Optimal Price Setting and Inflation Inertia in a Rational Expectations Model*

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Abstract

This paper presents and estimates a New Keynesian monetary model for the US economy. It proposes possible solutions to two problems in this model class, the lack of inflation inertia and persistence in versions of these models that insist on rigorous microfoundations and rational expectations, and the small contribution of technology shocks to business cycles.

Price setting takes the form of optimal two-part pricing policies formulated under conditions of upward-sloping firm-specific marginal cost curves. Furthermore, this form of price setting applies not only to prices and wages but also to user costs of capital. In this setting past inflation becomes a key determinant of current inflation, even though price setting is entirely forward-looking. Technology is modeled as a random walk, with technology growth shocks that follow a highly persistent process.

The model is estimated by Bayesian methods, and performs significantly better than a Bayesian VAR. It generates inertial and persistent inflation, and technology shocks account for a very large share of business cycle variation, especially at longer horizons.

JEL Classification Numbers:

Keywords: Inflation Inertia; Monetary Policy; Bayesian Estimation

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1 Introduction

A large body of research in monetary theory uses the assumption of nominal rigidities embedded in dynamic general equilibrium models. This model class, which gives rise to the so-called New Keynesian Phillips Curve (NKPC), has been quite successful in capturing many aspects of the dynamics of aggregate inflation and output. But some important problems remain, and have recently been much discussed. The most important is arguably the lack of inflation inertia and inflation persistence, and consequently the lack of significant real costs of disinflations, in those versions of New Keynesian models that insist on rigorous microfoundations and rational expectations. Inflation inertia refers to the delayed and gradual response of inflation to shocks, while inflation persistence refers to prolonged deviations of inflation from steady state following shocks. We propose three interrelated ways in which a rational expectations model can address this problem, and subject their contribution to a Bayesian econometric evaluation. Another empirical problem in New Keynesian models is the very small contribution of technology shocks to macroeconomic dynamics. We motivate and introduce a way of modeling technology shocks that greatly increases their contribution to the business cycle.

Given strong empirical evidence on inflation inertia[1] and on sizeable sacrifice ratios during disinflations[2], the inability of New Keynesian models to generate these effects is potentially a serious shortcoming. We survey the literature that has struggled with this problem, and then suggest a new approach. Ours is a structural, optimizing model with rational expectations. It relies neither on learning nor on ad hoc lagged terms in the Phillips curve.

The difficulties with the empirical performance of New Keynesian models have led different researchers to very different conclusions about the usefulness of structural modeling of the inflation process. On the one hand Rudd and Whelan (2005a/b/c) conclude that current versions of the NKPC fail to provide a useful empirical description of the inflation process, especially relative to traditional econometric Phillips curves of the sort commonly employed at central banks for policy analysis and forecasting. On the other hand we have papers like Cogley and Sbordone (2005) and Coenen and Levin (2004). The former conclude that the conventional NKPC provides a good representation of the empirical inflation process if a shifting trend in the inflation process is allowed for. However, the work of Paloviita (2004) suggests that a shifting inflation trend, while useful to improve the empirical fit of the NKPC, does not remove the need for an additional lagged inflation term. Coenen and Levin (2004) also find in favor of the conventional NKPC, in this case conditional on the presence of a stable and credible monetary policy regime and of significant real rigidities. But on the other hand, Altig, Christiano, Eichenbaum and Linde (2005), who employ similar real rigidities, continue to use indexation to lagged inflation to obtain a good fit for their model. The majority of the profession seems to hold an intermediate view, exemplified by Galí, Gertler and Lopez-Salido

[1] Mankiw (2001), Fuhrer and Moore (1995).

[2] Gordon (1982, 1997).

(2005), who find that backward-looking price setting behavior, of the sort that would generate high intrinsic inflation inertia, is quantitatively modest but nevertheless statistically significant.[3] The research program exemplified by Altig, Christiano, Eichenbaum and Linde (2005) and Eichenbaum and Fisher (2004) also falls into this category.

The view that there is significant structural inflation inertia left to be explained is our working hypothesis in this paper. In reviewing the currently dominant approaches that are based on the same working hypothesis, we find it useful to distinguish models that do or do not rely on rational expectations.

The latter category includes learning models such as Erceg and Levin (2003), and 'sticky information' as in Mankiw and Reis (2002). This literature mostly, although not exclusively, concentrates on private sector learning, or information acquisition, about monetary policy.[4] As such it has been successful in explaining inflation behavior observed during transitions between monetary regimes. But unless it is expanded to cover learning about all shocks in the model, it has less to say about the persistence observed during periods of stable monetary policy, meaning persistence in response to non-monetary shocks that affect the driving terms of pricing. Furthermore, learning is not the only candidate to explain persistence during transitions, structural inertia in a rational expectations model may be another. While we do feel that learning plays a very important role, the task we set ourselves in this paper is to see how far a rational expectations model alone, but one that features realistic pricing rigidities, can take us. But at the same time we want to take account of the results of Cogley and Sbordone (2005) concerning the importance of a shifting trend in the inflation target. As such, our model allows for a unit root in the central bank's inflation target and uses data on long-term inflation expectations to identify the shocks to that target.

A popular approach to introducing inflation inertia into rational expectations models is the 'hybrid' NKPC, introduced by Clarida, Galí and Gertler (1999) and Galí and Gertler (1999). This combines a rational forward-looking element with some dependence on lagged inflation. A similar role is played by indexation to past inflation in the work of Christiano, Eichenbaum and Evans (2005) and other more recent work. But Rudd and Whelan (2005c) make an important point concerning both of these approaches: At least as far as price setting is concerned, their microfoundations are quite weak, and they are as open to the Lucas critique as the traditional models they seek to replace. In our work we replace these pricing assumptions with rational, forward-looking optimization that is nevertheless capable of generating significant inertia. Moreover, in an important sense our price setting assumptions are less restrictive than even those of the conventional Calvo model.

Another area of active research within rational expectations models has been models of firm-specific capital.[5] A textbook treatment is contained in Woodford (2003). Often, as in the work of Altig, Christiano, Eichenbaum and Linde (2005) and Eichenbaum and Fisher (2004), this has been combined with index-

[3] However, Rudd and Whelan (2005c) criticize that result on various empirical grounds.
[4] An exception is Ehrmann and Smets (2003), who analyze cost-push shocks.
[5] Many authors have combined this with a non-constant elasticity of demand.

ation to generate inertia, and it is not always clear which of the two is the more important factor, but the work of Coenen and Levin (2004) suggests that firm-specific capital can be powerful even without indexation. The work of Bakshi, Burriel-Llombart, Khan and Rudolf (2003) shows why this is such an important idea. They demonstrate that conventional price-setting in a Calvo model without firm-specific capital has firms optimally choosing prices that imply a very large variability in demand and therefore in output. It is clear that in the real world such variability is very costly to firms, and one of the many reasons is the cost of adjusting firm-specific factors. If such factors are allowed for, an increase in the firm's price, by reducing demand, lowers marginal cost and thereby the amount by which the price optimally needs to be raised. Firm-specific factors need not be limited to capital, but can include labor adjustment costs, land, time delays to order intermediate goods, etc. In reality probably all of these are important, but modeling all of them may be too complex. We therefore adopt the same concept but simplify its modeling by way of a generalized upward-sloping short-run marginal cost curve. Our analytical results are indistinguishable, in substantive terms, from a model with firm specific capital. We would also add that firm-specific factors may not be the main consideration for a firm in avoiding output/demand volatility. Instead, highly volatile output demand induced by frequent relative price changes is likely to damage customer relationships, and the induced volatility in intermediate inputs demand will also damage relationships with suppliers of those inputs. The recent ECB (2005) survey evidence on price setting suggests that firms do indeed cite customer relationships much more frequently than input costs as reasons for avoiding large price changes. Such notions are encompassed in a generalized upward-sloping marginal cost curve.

Our work generates inflation inertia for three interrelated reasons. First, real marginal cost, the main driving force of inflation, is itself inertial. Second, the sensitivity of inflation to marginal cost is low. And third, for a given marginal cost, firms' optimal pricing behavior implies that past inflation is a very important determinant of current inflation.[6] We briefly explain each of these points in turn.

In realistic dynamic models it is common, and supported by independent empirical evidence, to introduce real rigidities that imply a delayed response of aggregate demand to shocks. This in turn implies a delayed response of marginal cost. Our own model follows this literature, in assuming both habit persistence in consumption and investment adjustment costs. But in addition we assume that *each* of the components of marginal cost is subject to pricing rigidities. Wage rigidities are commonly assumed, but if capital enters the production function, sticky wages alone may not be sufficient to make overall marginal cost inertial. We propose that user costs of capital are in fact also rigid. Interest rate margins on corporate bank loans and interest rates on corporate bonds change only infrequently, and so do dividend policies. As such, it seems doubtful that

[6]ECB (2005) refers to the first two factors as extrinsic persistence, and to the third as intrinsic persistence.

the prices firms pay for their capital services are as volatile as suggested by standard models. Of course we do not provide direct empirical evidence on this question in this paper, but we can and do assess the implications of this assumption for the statistical fit of our model.

The sensitivity of inflation to marginal cost is low in our model, and it depends on the same factors as in models of firm-specific capital. Our generalized upward-sloping marginal cost curve is derived from a quadratic cost of deviations of an individual firm's output from industry-average output. The consequence is that the sensitivity of inflation to marginal cost is decreasing in the steepness of the marginal cost curve and in the price elasticity of demand. The same type of quadratic term also features in wage setting and in the setting of user costs by an individual provider of capital, referred to as an intermediary.

Firms' price setting behavior in our model is both optimizing and forward-looking, yet past inflation becomes an important determinant of current inflation. We think of a price setting firm as operating in an environment with positive trend inflation where collecting and responding to information about the macroeconomic environment is costly, which is documented as an important consideration for real world price setting in Zbaracki, Ritson, Levy, Dutta and Bergen (2004). This idea, which is different from the menu costs idea of Akerlof and Yellen (1985), can be formally modeled, see Devereux and Siu (2004). But more commonly, as in Christiano, Eichenbaum and Evans (2005) and a large literature that follows Yun (1996), it is used - without explicit modeling of the adjustment costs - as a rationale for models in which firms *change* prices every quarter but only *reoptimize* their pricing policies more infrequently. As such these models are not inconsistent with the recent empirical evidence for price setting of Bils and Klenow (2004), Klenow and Kryvtsov (2004), and Golosov and Lucas (2003), which points to an average frequency of price changes of once every 1.5 quarters for consumer prices. We follow this literature, which therefore posits that in intervals between reoptimizations firms follow simple rules of thumb. The critical question is, what is a sensible rule of thumb? The Yun (1996) approach assumes that firms set their initial price and thereafter update at the steady state inflation rate. But of course this is the approach that has been found to give rise to almost no inflation inertia in New Keynesian models. The indexation approach of Christiano, Eichenbaum and Evans (2005) addresses that problem by assuming that non-optimizing firms index their price to past inflation. But in both cases firms can really only choose their initial price, while the rule of thumb itself is not a choice variable. This feature is what has been criticized by Rudd and Whelan (2005b) and some others as not consistent with the Lucas critique, or *ad hoc*.

We adopt a different approach - firms can *choose* both their initial price level and their rule of thumb, specifically the rate at which they update their own price, the 'firm-specific inflation rate'.[7] Their objective is to keep them as close as possible to their steadily increasing flexible price optimum between the times at which price changing opportunities arrive. Furthermore, as men-

[7] The approach was first introduced by Calvo, Celasun and Kumhof (2001, 2002).

tioned above, their choice is subject to an increasing firm-specific marginal cost curve, which biases firms towards adjusting mainly their updating rate unless the shocks they face are transitory. They would otherwise experience excessive relative price fluctuations and therefore costly output volatility throughout the duration of a pricing policy. At any point in time, this combination of firm-specific pricing policies and firm-specific marginal cost curves makes the historic pricing decisions of currently not optimizing firms an important determinant of current inflation. Or in other words, past inflation is an important determinant of current inflation. This is true even though firms that do optimize do so under both rational expectations and fully optimizing behavior. We emphasize that this modelling of price setting, by letting firms choose two instead of one pricing variable optimally, imposes fewer exogenous constraints on the firm's profit maximization problem than either the Calvo-Yun model or a model with indexation. In this important sense the model is therefore less *ad hoc*.

Finally, note that if price setters behave as in our model, their behavior can be quite similar to that implied by learning or sticky information in that at any time a large share of firm specific inflation rates was chosen based on macroeconomic information available at the time of the last reoptimization. We expect this similarity to become an important factor once our model is applied to transitions between different monetary regimes.

In several previous attempts to estimate DSGE models it has been common to either detrend the data or to assume that total factor productivity follows a trend-stationary process—see Juillard and others (2005) and Smets and Wouters (2004). We argue that both approaches impose limitations on the ability of DSGE models to explain key stylized facts at business cycle frequencies such as the strong comovement between hours worked and aggregate output. We allow for a more general stochastic process where there are both temporary changes in the growth rate of total factor productivity as well as highly autocorrelated deviations from an underlying steady-state growth rate. We show that the latter assumption helps the model to explain the strong comovement between hours worked and GDP in the short run as well as the strong positive correlation between consumption and investment over time. Interestingly, we show that shocks which are interpreted as revisions in medium-term growth prospects produce predictions for output, consumption, investment and hours worked that look very similar to what previous generations of non-DSGE models would have attributed to animal spirits, or persistent increases in consumer and business sentiment.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 discusses the estimation methodology, the calibration of parameters that determine the steady state, and the choice of Bayesian priors for parameters that drive the model's dynamics. Section 4 presents our Bayesian estimation results, divided into parameter estimates and impulse responses for a baseline case and a sensitivity analysis that compares the fit of the baseline case with various alternatives that restrict different sets of parameters. Section 5 concludes.

2 The Model

The economy consists of a continuum of measure one of households indexed by $i \in [0,1]$, a continuum of firms indexed by $j \in [0,1]$, a continuum of financial intermediaries indexed by $z \in [0,1]$, and a government.

2.1 Households

Household i maximizes lifetime utility, which depends on his per capita consumption $C_t(i)$, leisure $1 - L_t(i)$ (where 1 is the fixed time endowment and $L_t(i)$ is labor supply), and real money balances $M_t(i)/P_t$ (where $M_t(i)$ is nominal money and P_t is the aggregate price index):

$$Max \quad E_0 \sum_{t=0}^{\infty} \beta^t \left\{ S_t^c (1-v) \log(H_t(i)) - S_t^L \psi \frac{L_t(i)^{1+\frac{1}{\gamma}}}{1+\frac{1}{\gamma}} + \frac{a}{1-\epsilon} \left(\frac{M_t(i)}{P_t} \right)^{1-\epsilon} \right\} . \tag{1}$$

Throughout, shocks are denoted by S_t^x, where x is the variable subject to the shock. Households exhibit external habit persistence with respect to C_t^i, with habit parameter ν:

$$H_t(i) = C_t(i) - \nu C_{t-1} \ . \tag{2}$$

Consumption C_t^i is a CES aggregator over individual varieties $c_t(i,j)$, with time-varying elasticity of substitution $\sigma_t > 1$,

$$C_t(i) = \left(\int_0^1 c_t(i,j)^{\frac{\sigma_t - 1}{\sigma_t}} dj \right)^{\frac{\sigma_t}{\sigma_t - 1}} \quad , \tag{3}$$

and the aggregate price index P_t is the consumption based price index associated with this consumption aggregator,

$$P_t = \left(\int_0^1 P_t(j)^{1-\sigma_t} dj \right)^{\frac{1}{1-\sigma_t}} \quad . \tag{4}$$

Households accumulate capital according to

$$K_{t+1}(i) = (1-\Delta) K_t(i) + I_t(i) \ . \tag{5}$$

We assume that demand for investment goods takes the same CES form as demand for consumption goods, equation (3), which implies identical demand functions for goods varieties j.

In addition to capital, households accumulate money and one period nominal government bonds $B_t(i)$ with gross nominal return i_t.[8] Their income consists of nominal wage income $W_t(i) L_t(i)$, nominal returns to capital $R_t^k K_t(i)$, and lump-sum profit redistributions from firms and intermediaries $\int_0^1 \Pi_t(i,j) dj$ and

[8] All financial interest rates and inflation rates, but not rates of return to capital, are expressed in gross terms.

$\int_0^1 \Pi_t(i,z)dz$. Expenditure consists of consumption spending $P_tC_t(i)$, investment spending $P_tI_t(i)(1+S_t^I)$, where S_t^I is an investment shock, lump-sum taxation $P_t\tau_t$, quadratic capital and investment adjustment costs, and quadratic costs of deviating from the economywide average labor supply (more on this below). The budget constraint is therefore

$$\begin{aligned}
B_t(i) &= (1+i_{t-1})B_{t-1}(i) + M_{t-1}(i) - M_t(i) \\
&\quad + W_t(i)L_t(i) + R_t^k K_t(i) + \int_0^1 \Pi_t(i,j)dj + \int_0^1 \Pi_t^z(i,z)dz \\
&\quad - P_tC_t(i) - P_tI_t(i)(1+S_t^I) - P_t\tau_t(i) \\
&\quad - P_t\frac{\theta_k}{2}K_t(i)\left(\frac{I_t(i)}{K_t(i)} - \Delta\right)^2 - P_t\frac{\theta_i}{2}K_t(i)\left(\frac{I_t(i)}{K_t(i)} - \frac{I_{t-1}}{K_{t-1}}\right)^2 \\
&\quad - W_t\frac{\phi_w}{2}\frac{(L_t(i)-L_t)^2}{L_t} \quad .
\end{aligned} \tag{6}$$

We assume complete contingent claims markets for labor income, and identical initial endowments of capital, bonds and money. Then all optimality conditions will be the same across households, except for labor supply. We therefore drop the index i. The multiplier for the budget constraint (6) is denoted by λ_t/P_t, and the multiplier of the capital accumulation equation (5) is $\lambda_t q_t$, where q_t is Tobin's q. Then the first-order conditions for $c_t(j)$, B_t, C_t, I_t and K_{t+1}, are as follows:

$$c_t(j) = C_t\left(\frac{P_t(j)}{P_t}\right)^{-\sigma_t} \quad , \tag{7}$$

$$\lambda_t = \beta i_t E_t\left(\frac{\lambda_{t+1}}{\pi_{t+1}}\right) \tag{8}$$

$$\frac{S_t^c(1-v)}{H_t} = \lambda_t \tag{9}$$

$$q_t = 1 + \theta_k\left(\frac{I_t}{K_t} - \Delta\right) + \theta_i\left(\frac{I_t}{K_t} - \frac{I_{t-1}}{K_{t-1}}\right) + S_t^I \tag{10}$$

$$\begin{aligned}
\lambda_t q_t &= \beta E_t\lambda_{t+1}\Big[q_{t+1}(1-\Delta) + r_{t+1}^k \\
&\quad + \theta_k\left(\frac{I_{t+1}}{K_{t+1}} - \Delta S_{t+1}^I\right)\frac{I_{t+1}}{K_{t+1}} + \theta_i\left(\frac{I_{t+1}}{K_{t+1}} - \frac{I_t}{K_t}\right)\frac{I_{t+1}}{K_{t+1}} \\
&\quad - \frac{\theta_k}{2}\left(\frac{I_{t+1}}{K_{t+1}} - \Delta S_t^I\right)^2 - \frac{\theta_i}{2}\left(\frac{I_{t+1}}{K_{t+1}} - \frac{I_t}{K_t}\right)^2\Big]
\end{aligned} \tag{11}$$

We will return to the household's wage setting problem at a later point, as we will be able to exploit analogies with firms' price setting. Full derivations of all first-order conditions in the paper, their transformation into a stationary system through normalization by technology and the inflation target, and their linearization, are presented in a separate Technical Appendix (available on request).

2.2 Firms

Each firm j sells a distinct product variety. Heterogeneity in price setting decisions and therefore in demand for individual products arises because each firm receives its price changing opportunities at different, random points in time. We first describe the cost minimization problem and then move on to profit maximization.

2.2.1 Cost Minimization

The production function for variety j is Cobb-Douglas in labor $\ell_t(j)$ and capital $k_t(j)$:

$$y_t(j) = \left(S_t^y \ell_t(j)\right)^{1-\alpha} k_t(j)^{\alpha} \quad , \tag{12}$$

where

$$\ell_t(j) = \left(\int_0^1 L_t(i,j)^{\frac{\sigma_t^w - 1}{\sigma_t^w}} di \right)^{\frac{\sigma_t^w}{\sigma_t^w - 1}} \quad , \tag{13}$$

$$k_t(j) = \left(\int_0^1 k_t(z,j)^{\frac{\sigma^k - 1}{\sigma^k}} dz \right)^{\frac{\sigma^k}{\sigma^k - 1}} \quad , \tag{14}$$

where the last two equations state that each firm employs a CES aggregate of different labor and capital varieties supplied by different households and financial intermediaries. Let w_t be the aggregate real wage (the cost of hiring the aggregate (13)), and u_t the aggregate user cost of capital (the cost of hiring the aggregate (14)). These are determined in competitive factor markets and discussed in more detail below. Then the real marginal cost corresponding to (12) is

$$mc_t = A \left(\frac{w_t}{S_t^y} \right)^{1-\alpha} (u_t)^{\alpha} \quad , \tag{15}$$

where $A = \alpha^{-\alpha}(1-\alpha)^{-(1-\alpha)}$. Technology S_t^y is stochastic and consists of both i.i.d. shocks to the level of technology and of highly persistent shocks to the growth rate of technology:

$$S_t^y = S_{t-1}^y g_t \quad , \tag{16}$$

$$g_t = g_t^{gr} g_t^{iid} \quad ,$$

$$\ln g_t^{gr} = (1-\rho_g) \ln \bar{g} + \rho_g \ln g_{t-1}^{gr} + \hat{\varepsilon}_t^{gr} \quad ,$$

$$\ln g_t^{iid} = \hat{\varepsilon}_t^{iid} \quad .$$

Let $\tilde{Y}_t = \int_0^1 y_t(j)dj$, $\ell_t = \int_0^1 \ell_t(j)dj$, and $k_t = \int_0^1 k_t(j)dj$. Given that factor markets are competitive so that all firms face identical costs of hiring aggregates of capital and labor (13) and (14), we can derive the following aggregate input demand conditions:

$$\ell_t = (1-\alpha) \frac{mc_t}{w_t} \tilde{Y}_t \quad , \tag{17}$$

$$k_t = \alpha \frac{mc_t}{u_t} \tilde{Y}_t \quad . \tag{18}$$

2.2.2 Profit Maximization

Following Calvo (1983) it is assumed that each firm receives price changing opportunities that follow a geometric distribution. Therefore the probability $(1 - \delta)$ of a firm's receiving a new opportunity is independent of how long ago it was last able to change its price. It is also independent across firms, so that it is straightforward to determine the aggregate distribution of prices. Each firm maximizes the present discounted value of real profits. The first two determinants of profits are real revenue $P_t(j)y_t(j)/P_t$ and real marginal cost $mc_t y_t(j)$. In each case demand is given by

$$y_t(j) = Y_t \left(\frac{P_t(j)}{P_t} \right)^{-\sigma_t} \quad , \tag{19}$$

which follows directly from consumer demand functions (7) and identical demands from investors and government (see below). Two key features of our model concern first the manner in which firms set their prices when they receive an opportunity to do so, and the cost (through excessively large or small demand) of setting prices far away from prevailing average market prices P_t. To model the latter, we assume that firms face a small quadratic cost Φ_t of deviating from the output level of its average competitor, meaning the firm that charges the current market average price. The cost is therefore

$$\Phi_t = \frac{\phi}{2} Y_t \left(\frac{y_t(j) - Y_t}{Y_t} \right)^2 \quad . \tag{20}$$

The term Y_t in front of the quadratic term serves as a scale factor. As for price setting, we assume that when a firm j gets an opportunity to decide on its pricing policy, it chooses both its current price level $V_t(j)$ and the gross rate $v_t(j)$ at which it will update its price from today onwards until the time it is next allowed to change its policy. At any time $t + k$ when the time t policy is still in force, its price is therefore

$$P_{t+k}(j) = V_t(j)(v_t(j))^k \quad . \tag{21}$$

As for the possibility of introducing even more general price paths, it seems natural to focus on equilibria characterized by a constant expected long-run growth rate of the nominal anchor.[9] The model can then be solved by linearizing around that growth path, in which case it is sufficient to allow firms to specify their pricing policies up to the growth rate of their price path. This permits the use of conventional solution methods, which makes quantitative analysis much more straightforward.

Firms discount profits expected in period $t + k$ by the k-period ahead real intertemporal marginal rate of substitution and by δ^k, the probability that their period t pricing policy will still be in force k periods from t. They take into

[9] This includes both a constant steady state growth rate of the nominal anchor and a unit root in that growth rate, as in this paper.

account aggregate demand for their output (19). The firm specific index j can be dropped in what follows because all firms that receive a price changing opportunity at time t will behave identically. Their profit maximization problem is therefore

$$\underset{V_t,v_t}{Max} E_t \sum_{k=0}^{\infty} (\delta\beta)^k \lambda_{t+k} \left[\left(\frac{V_t (v_t)^k}{P_{t+k}} \right)^{1-\sigma_t} Y_{t+k} \right. \tag{22}$$

$$\left. -mc_{t+k} \left(\frac{V_t (v_t)^k}{P_{t+k}} \right)^{-\sigma_t} Y_{t+k} - \frac{\phi}{2} Y_{t+k} \left(\frac{y_{t+k}(j) - Y_{t+k}}{Y_{t+k}} \right)^2 \right] .$$

We define the front-loading term for price setting, the ratio of a new price setter's first period price to the market average price, as $p_t \equiv V_t/P_t$, cumulative aggregate inflation as $\Pi_{t,k} \equiv \prod_{j=1}^{k} \pi_{t+j}$ for $k \geq 1$ ($\equiv 1$ for $k = 0$), and the mark-up term as $\mu_t = \frac{\sigma_t}{\sigma_t - 1}$. Then the firm's first order conditions for the choice of its initial price level V_t and its inflation updating rate v_t are

$$p_t = \mu_t \frac{E_t \sum_{k=0}^{\infty} (\delta\beta)^k \lambda_{t+k} y_{t+k}(j) \left(mc_{t+k} + \phi \left(\frac{y_{t+k}(j) - Y_{t+k}}{Y_{t+k}} \right) \right)}{E_t \sum_{k=0}^{\infty} (\delta\beta)^k \lambda_{t+k} y_{t+k}(j) \left(\frac{(v_t)^k}{\Pi_{t,k}} \right)} , \tag{23}$$

$$p_t = \mu_t \frac{E_t \sum_{k=0}^{\infty} (\delta\beta)^k k \lambda_{t+k} y_{t+k}(j) \left(mc_{t+k} + \phi \left(\frac{y_{t+k}(j) - Y_{t+k}}{Y_{t+k}} \right) \right)}{E_t \sum_{k=0}^{\infty} (\delta\beta)^k k \lambda_{t+k} y_{t+k}(j) \left(\frac{(v_t)^k}{\Pi_{t,k}} \right)} . \tag{24}$$

The intuition for this result becomes much clearer once these conditions are log-linearized and combined with the log-linearization of the aggregate price index. As this is algebraically very involved, the details are presented in the Technical Appendix. We discuss the key equations here. They replace the traditional one-equation New Keynesian Phillips curve with a three-equation system in $\hat{\pi}_t$, $\hat{v}_t$ and an inertial variable $\hat{\psi}_t$:

$$E_t \hat{\pi}_{t+1} = \hat{\pi}_t \left(\frac{2}{\beta} - \delta \right) + \hat{v}_t \left((1-\delta)(1+\delta) \right) + \hat{\psi}_t \left(\delta(1+\delta) - \frac{2}{\beta} \right) \tag{25}$$

$$- \frac{2(1-\delta)(1-\delta\beta)}{(\delta\beta)(1+\phi\bar{\mu}\bar{\sigma})} \left(\widehat{mc}_t + \hat{\mu}_t \right) + \frac{(1-\delta)}{(1+\phi\bar{\mu}\bar{\sigma})} \left(E_t \hat{\mu}_{t+1} - \hat{\mu}_t \right) ,$$

$$E_t \hat{v}_{t+1} = \hat{v}_t + \frac{(1-\delta\beta)^2}{(\delta\beta)^2} \frac{\delta}{1-\delta} \hat{\psi}_t - \frac{(1-\delta\beta)^2}{(\delta\beta)^2} \frac{\delta}{1-\delta} \hat{\pi}_t \tag{26}$$

$$+ \frac{(1-\delta\beta)^2}{(\delta\beta)^2 (1+\phi\bar{\mu}\bar{\sigma})} \left(\widehat{mc}_t + \hat{\mu}_t \right) ,$$

$$\hat{\psi}_t = \delta \hat{\psi}_{t-1} + (1-\delta) \hat{v}_{t-1} - \hat{\varepsilon}_t^{\pi^*} . \tag{27}$$

Equations (25) and (26) show the evolution of the two forward-looking variables, $\hat{\pi}_t$ and $\hat{v}_t$. The most notable feature is the presence of the term $(1 + \phi\bar{\mu}\bar{\sigma})$ in the denominator of the terms multiplying marginal cost. It results from the upward-sloping firm-level marginal cost curve, and as long as $\phi > 0$ it makes prices less sensitive to changes in marginal cost. Note that both the steepness of the marginal cost curve ϕ and the elasticity of the demand curve $\bar{\sigma}$ affect this term. Equation (27) is, in deviation form and allowing for permanent changes in the inflation target $\hat{\varepsilon}_t^{\pi^*}$, the weighted average of all those past firm-specific inflation rates $\hat{v}_t$ that are still in force between periods $t-1$ and t, and which therefore enter into period t aggregate inflation. This term is inertial, and the degree of inertia depends directly on δ and therefore on the average contract length.

The following key equation follows from the differencing and log-linearization of the aggregate price index:

$$\hat{\pi}_t = \frac{1-\delta}{\delta}\hat{p}_t + \hat{\psi}_t \quad . \tag{28}$$

The two components of this equation reflect the two main sources of aggregate inflation inertia in response to shocks. The first term $\hat{p}_t$ represents inflation caused by significant instantaneous price changes (relative to the aggregate price level) of new price setters, so called 'front loading'. Note that in a Calvo-Yun model this is the only term driving inflation. But in our case the quadratic cost term means that significant front loading can be very costly, because it generally causes big deviations from industry average output during part of the duration of a pricing policy. New price setters will therefore respond as much as possible through changes in their updating rates $\hat{v}_t$. But these only slowly feed through to aggregate inflation via $\hat{\psi}_t$, which initially mainly reflects the continuing effects of price updating decisions made before the current realization of shocks. The result is that past inflation, by (28) and (27), becomes a key determinant of current inflation.

In our sensitivity analysis we will report not only the fit of our model, but also that of a Calvo (1983) model with Yun (1996) indexation to steady state inflation, augmented as in the baseline case by firm-specific marginal cost and sticky user costs. That model, in our case with markup shocks, gives rise to the following one-equation representation of the inflation process, the New Keynesian Phillips curve:

$$\hat{\pi}_t = \beta\hat{\pi}_{t+1} + \frac{((1-\delta\beta)(1-\delta))}{\delta(1+\phi\bar{\mu}\bar{\sigma})}\widehat{mc}_t + \frac{(1-\delta)}{\delta(1+\phi\bar{\mu}\bar{\sigma})}\left(\hat{\mu}_t - \delta\beta\hat{\mu}_{t+1}\right) \quad . \tag{29}$$

This equation can be directly derived from (25), (26) and (27) by setting $\hat{v}_t = \hat{\psi}_t = 0$. In other words, a firm in our model is always free to behave exactly like a Calvo-Yun price setter by front-loading all its price changes into the current price. However, this is generally far from optimal, especially if the processes driving inflation are highly persistent. And for aggregate inflation dynamics, as is well known, this kind of price setting implies very little inflation inertia and persistence.

2.3 Household Wage Setting

Every firm j must use composite labor (13), a CES aggregate with elasticity of substitution σ_t^w of the labor varieties supplied by different households. Firms' costs minimization, aggregated over all firms, yields demands

$$L_t(i) = L_t \left(\frac{W_t(i)}{W_t} \right)^{-\sigma_t^w} \quad , \tag{30}$$

where the aggregate nominal wage is given by

$$W_t = \left(\int_0^1 (W_t(i))^{1-\sigma_t^w} \, di \right)^{\frac{1}{1-\sigma_t^w}} \quad . \tag{31}$$

The term driving wage inflation is the log-difference between the marginal rate of substitution between consumption and leisure and the real wage. The marginal rate of substitution is given by

$$mrs_t = \frac{S_t^L \psi L_t(i)^{\frac{1}{\gamma}}}{\lambda_t} \quad . \tag{32}$$

Household nominal wage setting can then be shown to follow the same pattern as the price setting discussed in the previous subsection. With an appropriate change of notation, and after replacing $\widehat{mc_t}$ with $\widehat{mrs_t} - \hat{w}_t$, it leads to an identical set of equations to (25)-(28) above. The reader is referred to the Technical Appendix for details.

2.4 Financial Intermediaries

We assume that all capital is intermediated by a continuum of intermediaries indexed by $z \in [0,1]$. These agents are competitive in their input market, renting capital K_t from households at rental rate r_t^k. On the other hand, they are monopolistically competitive in their output market, lending capital varieties $k_t(z)$ to firms at rental rates $u_t(z)$. This gives rise to sluggish user costs of capital, which interact in the model with sticky wages to produce stickiness in marginal cost.

Every firm j must use composite capital, a CES aggregate with elasticity of substitution σ^k of the varieties supplied by different intermediaries. Firms' costs minimization yields demands

$$k_t(z) = k_t \left(\frac{u_t(z)}{u_t} \right)^{-\sigma^k} \quad , \tag{33}$$

where the overall user cost to firms is given by

$$u_t = \left(\int_0^1 (u_t(z))^{1-\sigma^k} \, dz \right)^{\frac{1}{1-\sigma^k}} \quad . \tag{34}$$

The profit maximization problem of the intermediary follows the same pattern as firms' problem. We define the gross intermediation spread as $s_t = u_t/r_t^k$ and the gross rate of change of user cost as $\pi_t^k = u_t/u_{t-1}$. With an appropriate change of notation and after replacing $\widehat{mc_t}$ with $-\hat{s}_t$, we obtain an identical set of equations to (25)-(28) above. The Technical Appendix contains the details.

2.5 Government

We assume that there is an exogenous stochastic process for government spending GOV_t

$$GOV_t = S_t^{gov}\overline{GOV} \quad , \tag{35}$$

with demands for individual varieties having the same form as consumption demand for varieties (7). The government's fiscal policy is assumed to be Ricardian, with the government budget balanced period by period through lump-sum taxes τ_t, and with an initial stock of government bonds of zero. The budget constraint is therefore

$$\tau_t + \frac{M_t - M_{t-1}}{P_t} = GOV_t \quad . \tag{36}$$

We assume that the central bank pursues an interest rate rule for its policy instrument i_t. Its quarterly inflation target π_t^* is assumed to follow a unit root process:

$$\pi_t^* = \pi_{t-1}^* \varepsilon_t^{\pi^*} \quad . \tag{37}$$

The year-on-year inflation rate is denoted as $\pi_{4,t} = \pi_t\pi_{t-1}\pi_{t-2}\pi_{t-3}$. The current year-on-year inflation target is simply the annualized quarter-on-quarter inflation target, $\pi_{4,t}^* = (\pi_t^*)^4$. Finally, the steady state gross real interest rate is given by $1/\beta_g$, where $\beta_g = \beta/\bar{g}$. Then we have

$$i_t^4 = \left[i_{t-1}^4\right]^{\xi^{int}} \left[\beta_g^{-4}\pi_{4,t}\right]^{1-\xi^{int}} \left[\frac{\pi_{4,t+1}}{\pi_{4,t}^*}\right]^{\xi^{\pi}} S_t^{int} \quad , \tag{38}$$

where S_t^{int} is an autocorrelated monetary policy shock. A *government policy* is defined as a set of stochastic processes $\{i_s,\, \pi_s^*,\, \tau_s\}_{s=t}^{\infty}$ such that, given stochastic processes $\left\{P_s,\, S_s^{int}\right\}_{s=t}^{\infty}$, the conditions (36) and (38) hold for all $s \geq t$.

2.6 Equilibrium

An *allocation* is given by a list of stochastic processes $\{B_s\,,\, M_s,\, C_s,\, I_s,\, L_s,\, K_s,$ $k_s,\, Y_s,\, L_t(i,j),\, k_t(z,j),\ i,j,z \in [0,1]\}_{s=t}^{\infty}$. A *price system* is a list of stochastic processes $\{P_s\,,\, W_s,\, R_s^k,\, U_s\}_{s=t}^{\infty}$. *Shock processes* are a list of stochastic processes $\{S_s^c,\, S_s^L,\, S_s^{inv},\, S_s^{gov},\, S_s^{int},\, \mu_s,\, \mu_s^w,\, S_s^y,\, \pi_s^*\}_{s=t}^{\infty}$. Then the equilibrium is defined as follows:

An equilibrium is an allocation, a price system, a government policy and shock processes such that *(a) given the government policy, the price system, shock processes, the restrictions on wage setting, and the sequence* $\{L_s\}_{s=t}^{\infty}$*, the allocation and the sequences* $\{V_s^w(i)\,,\ v_s^w(i),\ i \in [0,1]\}_{s=t}^{\infty}$ *solve households' utility maximization problem,*

(b) given the government policy, the price system, shock processes, the restrictions on price setting, and the sequence $\{Y_s\}_{s=t}^{\infty}$*, the allocation and the sequences* $\{V_s(j)\,,\ v_s(j),\ j \in [0,1]\}_{s=t}^{\infty}$ *solve firms' cost minimization and profit maximization problem,*

(c) given the government policy, the price system, shock processes, the restrictions on setting user costs, and the sequence $\{k_s\}_{s=t}^{\infty}$*, the sequences* $\{V_s^k(z)\,,$ $v_s^k(z),\ z \in [0,1]\}_{s=t}^{\infty}$ *solve intermediaries' profit maximization problem,*

(d) the goods market clears at all times,

$$Y_t = C_t + I_t + GOV_t \quad , \tag{39}$$

(e) the labor market clears at all times,

$$\ell_t = \int_0^1 \left[\left(\int_0^1 L_t(i,j)^{\frac{\sigma_t^w - 1}{\sigma_t^w}} di \right)^{\frac{\sigma_t^w}{\sigma_t^w - 1}} \right] dj \quad , \tag{40}$$

(f) the market for capital clears at all times,

$$\begin{aligned} k_t &= \int_0^1 \left[\left(\int_0^1 k_t(z,j)^{\frac{\sigma^k - 1}{\sigma^k}} dz \right)^{\frac{\sigma^k}{\sigma^k - 1}} \right] dj \quad , \\ K_t &= \int_0^1 \int_0^1 k_t(z,j) dz dj \quad . \end{aligned} \tag{41}$$

(g) the bond market clears at all times,

$$B_t = 0 \quad . \tag{42}$$

We have expressed market clearing conditions in terms of aggregate quantities and have ignored the underlying clearing conditions in terms of goods, labor or capital varieties. In aggregate quantities this problem is found in the inequalities, outside of steady state, of $\tilde{Y}_t \neq Y_t$ and $K_t \neq k_t$, but not in labor because we do not track an aggregate labor *supply* variable. It is however straightforward to show that $\overline{\tilde{Y}} = \bar{Y}$, $\hat{\tilde{Y}} = \hat{Y}$, $\bar{K} = \bar{k}$, and $\hat{K} = \hat{k}$, so that log-linearization that assumes equality between these aggregates is valid.

3 Estimation Methodology, Priors, and Calibration

3.1 Estimation Methodology

The model above model is log-linearized and then estimated in two steps in DYNARE-MATLAB. In the first step, we compute the posterior mode using an optimization routine (CSMINWEL) developed by Chris Sims. Using the mode as a starting point, we then use the Metropolis-Hasting (MH) algorithm to construct the posterior distributions of the model and the marginal likelihood.[10] We choose as our baseline case a particular combination of structural model features and priors for parameters, and use the parameter estimates for this case to construct impulse responses. Sensitivity analysis will be performed by either restricting certain parameters or shocks, or by removing some features of the structural model, and by comparing the marginal likelihood to that of the baseline case.

3.2 The Role of Unit Roots

Recent efforts at estimating DSGE models have been based mainly on data that were detrended either with linear time trends or with the Hodrick-Prescott filter—for examples see Smets and Wouters (2004) and Juillard, Karam, Laxton and Pesenti (2005). More recently there have been attempts to use Bayesian methods to help identify more flexible stochastic processes that contain permanent, or unit-root components—see Adolfson, Laseen, Linde and Villani (2005). This recent work is encouraging because it could potentially eliminate distortions in inference that can arise from prefiltering data.

Failing to account adequately for variation in the perceived underlying inflation objectives in DSGE models should be expected to seriously overstate the degree of structural inflation inertia and persistence if the model was estimated over a sample that had significant regime changes, with the central bank acting to change the underlying rate of inflation—see Erceg and Levin (2003). A similar argument applies to detrending inflation and interest rates with any procedure that removes too little or too much of the variation and persistence in the data.

Detrending productivity inappropriately could also bias key parameters that influence macroeconomic dynamics, as the behavioral responses of consumption, labor effort and investment will depend intricately on agents' forecasts of the future path of productivity. For example, under the assumption that productivity shocks are temporary deviations from a time trend standard models would predict a small rise in both consumption and leisure in the short run as the

[10] For one estimation run the whole process takes anywhere from 6-8 hours to complete using a Pentium 4 processor (3.0 GHz) on a personal computer with 1GB of RAM. DYNARE includes a number of debugging features to determine if the optimization routines have truly found the optimum and if enough draws have been executed for the posterior distributions to be accurate.

additional wealth generated by a productivity improvement would be consumed by distributing it over time. But an increase in leisure during periods of booms is at complete odds with the data at business cycle frequencies, which suggests clearly that GDP and hours worked are strongly and positively correlated. We show that if the model is simply extended to allow for shocks that result in highly persistent deviations of productivity growth from its long-term steady-state rate, it can generate a positive correlation between output and hours in the short run. This has important implications for modeling. Models that do not allow for a more flexible stochastic process for productivity run the risk of underestimating the importance of productivity shocks and producing significant bias in the model's key structural parameters.

For the reasons sketched out above we generally prefer to allow for unit roots in both underlying inflation objectives and the level of productivity, but we recognize that the case for the former in particular will obviously depend on the country and the sample that is being studied.[11] Over our sample with US data, which starts in the early 1990s, allowing for a unit root in inflation objectives is necessary because there is ample and convincing evidence that long-term inflation forecasts have declined significantly from values around 4 percent at the beginning of our sample to values around 2.5 percent at the end of the sample. Figure 1 plots three measures of long-term inflation expectations and the 10-year government bond yield, and all of them suggest that there was a gradual reduction in the perceived inflation target. A similar argument applies for productivity over this sample. Figure 2 reports measures of expected long-term growth from the same surveys and confirms that perceived long-term growth prospects for the United States have been revised up significantly over the last decade and have remained persistently higher than in the first half of the 1990s. Note, that such revisions in growth prospects are completely inconsistent with a trend-stationary view of productivity, which predicts that periods of above-trend levels should be followed by slower medium-term growth as the level of productivity reverts back to trend.

To estimate the model with unit roots in both productivity and inflation it was necessary to normalize the model by both technology and the inflation target, and to then transform it into a linearized form. After expressing all growing observable variables in first differences, the model can be readily estimated.

3.3 Data and Data Transformations

Our sample period covers 60 quarterly observations from 1990Q3 through 2005Q2. We employ the same 7 observable variables that have been employed in other studies (GDP, consumption, investment, hours, real wage, Fed funds rate, and inflation, as measured by the implicit GDP deflator), but we have added as an additional variable a measure of long-term inflation expectations to help identify

[11] For example, it may not be necessary to control for shifts in perceived inflation objectives in Inflation-Targeting countries over samples where the central bank has established a track record and managed to anchor long-term inflation expectations—see Levin, Natalucci and Piger (2004), Batini, Kuttner and Laxton (2005), Gürkaynak, Sack, and Swanson (2005).

perceived movements in the Fed's underlying inflation objectives. This measure is taken from a survey by Consensus Economics, which measures expected inflation between 6 and 10 years in the future, a period that is sufficiently far ahead for inflation to be expected to be on target. The data for GDP, consumption, investment, and real wages (all measured on a per capita basis) are all measured as annualized log first differences and the data for the Fed funds rate and the inflation rate (GDP deflator) are measured as annualized log first differences of the gross rate. The only variable that is measured in (de-meaned) log levels is hours worked per person. The sample period

Real GDP, investment, consumption and the GDP price deflator are taken from the US NIPA accounts. Hours worked are taken from the Labor Force Survey. The real wage is calculated by dividing labor income (from US NIPA) by hours and the GDP deflator.

After estimating the model in first differences and constructing impulse response functions (IRFs), we then cumulate the transformed IRFs so that we can report the results in units that are easier to interpret and compare with past studies that have ignored the presence of unit roots.

3.4 Calibration of Parameters that Determine the Steady State

The list of those model parameters that pin down the steady state are listed in the top panel of Table 1. We set the annual steady-state rate of productivity growth to 1.7 percent, the average over our sample. The rate of productivity growth and quarterly discount rate β together pin down the equilibrium real interest rate in the model. Given productivity growth of 1.7 percent, we set the discount rate at 0.999 to generate an equilibrium annual real interest rate of 2.1 percent. The quarterly depreciation rate on capital is assumed to be 0.025, implying an annual depreciation rate of 10 percent. The elasticities of substitution among goods, labor inputs and capital inputs are assumed be 5.35, 7.25 and 11.00 respectively, resulting in markups of 23%, 16% and 10%. These assumptions combined with a share of capital in valued added of 0.28 results in a labor income share of 0.59 and a capital-to-GDP ratio of 1.71. Given that government is assumed to absorb 18 percent of GDP in steady state, these assumptions imply that 62 percent remains for consumption and 20 percent for investment. Most of these values are similar to what have been employed in other DSGE models of the US economy—see Juillard, Karam, Laxton and Pesenti (2005) and Bayoumi, Laxton and Pesenti (2004). There are two exceptions. First, the share of capital of 0.28 looks lower than what is typically assumed, but this is the share in value added, not in output. Capital's share in output includes monopoly profits from three sectors, and is reasonable at 41 percent. Second, the mark-up in financial intermediation is a new concept in this literature. Our intuition is that this sector is more competitive than the goods and labor markets.

3.5 Specification of the Stochastic Processes

Table 2 reports the specifications of the stochastic processes for the 10 structural shocks in the model.[12] Following Juillard, Karam, Laxton and Pesenti (2005) we classify shocks as demand and supply shocks depending on the short-run covariance they generate between inflation and real GDP. Shocks that raise demand by more than supply and cause inflation to rise in the short run are classified as demand shocks, while shocks that produce a negative covariance between inflation and GDP are classified as supply shocks. Based on this classification system, shocks to government absorption, the Fed funds rate, the inflation target, consumption, and investment, $[\widehat{s_t^{gov}}, \widehat{s_t^{int}}, \hat{\pi}_t^*, \widehat{s_t^c}, \widehat{s_t^{inv}}]$, are all classified as demand shocks. In the case of the shock to the inflation target we assume that it follows a unit root, to account for permanent historical shifts in long-term inflation expectations. In all other cases we allow these shocks to be serially correlated. Shocks to wage and price markups as well as labor supply shocks, $[\widehat{\mu_t^w}, \widehat{\mu}_t, \widehat{s_t^L}]$, are classified as supply shocks. Labor supply shocks are assumed to be serially correlated, while both markup shocks have zero serial correlation.

The remaining 2 shocks determine the growth rate of productivity $(\widehat{g}_t)$ and are split into 2 components, $\widehat{g}_t^{gr}$ and $\widehat{g}_t^{iid}$. The first component $\widehat{g}_t^{gr}$ is assumed to be serially correlated $(\widehat{g}_t^{gr} = \rho_{gr}\widehat{g}_{t-1}^{gr} + \hat{\varepsilon}_t^{gr})$, while the second component is assumed to be white noise $(\widehat{g}_t^{iid} = \hat{\varepsilon}_t^{iid})$. The classification of the $\widehat{g}_t^{iid}$ shock is simple because increases in its value make output rise and inflation fall. However, the classification of the $\widehat{g}_t^{gr}$ shock as a demand or supply shock is more difficult. Interestingly, when shocks to this component are highly serially correlated they generate responses that are indistinguishable from what many professional forecasters would characterize as shocks to consumer and business confidence in that they result in sustained increases in aggregate demand and a temporary, but persistent, increase in inflation and hours worked.

3.6 Prior Distributions

Our assumptions about the prior distributions can be grouped into two categories: (1) parameters for which we have relatively strong priors based on our reading of existing empirical evidence and their implications for macroeconomic dynamics, and (2) parameters where we have fairly diffuse priors. Broadly speaking, parameters in the former group include the core structural parameters that influence, for example, the lags in the monetary transmission mechanism, while parameters in the latter category include the parameters that characterize the stochastic processes (i.e., the variances of the shocks and the degree of persistence in the shock processes). Our strategy is to estimate the model with a base-case set of priors and then to report results based on plausible alternatives.

The first, fourth and fifth columns of Table 3 report our assumptions about the prior distributions for the 12 structural core parameters of the model. On

[12] In their model of the US economy, Smets and Wouters (2004) also allow for ten structural shocks, six of which are specified as first-order stochastic processes and four of which are assumed to be white noise.

the household side this includes the habit-persistence parameter [v], the Frisch elasticity of labor supply [γ], the adjustment cost parameters on capital and investment [θ_k, θ_i]. There are six parameter characterizing pricing policies, the three parameters that determine the duration of pricing policies in the markets for goods, labor and capital [$\delta, \delta_w, \delta_k$] and the three quadratic cost parameters that determine the steepness of the marginal cost[13] curve for prices, wages, and user costs [ϕ, ϕ_w, ϕ_k]. Finally we have the two parameters of the interest rate reaction function [ξ_{int}, ξ_π]. The fourth column reports the type of distribution we assume (Beta, Normal, Inverted Gamma). Following standard conventions we will be using Beta distributions for parameters that fall between zero and one, inverted gamma (invg) distributions for parameters that need to be constrained to be greater than zero and normal (norm) distributions in other cases. The first column of each table reports our priors for the means of each parameter and the value in the fifth column represents a measure of uncertainty in our prior beliefs about the mean (measured as a standard error). The second and third columns report the posterior means of the parameters, and 90% confidence intervals that are based on 40,000 replications of the Metropolis-Hastings algorithm. The assumptions about and results for the remaining parameters are reported in a similar format in Tables 4 and 5.

3.6.1 Priors about Structural Parameters (Table 3)

Habit Persistence in Consumption [v]: We set the prior at 0.90 as high values are required to generate realistic lags in the monetary transmission mechanism and hump-shaped consumption dynamics—see Bayoumi, Laxton and Pesenti (2004) for a discussion of the role of habit persistence in generating hump-shaped consumption dynamics in response to interest rate shocks. This prior is somewhat higher than other studies such as Boldrin, Christiano and Fisher (2001), who use a value of 0.7.

Frisch Elasticity of Labor Supply [γ]: We set the prior at 0.50. Pencavel (1986) reports that most microeconomic estimates of the Frisch elasticity are between 0 and 0.45, and our calibration is at the upper end of that range, in line with much of the business cycle literature.[14]

Adjustment Costs on Changing Capital and Investment [θ_k, θ_i]: We set priors equal to 5 and 50 for θ_k and θ_i. These assumptions are based on analyzing the simulation properties of the model. The data do not seem to have much to say about these parameters other than that they cannot be zero or very large. This is not uncommon.

Duration of Pricing Policies [$\delta, \delta_w, \delta_k$]: The duration of pricing policies is $(1/(1-\delta))$. In the base case we set the prior equal to a three quarters duration for prices, wages and user costs, therefore the priors equal 0.66 for [$\delta, \delta_w, \delta_k$].

[13] Or the marginal rate of substitution minus the real wage (for wages), or minus the gross intermediation spread (for user costs).

[14] As discussed by Chang and Kim (2005), a very low Frisch elasticity makes it difficult to explain cyclical fluctuations in hours worked, and they present a heterogenous agent model in which aggregate labor supply is considerably more elastic than individual labor supply.

This is based on our reading of the empirical literature for the US and on the results cited in ECB (2005). In the US, consumer prices are re-set on average (slightly faster than) every two quarters, while the average for producer prices is four quarters. As our model does not distinguish between the two, it seems reasonable to choose an intermediate prior of three quarters. The priors for wages and user costs are set to the same value, but at least for user costs we will consider alternatives in the sensitivity analysis.

Steepness of Marginal Cost Curve $[\phi, \phi_w, \phi_k]$: Simulation experiments with the model suggest that plausible values for these parameters might fall between 0.50 and 2.0. In our base case we set the prior at 1.0. Our sensitivity analysis includes a case where all three of these parameters are restricted to be zero. There are significant interactions between these adjustment cost parameters and the duration parameters that will be explained below.

Interest Rate Reaction Function $[\xi_{int}, \xi_\pi]$: We impose prior means of 0.5 to be consistent with previous work, but we make these priors diffuse to allow them to be influenced significantly by the data.

3.6.2 Priors about Structural Shocks (Tables 4-5)

Persistence parameters for the structural shocks [ρ_{gov}, ρ_{inv}, ρ_c, ρ_{int}, ρ_{gr}, ρ_L, ρ_μ, ρ_{μ^w}]: Table 4 reports the assumptions about the priors for these parameters. With the exception of the shocks to the markups and the autocorrelated productivity shocks we set the prior means equal to 0.85 with a fairly diffuse prior standard deviation of 0.10. For the two markup shocks we impose zero serial correlation. These priors are consistent with other studies such as Smets and Wouters (2004) and Juillard, Karam, Laxton and Pesenti (2005).

We treat the prior on the serial correlation parameter for the productivity shocks differently. Here, we utilize a tight prior so that the model can generate highly persistent movements in the growth rate relative to its long-run steady state. As mentioned earlier, this is necessary to explain some facts in our sample (persistent upward revisions in expectations of medium-term growth prospects), but it is also more consistent with the data over the last century in the United States and other countries, where productivity growth has departed from its long-term average growth rate for as long as decades in many cases. Obviously, there will not be a lot of information in our short sample for estimating this parameter, and not surprisingly, the data will be silent on the matter as it should be.[15] We are considering adding expectations of long-term productivity growth to the list of observable variables to help identify this parameter, but have not attempted to do so at this point.

Structural shocks standard errors [$\sigma_{\hat{\varepsilon}^{gov}}$, $\sigma_{\hat{\varepsilon}^{inv}}$, $\sigma_{\hat{\varepsilon}^{c}}$, $\sigma_{\hat{\varepsilon}^{int}}$, $\sigma_{\hat{\varepsilon}^{\pi^*}}$, $\sigma_{\hat{\varepsilon}^{iid}}$, $\sigma_{\hat{\varepsilon}^{gr}}$, $\sigma_{\hat{\varepsilon}^{L}}$, $\sigma_{\hat{\varepsilon}^{\mu}}$, $\sigma_{\hat{\varepsilon}^{\mu^w}}$]: Table 5 reports our assumptions about the priors for these parameters. The strategy here was to develop rough priors of the means by looking at the model's impulse response functions, conditional on all the other

[15] Provided the researcher can provide sensible priors, Bayesian techniques offer a major advantage over other system estimators such as maximum likelihood, which in small samples can often allow key parameters such as this one to wander off in nonsensical directions.

priors, and then to form a diffuse prior around this mean in order to let the data adjust the parameters in a way that improves the overall fit of the model. The specific values for these priors are not intuitive, as they require a very detailed knowledge of the structure of the model. Consequently, the reader might be well-advised to turn to the model's IRFs (which are based on the model's posterior distribution) to interpret how important each one of these shocks is.

4 Estimation Results

4.1 Parameter Estimates

We have placed double arrows in the tables to indicate if the posterior mean is significantly higher or lower than the prior. By 'significant' we mean simply that it would have a discernible impact on the model's dynamics. We have used single arrows to indicate differences between the posterior and prior that we view as insignificant in this special sense. We use this terminology simply as an aid to help guide readers through tables that include a lot of numbers.

The posterior mean for habit persistence is 0.81, which is significantly below our prior of 0.90. The data and model prefer a higher estimate of the Frisch elasticity of labor supply (0.57 versus a prior mean of 0.50), larger adjustment cost parameter estimates on both capital (5.44 versus 5.00) and investment changes (54.7 versus 50.0), and significantly higher parameter estimates in the policy rule on the interest rate smoothing term (0.70 versus 0.50) and somewhat less so on the deviation of inflation from the perceived target (0.59 versus 0.50). The posterior estimates for the parameters that determine pricing duration is lower than the prior means for wages and user costs (0.54 versus 0.66), and higher for prices (0.70 versus 0.66). According to these estimates, the mean duration of pricing policies is 10 months in the goods market and 6.5 months in the labor and capital markets. The parameters determining the steepness of the marginal cost curve change little in all three markets (0.95, 1.01 and 0.92 versus 1.00). Broadly speaking, the range of parameter estimates does not look implausible.

The parameter estimates for the structural shock processes are reported in Tables 4 and 5. The results for the standard errors in Table 5 are not easy to interpret without understanding the model's properties (IRFs and variance decompositions). The estimates of the serial correlation parameters in Table 5 are more interesting. Aside from the persistent productivity growth shocks, the shock with the highest degree of serial correlation is government spending (0.99). Unsurprisingly, the data do not have very much of an influence over the parameter estimate of the growth shocks, producing a posterior mean that is nearly equal to the prior. What is most significant about these results is that our priors of a high degree of serial correlation for all processes are well within the estimated 90% confidence intervals. This means among other things that the shocks driving pricing are highly persistent, and as such generally require an optimal pricing response that makes firms change their firm-specific inflation rates. A model that rules this out imposes strong restrictions on optimal behavior and on macroeconomic dynamics. This, as we will see, is reflected in the fit of such models.

4.2 Impulse Response Functions

4.2.1 The IRFs for Demand Shocks

Figure 3 reports the impulse responses for a one-standard deviation increase in the Fed funds rate. The Fed funds rate increases by about 40 basis points and as a result output, consumption, investment, hours worked, and the real wage all fall in the short run and display hump-shaped dynamics that troughs after about three to four quarters. There is a similar small reduction in year-on-year inflation (which lags output) reflecting the significant inertia in the inflation process. Figure 4 reports the results for a permanent increase in the inflation target of .08 percentage points. As can be seen in the Figure this requires a temporary, but persistent, reduction in real and nominal interest rates, which results in a temporary boost to GDP, consumption, investment and hours worked. Interestingly, in both of these monetary-induced shocks the real wage is procyclical. This is a consequence of our estimation results on price and wage duration, which suggest that wages move faster than prices, so that a positive shock to the inflation target results in an increase in the real wage initially until prices catch up with wages. Figure 5 reports the results for a shock to government absorption. This shock is expansionary in the short run and induces higher output and work effort. However, to restrain inflationary forces, real interest rates rise and this crowds out consumption. Investment and work effort remain high for an extended period because this shock is estimated to be highly persistent. For the consumption shock in Figure 6, consumption rises in the short run and this eventually requires an increase in real interest rates to return inflation back to the inflation target. Inflation is highly persistent for this shock, and also for the investment shock in Figure 7. Here investment rises over the medium term and the rise in the real interest rate crowds out consumption sufficiently in the short run to generate the savings necessary to finance the higher level of investment. However, over time the higher level of capital permits a higher level of consumption. Finally, and as can be seen in all of these figures, inflation and output co-vary positively in the short run.

4.2.2 The IRFs for Supply Shocks

Figure 8 reports the results for a shock that reduces the wage markup and expands labor supply. In this case, the real wage falls and there is an expansion in output, hours worked, consumption and investment. Inflation falls and the Fed funds rate is reduced over time to gradually push inflation back up to its target. Figure 9 deals with a shock that reduces the price markup. This has very similar short-run qualitative effects to a wage-markup shock, except that the real wage rises in the short run. Figure 10 reports the results for a negative shock to labor supply. This induces an increase in the real wage and results in a reduction in output, consumption, investment and hours worked. Finally, we note that under all of these shocks, a negative covariance exists between output and inflation in the short run.

4.2.3 The IRFs for Productivity Shocks

Figure 11 reports the results for a temporary shock to the growth rate of productivity. While this results in an increase in output, consumption, investment and the real wage, there is a reduction in hours worked as workers consume more leisure. As pointed out by Gali (1999) and others, this feature severely constrains the potential role of productivity shocks in DSGE models as it implies a counterfactual strong negative correlation between hours worked and output.

Figure 12 shows that this problem does not arise with a persistent shock to the growth rate of productivity. GDP, consumption, investment, productivity and the real wage all trend up over time and have not converged to their new long-run values after a decade. Because it takes time to put capital into place, in the very short run the increase in output is accomplished partly through an increase in hours worked. However, as investment rises hours worked eventually decline and in the very long run return back to baseline. This last requirement is a condition for balanced growth. In the very short run inflation rises as demand increases by more than supply. Consequently, real interest rates rise in part to constrain these short-run inflationary forces, but they also rise persistently as the marginal product shifts upwards and then falls slowly over time until the level of the capital stock increases to its new steady-state level.

4.2.4 The Importance of Pricing Policies for Inflation Dynamics

Figure 13 illustrates the effect on inflation dynamics of the average contract length δ, δ^w, and $\delta^k$and the steepness of the marginal cost curve ϕ, ϕ^w, and ϕ^k. For the purpose of this exercise we maintain all parameters at those of our baseline experiment while allowing for different values of these six parameters. The shock we consider is a permanent increase in the inflation target by one percent per annum. We consider 16 cases, ranging from fast to slow price adjustment ($\delta = 0.25$, 0.5, 0.75, 0.9) and from flat to steep marginal cost curves ($\phi = 0.5$, 1, 2, 5). Two results stand out.

First, the most interesting difference between these parameter combinations concerns inflation inertia, rather than persistence. Inertia is dramatically lower for slower speeds of price adjustment, while higher speeds of price adjustment are characterized by an initial overshooting (by a factor of two) of inflation over its new target. Note that a standard New Keynesian model without indexation would exhibit no inertia whatsoever for a shock to the inflation target, inflation would immediately converge to the new target. In our model persistence would increase dramatically for very long contract lengths, as shown in the last row of plots. Contracts of such length are however clearly rejected by the data.

Second, the steepness of the marginal cost curve matters far less than contract length for this particular shock. In order for past inflation to become an important determinant of current inflation, historic pricing policies with their history of updating behavior must remain in force at least for some time. Otherwise even very steep marginal cost curves will not prevent firms from rapidly adjusting their prices, because they can do so in anticipation of soon being able to readjust their price again.[16]

4.3 Variance Decomposition of the Expected Growth Rate of Output

To understand the basic role of structural shocks in the model we examine how each shock contributes to changes in future output at different forecast horizons. Table 6 reports the contribution of each structural shock to output changes over horizons of 1, 4, 20, 40 and 100 quarters. Results are divided into demand shocks and supply shocks. In both cases, the row at the bottom of the table provides a measure of the total variance contribution of demand and supply shocks. In looking at these figures one needs to bear in mind our definition of a demand shock as one that gives rise to a positive short-run correlation of inflation and output. By this definition, which includes the persistent shock to productivity growth, demand shocks clearly account for much more of the variance in actual and expected GDP growth than supply shocks. This is true at all horizons, but especially in the long run. Important sources of variation in the short run include shocks to investment, consumption, interest rates and productivity growth. By far the two largest sources of variation in the longer run are shocks to productivity growth and investment. The latter is important because this shock is highly persistent, and subsequently has a highly persistent effect on output through the capital stock. The former however dominates in the very long run.

4.4 Comparing the DSGE Model's Fit with BVARs

The marginal data density provides a very useful summary statistic of the overall fit of the model and can be compared directly with other DSGE models estimated on the same data set or less restricted models such as vector autoregressive models (VARS). In cases where researchers have not prefiltered the data with some detrending technique the marginal data density will also provide a direct measure of out-of-sample forecasting performance.[17] Our initial

[16] This also suggests that the empirical finding of a very short contract length in Altig, Christiano, Eichenbaum and Linde (2005) may have more to do with the non-rational price updating behavior of their firms than with their estimated steepness of their marginal cost curve.

[17] One problem with prefiltering data such as output with filters such as the Hodrick-Prescott filter prior to estimation is that uncertainty in the estimates of the detrended values will not be accounted for by the estimates of the marginal data density of the estimated model. In other words, when researchers prefilter the data before estimation there will no longer be a direct correspondence between in-sample fit and out-of-sample forecasting performance. This

assessment of the empirical performance of the DSGE model will be based on comparing its marginal data density with the marginal data density of Bayesian VARS—see Sims (2003) and Schorfheide (2004).[18]

Table 7 reports the marginal likelihood of eight BVARs (1 to 8 lags) based on Sims and Zha (1998) priors.[19] The BVAR estimates were obtained by combining a specific type of the Minnesota prior with dummy observations. The prior decay and tightness parameters are set at 0.5 and 3, respectively. As in Smets and Wouters (2004), the parameter determining the weight on own-persistence (sum-of-coefficients on own lags) is set at 2 and the parameter determining the degree of co-persistence is set at 5. To obtain priors for the error terms we followed Smets and Wouters (2004) by using the residuals from an unconstrained VAR(1) estimated over a sample of observations that was extended back to 1980Q1.[20] The estimates reported in Table 7 suggest that the best fitting BVAR has 4 lags. As can be seen in the top row of Table 7 the estimates of the marginal data density obtained either from the Laplace approximation or from 40,000 replications of the Metropolis-Hastings algorithm suggests that the DSGE model provides a much better fit than even the best fitting BVAR over this sample. To test to see whether this was the result of the specific sample of observations that was used to develop priors for the error terms in the BVAR we considered two alternative shorter samples (1987:1-1990:2 and 1984:1-1990:2), but in both cases none of the BVARs produced a better fit than the DSGE model. We also considered the procedure suggested by Schorfheide (2004) for setting the priors on the error terms using the standard error of the endogenous variables on the presample and obtained the same basic findings. While the estimates of

problem with prefiltering data has not been limited to empirical work on DSGE models, but has plagued most of the empirical work on the generation of macro models that DSGE models are being developed to replace.

[18]It is well known that large dimensional unrestricted VAR models do not forecast very well without imposing some priors on the parameters and for that reason we compare the fit of the DSGE model with Bayesian VARs instead of unrestricted VARs. It is important to stress that we do not consider the BVARs as serious alternatives to a structural view about how the economy works because they offer little useful in this dimension, but they do provide a potentially useful metric for comparing the fit and out-of-sample forecasting performance of DSGE models when there is a paucity of alternative DSGE models readily available that can be used to assess any specific model. Because BVARs have been developed principally as forecasting models this approach might seem to suggest that the deck is being stacked against DSGE models, which in many cases impose serious cross-equation restrictions that could easily be rejected by the data.

[19]The marginal likelihood values for the BVAR were computed in DYNARE using a program developed by Chris Sims.

[20]The DSGE model was estimated over a sample from from 1990Q3 - 2005Q2. This choice was based on available measures of long-term inflation expectations from Consensus Economics. To extend our measure of long-term inflation expectations back we used an alternative measure available from the Survey of Professional Forecasters. As can be seen in Figure 1 the measure of long-term inflation expectations from Consensus Economics survey displays a similar pattern as the measure from the Survey of Professional Forecasters over the sample where both series exist.

the marginal data density of each BVAR changed for each sample none of the BVARS fit as well as the DSGE model.

4.5 Sensitivity Analysis

Table 8 compares the marginal data density of our baseline case estimation to various restricted versions of the model that cover assumptions about pricing. First we explore whether removing either sticky user costs of capital or firm-specific marginal cost curves or both improves the fit of the model relative to the baseline case. The best fit is obtained by removing sticky user costs from the model, but the baseline case is a very close second, suggesting that this feature is neither particularly useful nor detrimental. Upward-sloping firm-specific marginal cost curves on the other hand are essential. Note however that even the worst fitting version of our model fits better than the Bayesian VAR.

The opposite is true for the conventional Calvo-Yun model - even its best fitting version fits worse than the Bayesian VAR. The culprit for this unsatisfactory performance is of course the lack of structural inflation persistence, as all other features of that model are kept identical in this comparison. Note that upward-sloping firm-specific marginal cost curves by themselves do not appear sufficient to remedy this shortcoming.

Figure 14 and 15 display the estimated structural shock processes of the model. Figure 15 shows that our inclusion of inflation forecast data was successful in identifying a downward trajectory of the inflation target. A time-varying inflation target is often held to imply that structural inflation persistence is not a necessary additional feature of a New Keynesian model. Our above results suggest otherwise.

5 Conclusion

In this paper we have proposed a New Keynesian DSGE model that, based on our preliminary Bayesian estimation results, looks promising for addressing two major problems of this model class. First, it generates significant inflation inertia and persistence in a model without learning and without non-rational or *ad hoc* lagged inflation terms in the Phillips curve. Second, the modeling of technology shocks is such that they account for a large share of business cycle variations, especially at longer horizons. The fit of this model is superior, by a significant margin, to a Bayesian VAR, and we therefore have some confidence in the model's ability to fit the data. However, more work needs to be done to distinguish what features contribute to the overall fit of the model and what features are nonessential. In future work we aim to expand further on this analysis in a number of directions and then extend it to include open-economy and multi-country dimensions.

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Table 1: Assumptions About Parameters and Steady-State Ratios

Parameters:	Value
Discount Rate β	0.999
Share of Capital in Value Added α	0.28
Capital Depreciation Rate Δ	0.025
Share of Government Spending in Steady State Output ω_g	0.18
Steady State Quarterly Growth Rate $\bar{g}$	$(1.017)^{\frac{1}{4}}$
Elasticity of Substitution among Goods in Steady State $\bar{\sigma}$	5.35
Elasticity of Substitution among Labor Inputs in Steady State $\overline{\sigma_w}$	7.25
Elasticity of Substitution among Capital Inputs $\overline{\sigma_k}$	11.00
Steady-State Ratios:	
Labor's Income Share	0.59
Consumption-to-GDP Ratio	0.62
Investment-to-GDP Ratio	0.20
Government Spending-to-GDP Ratio	0.18
Annual Capital-to-GDP Ratio	1.71
Price Markup $\bar{\sigma}/(\bar{\sigma}-1)$	1.23
Wage Markup $\overline{\sigma_w}/(\overline{\sigma_w}-1)$	1.16
User Cost Markup $\overline{\sigma_k}/(\overline{\sigma_k}-1)$	1.10

Table 2: Specification of the Stochastic Processes

Assumptions about the Shocks	Stochastic Processes
Total Factor Productivity	$\widehat{g}_t = \widehat{g}_t^{gr} + \widehat{g}_t^{iid}$
Demand Shocks	
Government Absorption	$\widehat{s_t^{gov}} = \rho_{gov}\widehat{s_{t-1}^{gov}} + \hat{\varepsilon}_t^{gov}$
Investment	$\widehat{s_t^{inv}} = \rho_{inv}\widehat{s_{t-1}^{inv}} + \hat{\varepsilon}_t^{inv}$
Marginal Utility of Consumption	$\widehat{s_t^{c}} = \rho_{c}\widehat{s_{t-1}^{c}} + \hat{\varepsilon}_t^{c}$
Monetary Policy Reaction Function	$\widehat{s_t^{int}} = \rho_{int}\widehat{s_{t-1}^{int}} + \hat{\varepsilon}_t^{int}$
Inflation Target	$\hat{\pi}_t^* = \hat{\pi}_{t-1}^* + \hat{\varepsilon}_t^{\pi^*}$
Autocorrelated Growth Shocks	$\widehat{g}_t^{gr} = \rho_{gr}\widehat{g}_{t-1}^{gr} + \hat{\varepsilon}_t^{gr}$
Supply Shocks	
Price Markup	$\widehat{\mu}_t = \hat{\varepsilon}_t^{\mu}$
Wage Markup	$\widehat{\mu_t^w} = \hat{\varepsilon}_t^{\mu^w}$
Marginal Disutility of Labor	$\widehat{s_t^L} = \rho_L\widehat{s_{t-1}^L} + \hat{\varepsilon}_t^L$
I.i.d. Growth Shocks	$\widehat{g}_t^{iid} = \hat{\varepsilon}_t^{iid}$

Table 3: Estimation Results
Parameters

	Prior	Mean Estimate	90% Interval	Density	Std
v	0.90	0.81 $\Downarrow$	0.73-0.89	*Beta*	0.10
γ	0.50	0.57$\Uparrow$	0.44-0.71	*Normal*	0.10
δ	0.66	0.70 $\Uparrow$	0.65-0.75	*Beta*	0.10
δ_w	0.66	0.54 $\Downarrow$	0.43-0.63	*Beta*	0.10
δ_k	0.66	0.54 $\Downarrow$	0.40-0.66	*Beta*	0.10
ϕ	1.00	0.95 $\downarrow$	0.66-1.28	*Normal*	0.20
ϕ_w	1.00	1.01 $\uparrow$	0.68-1.28	*Normal*	0.20
ϕ_k	1.00	0.92 $\downarrow$	0.54-1.22	*Normal*	0.20
θ_k	5.00	5.44 $\uparrow$	3.80-7.05	*Normal*	1.00
θ_i	50.00	54.72 $\uparrow$	41.5-58.6	*Normal*	10.00
ξ_{int}	0.50	0.70 $\Uparrow$	0.54-0.83	*Normal*	0.20
ξ_π	0.50	0.59 $\Uparrow$	0.43-0.79	*Normal*	0.20

Table 4: Estimation Results Continued
Parameters

	Prior	Estimate	90% Interval	Density	Std
ρ_{gov}	0.85	0.99 $\Uparrow$	0.97-1.00	*Beta*	0.10
ρ_{inv}	0.85	0.81 $\downarrow$	0.71-0.95	*Beta*	0.10
ρ_c	0.85	0.84 $\downarrow$	0.75-0.96	*Beta*	0.10
ρ_{int}	0.85	0.86 $\uparrow$	0.80-0.94	*Beta*	0.10
ρ_{gr}	0.95	0.95 $=$	0.93-0.97	*Beta*	0.01
ρ_L	0.85	0.87 $\uparrow$	0.75-0.99	*Beta*	0.10

Table 5: Estimation Results Continued
Standard Deviation of Shocks

	Prior	Estimate	90% Interval	Density	std
$\sigma_{\hat{\varepsilon}^{gov}}$	0.025	0.0159 $\Downarrow$	0.0134-0.0184	*invg*	*inf*
$\sigma_{\hat{\varepsilon}^{inv}}$	0.2000	0.4898 $\Uparrow$	0.2795-0.6379	*invg*	*inf*
$\sigma_{\hat{\varepsilon}^{c}}$	0.0250	0.0310 $\Uparrow$	0.0192-0.0429	*invg*	*inf*
$\sigma_{\hat{\varepsilon}^{int}}$	0.0100	0.0039 $\Downarrow$	0.0032-0.0044	*invg*	*inf*
$\sigma_{\hat{\varepsilon}^{\pi^*}}$	0.0010	0.0002 $\Downarrow$	0.0002-0.0002	*invg*	*inf*
$\sigma_{\hat{\varepsilon}^{iid}}$	0.0010	0.0062 $\Uparrow$	0.0051-0.0071	*invg*	*inf*
$\sigma_{\hat{\varepsilon}^{gr}}$	0.2000	0.1076 $\Downarrow$	0.0492-0.1449	*invg*	*inf*
$\sigma_{\hat{\varepsilon}^{L}}$	0.0050	0.0071 $\Downarrow$	0.0011-0.0205	*invg*	*inf*
$\sigma_{\hat{\varepsilon}^{\mu}}$	0.0250	0.0314 $\Uparrow$	0.0218-0.0403	*invg*	*inf*
$\sigma_{\hat{\varepsilon}^{\mu^w}}$	0.0250	0.1278 $\Uparrow$	0.0731-0.1562	*invg*	*inf*

Table 6: Contributions of Shocks to Future Level Changes in Output (N Quarters Ahead

Quarters Ahead	1	4	20	40	100
Demand Shocks					
$\sigma_{\hat{\varepsilon}^{gr}}$	14.4	27.4	61.0	67.7	69.8
$\sigma_{\hat{\varepsilon}^{gov}}$	1.3	1.5	0.4	0.4	0.6
$\sigma_{\hat{\varepsilon}^{inv}}$	39.6	25.9	19.0	20.2	20.2
$\sigma_{\hat{\varepsilon}^{c}}$	13.3	14.7	8.7	3.9	2.1
$\sigma_{\hat{\varepsilon}^{int}}$	17.2	16.3	6.0	3.3	2.3
$\sigma_{\hat{\varepsilon}^{\pi^*}}$	0.6	0.6	0.2	0.1	0.1
Demand Shocks Sum	86.4	86.4	95.3	95.6	95.1
Supply Shocks					
$\sigma_{\hat{\varepsilon}^{iid}}$	7.1	6.0	1.4	1.1	0.9
$\sigma_{\hat{\varepsilon}^{L}}$	3.1	3.9	2.3	2.8	3.7
$\sigma_{\hat{\varepsilon}^{\mu}}$	1.4	1.4	0.4	0.2	0.1
$\sigma_{\hat{\varepsilon}^{\mu^w}}$	2.0	2.3	0.6	0.3	0.2
Supply Shocks Sum	13.6	13.6	4.7	4.4	4.9

Table 7: Comparison of Marginal Likelihoods with BVARs

	Marginal Likelihood
Base Case Model (Laplace Approximation)	-716.51
Base Case Model (MH Replications = 40,000)	-705.60
BVAR (1 lag)	-734.16
BVAR (2 lag)	-736.50
BVAR (3 lag)	-733.16
BVAR (4 lag)	-725.07
BVAR (5 lag)	-725.61
BVAR (6 lag)	-728.81
BVAR (7 lag)	-730.00
BVAR (8 lag)	-733.92

Table 8: Comparison of the base-case DSGE model with DSGE models estimated with different assumptions

	Marginal Likelihood
Base-Case Model	-705.6
No sticky user costs (ϕ_k=0, $\delta_k = 0.001$)	-704.2
No upward-sloping MC curve ($\phi = \phi_w = \phi_k = 0$)	-719.6
No sticky user costs, no upward-sloping MC curve	-724.9
Calvo Model, Base-Case	-796.9
Calvo Model, No sticky user costs	-763.2
Calvo Model, No upward-sloping MC curve	-728.1

Figure 1: Measures of Long-Term Inflation Expectations and Interest Rates

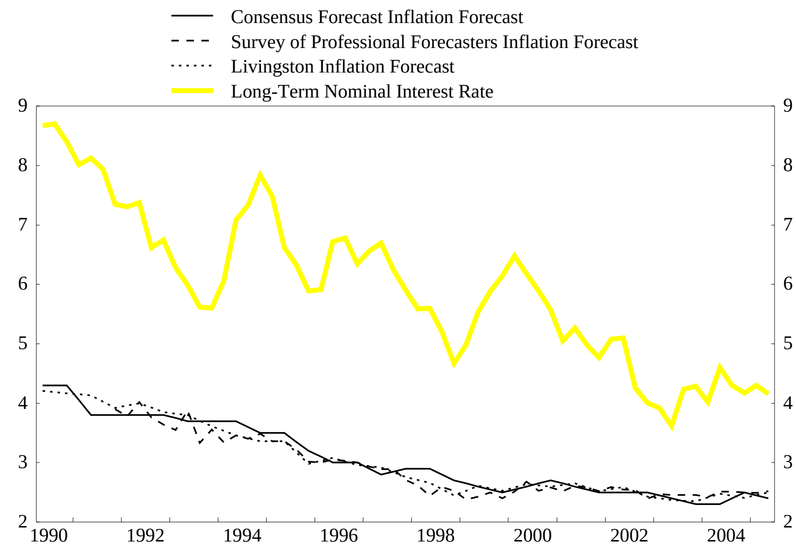

Figure 2: Measures of Expected Long-Term Growth

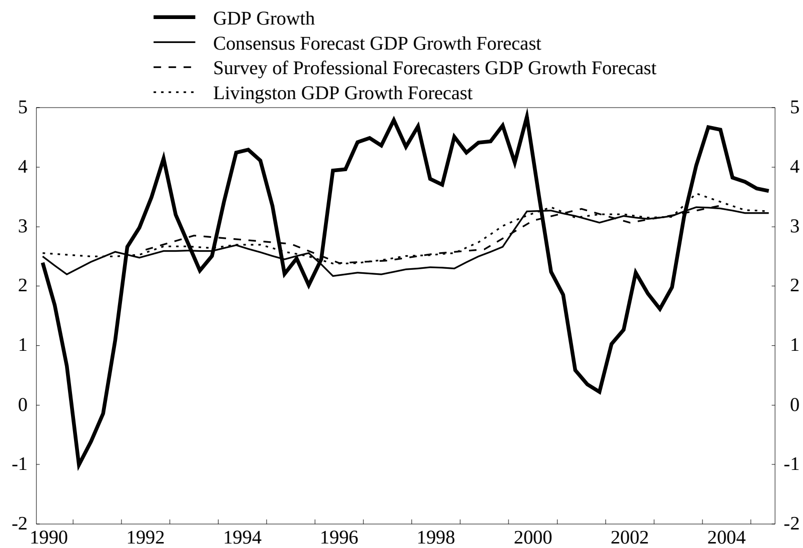

Figure 3: Shock to the Fed Funds Rate (Demand)

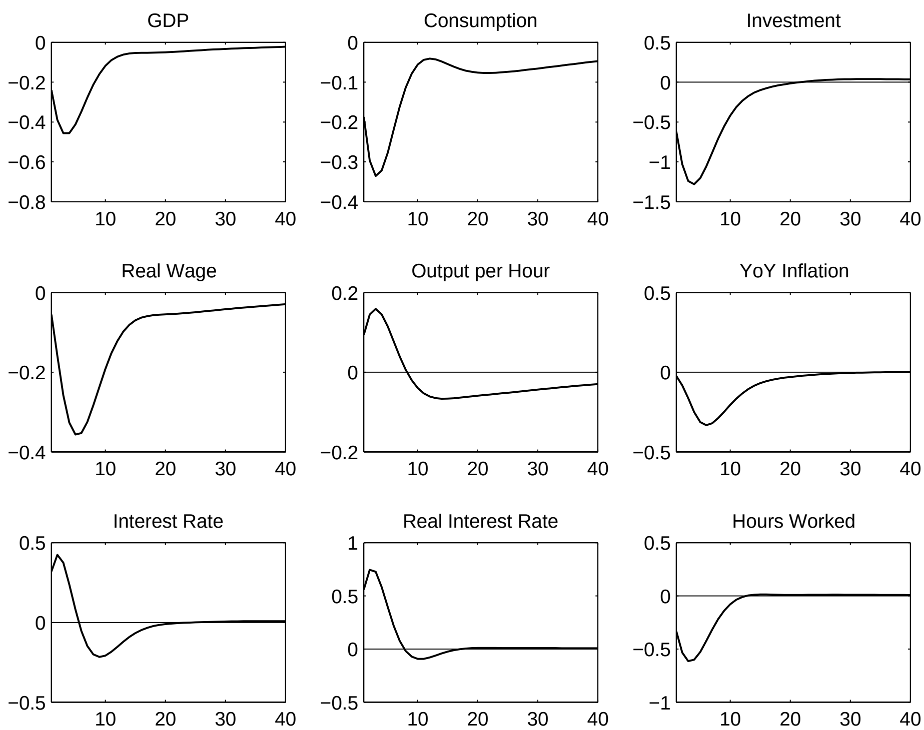

Figure 4: Shock to the Inflation Objective (Demand)

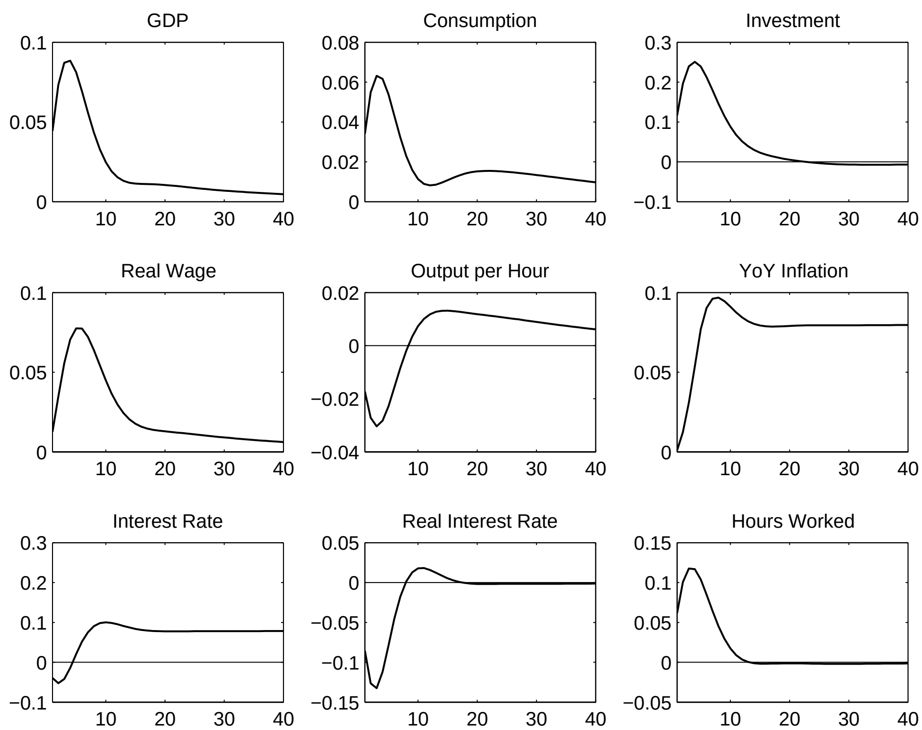

Figure 5: Shock to Government Absorption (Demand)

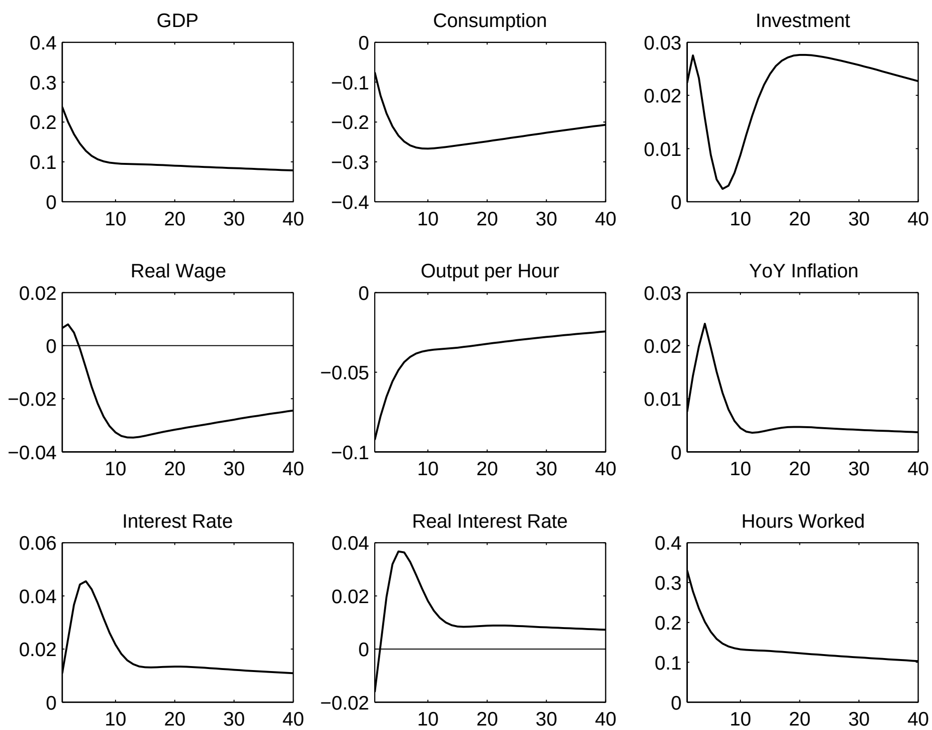

Figure 6: Shock to Consumption (Demand)

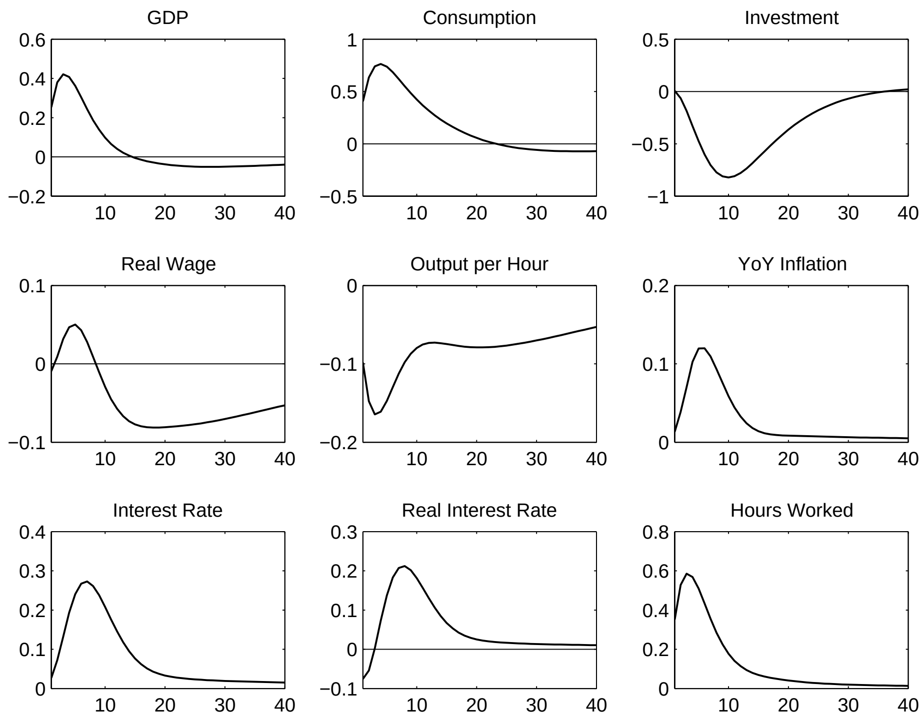

Figure 7: Shock to Investment (Demand)

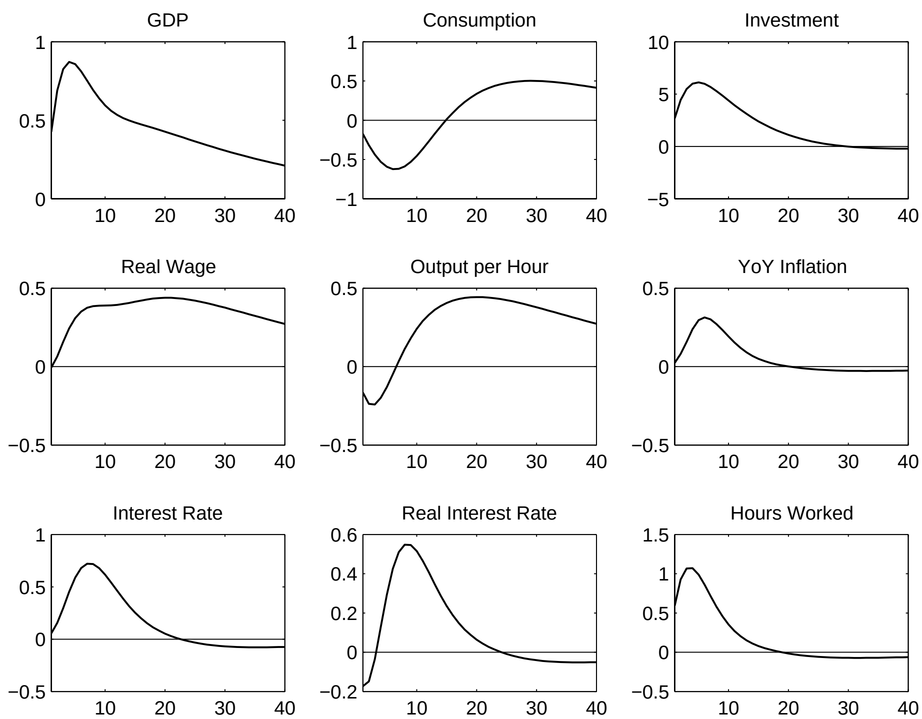

Figure 8: Shock to Wage Markup (Supply)

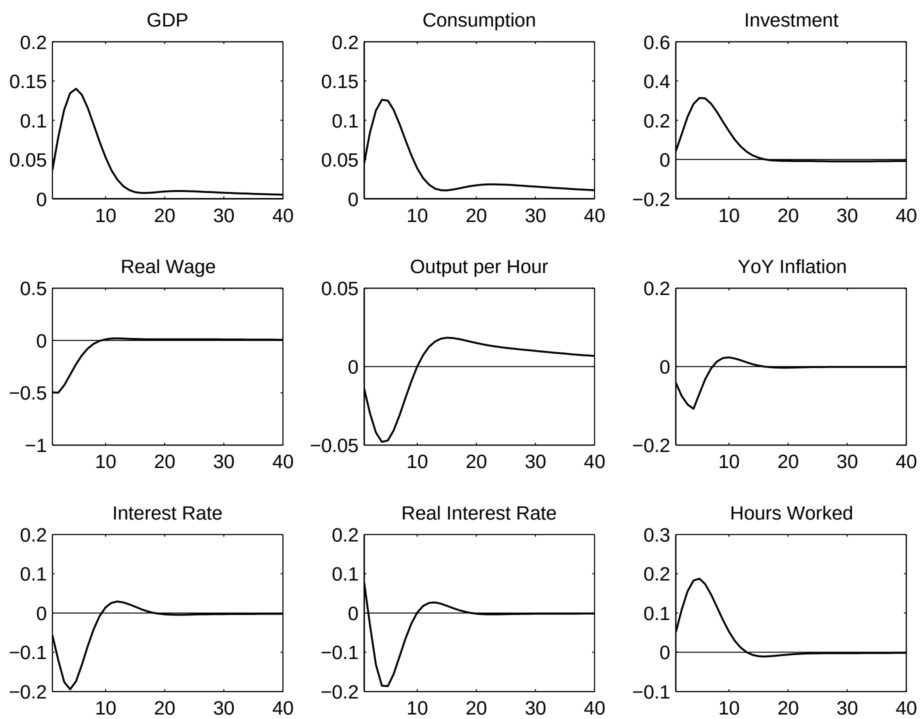

Figure 9: Shock to Price Markup (Supply)

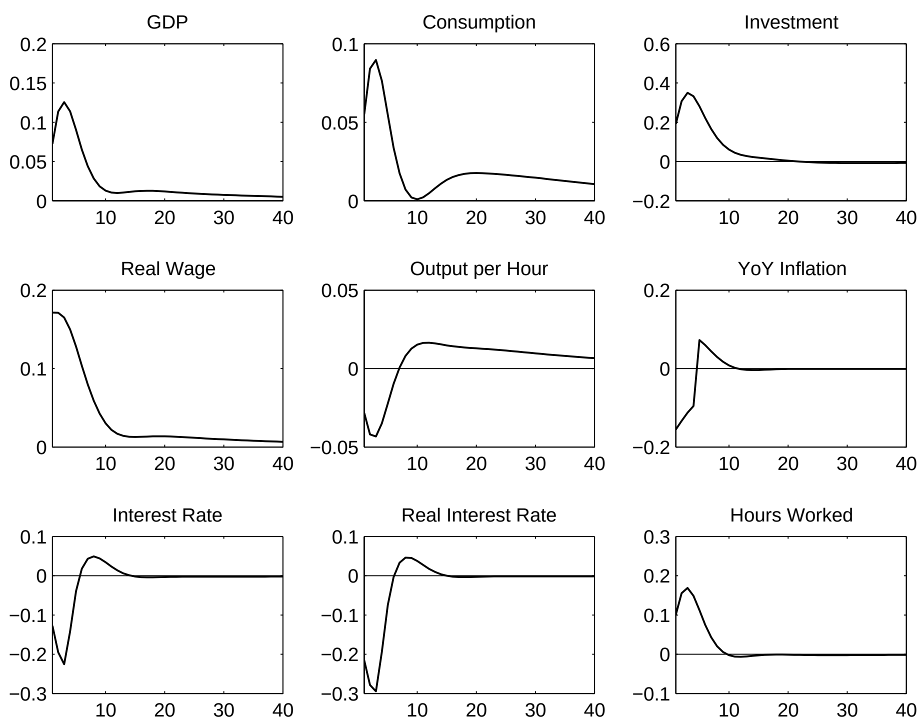

Figure 10: Shock to Labor Effort (Supply)

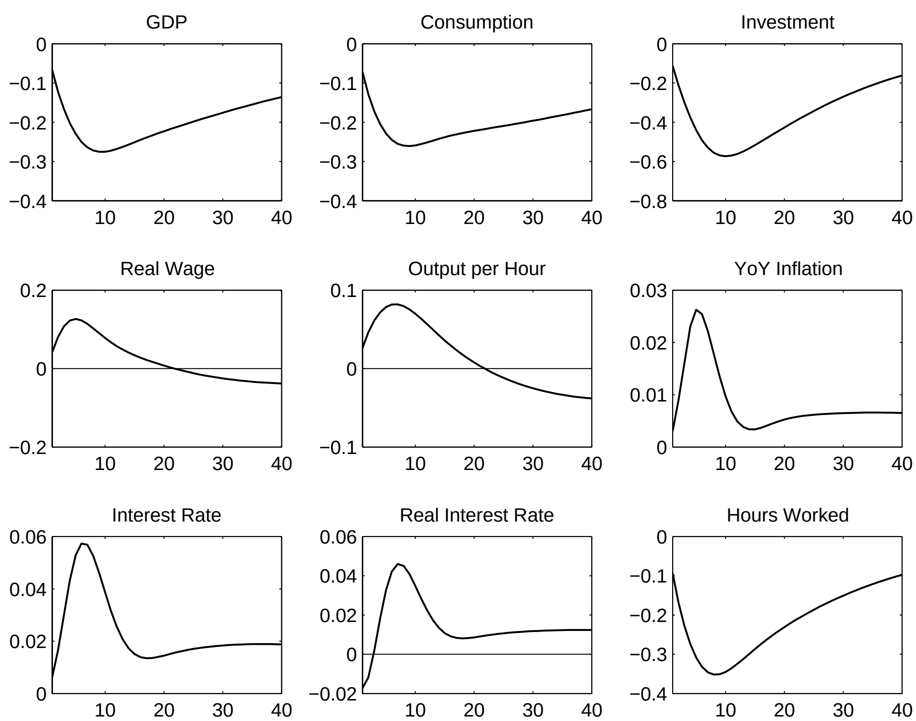

Figure 11: Shock to Productivity **Level** (Supply)

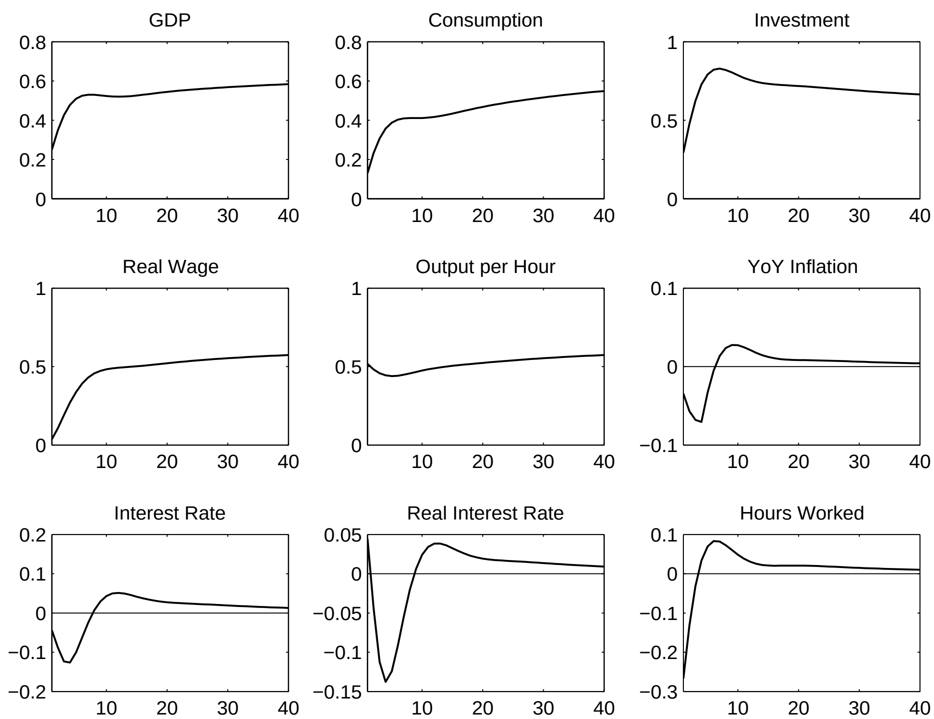

Figure 12: Shock to Productivity **Growth** (Demand)

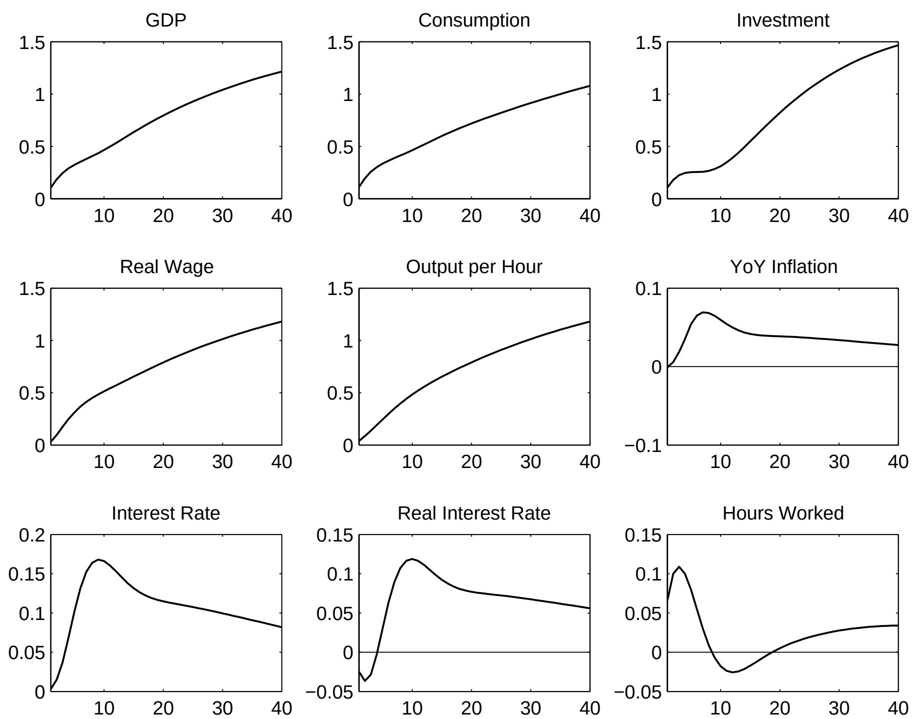

Figure 13: Inflation Target Shock and Inflation Dynamics

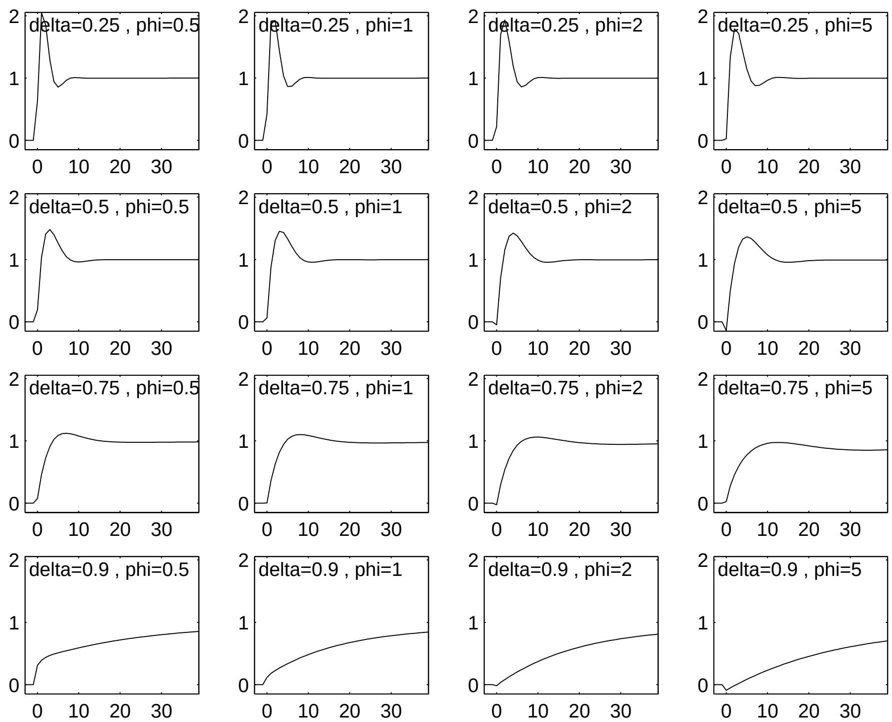

Figure 14: Estimated Structural Shocks

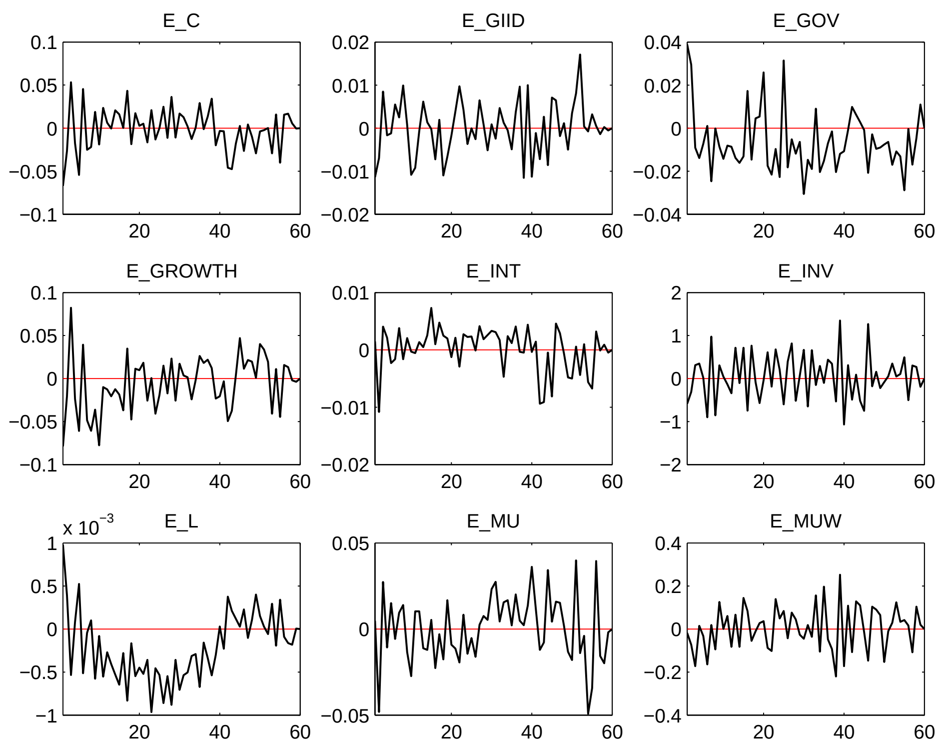

Figure 15: Estimated Shocks to the Inflation Target