\psi_t/\psi) &= s_x \log(p_{xt}/p_x) + s_n \log(w_t/w) + s_k \log(q_t/q) \\ &= s_n \log(w_t/w) + s_k \log(q_t/q)\end{aligned}$$

with the factor shares given by $s_n = (1-s_x)\alpha$; and $s_k = (1-s_x)(1-\alpha)$. The second equality follows the assumption that materials input is a perfect substitute for both consumption and investment. Thus, materials input has a relative price of one.

The last expression highlights the quantitative importance of introducing materials input for the relationship between real marginal cost and the prices of labor and capital input. For example, assuming that materials inputs have a cost share $s = 1/2$ of gross output, and that labor's share in net output is also 2/3, then it follows that $s_n = (1/2)*(2/3) = 1/3 = .333$ and $s_k = (1/2)*(1/3) = 1/6 = .166$. Thus, the introduction of materials input substantially reduces the responsiveness of real marginal cost to changes in w and q.

Marginal cost and factor supply: In the fixed proportion case, net output, labor and utilization all move proportionately ($\log(y_t/y) = \log(n_t/n) = \log(z_t/z)$). Hence, factor prices must be completely determined on the factor supply side. Using (2.1), the response of the rental rate to output is

$$\log(q_t/q) = \xi \log(y_t/y).$$

In contrast to the standard view, the rental rate now depends on the supply elasticity for capital services.

Continuing to assume that the labor supply function is $\log(n_t/n) = \zeta_w \log(w_t/w) - \zeta_y \log(y_t/y)$, it follows that the wage rate's response to output is

$$\log(w_t/w) = \frac{1+\zeta_y}{\zeta_w} \log(y_t/y)$$

Notice that the real wage is less sensitive to output than in the previous solution, in which the comparable coefficient is $\frac{1/\alpha+\zeta_y}{\zeta_w}$. There is a smaller effect in the numerator because labor demand does not need to bear the entire burden of producing increased output: utilization is varied one-for-one with labor.

Combining these expressions with the loglinear equation governing the relationship between marginal cost and factor prices, we find that

$$\begin{aligned}\log(\psi_t/\psi) &= (1-s_x)(1-\alpha)\log(q_t/q) + (1-s_x)\alpha \log(w_t/w) \\ &= (1-s_x)[(1-\alpha)\xi + \alpha\frac{1+\zeta_y}{\zeta_w}] \log(y_t/y) = \phi \log(y_t/y).\end{aligned}$$

A number of key results follow from this expression concerning the determinants of the elasticity of real marginal cost with respect to output, which we again call ϕ. First, the use of intermediate inputs (incorporated by the term s_x), as well as elastic factor supply (small ξ and large ζ_w) reduce the sensitivity of marginal cost to output. In concert, these features can have a particularly powerful effect. Second, it is a general equilibrium labor supply elasticity that is relevant for the elasticity of marginal cost ϕ, i.e., one which takes into account shifts (ζ_y) as well as its slope (ζ_w). These features will also carry over to the model that we develop in section 4 below.

A benchmark calculation under the alternative view: We can use this expression to undertake a benchmark calculation similar to that done for the standard view above, where we learned that a lower bound was $\phi = 3$. As an example, suppose that the share of materials in gross costs is one-half ($s_x = 1/2$) and that the share of labor in value added is two-thirds ($\alpha = 2/3$). Mulligan [1998] suggests that labor supply elasticities with both intensive and extensive margins can easily be as large as 2, and Basu and Kimball's [1997] empirical work suggests a utilization elasticity of $\xi = 1$, although larger values are also not unreasonable. Then, if there are no general equilibrium effects on labor supply, the computed lower bound for $\phi = (1/2) * [(1/3) * 1 + (2/3) * (1/2)] = (1/3) = .333$. The elasticity of marginal cost is higher if there are general equilibrium effects on labor supply. For example, using a standard value of $\zeta_y = 1$, then $\phi = (1/2) * [(1/3) * 1 + (2/3) * (2/2)] = 1/2 = .50$.[10] Thus, models constructed under our alternative view can easily yield an elasticity of real marginal cost with respect to output that is much less than unity.

3. A fully articulated macro model

The macroeconomic models that we study involve complete specification of microeconomic foundations, while building in the supply-side mechanisms highlighted above. Our discussion stresses three key ingredients, treating each in a separate subsection: the nature of dynamic pricing given marginal cost, the effect of materials input on marginal cost, and the effect of factor supply on marginal cost.

3.1. Dynamic Pricing

Dotsey, King, and Wolman [1999] describe a model of firm pricing that (i) highlights the roles of monopolistic competition and price stickiness stressed by New Keynesian economics;

[10] The sense in which $\zeta_y = 1$ is a standard value is based on the discussion of footnote 7: it is consistent with balanced growth ($\sigma = 1$) and consumption equal to output ($\tau = 1$), which is a condition frequently imposed in small macro models of the form developed in the current section.

(ii) can to handle a wide range of time-dependent pricing models (including that of Calvo [1983] and the models in the style of Taylor [1980]) as well as state-dependent pricing; and (iii) is operational because it can be integrated easily into a complete general equilibrium model. In this subsection, we give a quick summary of that approach.

As is standard in the literature, we assume that each firm j faces a demand curve for its product which takes the constant elasticity form (as in Blanchard and Kiyotaki [1987], and Rotemberg [1987]):

$$d_{jt} = (\frac{P_{jt}}{P_t})^{-\varepsilon} d_t$$

where P_{jt} is the firm's nominal price, P_t is the price level, ε is the elasticity of demand, and d_t is an aggregate demand shifter that will be discussed further below.

Some key features of pricing adjustment frictions in our economy are highlighted in Figure 3.1, which is taken from Dotsey et al. [1999] with slight modification. Within each period, some firms will adjust their price and all adjusting firms will choose the identical nominal value, which we call P_t^*. We now assume that there is a discrete distribution of firms at the start of each period, with a fraction θ_{jt} of type j firms ($j = 1, 2, ., J$) having last set their price j periods ago at the level P_{t-j}^*, so that we refer to j as the vintage of the price. If these firms do not adjust at date t, they will continue to charge P_{t-j}^*.[11] In period t, a fraction $1 - \eta_{jt}$ of vintage j firms decides to adjust its price and a fraction η_{jt} decides not to adjust its price (all vintage J firms choose to adjust). The total fraction of adjusting firms (ω_{0t}) satisfies

$$\omega_{0t} = \sum_{j=1}^{J} (1 - \eta_{jt})\theta_{jt}. \tag{3.1}$$

There are corresponding fractions of firms,

$$\omega_{jt} = \eta_{jt} \cdot \theta_{jt}, \tag{3.2}$$

that maintain during period t the price which they previously set in period $t - j$. These "end of period" fractions are useful because they serve as weights in various aggregation contexts throughout the paper. For example, the perfect price level index is given by

$$P_t = \left[\sum_{j=0}^{J-1} \omega_{jt} \cdot \left(P_{t-j}^*\right)^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}}, \tag{3.3}$$

in this economy. The "beginning of period" fractions are mechanically related to the "end of period" fractions:

[11] Since all firms are in one of these situations, $\sum_{i=1}^{J} \theta_{it} = 1$.

$$\theta_{j+1,t+1} = \omega_{jt} \text{ for } j = 0, 1, .., J-1. \tag{3.4}$$

Time dependent models: If the adjustment fractions η_j are treated as fixed through time, as in our analysis of section 4.1 below, then Figure 3.1 summarizes the mechanics of models of randomized price-setting opportunities, generalizing the specification of Calvo [1983] along lines suggested by the analysis of Levin [1991].[12] In this setting, η_j plays two roles: it is the fraction of firms given the opportunity to adjust within a period and it is also the probability of an individual firm being allowed to adjust after j periods, conditional on not having adjusted for $j-1$ periods.

State dependent models: When we consider state dependent pricing in section 4.5 below, we employ randomized fixed costs of adjustment to induce discrete adjustment by individual firms, while allowing for an adjustment rate that responds smoothly to the aggregate state of the economy.

While these are very different economic models, the firm's optimal pricing decision can be described using a dynamic programming approach in both the time-dependent and state-dependent pricing settings. We accordingly focus on the SDP setting and then specialize to TDP.

Since it must choose between continuing with a fixed nominal price, which implies a relative price of p_t, and paying a fixed cost of adjusting its price (ξ), the representative firm solves

$$v(p_t, \xi_t) = \max \left\{ \begin{array}{c} \pi(p_t) + \beta E_t \frac{\lambda_{t+1}}{\lambda_t} v(p_t \frac{P_t}{P_{t+1}}, \xi_{t+1}), \\ \max_{p_t^*}[\pi(p_t^*) + \beta E_t \frac{\lambda_{t+1}}{\lambda_t} v(p_t^* \frac{P_t}{P_{t+1}}, \xi_{t+1})] - w_t \xi_t \end{array} \right\}, \tag{3.5}$$

where $\frac{\lambda_{t+1}}{\lambda_t}$ is the ratio of future to current marginal utility and is the appropriate discount factor for future real profits. The relative price of a firm that last set its price j periods ago would be $p_t = (P^*_{t-j}/P_t)$ and real profits are given by $\pi(p_t) = (p_t) \cdot d_t - \psi_t \cdot d_t = [(p_t)^{1-\varepsilon} - \psi_t \cdot (p_t)^{-\varepsilon}]d_t$.[13]

For the state dependent setting, a smooth macro model is obtained in Dotsey, King, and Wolman [1999] by assuming that there is a continuous distribution of finite fixed menu costs of changing prices across a large number of firms. In the time dependent case, the fixed cost is either zero or infinite depending on when the firm last changed its price.

The dynamic program (3.5) implies that the optimal price satisfies an Euler equation that involves balancing pricing effects on current and expected future profits. That is, as

[12] Calvo assumes that $\eta_j = \eta$, whereas Levin allows η_j to depend on j, as we do below.

[13] In writing out the problem we have, for convenience, suppressed explicit notation of the state of the economy. John and Wolman [2000] show that there is a unique bounded function $v(p, \xi)$ that satisfies 3.5.

part of an optimal plan, adjusting firms choose a price that satisfies

$$0 = \frac{\partial \pi(p_t)}{\partial p_t^*} + \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \frac{\partial v(p_t^* \frac{P_t}{P_{t+1}}, \xi_{t+1})}{\partial p_t^*}. \tag{3.6}$$

Further, for any given state of the economy there is a unique cutoff price adjustment cost that faces each firm charging a relative price of p. All firms that draw an adjustment cost less than this cutoff will optimally choose to adjust their price. Thus, in the state-dependent model there will be an endogenous fraction of firms from each vintage, $(1 - \eta_{jt})$ that will choose to adjust their price. Further, since all price adjusters face the same dynamic program going forward, they will choose an identical price. Finally, as long as the inflation rate is non-zero and the maximum adjustment cost is finite, there will be a maximum number of periods that any firm will leave its price unchanged and thus the state vector for this problem is finite.

Iterating the Euler equation (3.6) forward, the optimal relative price, p_t^*, can be written as an explicit function of current and expected future variables:

$$p_t^* = \frac{\varepsilon}{\varepsilon - 1} \frac{\sum_{j=0}^{J-1} \beta^j E_t \{(\omega_{j,t+,j}/\omega_{0,t}) \cdot (\lambda_{t+j}/\lambda_t) \cdot \psi_{t+j} \cdot (P_{t+j}/P_t)^{\varepsilon} \cdot d_{t+j}\}}{\sum_{j=0}^{J-1} \beta^j E_t \{(\omega_{j,t+j}/\omega_{0,t}) \cdot (\lambda_{t+j}/\lambda_t) \cdot (P_{t+j}/P_t)^{\varepsilon - 1} \cdot d_{t+j}\}}, \tag{3.7}$$

where $(\omega_{j,t+,j}/\omega_{0,t}) = \left(\eta_{j,t+j} \cdot \eta_{j-1,t+j-1} \cdot .. \cdot \eta_{1,t+1}\right)$ is the probability of non-adjustment from t through $t+j$. The pricing rule (3.7) is a natural generalization of the type derived in time-dependent settings with exogenous adjustment probabilities that are constant through time, as in Calvo [1983] (see for example King and Wolman [1996] and Yun [1996]). According to (3.7), the optimal relative price is a fixed markup over real marginal cost ($p^* = \frac{\varepsilon}{\varepsilon - 1}\psi$) if real marginal cost and the price level are expected to be constant over time. More generally, (3.7) illustrates that the optimal price varies with current and expected future demands, aggregate price levels, real marginal costs, discount factors, and adjustment probabilities. All except the last are also present in time-dependent models. Intuitively, firms know that the price they set today may also apply in future periods, so the expected state of the economy in those future periods affects the price that they choose today. If, for example, marginal cost is expected to be high next period a firm will set a high price in the current period, so as not to sell at a loss next period. Similarly, if demand is expected to be high next period, the firm will set a higher price today so that one period of inflation leaves it closer to maximizing static profits next period. The conditional probability terms $(\omega_{j,t+,j}/\omega_{0,t})$ are present in time-dependent models, but they are not time-varying. In our setup, these conditional probability terms effectively modify the discount factor in a time-varying manner: a high probability of adjustment in some future period leads the firm to set a price that heavily discounts the effects on profits beyond that period.

3.2. Materials input, marginal cost, and aggregation

We now turn to detailed development of the materials input linkages in our model. We have previously outlined the effects of material inputs on marginal cost in section 2 above, so that the current discussion concentrates on the microeconomic structure of materials input linkages and aggregation with materials inputs. Our modeling of materials inputs follows the roundabout input output structure of Basu [1995] and is also adopted by Bergin and Feenstra [2000] and Huang and Liu [2004].

3.2.1. Microeconomic structure of materials

We think of all firms as buying units of a materials aggregate x from an "intermediary" who assembles these from the products of individual firms of various types. We assume that this firm has technology

$$x_t = [\sum_{j=0}^{J-1} \omega_{jt} b_{jt}^{\vartheta}]^{\frac{1}{\vartheta}}$$

where b_{jt} is the amount of product j that the intermediary demands from each firm of type j. Cost minimization on the part of the intermediary leads to

$$b_{jt} = [\frac{P_{jt}}{P_{xt}}]^{\frac{1}{\vartheta-1}} x_t$$

and

$$P_{xt} = [\sum_{j=0}^{J-1} \omega_{jt} P_{jt}^{\frac{\vartheta}{\vartheta-1}}]^{\frac{\vartheta-1}{\vartheta}}$$

We also assume that the materials aggregator has the same demand elasticities as the consumption and investment aggregators (so that $-\varepsilon = \frac{1}{\vartheta-1}$): a simple story is that all consumers and investors desire the same final good assembled by the intermediary. This assumption also implies that $P_{xt} = P_t$. Hence, the microeconomic model delivers the implication – used above in our analysis of marginal cost – that the relative price P_{xt}/P_t is constant.

3.2.2. Aggregation

If firms of type j purchase quantity x_{jt} of the materials aggregate, then the intermediary's resource constraint is

$$x_t = [\sum_{j=0}^{J-1} \omega_{jt} x_{jt}]$$

and its total expenditure $[\sum_{j=0}^{J-1} \omega_{jt} P_{jt} b_{jt}] = P_{xt} x_t = P_{xt} [\sum_{j=0}^{J-1} \omega_{jt} x_{jt}]$.

All firms of type j will face total demand

$$b_{jt} + c_{jt} + i_{jt} = y^g_{jt} = G(x_{jt}, n_{jt}, k^s_{jt}).$$

Notice that x_{jt} is the demand for the materials aggregate by firms that have held their price fixed for j periods. By contrast b_{jt} is the materials demand by all firms for the product of firms that last adjusted their price j periods in the past.

Under constant returns to scale and global factor markets, we can define aggregate gross output as in Yun [1996] and, because all firms choose the same factor input ratios, it is consistent with an aggregate gross output production function.

$$y^g_t = [\sum_{j=0}^{J-1} \omega_{jt} y^g_{jt}] = G(x_t, n_t, k^s_t)$$

However, this real quantity does not correspond to national output measures. To obtain these, we want to net out materials to generate an aggregate measure of value-added. To this end, adding up across all of the markets, we get that

$$\sum_{j=0}^{J-1} \omega_{jt}[P_{jt}(c_{jt} + i_{jt})] = [\sum_{j=0}^{J-1} \omega_{jt} P_{jt}(y^g_{jt} - b_{jt})] = [\sum_{j=0}^{J-1} \omega_{jt} P_{jt} y^g_{jt}] - P_{xt} x_t$$

where the right-hand side is the desired measure of nominal value added. To express this in real terms, we can divide through by the perfect price index and use the aggregation properties of demand

$$c_t + i_t = [\sum_{j=0}^{J-1} \omega_{jt} p_{jt} y^g_{jt}] - x_t,$$

so that one way to measure aggregate real value-added is as consumption plus investment.

More conventionally, looking at the firms' payments, we have

$$\sum_{j=0}^{J-1} \omega_{jt}[p_{jt} y^g_{jt} - x_{jt}] = \sum_{j=0}^{J-1} \omega_{jt}[w_t n_{jt} + q_t k^s_{jt} + \pi_{jt}]$$

so that aggregate value-added can also be described as a sum of wages plus capital income plus profits.

Finally, actual gnp calculations in the U.S. and other countries more closely resemble the adding up of gross output less materials expenditures. For nominal gnp in our economy, this would be:

$$Y_t = [\sum_{j=0}^{J-1} \omega_{jt}(P_{jt} y^g_{jt} - P_t x_{jt})]$$

and for real gnp at benchmark relative prices of unity this would be:

$$\overline{y}_t = [\sum_{j=0}^{J-1} \omega_{jt}(y^g_{jt} - x_{jt})] = G(x_t, n_t, k^s_t) - x_t$$

An implicit price deflator would then is $\overline{P}_t = Y_t/\overline{y}_t$, so that $c_t + i_t = (\overline{P}_t/P_t)\overline{y}_t$. For our quantitative economies, though, we find small variation in $(\overline{P}_t/P_t)$. Hence, while we use $c_t + i_t$ to measure variations in real output, there would be small differences if we looked at $\overline{y}_t$.

3.3. Factor Supply

In our model economy, aggregate labor input varies on both the extensive and intensive margins, which can make the supply of labor services quite elastic. We also allow for variable utilization of capital, which can in turn make the supply of capital services fairly elastic. The following two subsections describe the key details of these supply-side mechanisms.

3.3.1. Supply of Labor

In order to build a model in which some potential labor suppliers work while others do not, we assume that each of a continuum of agents faces a random discrete cost of going to work, which may be high or low in any particular period. To avoid having to carry along a distribution of wealth, we assume that these risks are fully pooled.

The labor supply behavior of the economy can then be studied by looking at a large household, which maximizes

$$\max_{c^e_t, c^h_t, e_t, l_t} \{\sum_t \beta^t[(e_t u(c^e_t, l_t) + (1 - e_t)u(c^o_t, 1)]\}$$

$$\text{subject to: } [e_t c^e_t + (1 - e_t)c^h_t + \varphi(e_t) \leq [e_t w_t(1 - l_t) + \pi_t] + q_t k^s_t - i_t$$

where e is the fraction of household members that participate in the work force, c^e is the consumption of workers, l is the leisure of workers, c^o is the consumption of nonworkers, φ is a strictly increasing cost function of going to work, w is the wage rate, π are total profits remitted by household owned firms, q is the rental rate on capital services, k^s, and i is the amount of investment expenditure.

The utility function is of the class of functions discussed in King and Rebelo [1999]. Specifically,

$$u(c, l) = (1/(1 - \sigma))[c^{1-\sigma} v(1 - h)^{1-\sigma} - 1]$$

where hours per employed worker are $h = 1 - l$. Basu and Kimball [2000] explore the usefulness of this class of utility functions for matching both longrun properties of consumption and leisure as well as for providing a better fit for cyclical consumption behavior. We parameterize both the function φ, which governs the responsiveness of labor effort, and the function v, which controls the elasticity of labor at the intensive margin, to match the empirical labor elasticities estimated by Mulligan [1998].[14] We also perform experiments where we alter these elasticities to check how sensitive our results are to alternative calibrations.

3.3.2. Capital use and accumulation

For simplicity, we think of households owning the stock of capital and renting its services to firms at rental rate q_t. The household's income from renting services is $q_t k_t^s = q_t z_t k_t$, where z_t is the utilization rate. The law of motion for the capital stock is given by

$$k_{t+1} = (1 - \delta(z_t))k_t + \mu[i_t/k_t - \delta(z_t)]k_t$$

which reflects two influences. First, a higher utilization rate raises the depreciation rate on capital, i.e., $\delta(z)$ is a positive, increasing and convex function of the utilization rate. Second, there are costs associated with the rapid accumulation of capital: μ is positive and increasing in i/k but there are diminishing returns (μ is concave). We have chosen a specification where adjustment costs apply to gross investment so that our specification is directly comparable to that used by CKM.[15]

3.3.3. Efficient supply behavior

It is useful to break the efficiency conditions into two parts: (i) those which govern labor and consumption; and (ii) those which govern investment, utilization and capital accumulation.

Efficient work effort, participation, and consumption decisions require the following four conditions, in which λ_t is the Lagrange multiplier on the household budget constraint. First, the marginal utility of consumption by participating individuals and by nonparticipating

[14] Although Mulligan's [1998] model includes only an extensive margin, we hve chosen to use both an intensive and extensive margin so that both hours per worker and hours can behave differently. Our reliance on a greater extensive elasticity is motivated by the observations that aggregate hours are more volatile than hours per worker. As Mulligan [2001] points out the aggregate implications of models with and without extensive margins are similar when there are no economically important time aggregation effects. Presumably we could have derived a model with only indivisible labor, as in Rogerson [1988], that would replicate the results in the paper.

[15] We have also explored adjustment costs on gross investment, $k_{t+1} = [1 - \delta(z_t)]k_t + \mu[i_t/k_t]k_t$, with little or no change in our results.

workers must be equated to the multiplier, as a condition of efficient risk-sharing. Second, hours per employed worker (h_t) are governed by the familiar requirement that the marginal value of foregone leisure must be equal to the value of working. Third, the rate of participation (e_t) is governed by the requirement that the utility cost of adding the marginal entering worker must just be matched by the gain in terms of additional income, which is wh less the consumption costs of going to work.

$$(c_t^e)^{-\sigma}v(1-h_t)^{1-\sigma} = \lambda_t \tag{3.8}$$

$$(c_t^o)^{-\sigma}v(1)^{1-\sigma} = \lambda_t \tag{3.9}$$

$$(c_t^e)^{1-\sigma}v(1-h)^{-\sigma}v'(1-h) = \lambda_t w_t \tag{3.10}$$

$$(1/(1-\sigma))[-(c_t^o)^{1-\sigma}v(1) - (c_t^e)^{1-\sigma}v(1-h_t)^{1-\sigma}] = \lambda_t[w_t h_t - (c_t^e - c_t^h) - \varphi'(e_t)] \tag{3.11}$$

Taken together, these expressions determine a level of labor supply, $n_t = h_t e_t$, that contains variations on both the intensive and extensive margins.

As in many investment models, notably that of Hayashi [1982], an efficient rate of investment equates the current cost of the investment good λ_t to the value of the change in the capital stock resulting from the additional investment ($\nu_t \mu'[i_t/k_t - \delta(z_t)]$). An efficient utilization rate equates the benefits of additional capital services, $q_t\lambda_t$, with the cost of replacing the worn out capital stock $\nu_t(1 + \mu'[i_t/k_t - \delta(z_t)])\delta'(z_t)$, where ν_t is the Lagrange multiplier on the capital accumulation constraint.

$$\lambda_t = \nu_t \mu'[i_t/k_t - \delta(z_t)]$$

$$q_t\lambda_t = \nu_t(1 + \mu'[i_t/k_t - \delta(z_t)])\delta'(z_t)$$

Note that this pair of restrictions implicitly determines the utilization rate z and the investment rate i/k as functions of v_t, q_t and λ_t. Finally, efficient capital accumulation places restrictions on how capital's shadow price ν_t evolves over time.

$$\nu_t = \beta E_t\{\nu_{t+1}(1 - \delta_{t+1} + \mu_{t+1})\} - \beta E_t\{\lambda_{t+1}(i_{t+1}/k_{t+1})\} + \beta E_t\{q_{t+1}\lambda_{t+1}z_{t+1}\}$$

where $\mu_{t+1} = \mu(i_{t+1}/k_{t+1} - \delta(z_{t+1}))$ and $\delta_{t+1} = \delta(z_{t+1})$. That is: the cost of a unit of

capital at t is equated to the benefit of a unit at t+1. This future benefit involves having $(1 - \delta_{t+1} + \mu_{t+1})$ units of future capital and having more rental income $q_{t+1}\lambda_{t+1}z_{t+1}$, but is reduced by having more future investment (at a given efficient future rate of investment (i_{t+1}/k_{t+1}).

Our introductory model simply assumed that $\log(q_t/q) = \xi \log(z_t/z)$. Combining the first two efficient factor supply conditions yields $q_t\lambda_t = (\nu_t + \lambda_t)\delta'(z_t)$. Approximating this condition yields $\log(q_t/q) = \xi \log(z_t/z) + \frac{v}{v+\lambda}[\log(\nu_t/\nu) - \log(\lambda_t/\lambda)]$.with $\xi = z\delta''/\delta'$ so that ξ is linked to the rate at which depreciation costs rise with use.

3.4. Calibration

To make our discussion on persistence readily comparable to the analysis of CKM, we opt for many of their parameter settings in calibrating our model. In particular, we retain their values for the agents discount factor, β, the coefficient of relative risk aversion, σ, depreciation δ, average hours worked, n, labor's share in value added, α, and the demand elasticity ε. Their parameter choices for these variables are consistent with standard real business modeling and estimated markups. The remaining features of our calibration are discussed next. The full set of calibration assumptions is listed in table 3.1

Labor supply: The parameters of the household's preferences and its cost of going to work function were set to achieve a participation rate of seventy percent ($e = .70$), which is consistent with average U.S. labor participation rates. To match the CKM assumption that average hours per population member was 1/3 of available time, we then require that steady state hours per worker is .476 of available time. The cost of going to work function φ is parameterized so that the extensive margin labor supply elasticity is 1.6 and the utility function $\nu(1-h)$ is parameterized so that the intensive margin labor supply elasticity is .4.[16] The total matches the labor supply elasticity value of 2 in the CKM benchmark and is consistent with estimates in Mulligan [1998], while Solon, Barsky, and Parker [1994] estimate labor supply elasticities to be between 1 and 1.4.

Utilization and investment adjustment costs: Elasticity of marginal depreciation costs, $\xi = z\delta''/\delta'$, set equal to unity based on Basu and Kimball [1997].[17] Steady state utilization is set at .82, which is the U.S. average capacity utilization rate. We parameterize our adjustment cost function so that investment is twice as volatile as output.[18]

[16] While there are various measures of total labor supply elasticity, there is little guidance on how to attribute the elasticity to each margin. One potential avenue is to use the relationships implied by the model. In our model, $n = h * e$, and $\ln h = \eta_h * \ln w$ and $\ln e = \eta_e * \ln w$. Running the regression $\ln n = b * \ln h + e$ gives the regression coefficient $b = \eta_h/(\eta_h + \eta_e)$. Using band pass filtered data over a sample 1964-2003 yields a regression coefficient equal to .3 implying that η_h is 30% of the total elasticity. Thus, are parameterization is consistent with this evidence.

[17] We also make investment adjustment costs apply to net rather than gross investment. The practical effect of adjustment costs applied to gross investment is to make marginal costs rise with utilization for another reason besides the depreciation mechanism studied in the current analysis.

[18] This is consistent with the estimated impulse response functions in Christiano, Eichenbaum, and Evans

Production function share parameters: We set the steady state ratio of materials inputs to gross output $x/y^g = 1/2$, which is consistent with evidence from Jorgenson's web page on materials share of output in the U.S., and we set labor's share of value-added to two thirds.[19]

Production function elasticities: Various empirical studies suggest that there is a small elasticity of substitution between materials inputs and value-added, and Basu [1996] points out that these estimates are probably biased upward. We, therefore, make the benchmark elasticity of substitution equal one-tenth (close to fixed proportions). We follow many studies in assuming a unit elasticity of substitution between labor and capital, i.e., that the value-added function is Cobb-Douglas.

Table 3.1 Model Parameters

β	$.97^{.25}$
σ	1
extensive n^s elasticity	1.6
intensive n^s elasticity	.4
n	1/3
e	.7
ξ	1
z	.82
$\delta(z)$	.08
adjustment costs	$\frac{\Delta i}{i}/\frac{\Delta y}{y} = 2$
labor's share	2/3
materials input share	1/2
elasticity of substitution materials	1/10
demand elasticity,ε	10
interest elasticity of m^d	0

4. Persistence in the fully articulated model

In this section, we discuss how the fully articulated economy responds to a monetary disturbance to money growth, where our money supply process is the same as that used in CKM,

[2005]. CKM base their calibration on the relative unconditional volatilities of investment and output, but we choose to base our calibration on the conditional behavior of these two variables. This choice seems more consistent with the model, since we only consider money supply disturbances.

[19] We thank an anonymous referee for calling our attention to this data. Comparing our calibration to other papers in the literature, we appear to have chosen the lower bound. Basu [1995] indicates that materials share may be a good bit higher than .5, and Huang and Liu [2004] look at shares as high as .7.

$\Delta \ln M_t = .57\Delta \ln M_{t-1} + e_{m,t}$.

4.1. Price stickiness

To make for ready comparability with the literature, we assume that price adjustment is time dependent for most of this section. Specifically, we assume that there is exogenous price rigidity with a degree specified by the nonadjustment rates (η) and stationary fractions (ω) in Table 4.1, so that no firm holds its price fixed for more than four periods ($J = 4$) and some adjust more frequently. One way to more precisely gauge the degree of price stickiness is to calculate the average age of a price in the economy at the end of each period, $\omega_0 1 + \omega_2 2 + \omega_3 3 + \omega_4 4$. Using the numbers in Table 4.1, this average is 1.98, so that a random visit to a firm in the economy would conclude that it had a two quarter old price. In a Tayloresque model, such as those studied by Chari, Kehoe, and McGrattan [2000], our specification would be similar to the $J = 3$ model because that would deliver a nearly identical average price age (since $\frac{1}{3}(1 + 2 + 3) = 2$). In assessing the degree of price stickiness associated with this number, it is important to stress that our simulations of the fully articulated models assume that p^* is set after the monetary shock takes place. Thus, there is complete neutrality if prices are fixed for one quarter. In terms of generating persistence, this is a conservative assumption – relative to that employed in some other studies – in which firms adjust prices before seeing the current monetary shock.

Table 4.1

j	Nonadjustment Rate (η)	Stationary Fraction (ω)
0		.41
1	.73	.30
2	.63	.19
3	.56	.10

The nonadjustment probabilities in Table 4.1 are related to the probabilities that a currently adjusting firm attaches to the time that its price will be fixed. The probability of holding the price fixed for exactly one period is $(1 - \eta_1)$; for exactly two periods it is $\eta_1(1 - \eta_2)$, for exactly three periods it is $\eta_1\eta_2(1 - \eta_3)$, and for exactly four periods it is

$\eta_1\eta_2\eta_3$. Thus, the expected duration of price stickiness may be shown to be 2.41 quarters.[20]

The Table 4.1 values were obtained from assuming–as in Dotsey, King, and Wolman [1999]–a particular distribution function for adjustment costs as well as a steady state inflation rate of .28*percent* (less than three-tenths of one percent per year). This distribution involves a maximum adjustment cost parameter, implying that the highest cost faced by a firm adjusting its price is just over .01 percent of its quarterly wage bill (one-one hundredth of a percent of its wage costs). Given the small steady state inflation rate, these very small adjustment costs were enough to produce a price distribution spread out over a year as displayed in Table 4.1.

Our strategy is to initially fix the $\omega's$ at their steady state levels, exploring time-dependent pricing models in sections 4.2 and 4.3. We then turn to a fully state-dependent pricing model in section 4.5 below. This is an essential check on the model, because it determines whether preventing firms from optimally changing their prices has important implications for their behavior. If it does, then the results of the time-dependent exercise are called into question, because firms are being prevented from behaving in an optimal fashion.[21]

4.2. Persistence under the standard view

Figure 4.1 highlights the fact that there is only a small impact effect of money on real activity and there is little persistence in real economic activity, when marginal cost is governed by the standard view. This is a special case of our model, which abstracts from materials inputs and capacity utilization. In this example, we also use the same specification of leisure in the utility function as CKM. Specifically, $v(1-h) = (1-h)^{1.5}$, which implies a labor supply elasticity of 2 when h=1/3. Figure 4.1 replicates the key finding of Chari, Kehoe and McGrattan [2000];, namely, that there is no endogenous persistence.

Even though only 41percent of the firms are adjusting, the price level moves substantially on impact (an increase of about .7) because those firms make large price adjustments, as discussed further below. In terms of the dynamics of output, the impact effect is 0.32 and the total multiplier is .87. The mean lag is 1.83 quarters, which is less than the average age

[20] This can be easily computed, as follows:

$$\begin{aligned} D &= (1-\eta_1) + 2*\eta_1(1-\eta_2) + 3*\eta_1\eta_2(1-\eta_3) + 4*\eta_1\eta_2\eta_3 \\ &= [1-\frac{\omega_1}{\omega_0}] + 2*[\frac{\omega_1}{\omega_0} - \frac{\omega_2}{\omega_0}] + 3*[\frac{\omega_2}{\omega_0} - \frac{\omega_3}{\omega_0}] + 4*\frac{\omega_3}{\omega_0} \\ &= 1 + \frac{\omega_1}{\omega_0} + \frac{\omega_2}{\omega_0} + \frac{\omega_3}{\omega_0} = \frac{1}{\omega_0} \end{aligned}$$

[21] In recent work, Dotsey and King [2005], we have found that certain popular New Keynesian persistence generating mechanisms are significantly affected by the presence of state dependence.

of a price in this economy.

There are also notable implications for the comovement of output, labor, and marginal cost. The production structure requires that labor input is substantially more volatile than output. The real rental rate, the real wage rate, and real marginal cost rise dramatically in response to the monetary disturbance: the 0.32 percent increase in output and the .48 percent increase in labor input lead to a rise in real marginal cost that is .63 percent, implying an elasticity of marginal cost with respect to output of about 2. Hence, an initial rise in real marginal cost and an initial interval of high expected inflation motivates firms to raise their prices aggressively. Those firms which can adjust their price do so by nearly the full amount of the long-run 2 percent increase, as shown by the P^* series in the lower-left panel of Figure 4.1. In the jargon of the literature, they "frontload" their price increase.

As in all our simulations, investment adjustment costs are set so that investment responds twice as much as output. This setting is consistent with the evidence presented in Christiano, Eichenbaum, and Evans [2005]. In this regard, we are following the spirit – but not the details – of the approach taken in CKM [2000].[22]

4.3. Persistence with real flexibilities

When marginal cost is based on a supply-side with real flexibilities and using the same degree of exogenous stickiness, there is an important impact effect of money on real activity and there is substantial persistence in real economic activity as highlighted in Figure 4.2. The benchmark model displayed there has the following structural characteristics: a materials inputs share of 1/2, variability of capacity utilization (an elasticity of the rental rate to the rental price of unity), and substantial labor supply variation due to variations on the extensive margin. Specifically, there is a Frisch labor supply elasticity of 2 for total hours, which involves an elasticity of .4 in hours per employed worker and of 1.6 in terms of employment.[23]

Turning to the details shown in Figure 4.2, the price level moves only by about .4 percent in response to a one percent monetary expansion on impact, although 41 percent of the firms are again free to adjust their prices. The smaller response exhibited in this setting occurs because price adjusting firms now choose to raise their prices only one-for-one with the money

[22] CKM [2000] specify a quadratic investment- adjustment cost model, with costs depending on net investment. They adjust the single free parameter of that specification so that the response of investment relative to output – specifically the relative standard deviation of HP filtered data from the model—matches that in the U.S. data.

[23] There is, of course, a smaller general equilibrium labor supply elasticity because consumption rises in response to the monetary disturbance. Judging from the relative height of impact effects, this elasticity is slightly greater than unity, because the real wage rises by about .5, while labor and output rise by over .6.

stock, reflecting both the smaller increase in real marginal cost and the smaller extent of expected inflation. There is an impact effect on real output of .54 percent and a total multiplier of 2.6, which is distributed over eight quarters. The elongated impulse response is reflected in a larger mean lag of 2.52, which is 40 percent larger than in the simple model just presented.

The benchmark model is also more closely in accord with other aspects of business cycles. Both materials and total hours rise roughly one-for-one with output while utilization increases by approximately 75 percent of the increase in output. Materials respond in this way because they have a low substitution elasticity (about one-tenth) for value-added. Hours respond somewhat more aggressively than utilization because they are supplied more elastically than capital services. Thus, the real rental rate responds somewhat more than wages.

Marginal cost moves by one-half as much as the average of the real factor rental rates because the share of value added in total costs is one-half. Judging again from impact effects, the elasticity of real marginal cost with respect to output is about .33 (the impact effect on marginal cost is about .18 and the impact effect on output is about .54). Since real marginal cost does not rise dramatically in response to the monetary disturbance, adjusting firms increase their price much less aggressively than in the previous experiment reported in Figure 4.1.

Another interesting feature of the impulse responses is their hump shape. The responses of both output and inflation reach their peak about three quarters after the shock. While not as drawn out as the empirical impulse responses in CEE [2004], the effect of the money shock lasts for a little over two years despite an average length of price fixity of only 2.4 quarters.

4.4. A recurrent interest rate puzzle

In both Figures 4.1 and 4.2, there is substantial expected inflation, which is an inevitable result of short-run price stickiness coupled with a higher long-run path of the price level. The total necessary rise in the price level is about 1.8percent, which is distributed over an eight quarter adjustment interval. The extent of expected inflation is highest in the first few quarters, so that the upward pressure on the nominal interest rate is greatest at that time. This degree of expected inflation results in a rise in the nominal interest rate in response to expansionary monetary policy. That is: the model fails to produce a liquidity effect in response to this particular monetary disturbance.[24]

[24] Keen [2004] explores the extent to which financial market frictions can produce a liquidity effect in combination with sticky prices, as well as reviewing prior literature on this topic. While he imbeds the standard view of marginal cost in his models, it would be interesting to explore the power of liquidity effect

4.5. Persistence with state-dependent pricing

We now investigate whether state-dependent dynamic behavior changes the response of the model economy. There are some aspects of the dynamic responses illustrated in Figure 4.3 which are very predictable: there is a smaller impact effect of money on output, (.45 rather than .54), which is consistent with the idea that state-dependent pricing is inevitably less sticky than time-dependent pricing. There is also a smaller total effect (2.24 rather than 2.65) which is again consistent with a smaller amount of stickiness. But there is considerable persistence, as reflected in a mean lag of 2.59. Further, the "hump shaped" effect of money on output remains.

Comparison of state-dependent pricing with time-dependent pricing is quite important in the analysis of persistence mechanisms, as we argue in Dotsey and King [2005]. If pricing behavior changes drastically across the two experiments shown in 4.1 and 4.2, then firms constrained to act in a time-dependent fashion are foregoing profits, with an extent of the loss governed by the magnitude of assumed adjustment costs. As shown in figure 4.3, considerable persistence remains even when pricing is state-dependent. Thus, the real flexibility mechanisms that we explore in this paper are robust to state dependent pricing.[25]

4.6. Robustness to details of production structure

In this section we investigate how the individual core components of our "real flexibilities" view contribute to overall persistence. The basic summary statistics on output responses—impact multiplier, total multiplier, and mean lag—are displayed in Table 4.2, which also describes the cases and the location of additional figure information as well as reporting an "impact" elasticity of marginal cost to output. Comparing the sum of the lagged responses as well as the mean lag generated by the various perturbations with those of the standard model, one sees that generally the three core components: materials inputs, elastic labor supply on the extensive margin, and variable utilization of capital contribute to greater persistence.

mechanisms using our view of marginal cost.

[25] This is not the case for some other prominent New Keynesian persistence mechanisms such as firm specific factors (see Dotsey and King [2005]).

Table 4.2:
Summary of Sensitivity Analysis

case	figure(s)	description	impact		multiplier	
			elasticity	impact	total	mean
1	4.4A/4.1	standard view (CKM)	1.97	.32	.87	1.83
2	4.4B	elastic factors but no materials		.46	1.68	1.89
3	4.4C	materials with inelastic factors		.27	.75	1.88
4	4.4D	materials and elastic labor		.48	2.12	2.57
5	4.4E	materials and utilization		.36	1.59	1.43
6	4.4F/4.2	benchmark		.54	2.65	2.52
7	4.3	benchmark (sdp)		.45	2.24	2.59

Note: The cases are discussed in the text. The impact elasticity is a ratio of the impact effect of a monetary shock on real marginal cost to the effect on output. The total multiplier is the sum of impulse responses at up to a 20-quarter horizon. If these impulse responses are $\{\kappa_j\}_{j=0}^{20}$, then the mean lag is constructed as $[\sum_{j=0}^{20}(j\kappa_j)]/\sum_{j=0}^{20}(\kappa_j)$.

Additional detail on model implications is provided in Figure 4.4, which graphs output and marginal cost for cases (1-5), building up to the benchmark case 6 that is also displayed in Figure 4.2. Figure 4.4.A is the output and marginal cost responses in the CKM case.[26] Figure 4.4.B. sets the material share equal to zero while retaining labor supply on the extensive margin and variable capacity utilization, with the same elasticities as in the benchmark model. In this case the marginal cost elasticity is .69 and there is substantial persistence. Figure 4.4.C keeps a materials share of one-half but eliminates both labor supply elasticity on the extensive margin and variable capacity utilization: it illustrates why some researchers have thought that reasonable materials input shares would not, by themselves, generate a substantial amount of persistence.[27] Figure 4.4D eliminates variable capital utilization from our benchmark: it shows that the combination of materials input and elastic labor supply can generate a small elasticity of marginal cost with respect to output (about .5) and substantial persistence. However, as we have stressed earlier, the fixed capital stock implies that labor is much more volatile than output in this case. Figure 4.5E displays the case

[26] This case has already been displayed in Figure 4.1 and its parameterization has already been described in the text.

[27] For example, it is apparently for this reason that Bergin and Feenstra [2000] are led to explore the influence of demand specifications that differ from the CES form employed here.

with materials input and utilization, but without labor supply elasticity on the extensive margin. Finally, Figure 4.5F is the benchmark model, also shown in Figure 4.2, that has an elasticity of marginal cost with respect to output of .33. Taken together, the panels of this figure indicates how each structural feature contributes to the dampening of the response of marginal cost to output drawing out the response of output to a monetary shock.

4.7. Some robustness checks to other model features

To explore the robustness of our persistence result to parameters and model features, we now perform some additional analysis.

4.7.1. Interest rates and money demand

We have seen that a recurrent feature of the model economies displayed in Figures 4.1, 4.2, and 4.3 is the rise in the nominal interest rate when there is a positive monetary injection. Previously, we traced this finding to two properties of the model. First, there is a substantial rise in expected inflation, which must occur because there is short-run price stickiness coupled with a long-run rise in the price level. Second, there are relatively small variations in the real rate of interest.

We now introduce an interest-sensitive money demand function, written in a semilogarithmic form

$$\log M_t - \log P_t = \log y_t - \zeta R_t$$

We do not derive this relationship from an underlying microeconomic specification of preferences or transactions costs. Instead, our approach relies on the idea that explicitly derived movements in monetized exchange typically imply small variations in (i) resource costs of using alternative media and (ii) in substitution effects arising from "wedges of monetary inefficiency." Experiments with many optimizing models of money demand have convinced us that this is a good approximation; it also has the added feature that any consequences of altering the demand for money can be traced directly to its implications for the behavior of aggregate demand, as in the IS-LM model.

To think about the issues, start with our benchmark model in Figure 4.2 that sets the interest sensitivity of money demand (ζ) equal to zero. In this case, there is a given rise in net output (call it $\log(y_0^b)$), the price level, and an associated rise in the nominal interest rate (call it R_t^b). Now, suppose that we raise ζ from zero to some positive number: what is wrong with our prior solution? There is now an excess supply of money, because money demand is lower given that the monetary shock raises the nominal interest rate. Hence, any new solution must move in the direction of: (i) a higher output level, so as to raise the real demand for money; (ii) a higher price level, so as to reduce the real supply of money; or (iii) a lower nominal interest rate, so as to raise the real demand for money.

These three responses are all mutually consistent. First, a higher output level automatically increases the demand for money, reducing the excess supply. Second, a higher output level raises real marginal cost and encourages firms to increase their prices, so that there will be a greater rise in the price level. Third, given that there is a higher initial price level, there is less expected inflation which must take place in order to reach the higher long-run price level. In sum, the rise in the nominal rate means that there is an additional aggregate demand stimulus in the model (exactly the opposite of the standard IS-LM model's cushioning of aggregate demand).

Panels A and B of Figure 4.5 illustrate the dynamic effects of a monetary shock in our benchmark model of section 4.2, using values of $\zeta = 1$ and $\zeta = 8$.[28] These graphs show that the introduction of interest-sensitive money demand has the effects discussed above, yielding a substantially larger impact effect of money on output. Specifically, the impact effects on output and the price level of a one percent monetary change are .96 and .52 in with $\zeta_R = 1$, as compared to the benchmark values of .54 and .44 in Figure 4.2. There is also a smaller rise in the nominal interest rate (not shown). With a greater interest-sensitivity ($\zeta = 8$), there are larger effects of money on output and prices. Here the impact effects are 2.57 and .77 respectively. Since these economies display a small elasticity of marginal cost with respect to output, it is perhaps not too surprising that the bulk of the effect is concentrated on output rather than on prices. This is particularly true because the interest-rate-induced changes in the demand for money are transitory relative to the dynamics displayed in Figure 4.2.

Panels A and B of figure 4.5 also show the effect of interest-sensitive money demand on the overall shape and measure of persistence displayed by the impulse response function. For the smaller interest sensitivity, the total effect is larger (3.33) than it was for the benchmark case (2.65) shown in Figure 4.2, in which money demand was interest-insensitive. There is however, less persistence with the mean lag falling to 1.99. These conclusions are reinforced

[28] Our money-demand sensitivities are not large as those implicit in CKM [2000], who use a money demand specification with an elasticity of .39 that is identified from the long-run (low frequency) behavior of real balances and the nominal interest rate. The semielasticity ζ is related to an elasticity ε via $\zeta = \varepsilon/R$, where R is the stationary interest rate. In our analysis, an annual nominal interest rate of 6 percent is a nominal interest rate of $.06/4 = .015$ per quarter. Hence, $\varepsilon = .39$ corresponds to $\zeta = 26$.

We use more modest values, as in King and Watson [1996], because we believe that there is a smaller short-run elasticity of money demand that is pertinent for business cycle analysis. The incorporation of a money demand function with a distinction between short and long-run elasticities into business cycle models is a promising line of research.

for the higher sensitivity, but persistence is not totally eliminated by interest-sensitive money demand.

4.7.2. Utilization

We now look at utilization elasticities of .5 and 2, motivated by the fact that this parameter is not estimated precisely (see Basu and Kimball [1997]). These results are depicted in panels C and D of figure 4.5. Visual inspection indicates that the model's properties are only marginally affected by this change in calibration. That is to be expected given the results in panel D of figure 4.4, where there is still substantial endogenous persistence even when there is no avenue for utilizing capital more intensively.

4.7.3. Labor supply elasticities

There is substantial disagreement over the size of labor supply elasticities. To investigate how sensitive our results are to our parameterization of a labor supply elasticity of 2, with elasticities of .4 and 1.6 on the intensive and extensive margins, we double each elasticity in panel C and halve each elasticity in panel D. The model results are indeed sensitive to these changes. With more elastic labor, the impact effect on output in now .58, the total multiplier rises to 8.88 and the mean lag rises to 2.76. The behavior of marginal cost is more subdued: the elasticity of marginal cost with respect to output falls to .25, from .33 in the benchmark. With a lower labor supply elasticity of one, the impact effect is reduced to .48, while the total multiplier and mean lag fall to 4.29 and 2.15 respectively. Marginal cost responds more aggressively, with an elasticity of .52. However, there is still greater persistence than in the CKM specification, and the impulse response functions are still hump shaped. The effect of the monetary shocks dissipates a little more quickly than in the benchmark specification, but huge labor supply elasticities are not required to generate important increases in persistence in the presence of materials and capital utilization.

5. Summary and conclusions

One of the most intensively active areas of macro research over the last decade has been the development of fully optimizing general equilibrium business cycle models that feature imperfect competition and sticky prices. These models of the new neoclassical synthesis can be used to evaluate the influences of monetary shocks and monetary policy rules on economic activity, as real business cycle models were previously used to study the effects of productivity. Early efforts to explore the empirical implications of these sticky price models for the volatility and comovement of nominal and real aggregates, such as that of King and Watson [1996], utilized the standard one-sector production function employed in early real business cycle research. These explorations were disappointing, in that simulations from the sticky price models arguably performed much worse than benchmark real business cycle models.

Recently Chari, Kehoe, and McGrattan [2000] have stressed that such models contain a substantial persistence problem. That is, monetary shocks have only transitory effects on real activity effects that do not persist beyond the duration of the exogenously imposed price fixity. In this paper, we trace the persistence problem to the supply side of the standard model, which makes marginal cost highly sensitive to changes in output, thus leading to aggressive price responses by those firms that adjust prices.

We incorporate empirically realistic real flexibilities into the supply side of the macroeconomic model by including important roles for materials inputs, variable capacity utilization, and variation in employment along an extensive margin. These modifications dramatically reduce the elasticity of marginal cost with respect to output and thus lead to more gradual price adjustment, which in turn implies greater persistence in economic activity. There are additional gains to using this more realistic supply side, in that we are able to match other empirical regularities that are at variance with the standard model. For example, our model produces near one-for-one comovement of output, hours, and materials and substantial comovement with capacity utilization. This comovement is a direct outgrowth of the real flexibilities view of production. Further, the real flexibilities view also results in models that have generate hump-shaped and persistent responses of real activity to monetary shocks.

Having shown the potential importance of supply-side real flexibilities, we think that there is important work to be done on refining estimates of crucial parameters–such as the elasticity of employment response and capacity utilization–as well as exploring the robustness of our results to alternative models of utilization and sectoral interrelationships in production. For example, it seems clear that some materials prices are procyclical but that others are lagging.

Other lines of macroeconomic research also may benefit from incorporating the real flexibilities view taken in this paper. Some macroeconomists such as Ball and Romer [1990] have added real wage rigidities into macroeconomic models that include nominal price rigidities of the form studied in this paper. We interpret this approach as providing an alternative explanation of why labor input is volatile while real wages are not. But if such approaches are to generate one-for-one comovement of output and hours, then it seems that they must also incorporate variable capacity utilization. Further, even if real wage movements are modest, marginal cost can still rise substantially if fixed capital input leads to sharply diminishing marginal products. Variable utilization and variable materials inputs serve to mitigate the effects of a largely predetermined capital stock. Therefore, taking a broader view of production will enhance the empirical properties of models with real wage rigidities. Along these lines, Christiano, Eichenbaum, and Evans [2005] incorporate both sticky nominal wages and varying capital utilization and find that they are important in helping their model match their estimates of the dynamic effects of monetary policy shocks. However, relative to that analysis, our work shows that there can be substantial persistence in sticky price models without real wage rigidities.

Given that persistence need not be a problem for this class of models, research on quantitative general equilibrium models can now focus on some other important issues. First, it is important to explore mechanisms that can change the dynamics of the nominal interest rate, since this rises in response to a positive monetary shock. Thus, the model fails to generate a liquidity effect. Although there is some empirical debate concerning the extent of this effect and whether it is time varying (see Gordon and Leeper [1992]), most economists believe that it is a feature of the economy. A crucial ingredient in the model's counterfactual response is that expected inflation rises rapidly. Increases in expected inflation at some horizons are inevitable because the long-run price level rises in response to the shock and the short-run price level is fairly sticky. Second, there is broad consensus that central banks use the interest rate rather than a money stock as an instrument. Interest rate policy rules can have important implications for the way the economy responds to monetary policy shocks, as stressed by Dotsey [2004A, 2004B]. It is, therefore, important to investigate whether monetary policy shocks give rise to persistent macroeconomic fluctuations when the central bank is following an interest rate rule, and, specifically, whether the liquidity effect puzzle carries over to such a setting. Third, we have studied the dynamic effects of monetary policy shocks under the assumption that agents correctly understand the persistent nature of the process generating the money supply and the inflationary objectives of the central bank. In some post war business cycle episodes this assumption seems inappropriate, so that it appears important to examine dynamic responses using alternative assumptions of expectations formation. Finally, we think that detailed empirical appraisal of this class of models is essential and that the supply-side articulated in this paper may improve their performance as positive models of business cycles.[29]

[29] Sims [1989] recommends the comparison of quantitative model impulse responses with those from estimated vector authoregressions, which is a natural proposal for the models in this paper.

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Figure 3.1
Evolution of "vintages" of price-setters

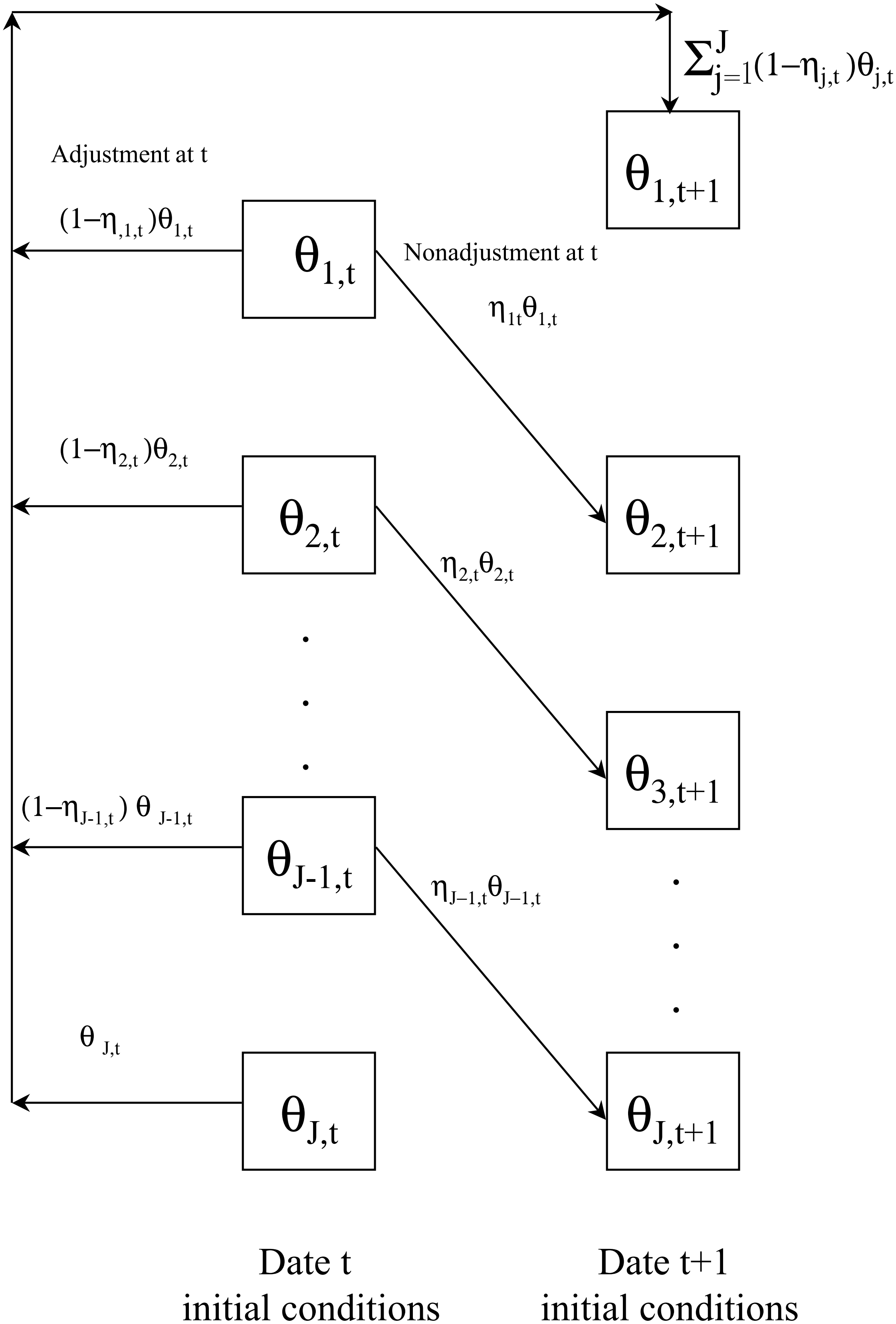

Figure 4.1 CKM Specification

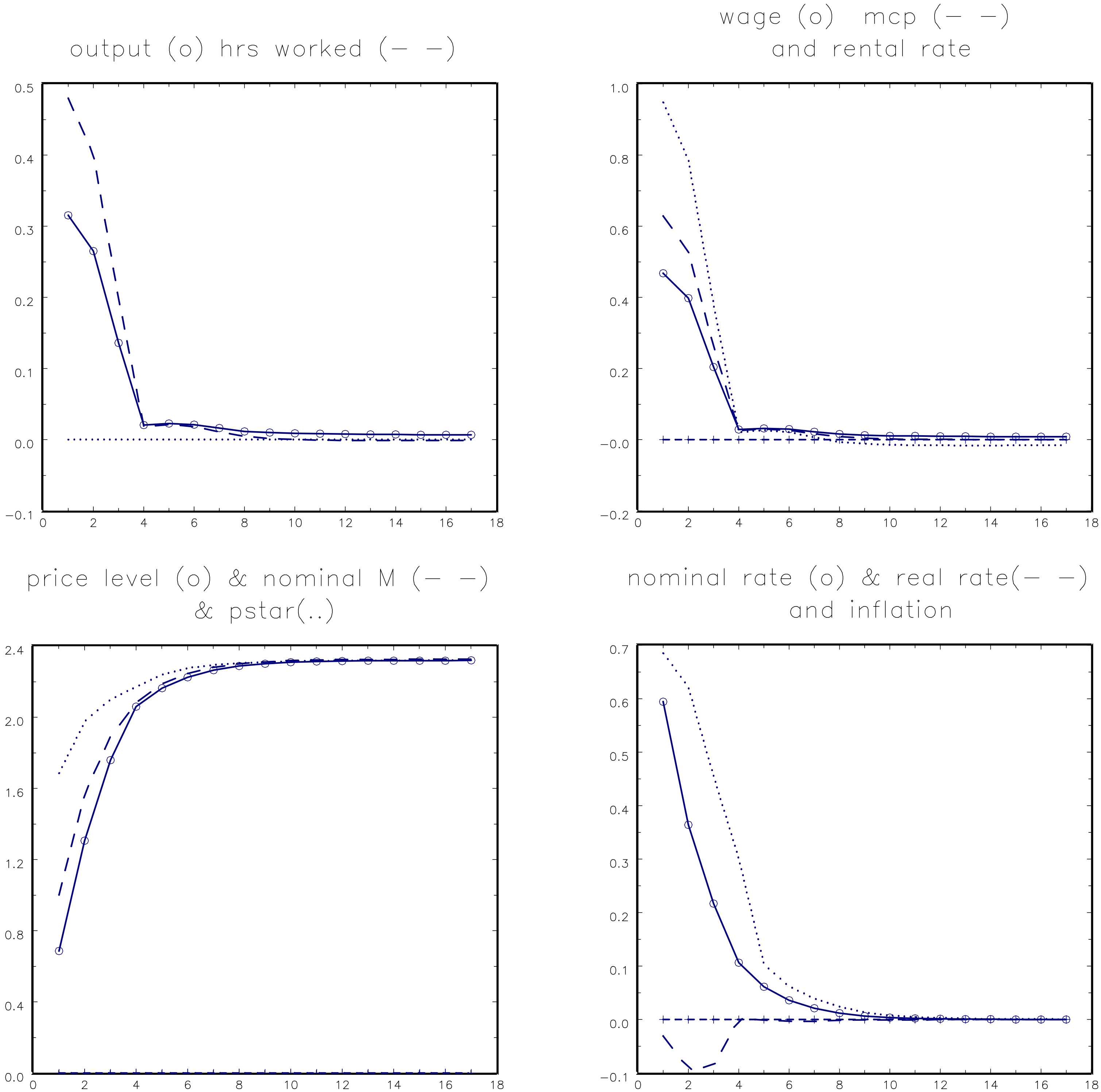

Figure 4.2 Benchmark

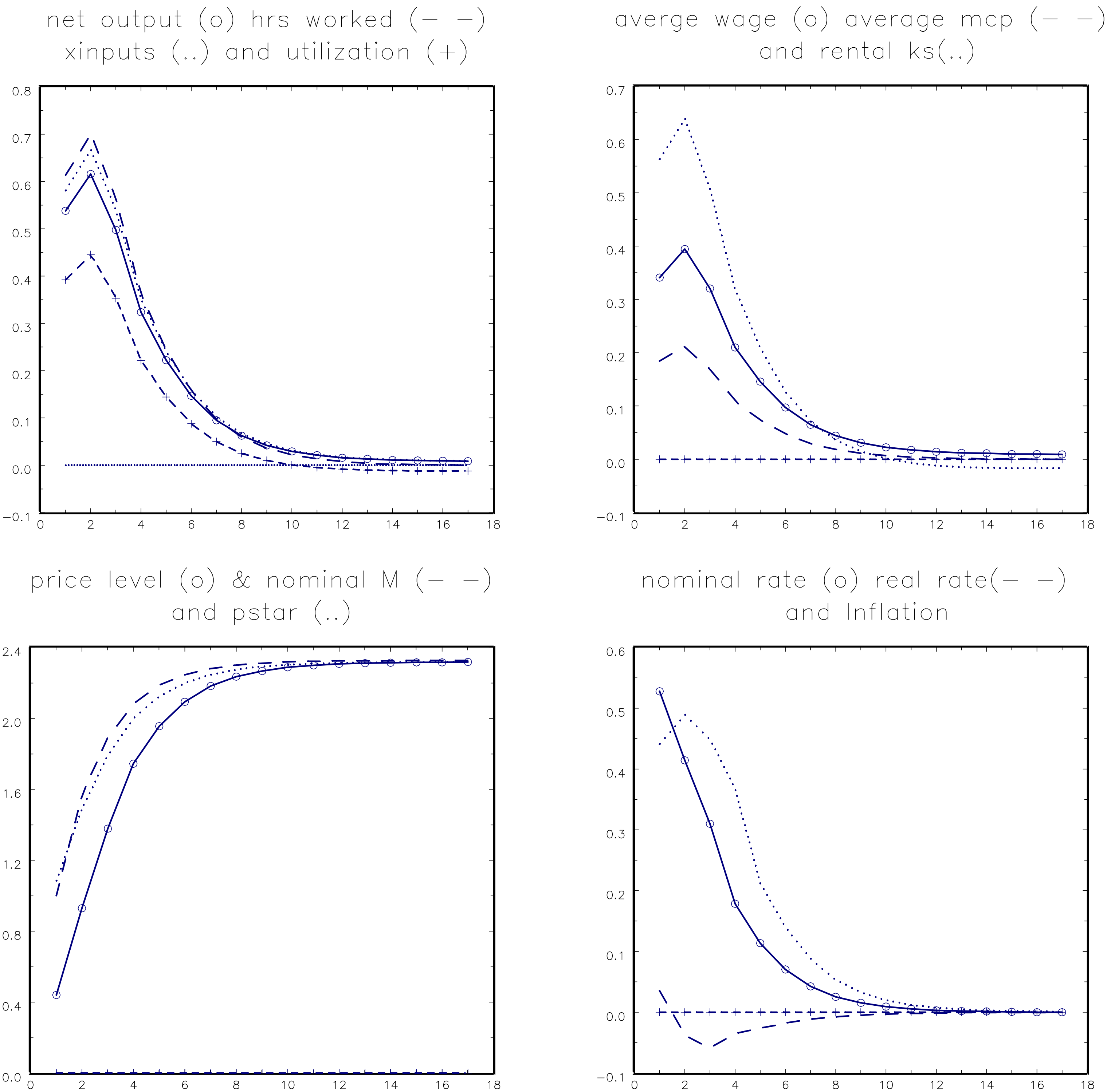

Figure 4.3 Benchmark with SDP

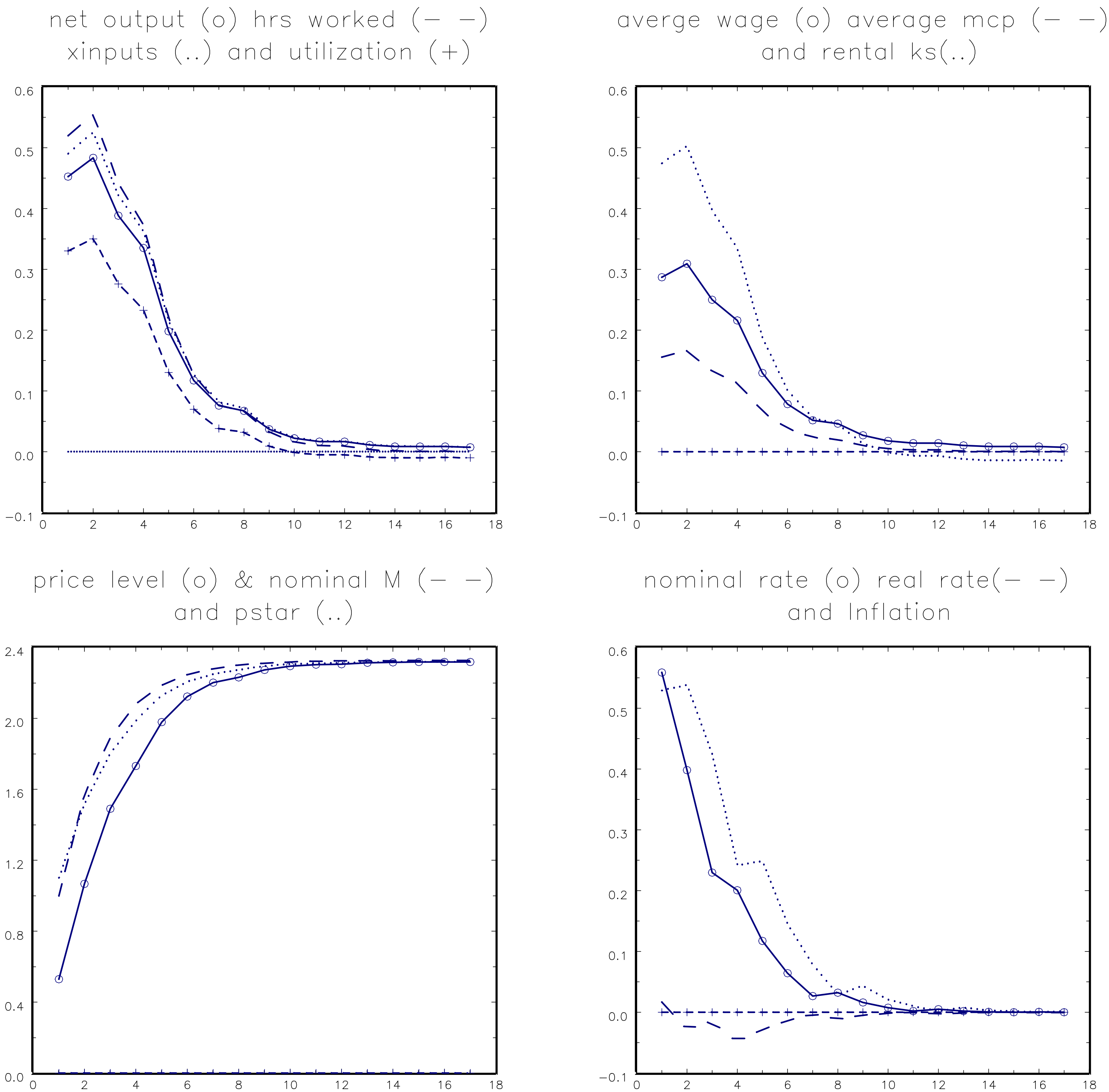

Figure 4.4 Sensitivity Of Responses in output (o) and marginal cost (- -)

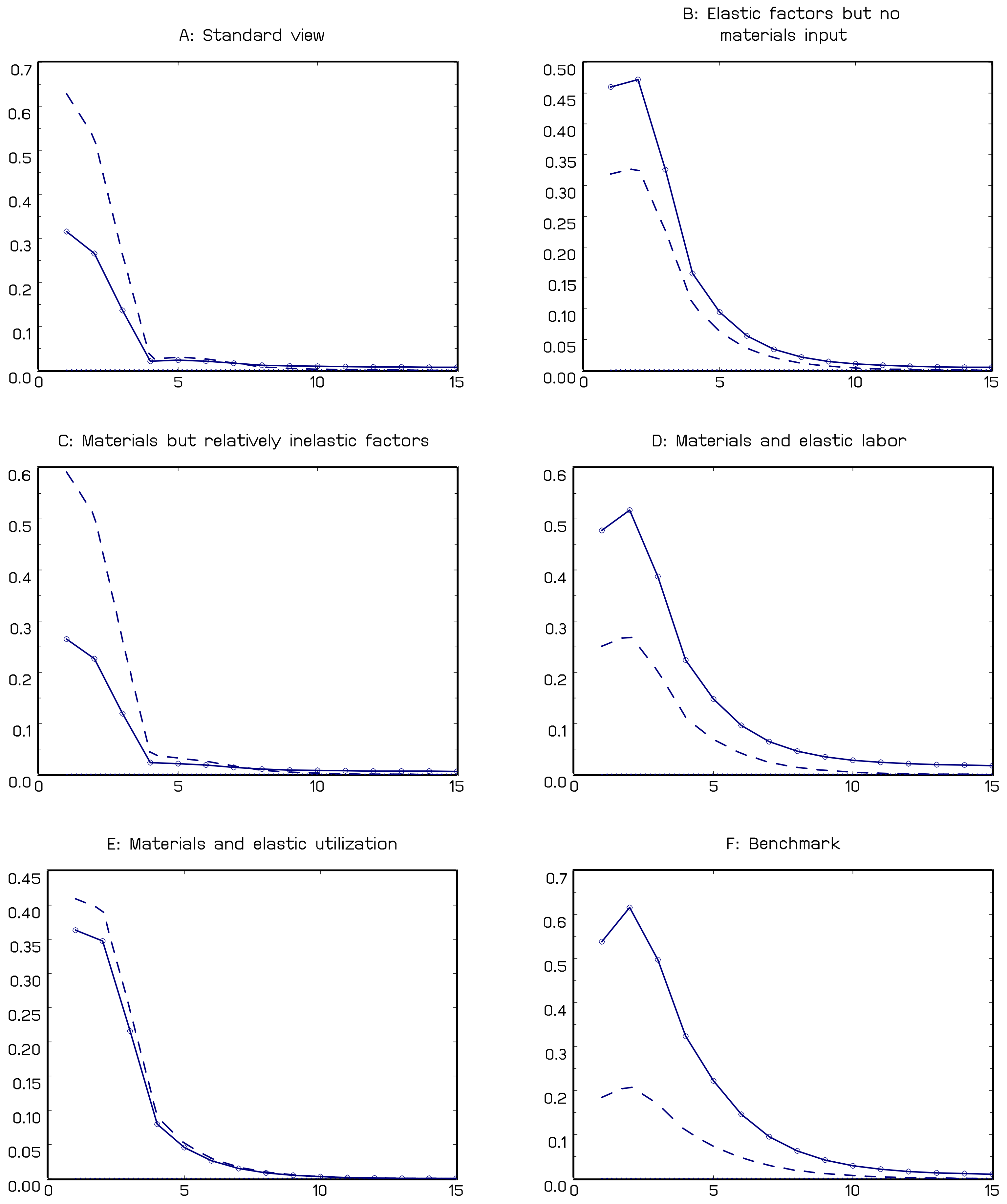

Figure 4.5 Robustness
output (o) P (--) and marginal cost (..)