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Monetary Policy Under Uncertainty in Micro-Founded Macroeconometric Models

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Uncertainty is not just an important feature of the monetary policy landscape; it is the defining characteristic of that landscape.

Alan Greenspan (2003)

1 Introduction

Eight years ago, two *Macroeconomics Annual* papers—Goodfriend and King (1997) and Rotemberg and Woodford (1997)—played a central role in stimulating a burgeoning research program regarding the monetary policy implications of macroeconomic models with explicit microeconomic foundations.¹ This research program incorporates two crucial elements compared with more traditional monetary policy analysis. First, reflecting the influence of the Lucas (1976) critique, the emphasis on explicit microeconomic foundations is intended to ensure that the resulting structural equations are reasonably invariant to the choice of monetary policy. Second, this research follows the standard public finance approach of determining the policy regime that maximizes household welfare and then evaluating the performance of alternative policies relative to this benchmark.

After initially focusing on small stylized models, this line of research has subsequently proceeded to analyze *micro-founded macroeconometric models* that incorporate an expanded set of nominal and real rigidities and hence can be matched more closely to observed aggregate data. For example, Christiano, Eichenbaum, and Evans (2005) (henceforth CEE) specified a dynamic general equilibrium model with a number of distinct structural features: staggered wage and price setting with partial indexation, habit persistence in consumption, endogenous capital accumulation with higher-order adjustment costs, and variable capacity utilization.² Smets and Wouters (2003a) (henceforth SW) later

applied full-information Bayesian methods to estimate essentially the same specification (augmented by a larger set of structural disturbances) and found that the model is competitive with an unrestricted Bayesian vector autoregression (VAR) in terms of goodness-of-fit and out-of-sample forecasting performance.³

In this paper, we investigate the design of monetary policy when the central bank faces uncertainty regarding the true structure of the economy. Of course, a long-established literature has considered this topic using traditional structural macroeconomic models, building on the seminal work of Brainard (1967).⁴ Nevertheless, recent analysis of small stylized micro-founded models has demonstrated that the implications of uncertainty can be markedly different when the policymaker's goal is to maximize household welfare because the welfare function itself depends on the specification and parameter values of the model.⁵

By using a micro-founded macroeconometric modeling framework, we can examine the policy implications of several aspects of uncertainty that may be more difficult to consider in a small stylized model. First, by applying Bayesian methods, we can use the posterior distribution of the model parameters to determine whether simple rules that perform well in the baseline economy are robust to *parameter uncertainty*, that is, to the range of parameter values that are reasonably consistent with the observed data. Second, we can gauge the degree of *innovation uncertainty* by evaluating the extent to which the policy conclusions are sensitive to alternative assumptions regarding the nature and incidence of the structural shocks to the model. Finally, we can explore the implications of *specification uncertainty* by changing specific features of the model such as the role of money balances or the structure of nominal contracts.⁶

As the baseline specification for our analysis, we use a micro-founded macroeconometric model similar to those studied by CEE and SW. Applying a Bayesian procedure to estimate this model with post-war U.S. data, we set the baseline values of the model parameters using the mean of the posterior distribution. We employ Lagrangian methods to determine the optimal policy under commitment in the baseline economy. Finally, we use second-order perturbation to solve the model and compute the level of welfare under the optimal policy as well as for alternative simple rules.⁷

We find that a simple interest rate rule that responds solely to nominal wage inflation and the lagged interest rate yields a welfare out-

come that nearly matches that under the fully optimal policy.⁸ Because this rule involves only observable variables and does not require a measure of the output gap, the natural rate of interest, or forecasts of variables, the rule can be implemented without assuming that the policymaker knows the correct specification of the model or the true values of the model parameters.

The near-optimality of the simple wage stabilization rule is directly attributable to the overriding importance of nominal wage inertia in determining the welfare costs of aggregate fluctuations in the baseline economy. This inertia reflects the relatively long duration of nominal wage contracts as well as the nearly uniform degree of indexation to lagged inflation. Furthermore, under our baseline specification of Calvo-style contracts with an exogenous probability of reoptimization, many wage contracts remain in effect much longer than the one-year average duration. Thus, as emphasized by Erceg, Henderson, and Levin (2000), stabilizing aggregate wage inflation helps alleviate the degree of cross-sectional dispersion in real wages and thereby minimizes the associated inefficiencies in employment of differentiated labor services and in the allocation of leisure across households.

The simple wage stabilization rule is robust to parameter uncertainty and innovation uncertainty and to some modifications of the baseline model specification. For example, this rule yields near-optimal performance for variations of model parameters based on the estimated posterior distribution, a finding consistent with earlier work regarding the importance of parameter uncertainty.⁹ However, this rule is not robust across the full range of estimates of model parameters seen in the literature, which often lie in the extreme tails of our estimated posterior distribution. Thus, research that reduces this type of uncertainty regarding certain key parameter values could be used to design monetary policy that yields a significant increase in welfare. The performance of the wage stabilization rule is also relatively insensitive to various assumptions regarding the nature and incidence of the innovations and to augmenting the model to incorporate monetary frictions.

Nevertheless, this rule is not robust to alternative specifications of the wage-contracting mechanism. In particular, the welfare costs of nominal wage variability are much smaller when wages are determined by Taylor-style contracts with the same average duration as in our baseline specification of Calvo-style contracts.¹⁰ Thus, the simple wage stabilization rule is no longer nearly optimal, and better welfare

outcomes are provided by other simple rules that respond to price inflation and real economic variables. Of course, as Hall (2005) emphasizes, neither Calvo-style nor Taylor-style contracts provide the ideal microeconomic foundations for the determination of nominal wages and employment. Thus, our results should be interpreted as highlighting the extent to which additional research regarding the structure of labor markets is likely to have substantial benefits for the design of monetary stabilization policy.

The remainder of this paper is organized as follows. Section 2 provides an overview of the baseline model specification. Section 3 briefly describes the estimation procedure and the posterior distribution of the model parameters. Section 4 characterizes the optimal policy in the baseline economy and compares the performance of alternative simple rules. Sections 5 and 6 analyze the implications of parameter uncertainty and innovation uncertainty, respectively. Section 7 considers several types of specification uncertainty. Section 8 concludes. The appendix contain some additional derivations and results.

2 The Model

As in CEE and SW, our baseline model incorporates a number of mechanisms that can induce intrinsic persistence in the propagation of shocks, including habit persistence in consumption, costs of adjustment for investment and capacity utilization, and staggered nominal wage and price contracts with partial indexation. The model also includes a number of exogenous disturbances (assumed to be mutually uncorrelated) that account for the stochastic variation in the observed data used in our estimation procedure.

2.1 Household Preferences

The economy has a continuum of infinitely lived households. The conditional welfare of a given household $h \in [0, 1]$ at a given time t is defined as the discounted sum of expected period utility:

$$W_t(h) = E_t \sum_{j=0}^{\infty} \beta_{t+j}^j V_{t+j}(h), \quad (4.1)$$

where the subjective discount factor is $\beta_t = \beta Z_t^b$ and we define $\beta_{t+j}^j = \prod_{s=0}^j \beta_{t+s}$. Thus, the steady-state subjective discount factor is given by the parameter $0 < \beta < 1$, while stochastic variation in the rate of time

preference is induced by the exogenous disturbance Z_t^b ; we assume that the logarithm of this disturbance follows an AR(1) process.

The period utility function of a given household h at time t is specified as follows:

$$V_t(h) = \frac{(C_t(h) - \theta C_{t-1}(h))^{1-\sigma}}{1-\sigma} - \frac{Z_t^L (L_t(h))^{1+\chi}}{1+\chi} + \mu_0 \frac{Z_t^m (M_t(h))^{1-\kappa}}{1-\kappa} \quad (4.2)$$

where $C_t(h)$ denotes the household's total consumption, $L_t(h)$ denotes its labor hours, and $M_t(h)$ denotes its real cash balances.¹¹ The preference parameters, σ , χ , κ , and μ_0 , are strictly positive, while θ lies in the unit interval. The exogenous disturbance Z_t^L induces stochastic variation in household preferences for leisure relative to consumption, and Z_t^m is an exogenous shock to money demand; the logarithm of each shock is assumed to follow an AR(1) process.

Habit persistence in consumption is an important but somewhat controversial feature of this specification. In particular, for positive values of θ , the household's lagged consumption effectively serves as a reference value in determining the period utility generated by current consumption.¹² Recent empirical analysis of aggregate data has obtained substantial evidence of habit persistence; for example, CEE emphasize its role explaining the hump-shaped behavior of aggregate consumption in response to a monetary policy shock. Nevertheless, it should be noted that micro-level studies have occasionally obtained results that directly conflict with the macro evidence.¹³

Of course, the curvature parameters of the utility function also remain quite controversial. Some studies have argued that σ is around unity, while others find much larger values.¹⁴ Furthermore, microeconomic studies have typically obtained estimates of χ that are significantly greater than unity, whereas some macroeconomists have argued that the aggregate data are consistent with a near-zero value of χ , corresponding to a very high intertemporal elasticity of leisure for the representative household.¹⁵

Finally, while this specification allows real money balances to directly influence household utility, most of our analysis will focus on the cashless economy emphasized by Woodford (2003) and others; this economy corresponds to the limiting case in which μ_0 becomes arbitrarily small. Later in the paper, however, we will revisit this issue and examine the policy implications of incorporating a nontrivial role for money into the model.

2.2 Production and Prices

The final composite good—used for both consumption and investment—is obtained by bundling together a continuum of differentiated intermediate goods using a Dixit-Stiglitz aggregator function. As in SW, we allow the elasticity of substitution between different goods to exhibit exogenous temporal variation; that is, $\lambda_t^p = Z_t^p \lambda^p$. The parameter $\lambda^p > 0$ determines the steady-state markup rate, while the exogenous disturbance Z_t^p (assumed to have an i.i.d. log-normal distribution) shifts the desired markup at each point in time. A given firm, indexed by $i \in [0, 1]$, as the sole producer of intermediate good i , faces a downward-sloping demand curve, and its elasticity of demand $-(1 + \lambda_t^p)/\lambda_t^p$ is invariant to the firm's level of production.¹⁶

Interestingly, the steady-state markup parameter λ^p does not influence the first-order dynamics of the model economy and hence cannot be estimated using the methods employed in this paper. Nevertheless, this parameter does affect the second-order properties of the model, including the welfare performance of monetary policy rules. In light of the available evidence from disaggregated data, we set $\lambda^p = 0.20$ in the baseline version of the model, and then consider alternative values from 0.1 to 0.5.¹⁷

Every intermediate-goods producer has an identical production function that determines the gross output of good i as a Cobb-Douglas function of the firm's employment of labor services $N_t(i)$, its rental of capital services $\tilde{K}_t(i)$, and the exogenous economy-wide productivity factor A_t :

$$Y_t(i) = A_t \tilde{K}_t(i)^\alpha N_t(i)^{1-\alpha} - \Phi \quad (4.3)$$

where the parameter α represents the share of capital in gross output, and we assume that the logarithm of the productivity factor follows an AR(1) process. As in CEE and SW, every firm hires its capital and labor services on competitive economy-wide markets and hence has the same marginal cost of production.

The firm's net output $Y_t(i)$ reflects the presence of the fixed overhead cost Φ . This fixed cost induces locally increasing returns to scale for each individual firm and generates procyclical total factor productivity at the aggregate level. Thus, inferences about the value of Φ can be made using both micro-level and macro-level data.

In the baseline version of the model, we assume that prices are determined by Calvo-style nominal contracts with partial indexation.¹⁸ In

particular, every firm faces a constant probability $1 - \xi_p$ of reoptimizing its price contract in any given period, where $\xi_p \in [0, 1]$; thus, price contracts have an average duration $1/(1 - \xi_p)$. Whenever the contract is not reoptimized, the firm's price is adjusted automatically by the lagged rate of inflation raised to the power $\gamma_p \in [0, 1]$.

This specification of price-setting behavior provides formal underpinnings for the hybrid New Keynesian Phillips curve.¹⁹ In particular, the indexation parameter γ_p determines the relative weight on the backward-looking versus forward-looking terms in the hybrid Phillips curve. While the magnitude of these weights is subject to ongoing controversy, recent analysis of aggregate data seems to be largely consistent with the available microeconomic evidence indicating that indexation is not a typical characteristic of price adjustment.²⁰

Under the assumption that all firms have the same marginal cost, the responsiveness of inflation to current marginal cost is determined solely by the parameter ξ_p . Typically, as in SW, the estimated value of ξ_p tends to imply a relatively long average duration of price contracts that is inconsistent with recent microeconomic evidence.²¹ Several recent studies have shown that incorporating additional real rigidities—such as quasi-kinked demand and firm-specific capital—yields more plausible estimates of the degree of nominal rigidity.²² Nevertheless, analyzing the second-order implications of these mechanisms poses some technical challenges that remain to be addressed in the literature.

2.3 Investment and Capacity Utilization

Households own the entire stock of physical capital K_t . Capital accumulation is subject to adjustment costs that are assumed to be proportional to the squared *growth rate* of investment rather than the more traditional formulation involving the squared *level* of investment. As emphasized by CEE, this specification of adjustment costs can generate a hump-shaped response of aggregate investment to a monetary policy shock, consistent with the implications of an identified vector autoregression. While the formal microeconomic foundations of this mechanism were initially opaque, Basu and Kimball (2003) have subsequently shown that very similar implications can be obtained in a framework with planning delays in investment.

Thus, the capital stock owned by a given household $h \in [0, 1]$ evolves as follows:

$$K_t(h) = (1 - \delta)K_{t-1}(h) + \left[1 - \zeta^{-1} \frac{1}{2} \left(Z_t^I \frac{I_t(h)}{I_{t-1}(h)} - 1 \right)^2 \right] I_t(h) \quad (4.4)$$

where $K_t(h)$ denotes the household's beginning-of-period capital stock, and $I_t(h)$ denotes the gross investment during period t . The depreciation rate is given by δ , and the parameter ζ gauges the magnitude of investment adjustment costs.²³ Finally, the exogenous disturbance Z_t^I acts as an economy-wide shock to investment demand; its logarithm follows an AR(1) process.

In each period, the aggregate flow of capital services \tilde{K}_t to the intermediate goods sector is defined as the capacity utilization rate U_t multiplied by the predetermined level of the physical capital stock, K_{t-1} . The capacity utilization rate can vary from its steady-state value of unity, but such variations are associated with a real resource cost. In particular, we specify the resource cost $\Psi_t(h)$ incurred by a given household h as a constant elasticity of substitution (CES) function of its capacity utilization $U_t(h)$:

$$\Psi_t(h) = \mu \frac{U_t(h)^{1+\psi^{-1}} - 1}{1 + \psi^{-1}} \quad (4.5)$$

where $\psi \geq 0$ and $\mu > 0$.²⁴

As emphasized by CEE, variable capacity utilization can effectively enhance the short-term flexibility of the economy in response to aggregate shocks. Nevertheless, the magnitude of the utilization cost parameter ψ is currently subject to a great deal of uncertainty due both to the scarcity of microeconomic evidence and to conflicting results from recent macroeconomic analysis. For example, CEE find that variations in capacity utilization play an important role in explaining the sluggish response of inflation to a monetary policy shock, whereas the results of Altig, Christiano, Eichenbaum, and Linde (2004) suggest that the aggregate effects of a technology shock are consistent only with relatively limited variations in capacity utilization.

Finally, following SW, we include an external finance premium shock Z_t^q (assumed to have an i.i.d. log-normal distribution), which acts as a wedge between the risk-free real interest rate and the required expected rate of return on physical capital. Recent analysis of firm-level data has obtained precise estimates of the magnitude and cyclical behavior of the external finance premium (see Levin, Natalucci, and Zakrajsek 2004). However, further theoretical and empirical research is

clearly needed to elucidate the underpinnings and implications of this mechanism.

2.4 *Employment and Wages*

Households provide a continuum of differentiated labor services, which are bundled together using a Dixit-Stiglitz aggregator function and then rented to the intermediate sector. As in SW, we allow the elasticity of substitution between different types of labor services to exhibit exogenous temporal variation; that is, $\lambda_t^w = Z_t^w \lambda^w$. The parameter $\lambda^w > 0$ determines the steady-state markup of real wages over the marginal rate of substitution between consumption and leisure. The exogenous disturbance Z_t^w (assumed to have an i.i.d. log-normal distribution) shifts the desired wage markup at each point in time. Given this specification, a given household $h \in [0, 1]$, as the sole provider of the labor service of type h , faces a downward-sloping labor demand curve with elasticity $-(1 + \lambda_t^w)/\lambda_t^w$.

In the baseline version of the model, we assume that wages are determined by Calvo-style nominal contracts with partial indexation. In particular, each household faces a constant probability $1 - \xi_w$ of reoptimizing its wage contract in any given period, where $\xi_w \in [0, 1]$. Whenever the contract is not reoptimized, the household's wage is automatically adjusted by the lagged rate of price inflation raised to the power $\gamma_w \in [0, 1]$.

The steady-state markup parameter λ^w and the contract wage parameter ξ_w cannot be identified independently from the log-linear dynamics of the model. Given the scarcity of disaggregated evidence on these two parameters, we proceed by calibrating $\lambda^w = 0.20$ (the same baseline value as for λ^p) and estimating the value of ξ_w .²⁵ We will then gauge the policy and welfare implications of alternative combinations of these two parameters that yield the same first-order behavior of the model.

Because the wage-setting mechanism has crucial implications for the design of optimal monetary policy, we will also consider two modifications to the baseline specification, namely, indexation of wages to lagged wage inflation instead of lagged price inflation and the use of fixed-duration Taylor-style wage contracts instead of Calvo-style contracts. As we will see, these alternative specifications yield significantly different implications for monetary policy and welfare.

2.5 *Fiscal and Monetary Policy*

We assume that government spending is exogenously determined and exhibits persistent variations; in particular, its logarithm follows an AR(1) process. As is evident from the previous discussion, government spending has no direct effects on either utility (through purchases of public goods) or production (perhaps via a stock of public capital); consideration of these channels, as well as automatic fiscal stabilizers, is deferred to future research.

Furthermore, we assume that the government offsets the steady-state effects of monopolistic distortions by enacting the appropriate magnitude of production and employment subsidies, which are financed via a constant level of lump-sum taxes. Thus, the deterministic steady state is Pareto-optimal in the baseline model with a zero inflation rate. Under these assumptions, we can focus our analysis on the stabilization task of monetary policy, abstracting from the complications that would arise if the central bank also played a role in trying to offset the effects of steady-state distortions.²⁶

In estimating the model, we use a fairly simple monetary policy rule in which the short-term nominal interest rate responds to the lagged interest rate as well as to deviations of aggregate price inflation from target and of actual output from the level that would prevail in the absence of nominal inertia. This specification includes two additional exogenous shocks, namely, persistent AR(1) shifts in the inflation objective and transitory white-noise shocks to the current policy rate. In our normative analysis, of course, we consider the full Ramsey policy as well as alternative specifications of simple policy rules, and we assume that monetary policy does not exhibit any exogenous stochastic variation.

3 **Model Estimation**

We employ Bayesian methods to estimate the log-linearized version of the model, using quarterly U.S. data over the period 1955:1 through 2001:4.²⁷ In particular, we treat seven aggregate variables as directly observed: real consumption, real investment, real gross domestic product (GDP), real wages, total hours, GDP price inflation, and the federal funds rate.²⁸ Because the rest of the model variables (such as the capital stock) are treated as unobserved, we use the Kalman filter in computing the likelihood function of the model.

As widely recognized in earlier work, certain structural parameters are not well-identified from the cyclical dynamics of the data. There-

fore, we use long-term historical averages to specify the values of these parameters: the capital share parameter $\alpha = 0.36$, the discount factor $\beta = 0.99$ (corresponding to a steady-state real interest rate of about 4 percent), and the depreciation parameter $\delta = 0.025$ (corresponding to an annual rate of about 10 percent). Similarly, we calibrate the output shares of consumption, investment, and government spending at $c_y = \bar{C}/\bar{Y} = 0.56$, $i_y = 0.24$, and $g_y = 0.20$, respectively.²⁹ Finally, we set the wage and price markup parameters $\lambda^w = \lambda^p = 0.2$; in the following section, we will consider the implications of alternative values for these two parameters.

We formulate independent prior densities for each of the other thirty-one parameters of the model, namely, ten parameters related to preferences and technology, five coefficients of the empirical interest rate reaction function, and sixteen parameters of the data-generating processes for the disturbances. Overall, our prior is consistent with the previous literature and is relatively uninformative for most of the parameters; details are given in the appendix.³⁰ Given these priors, we characterize the posterior distribution using a Metropolis-Hastings Markov chain Monte Carlo (MCMC) algorithm. Our estimation methodology is broadly similar to that of Lubik and Schorfheide (2005); further details are provided in the appendix.³¹

In the remainder of this section, we focus on characterizing the posterior distribution of the key structural parameters. Table 4.1 reports the posterior means and the 5 percent and 95 percent bounds for each of these parameters. Corresponding results for the parameters of the shock processes may be found in the appendix.

As depicted in figure 4.1, the macroeconomic data are quite informative regarding the parameters related to price and wage determination. In light of recent micro-based evidence obtained by Bils and Klenow (2004) and Golosov and Lucas (2003), we specify a prior mean of 0.38 for the Calvo price-setting parameter ξ_p , corresponding to an average contract duration of about 1.5 quarters; we employed the same prior mean for the Calvo wage parameter ξ_w . In contrast, the posterior mean estimates for these two parameters imply an average contract duration of about five quarters, similar to the findings of CEE and SW.³² Furthermore, the posterior probability intervals of these estimates are relatively narrow, suggesting a fairly clear disconnect between the micro and macro evidence.

We impose relatively uninformative priors on the degree of price and wage indexation. The estimate of the degree of price indexation is

Table 4.1
Estimation Results

Parameter	Posterior Mean	90% Probability Interval
ξ_p Calvo prices	0.83	0.81–0.86
ξ_w Calvo wages	0.79	0.72–0.85
γ_p Price indexation	0.08	0.00–0.21
γ_w Wage indexation	0.79	0.43–1.00
ζ Investment adjustment	0.56	0.27–0.86
σ Consumption utility	2.19	1.68–2.74
θ Consumption habit	0.29	0.20–0.38
χ Labor utility	1.49	0.95–2.12
ϕ Fixed cost	1.09	1.06–1.11
ψ Capital utilization	0.21	0.12–0.31

near 0 and relatively precisely estimated; in contrast, the degree of wage indexation is found to be substantial but very imprecisely estimated. The lack of price indexation differs from SW but is consistent with the findings of Ireland (2001) and Edge, Laubach, and J. Williams (2003).

The macroeconomic data are somewhat less informative regarding other structural parameters. Figure 4.2 repeats the previous figure for the structural parameters not related to price and wage determination. Overall, the resulting estimates are consistent with estimates from the literature. Except for the parameters determining capacity utilization costs and habit persistence, the posteriors do not differ greatly from the respective priors. The finding of a relatively tight posterior distribution for the capacity utilization cost parameter occurs despite the imposition of a relatively loose prior and contrasts with the wide dispersion of estimates of this parameter in the literature.

One structural parameter that deserves further discussion is the returns to scale in production, ϕ . We chose a relatively tight prior centered on 1.08 for this parameter, based on the estimates of Basu (1996) and Basu and Fernald (1997), who find fixed costs of between 3 and 10 percent. Our resulting mean estimate is 1.09. By comparison, when we imposed an uninformative prior, the mode estimate exceeded 2, a result consistent with the findings of SW but contrary to the micro evidence. Despite this difference in point estimates, in fact the data were not terribly informative about this parameter, as seen in the figure. Interestingly, imposing our prior on ϕ resulted in a small estimate of

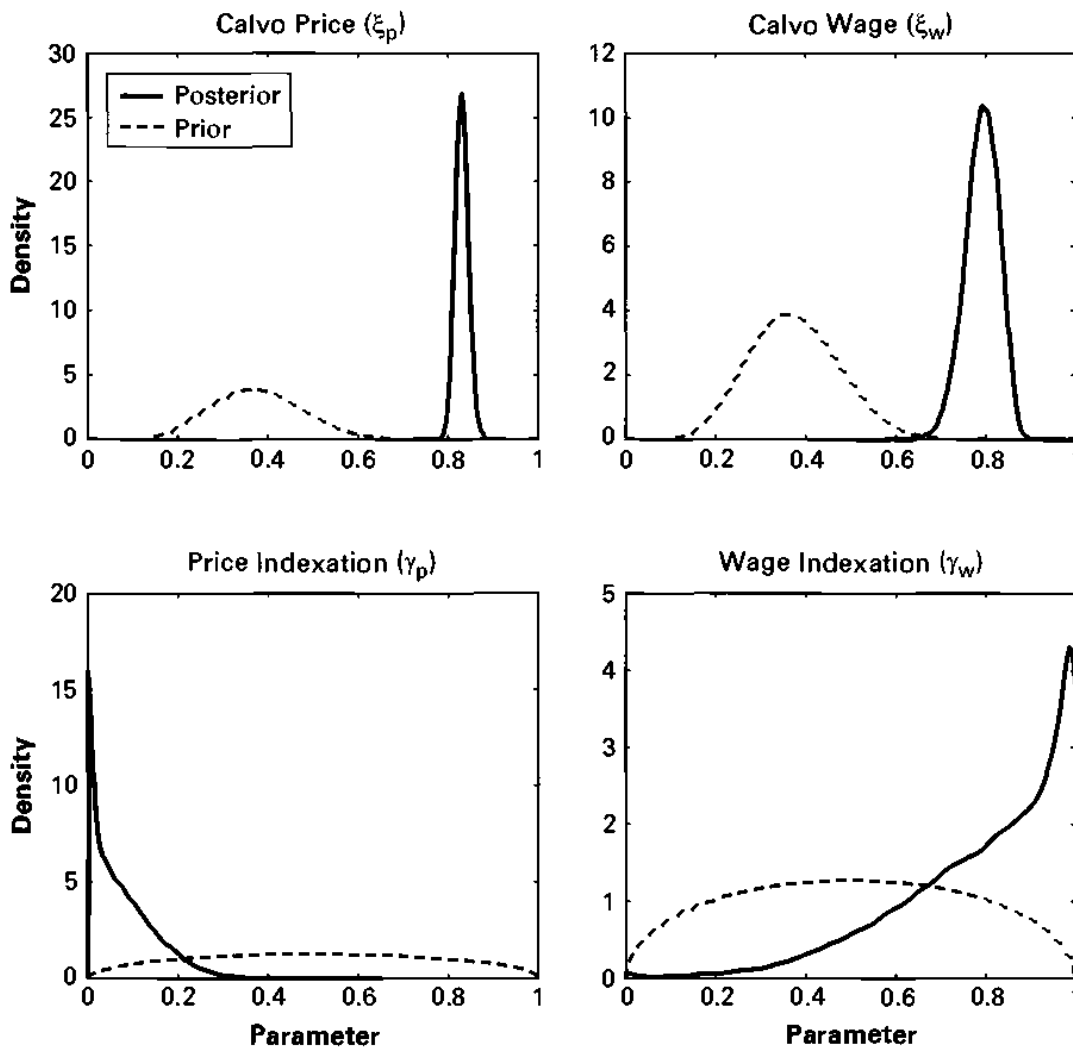


Figure 4.1
 Estimated Posterior Distributions (Solid Lines) and Prior Distributions (Dashed) for the Price and Wage Parameters

investment adjustment costs. Our estimate of investment adjustment costs are noticeably lower than SW but more in line with those reported by Altig, Christiano, Eichenbaum, and Linde (2004).

For the monetary policy reaction function, we obtain the following estimation results:

$$r_t = \underset{(0.03)}{0.84}r_{t-1} + \underset{(0.3)}{0.16}[2.7(\pi_{t-1} - \pi_{t-1}^*) + \underset{(0.07)}{0.10}y_{t-1}] + \underset{(0.06)}{0.26}\Delta\pi_t + \underset{(0.07)}{0.51}\Delta y_t + \eta_t^r$$

where the estimated standard error of each coefficient is enclosed in parentheses. This reaction function exhibits a high degree of inertia, a

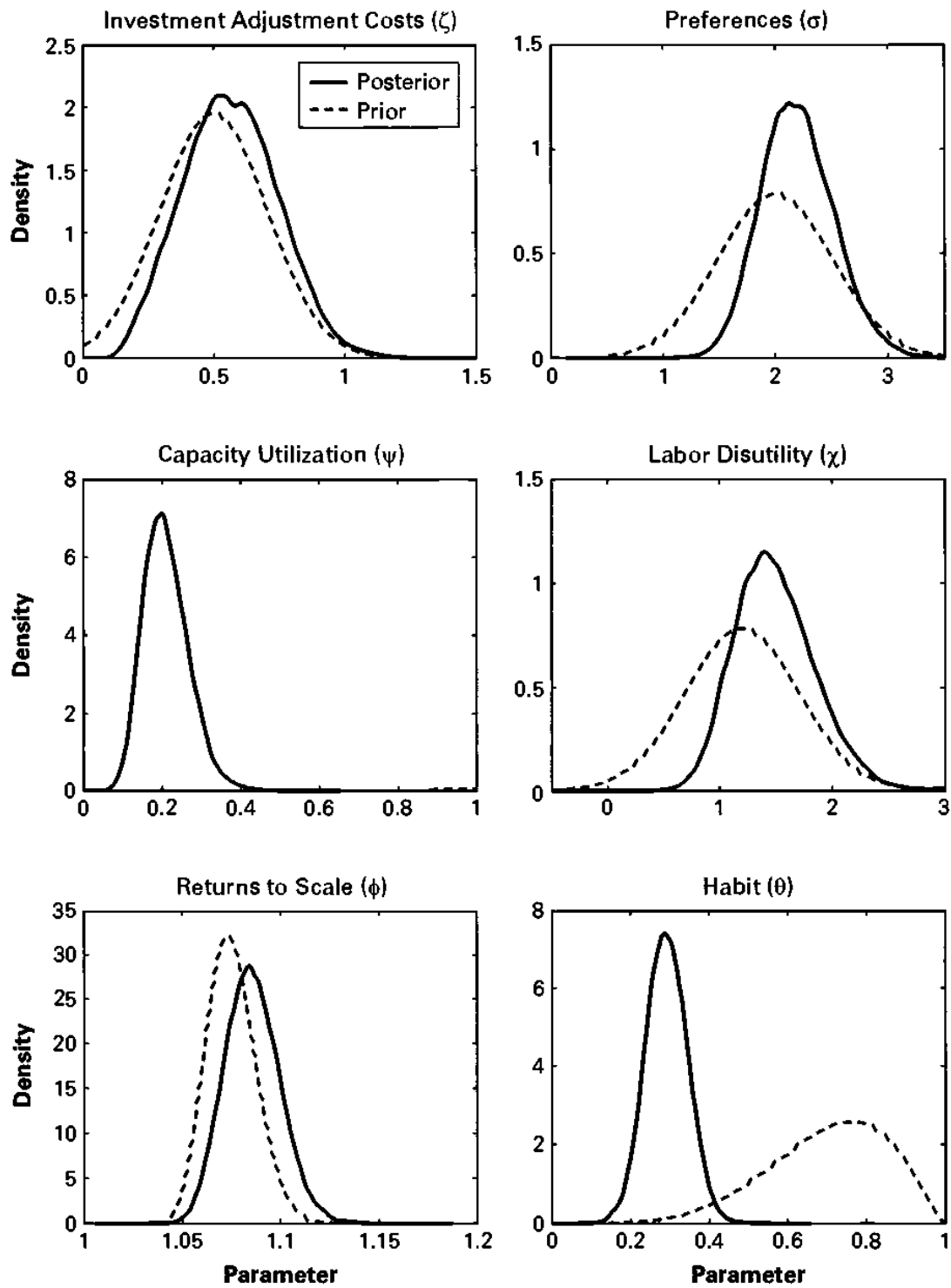


Figure 4.2
 Estimated Posterior Distributions (Solid Lines) and Prior Distributions (Dashed) for Structural Parameters

strong long-run response to inflation, modest sensitivity to the level of the output gap, and a sizeable response to changes in the output gap.

As for the monetary policy shocks, we find that the inflation target π_t^* has significant variation and exhibits very high persistence approaching that of a random walk, while the transitory disturbance η_t' has negligible variance. It should be noted that our modeling framework does not provide any rationale or potential benefits from a time-varying inflation target or from idiosyncratic disturbances to the policy rule. Thus, given our focus on policies that maximize social welfare, we henceforth eliminate these two shocks by setting their variances to 0.

4 Optimal Monetary Policy

In this section, we characterize the monetary policy implications of the baseline model at the posterior mean values of the estimated parameters, abstracting from uncertainty about the true structure of the economy. We start by considering the optimal policy under commitment that maximizes conditional expected welfare and then compare the performance of simple rules in which the short-term interest rate is adjusted in response to one or more observable variables.

4.1 *The Optimal Policy Problem*

The optimal policy under commitment can be computed by formulating an infinite-horizon Lagrangian problem in which the central bank maximizes conditional expected social welfare subject to the full set of nonlinear constraints implied by the private sector's behavioral equations and the market-clearing conditions of the model economy.³³ The first-order conditions of this problem are obtained by differentiating the Lagrangian with respect to each of the endogenous variables (including the policy instrument) and setting these derivatives to 0. Of course, performing these derivations by hand would be extremely tedious; thus, we utilize the symbolic Matlab procedures developed by Levin and Lopez-Salido (2004).³⁴

We then proceed to analyze the behavior of the economy under optimal policy by combining the central bank's first-order conditions together with the private sector's behavioral equations and the market-clearing conditions. Thus, the size of the model is much larger under the optimal policy because these first-order conditions take the place of a single interest rate reaction function, while the set of Lagrange

multipliers is added to the list of model variables. Nevertheless, it should be emphasized that no new parameters have been added to the model because the central bank's first-order conditions involve the same structural parameters as in the behavioral equations and market-clearing conditions.

Because this set of nonlinear equations involves rational expectations, numerical methods are required to characterize the equilibrium properties of the stochastic economy.³⁵ Furthermore, while the first-order dynamics can be investigated by log-linearizing the model, higher-order methods are needed to evaluate conditional expected welfare.³⁶ Therefore, we employ the Dynare software package of Juillard (2001) to compute the second-order approximation of the model economy.³⁷

Finally, as in Levin and Lopez-Salido (2004), our analysis is focused on evaluating the *welfare cost of business cycles*; that is, for each monetary policy regime, we measure how conditional expected welfare changes in response to the stochastic variation of the model economy.³⁸ Throughout the paper, welfare costs are expressed in terms of the equivalent percentage decline in steady-state consumption.

4.2 *Characteristics of Optimal Policy*

The deterministic steady state of the baseline economy is characterized by a 0 inflation rate. In particular, as noted above, we assume that fiscal subsidies offset the steady-state monopolistic distortions to production and employment, while money is essentially absent from the baseline specification. Thus, in the absence of stochastic shocks, the central bank's sole task is to choose the constant inflation rate that minimizes the degree of cross-sectional dispersion in prices and wages; indeed, by maintaining a 0 inflation rate, monetary policy succeeds in implementing the Pareto-optimal equilibrium in steady state.

The first-order implications of the optimal policy are shown in figure 4.3, which depicts the response of selected macro variables to an exogenous rise in the productivity factor.³⁹ The optimal policy (solid line) yields a path of short-term real interest rates that closely resembles that of the real business cycle (RBC) economy with flexible wages and prices (dotted line); in contrast, real interest rates are nearly constant under the empirical reaction function (dashed line). In the RBC economy, real wages initially rise about 0.75 percent; with a constant price level, this adjustment occurs solely through a surge in nominal wage inflation. In contrast, the optimal policy for the baseline economy is

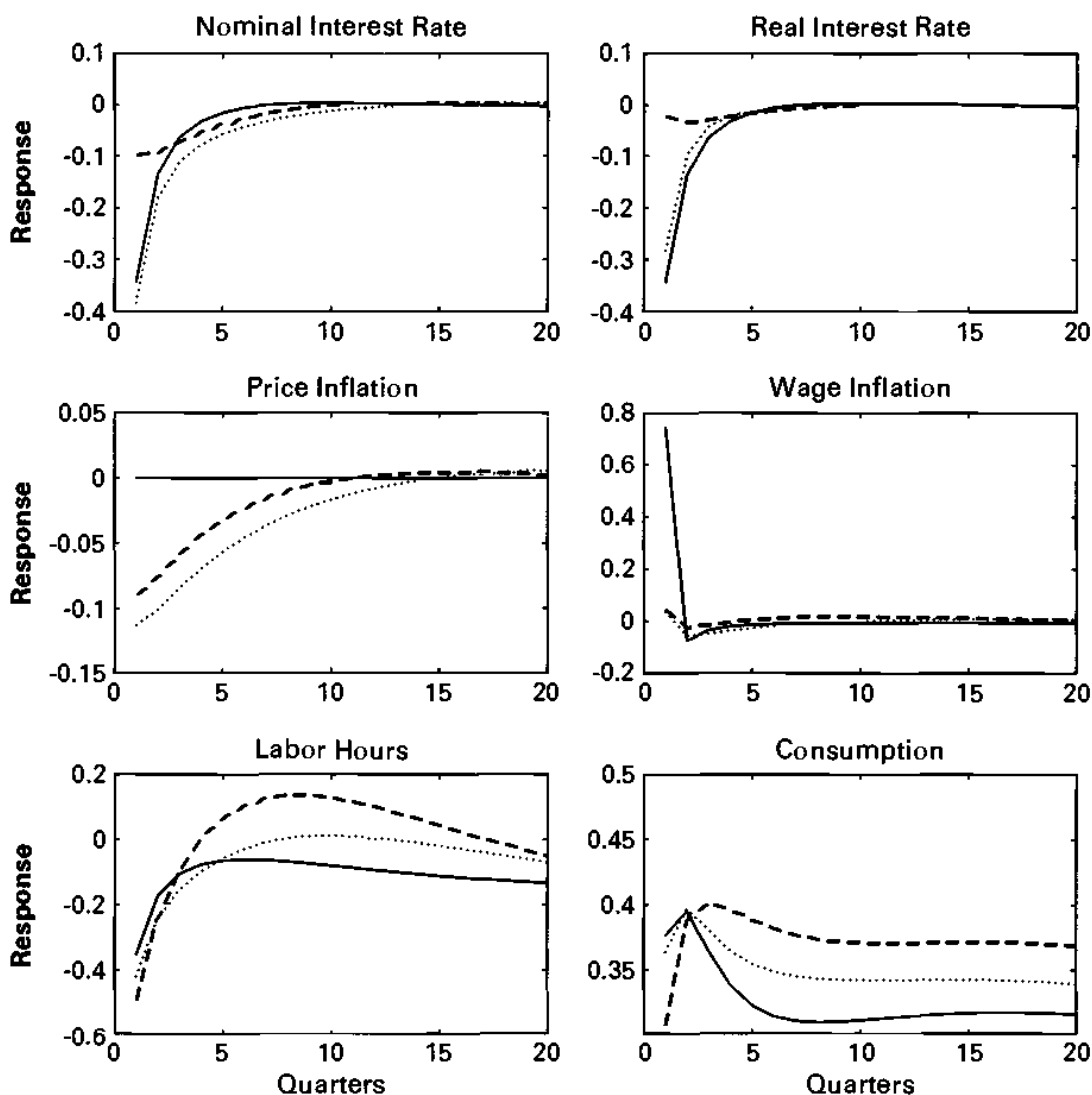


Figure 4.3
 Impulse Responses for One Standard Deviation Positive Shock to Productivity: Optimal Policy (Solid Lines), Empirical Reaction Function (Dashed), RBC Economy (Dotted Lines)

mainly oriented towards minimizing cross-sectional dispersion in wage rates and hence permits a noticeable decline in prices while nominal wage inflation remains close to 0.

Under the optimal policy (as in the RBC economy), the positive shock to productivity induces a substantial decline in aggregate labor hours that is gradually reversed over the subsequent year. Under the empirical reaction function, labor hours decline only for a single quarter and then rise above baseline. These findings relate to the debate regarding the empirical evidence of the response of hours to productivity shocks and the sensitivity of these results to monetary policy.

Table 4.2
The Welfare Cost of Business Cycles

Empirical reaction function	-2.57
Optimized price inflation rule	-2.60
Optimized wage inflation rule	-2.13
Optimal policy	-2.01

We now compare the welfare implications of these policies for the baseline economy with stochastic variation in all of the exogenous disturbances except the monetary policy shocks. For each policy, table 4.2 reports the welfare cost of business cycles in terms of the equivalent percentage point change in steady-state consumption; this table also indicates welfare outcomes for two simple rules that are discussed further below.

Under the empirical reaction function, the welfare cost of business cycles in the baseline model is equivalent to a permanent 2.6 percent reduction in household consumption. The optimal policy is associated with a markedly lower cost of business cycles, equivalent to about 2 percent of steady-state consumption. It should be noted that these welfare costs are an order of magnitude larger than in the results emphasized by Lucas (2003) mainly because staggered contracts induce substantial cross-sectional dispersion in relative prices and wages.⁴⁰

To gauge these welfare results more concretely, we note that U.S. personal consumption expenditures were about \$28,000 per person in 2004; thus, switching from the empirical reaction function to the optimal policy would permanently raise welfare by about \$160 per person, while eliminating all stochastic variation in the economy would generate a permanent welfare gain exceeding \$700 per person. As we will see below, however, the magnitude of the welfare costs can be quite sensitive to the parameter values of the model as well as to the specification of the innovations and the determination of wages and prices.

4.3 Simple Policy Rules

We now consider the performance of simple policy rules with coefficients chosen to maximize welfare in the baseline model.⁴¹ In particular, we examine rules with the following form:

$$r_t = r_i r_{t-1} + r_\pi \pi_t + r_\omega \omega_t \quad (4.6)$$

where the nominal interest rate r_t responds to the price inflation rate π_t and the nominal wage inflation rate ω_t as well as to the lagged nominal interest rate. This type of rule is operational in the sense of McCallum (1999): the policy instrument is determined only by observable variables and not by model-specific constructed data such as the natural rates of interest and output, and forecasts of variables (which require knowledge of the economy).⁴² Furthermore, it is equivalent to targeting a deterministic path for the level of wages or prices; such policies have been shown to perform very well in the presence of the 0 lower bound on nominal interest rates.⁴³

Given the role of wage dispersion in determining the welfare cost of business cycles, it is useful to consider policy rules that respond directly to nominal *wage* inflation, as suggested by Erceg, Henderson, and Levin (2000).⁴⁴ Therefore, we consider a hybrid rule that responds differentially to both price and wage inflation, as well as rules that respond to price inflation alone. Optimizing the coefficients of the hybrid rule to maximize welfare in the baseline model, we find that $r_\omega = 3.2$ while $r_\pi = 0$. Thus, given that the optimized rule does not actually respond to price inflation, we simply refer to this rule as the *benchmark wage inflation rule*. We then compare its performance to an alternative rule that does not respond to wages—henceforth referred to as the *benchmark price inflation rule*—for which welfare optimization yields $r_\pi = 2.1$.

As indicated in table 4.2, the benchmark wage inflation rule yields a welfare outcome nearly identical to the optimal policy; indeed, following this simple wage inflation rule rather than the optimal policy would incur a welfare cost equivalent to less than \$35 per person per year. In contrast, the benchmark price inflation rule yields a welfare loss that is roughly the same as under the empirical reaction function.

The impulse responses to the technology shock under the benchmark wage inflation rule mimics closely those of the optimal policy, as seen in figure 4.4. One difference is that the benchmark wage inflation rule initially tightens monetary policy, causing a slightly excessive fall in labor hours and consumption at the onset of the shock. After a few quarters, however, the benchmark wage inflation rule gets back on track, and the paths of labor hours, consumption, and price and wage inflation are virtually identical to those obtained under the optimal policy. In contrast, the benchmark price inflation rule is overly

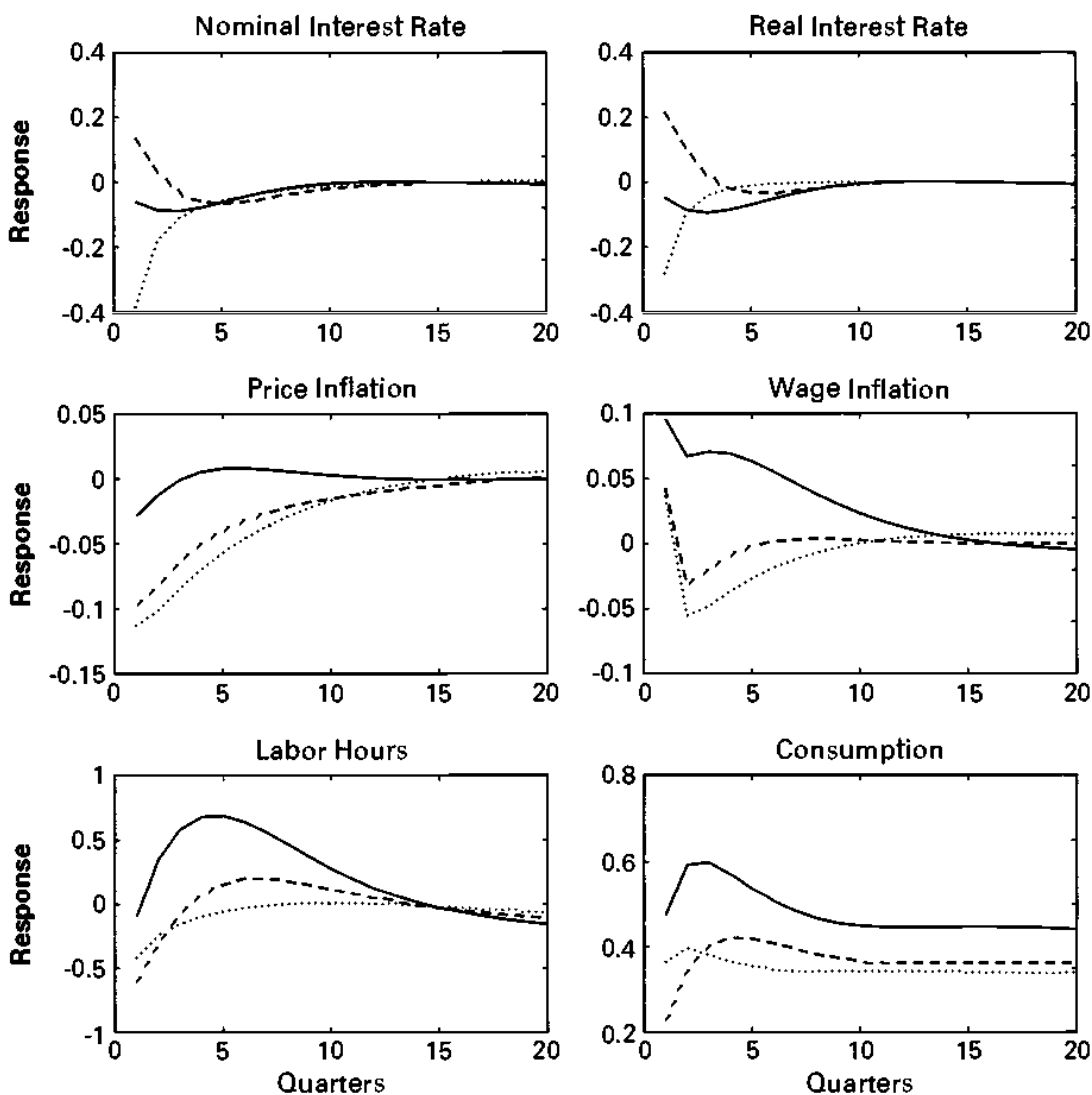


Figure 4.4
 Impulse Responses for One Standard Deviation Positive Shock to Productivity: Optimal Policy (Solid Lines), Optimized Wage Inflation Rule (Dashed Lines), and the Optimized Price Inflation Rule (Dotted Lines)

stimulative at the onset of the shock, keeping price inflation near baseline but generating excessive nominal wage inflation.

5 Parameter Uncertainty

In this section, we explore the sensitivity of household welfare to variations in the parameters under the wage inflation policy rule optimized to the baseline parameters discussed in Section 3. We evaluate the performance of this rule in comparison with that of the optimal policy determined using the true values of the model parameters.

5.1 *Estimated Parameters*

We start by considering the effect of uncertainty as measured by our estimated posterior distribution. We compute the welfare losses associated with joint parameter uncertainty of the ten structural parameters together.⁴⁵ For this purpose, we randomly select 5,000 draws of the parameter vector from the posterior distribution described above. For each draw, we compute welfare under the optimal policy for the true set of parameters and under the benchmark wage inflation policy. Note that this method incorporates the covariance between the model parameters, allowing for the possibility that particular combinations of parameter realizations may have sizeable effects on outcomes. Figure 4.5 reports the results from this exercise; the upper panel shows the resulting distributions of welfare losses under the two policies, and the lower panel shows the distribution of the relative welfare loss equal to the difference in welfare between the optimal policy and the benchmark wage inflation rule.

Uncertainty about the structural parameters implies a great deal of uncertainty regarding the welfare loss associated with fluctuations, but far less uncertainty regarding the performance of the benchmark wage inflation rule relative to the optimal policy. As seen in the upper panel of the figure, the distribution of welfare losses under either policy is wide with a relatively long left tail. Under the optimal policy, the median welfare loss is 2.1 percent, just 0.1 percentage point larger than for the posterior mean estimates, but the 90 percent confidence interval for the welfare loss ranges from 4.3 percent to 0.9 percent. The results under the benchmark wage inflation rule are comparable. Thus, parameter uncertainty can easily make the welfare costs of fluctuations more than double what we estimate, or half as large, for that matter. However, as the lower panel of the figure shows, the performance of the benchmark wage inflation rule relative to the optimal policy is remarkably robust to parameter uncertainty. Indeed, the mean relative welfare loss, evaluated over the posterior distribution, is 0.14 percent, compared to 0.12 percent assuming no uncertainty, and the 90 percent probability interval for the relative welfare loss is fairly narrow, ranging from 0.06 to 0.35 percent.

Because the benchmark rule performs so well across the posterior distribution, it is not surprising that taking account of parameter uncertainty as measured by the posterior distribution has almost no effect on the parameters or expected performance of the optimized wage inflation rule. We computed the coefficient of a wage inflation rule that

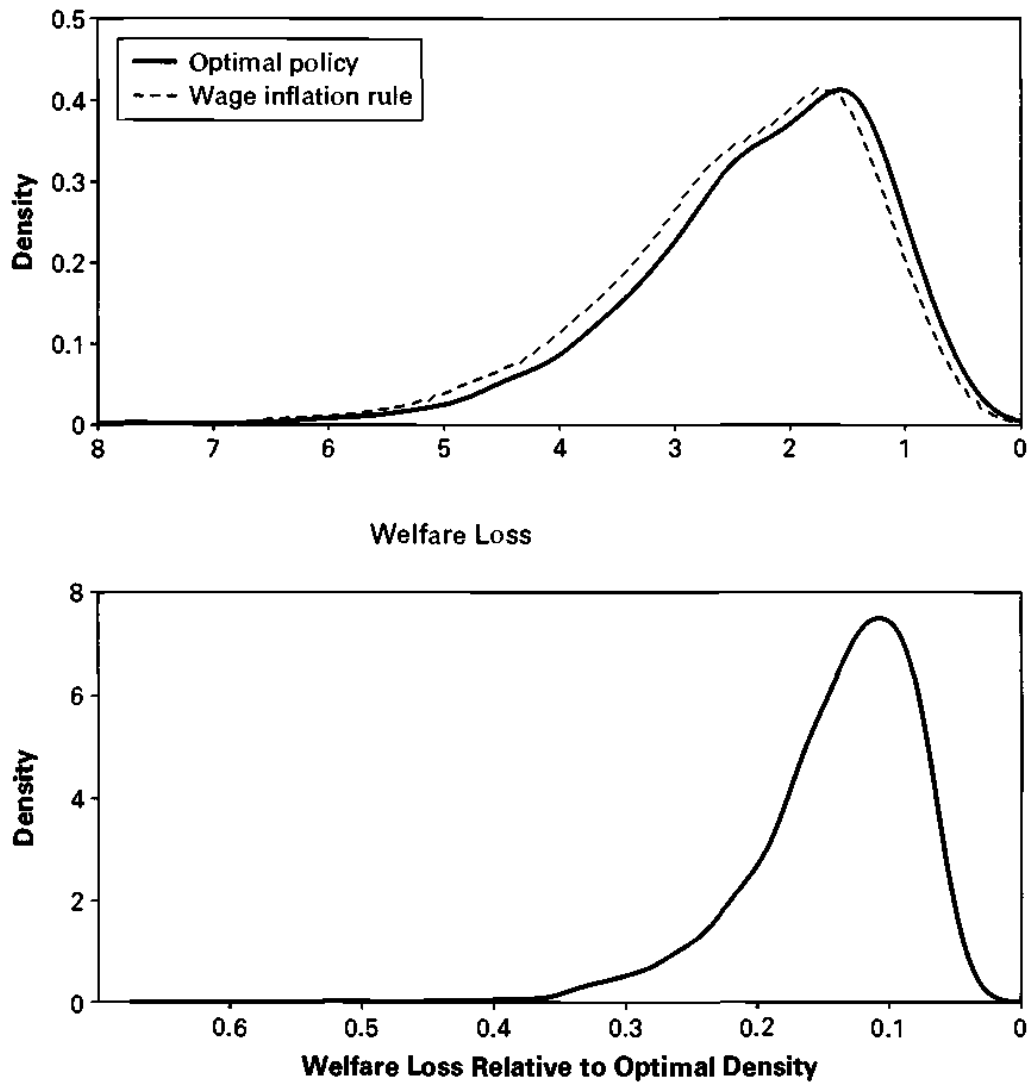


Figure 4.5

The Distribution of Welfare Losses for the Estimated Posterior Distribution

Note: The top panel represents welfare losses relative to the steady state for the optimal policy tuned to each parameter draw (solid line) and the benchmark wage inflation rule (dashed line). The bottom panel represents the difference in welfare loss between the optimal and benchmark wage inflation rule.

maximizes expected welfare integrating over the posterior distribution as above. The optimal coefficient equals 2.9, slightly lower than the value of 3.2 in the case of no uncertainty. But this rule yields an increase in expected welfare relative to the benchmark wage inflation rule of only 0.0004 percent. Thus, the existence of parameter uncertainty, as measured by the posterior distribution, is nearly irrelevant for designing policy in this model. Of course, a significant reduction in this uncertainty could have implications for the design of policy and welfare, as we examine next.

The degree of parameter uncertainty represented by the posterior distribution likely understates the true degree of uncertainty that policymakers face. As discussed in Onatski and N. Williams (2003) and Lubik and Schorfheide (2005), the mean and spread of the posterior distributions are highly sensitive to the assumed prior distributions. Point estimates and their standard errors are sensitive to estimation methodology, sample, and the values of calibrated parameters.⁴⁶ This sensitivity is illustrated by the wide range of point estimates for various model parameters found in what are nearly identical models studied in CEE, SW, and this paper.

Given this concern that the degree of parameter uncertainty may exceed that implied by the posterior distribution, we now examine the robustness of the benchmark wage inflation rule to a much wider set of parameter values. A second goal of this analysis is to uncover which parameters entail costly consequences when an estimate is far from the true value. To facilitate our analysis, we vary specific parameters one at a time, holding all other parameters at their respective mean estimates. We focus our analysis on the difference in welfare between that found under the benchmark wage inflation rule and the optimal policy for the specified parameter. Again, we measure the potential loss in switching from the optimal policy (assuming that the true parameter value is known) to the benchmark wage inflation rule (optimized for the baseline parameters).

We start with the parameters describing price and wage determination. Figure 4.6 plots the differences in the consumption-equivalent welfare losses between the optimal policy and the benchmark wage inflation rule as the four parameters related to price- and wage-setting are varied. The results for the Calvo parameters are shown in the upper panels; the results for the indexation parameters are shown in the lower panels. The vertical lines indicate the 5 percent and 95 percent posterior bounds for the parameters calculated from the MCMC simulations. If the resulting plotted line is horizontal, estimation error for that parameter has no welfare costs, while a steeply sloped line indicates that parameter estimation error carries high costs and that better estimates could have a large social benefit.

Although uncertainty regarding the wage and price parameters based on the estimated probability intervals has very modest implications for the performance of the benchmark wage inflation rule, looked at from a broader or an explicitly min-max perspective, reducing uncertainty about price- and wage-setting parameters could yield

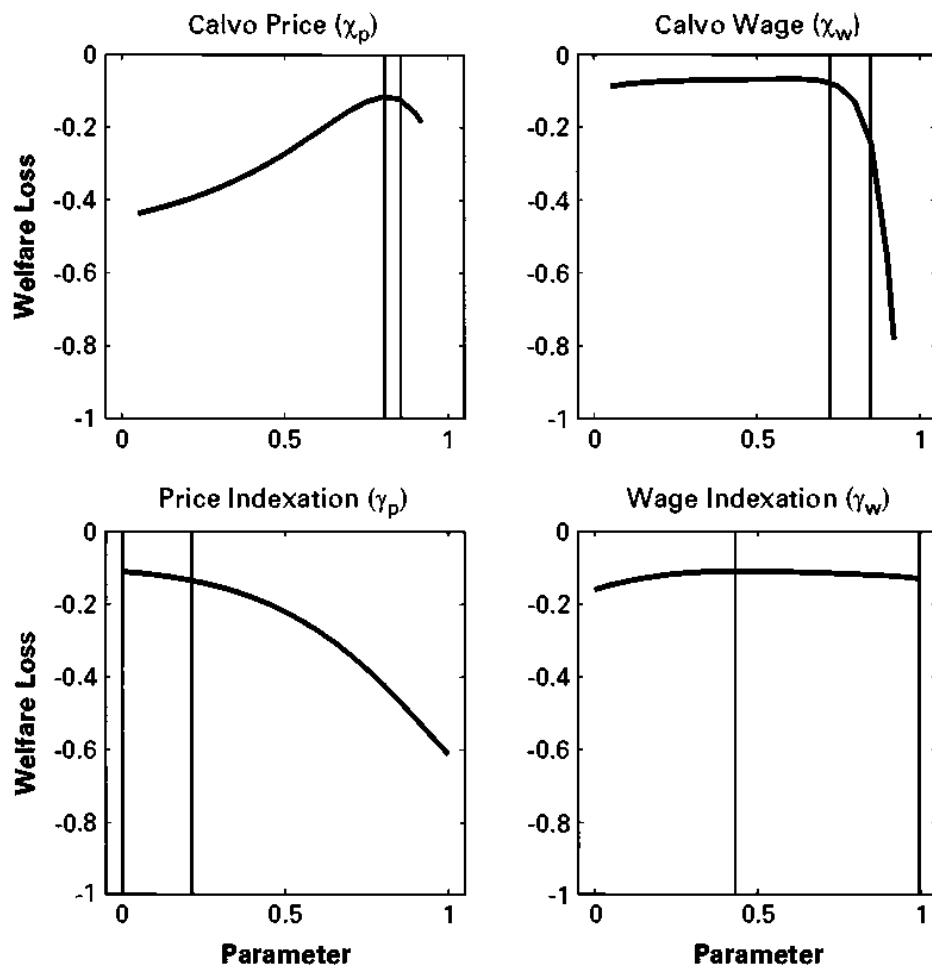


Figure 4.6

Parameter Uncertainty: Price and Wage Setting

Note: The difference in welfare between the benchmark wage inflation rule and the optimal policy. The two vertical lines indicate the 5 and 95 percent bounds from the posterior distributions.

moderate benefits in terms of monetary policy design and welfare. The relative performance of the benchmark wage inflation rule is sensitive to very high values of the Calvo wage parameter. For the other Calvo price and indexation parameters, the performance of the benchmark wage inflation policy drops off if prices are reoptimized very frequently or if a high share of contracts is indexed, neither of which is likely according to the posterior distribution. For example, consider the case that the true Calvo price parameter, ξ_p , is as low as some of the micro evidence suggests. According to the posterior distribution, such a low value is extremely unlikely. But if true, knowledge of this parameter could be used to design a monetary policy that yields a moderate improvement in welfare. The same applies for the Calvo

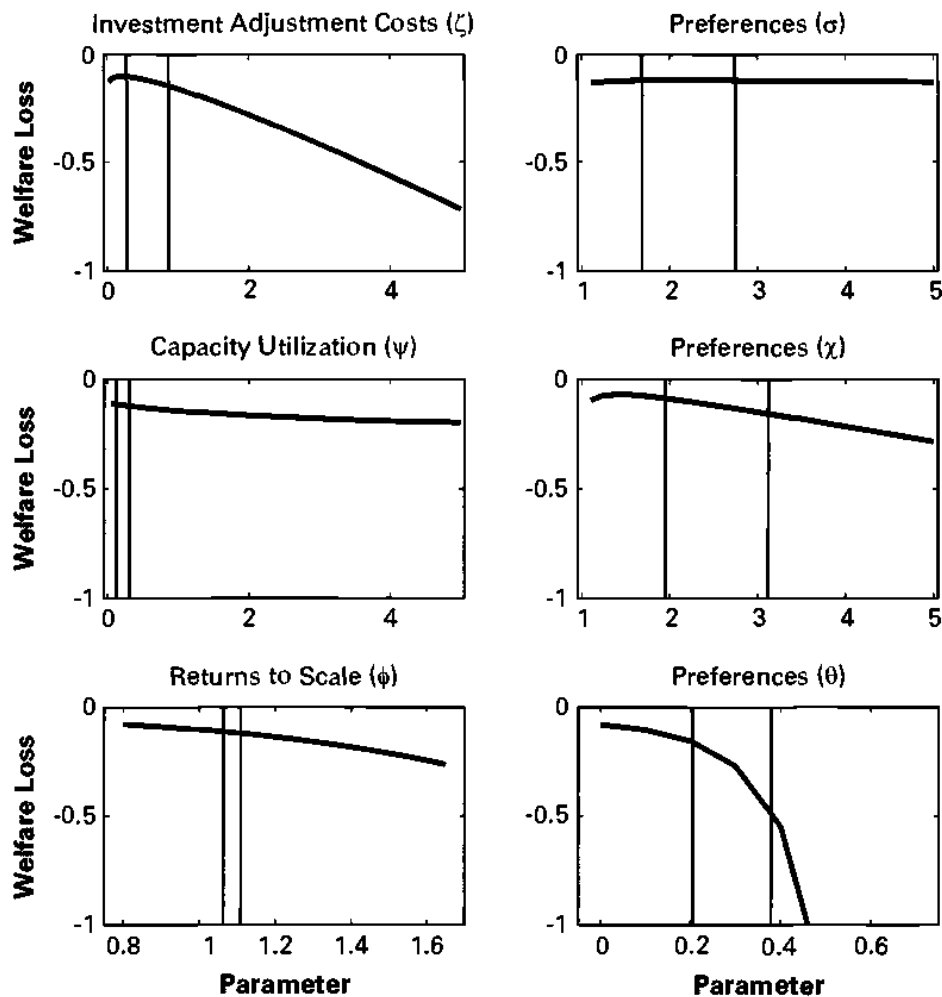


Figure 4.7
 Parameter Uncertainty: Other Structural Parameters
 Note: The difference in welfare between the benchmark wage inflation rule and the optimal policy. The two vertical lines indicate the 5 and 95 percent bounds from the posterior distributions.

wage and price indexation parameters. Although the degree of wage indexation is imprecisely estimated, the relative welfare loss is nearly invariant to the value of this parameter.

Figure 4.7 plots the results for the parameters related to preferences and technology. Given the estimated precision of these parameter estimates, parameter uncertainty has trivial implications for welfare and therefore for policy. For example, although χ , the parameter measuring the disutility of labor, is imprecisely estimated, it has only a modest effect on relative welfare.

It should be noted that the parameter ϕ , which measures the degree of increasing returns, does have a significant effect on relative welfare

under the benchmark wage rule. With a loose prior, we would estimate a value for this parameter near 2. Assuming that the results of the literature indicating at most modest increasing returns are true, the resulting reduction in uncertainty has a large effect on welfare in this model, assuming policy is designed to be optimal at the baseline estimates. Moreover, our estimate of the habit persistence parameter is on the low side of recent estimates, which tend to find values in the 0.5–0.7 range. Once again, we find such values to be unlikely, but we find a significant drop in the performance of the benchmark wage inflation rule when the habit parameter increases past 0.5. Finally, knowledge of the true magnitude of investment adjustment costs would be valuable for policy design.

5.2 *Steady-State Markups*

As noted above, we cannot estimate the steady-state price and wage markups using the first-order dynamics of the model but instead calibrate both to be 20 percent. Given the uncertainty regarding the values of these parameters, we briefly explore the implications of alternative calibrations of the steady-state markups for monetary policy.

The magnitude of welfare losses depends on the steady-state price markup, but the performance of the benchmark wage inflation rule relative to the optimal policy is insensitive to this parameter. We evaluate the welfare losses under four representative monetary policies analyzed above as λ^p is varied from 0.1 to 0.5, holding all other parameters fixed. Recall that the steady-state price markup does not affect the first-order properties of the system.⁴⁷ The results are shown in the upper part of table 4.3. Welfare losses are larger when the steady-state price markup is smaller, reflecting the effect of greater dispersion when goods are more highly substitutable. The relative performance of the various policies is insensitive to the value of the steady-state price markup.

The welfare losses are highly sensitive to the value of the steady-state wage markup, and for very high values of this parameter, the performance of the benchmark price inflation policy rule approaches that of the benchmark wage inflation rule. In considering the effects of variations in λ^w , we vary the value of Calvo wage parameter, ξ_w , so that the first-order properties of the model are constant.⁴⁸ We hold all other parameter values fixed at baseline values. Note that even with a high steady-state wage markup, the benchmark wage inflation policy rule performs well, although the difference between it and the rules

Table 4.3
Welfare Losses and the Steady-State Markups

Experiment	Optimal Policy	Empirical Reaction	Benchmark Wage Inflation Rule	Benchmark Price Inflation Rule
<i>Price markup: λ^p</i>				
0.10	-2.13	-2.72	-2.23	-2.64
0.20	-2.01	-2.57	-2.13	-2.60
0.50	-1.92	-2.48	-2.07	-2.57
<i>Wage markup: λ^w</i>				
0.05	-4.91	-7.94	-6.05	-7.90
0.10	-3.18	-4.43	-3.47	-4.44
0.20	-2.01	-2.57	-2.13	-2.60
0.50	-1.15	-1.42	-1.30	-1.45

that respond to price inflation is much smaller than in the baseline model.

6 Innovation Uncertainty

We now consider alternative assumptions regarding the set of shocks in the model. In computing welfare, we have had to take a stand on each shock as to whether it reflects shifts in fundamentals, the effects of distortions, or measurement error. In particular, we have assumed that the wage and price shocks and the shocks to the external finance premium are distortionary, while the remaining shocks reflect shifts in fundamentals. We now revisit these assumptions and evaluate the performance of the various monetary policies under alternative assumptions regarding the nature of innovations.

The baseline model is admittedly profligate in specifying shocks. In particular, the external finance premium has a large estimated variance and may be important for welfare according to the model but arguably lacks micro-foundations. It is important to note that we have assumed that this shock does not affect fundamentals but instead represents inefficient fluctuations in an external finance premium or a type of "animal spirits" that monetary policy should counteract. Therefore, we consider an alternative model specification in which these shocks do not exist; that is, Tobin's Q strictly follows fundamentals. We assume that these shocks represent measurement error evident in estimating

Table 4.4
Welfare Under Innovation Uncertainty

Experiment	Optimal Policy	Empirical Reaction	Benchmark Wage Inflation Rule	Benchmark Price Inflation Rule
Baseline specification	-2.01	-2.57	-2.13	-2.60
<i>Eliminate shocks to:</i>				
External finance premium	-2.00	-2.55	-2.11	-2.57
Price markup	-1.95	-2.51	-2.04	-2.48
Wage markup	-0.22	-0.44	-0.30	-0.65
Time preference	-2.29	-2.78	-2.38	-2.76
Labor disutility	-2.24	-2.79	-2.36	-2.79
<i>Assume shocks distortionary</i>				
Time preference	-2.58	-3.35	-2.68	-3.08
Labor disutility	-2.46	-3.14	-2.59	-3.01

the model but that they have no effects on the actual allocation of resources. We do not re-estimate the model, but rather we simply set the variance of the external finance premium shocks to 0.⁴⁹ The second line of table 4.4 reports the results from this experiment. Eliminating the external finance premium shocks has little effect on welfare or on the relative performance of the various policy rules.

We further examine how the policy rules perform under alternative assumptions regarding the nature of shocks to price and wage markups. In the baseline model, these shocks are viewed as being distortionary movements in markups. We now consider the possibility that these disturbances simply reflect measurement error that the econometrician faces in estimating the model. In implementing this idea, we do not re-estimate the model, but instead simply zero out the markup innovations. We continue to assume that the policymaker is able to measure wage and price inflation accurately, that is, absent measurement error. (If the markup shocks in fact represented measurement error that the policymaker confronts, then the performance of the policy rules that we consider would deteriorate.) We consider each shock in isolation and the combined effect. The results are shown in the upper part of table 4.4.

Eliminating either markup shock reduces the welfare costs of fluctuations but does not alter the relative performance of the various policy rules. In either case, the welfare gap between the optimal policy and

the benchmark wage inflation rule is reduced relative to that in the baseline specification. The price shocks have relatively little effect on welfare; the wage shocks, however, are an important source of welfare loss under both the optimal and the benchmark policies but nevertheless have little effect on the relative performance of the benchmark wage inflation policy rule.

Finally, we consider the nature of disturbances to preferences. In the baseline model, we have assumed that shocks to time preference and the disutility of labor reflect fundamental movements in the economy that monetary policy should accommodate. We consider two alternative assumptions. First, we assume that the shocks merely reflect measurement error and evaluate the four policies under the assumption that the preference shock does not exist. As before, we consider each shock in isolation. Eliminating either preference shock increases welfare under the various policies by about 0.25 percentage point; that is, stochastic shocks to preferences are welfare-enhancing in our baseline model.⁵⁰ The performance of the benchmark wage inflation rule relative to the optimal policy is almost unchanged. Second, we consider the assumption that the preference shocks reflect nonfundamentals, such as changes in tax rates. The results are shown in the lower section of table 4.4. In this case, the welfare losses are significantly higher than in the baseline model, but again the performance of the benchmark wage inflation rule relative to the optimal policy does not deteriorate.

Regardless of the assumption about the nature of these shocks, the benchmark wage inflation rule is nearly optimal and outperforms the estimated and benchmark price inflation rules by a significant margin. In summary, although innovation uncertainty exacerbates the already significant uncertainty about the magnitude of the welfare costs of fluctuations, the benchmark wage inflation rule is remarkably robust to changes in assumptions regarding the nature of shocks hitting the economy.

7 Specification Uncertainty

We now proceed to consider the broader problem of specification uncertainty in the sense of Leamer (1978).⁵¹ In specifying the baseline model, we made numerous choices that affect the parameter estimates, the structure of the model, and the determinants of welfare. In this section, we analyze the sensitivity of optimal policies to alternate assumptions regarding the model specification and evaluate the

marginal benefit of reducing uncertainty of each of the key specification issues in terms of social welfare. As in the preceding section, this analysis provides information on the value, from the perspective of monetary policy, of improving our knowledge of specification issues and suggests where the highest payoffs are for further research in this area. While the list of specifications we consider is far from exhaustive, it provides some examples of the type of specification uncertainty that may be important for policy analysis.

7.1 *Monetary Frictions and Working Capital*

Our baseline model can be viewed as a cashless economy that completely abstracts from monetary frictions. We now investigate the policy implications of incorporating household demand for money as well as working-capital considerations for firms. First, we permit the scale parameter μ_0 to have a nontrivial value, so that real money balances have direct effects on household utility. Second, following CEE, we assume that firms must borrow from financial intermediaries to cover their wage bill and then repay the loan at the end of the period. Thus, assuming that these funds can be obtained at the gross risk-free nominal interest rate, firms' total labor costs are now given by $R_t W_t L_t$.

Since we specify that policy is conducted via an interest rate rule, we do not need to concern ourselves with market clearing in the loan market. This would only serve to pin down the value of broad money. Instead, we simply append the portfolio allocation decision to determine the household's cash balances (which now affect welfare), and we incorporate the effects of working capital on firms' labor demand and marginal costs. We then re-estimate the model, using data on cash balances in addition to the seven variables noted above.⁵² The mode estimate of the preference parameter κ is 11.4, while the mode estimates of all other model parameters are nearly the same as in the baseline specification.⁵³

The modified model has two key implications for policy. First, owing to the effects of nominal interest rates on costs and money balances, the optimal inflation rate is no longer 0 but is instead slightly below 0. Second, there is a cost to highly variable nominal interest rates that is absent in the baseline model and a resultant benefit to smoothing interest rates. As a result, the optimal wage inflation policy rule responds less aggressively to wage inflation, with a coefficient of 1.5, compared to 3.2 in the baseline model.⁵⁴ The benchmark wage inflation rule

yields a welfare loss of 0.07 percentage points in terms of permanent consumption greater than a rule optimized for this alternative model with monetary frictions and working capital.

7.2 *Alternative Models of Wage Setting*

A key result in our analysis is the importance of stabilizing wages owing to the distortions associated with wage dispersion under Calvo-style contracts. Given the central role of this channel, we consider alternative specifications of wage setting that have significant effects on the welfare implications of sticky wages and on optimal policy. In particular, we consider two alternative specifications in which the effects of wage dispersion on welfare are muted relative to the Calvo-style model.⁵⁵

We first consider a modest modification to the indexation of wages in the model and assume that nonoptimized wages are indexed to last period's *wage* inflation rate, as opposed to the rate of *price* inflation. This modification reduces the effects of fluctuations in wage inflation on wage dispersion and thereby on welfare.⁵⁶ Table 4.4 reports the results from this specification for four specifications of monetary policy. Not surprisingly, the consumption-equivalent loss in conditional welfare under the optimal policy is somewhat smaller than in the baseline model.

The relative performance of the benchmark wage inflation rule is considerably worse, however, under this form of wage indexation and is dominated by the rule that responds only to price inflation. Under the benchmark wage inflation policy rule, the consumption-equivalent loss in conditional welfare is 0.6 percentage points larger than under the optimal policy and 0.3 percentage points higher than under the benchmark price inflation rule. In fact, with this specification of wage indexation, the benchmark wage inflation policy rule does slightly *worse* than the estimated policy rule. Evidently, the result that a simple policy rule designed to maximize welfare should respond exclusively to wage inflation is not robust to changes in the model of wage determination, even to this seemingly innocuous change in the model specification.

We now consider a more substantive change in the specification of wage and price determination, and assume that contracts have fixed duration as in Taylor (1980); see also Chari, Kehoe, and McGrattan (2000).⁵⁷ Compared with the baseline specification of Calvo-style contracts with random duration, this alternative specification limits

Table 4.5
Welfare Under Uncertainty Regarding Wage Setting

Experiment	Optimal Policy	Empirical Reaction	Benchmark Wage Inflation Rule	Benchmark Price Inflation Rule
Baseline specification	-2.01	-2.57	-2.13	-2.60
Wage-wage indexation	-1.85	-2.34	-2.46	-2.15
Taylor contracts	-0.35	-0.41	-0.85	-0.50

the degree of price and wage dispersion—and the associated welfare costs—resulting from the presence of some prices and wages that have not been reoptimized for many periods.

We suppose that nominal wages and prices are determined by staggered contracts that are reset every M periods. Thus, at t the distribution of wages is given by $\{W_{t,j}\}$ where $j = 1, \dots, M$ denotes the number of periods since the last reset. In particular, we assume that all price and wage contracts last for four quarters, implying mean contract durations somewhat shorter than implied by our posterior mean estimates of the Calvo update parameters, ξ_p and ξ_w . We do not change any other parameter estimates and revert to the baseline assumption that wages are indexed to past price inflation. The results are reported in table 4.5. As expected, replacing Calvo-style wage and price setting with Taylor-style contracts significantly reduces wage and price dispersion and hence the welfare costs associated with fluctuations.

With Taylor-style staggered wages and prices, the relative performance of the benchmark wage inflation rule falls dramatically, while the estimated policy rule is nearly optimal. The benchmark price inflation rule outperforms the benchmark wage inflation rule but falls behind the estimated rule. With Taylor price and wage contracts, the welfare costs associated with price and wage dispersion are relatively modest and therefore the optimal policy focuses on coming close to the real allocation in the flexible wage and price economy. The estimated rule accomplishes this balance very well, while the benchmark price inflation rule is somewhat less effective owing to a lack of response to the output gap. The performance of the benchmark wage inflation rule suffers more significantly because it implicitly puts far too much emphasis on stabilizing nominal wage inflation relative to achieving the flexible wage and price real allocation.⁵⁸

Finally, it should be noted that the welfare cost of business cycles and the performance of alternative monetary policies are sensitive not only to the structure of nominal contracts but to the specification of household preferences. For example, as in CEE and SW, our analysis has followed Erceg, Henderson, and Levin (2000) in assuming that each individual household provides a distinct labor service, whereas Schmitt-Grohé and Uribe (2004) assume that each household has a continuum of members providing all types of labor services and that the household's utility depends only on its total hours of work. While such assumptions might seem to be merely technical details, in fact these differences have fairly dramatic consequences for the first-order dynamics of wage inflation, the second-order effects of cross-sectional wage dispersion, and the design of welfare-maximizing policy rules.⁵⁹

8 Conclusion

Over the past decade, there has been remarkable progress in developing empirical micro-founded macroeconomic models for monetary policy analysis. In this paper, we have drawn on and extended this literature to consider the design of policy under uncertainty. By confronting a fully specified dynamic stochastic general equilibrium model with the data, we can directly gauge the uncertainty associated with the model parameters as well as the implications of alternative assumptions about the model specification.

Our analysis indicates that the welfare cost of business cycles is quite large—an order of magnitude larger than the findings emphasized by Lucas (2003)—and arises mainly due to inefficiencies associated with cross-sectional dispersion in wages and employment. As a direct consequence, we find that the welfare outcome associated with optimal policy under commitment is closely matched by a very simple rule that responds solely to nominal wage inflation. Furthermore, the performance of this benchmark wage inflation rule is robust to uncertainty about the structural parameters and the particular shocks hitting the economy. The performance of this rule, however, is very sensitive to the specification of wage and price determination, suggesting that a hybrid rule involving both wage and price inflation might be more robust across a broader class of models.

These findings underscore the central importance of labor markets for analyzing the welfare costs of macroeconomic fluctuations and the

design of monetary policy. Of course, the crucial role of wage setting and employment dynamics has long been recognized, and recent research has refocused interest on these issues; see Hall (2005). Thus, further progress in formulating micro-founded specifications of labor market behavior and comparing the empirical performance of these specifications is likely to have substantial payoffs for the design of monetary policy.

Finally, while our analysis has emphasized the implications of policymaker uncertainty regarding the true structure of the economy, we have abstracted completely from the role of learning by policymakers or private agents. Nevertheless, we recognize that the learning mechanism is crucial for understanding the evolution of the economy in response to changes in the monetary policy regime—such as the Volcker disinflation—and to other aggregate disturbances.⁶⁰ Thus, incorporating learning in micro-founded macroeconomic models and reconsidering the policy implications represents a natural direction for future research.⁶¹

9 Appendix

9.1 *The Nonlinear Model*

9.1.1 The Baseline Model The text describes the household side, and we now fill in some detail on the firm side. Define the capacity utilization cost function from equation (4.5) by:

$$\Psi(U_t) = \mu \frac{U_t^{1+\psi^{-1}}}{1 + \psi^{-1}}$$

where ψ is the inverse of the elasticity of utilization cost with respect to utilization, and μ is chosen so that steady state utilization costs are 0. Also define the investment adjustment cost function from equation (4.4) by:

$$S(Z_t^I I_t(i)/I_{t-1}(i)) = \zeta^{-1} \frac{1}{2} \left(Z_t^I \frac{I_t(i)}{I_{t-1}(i)} - 1 \right)^2$$

Note that adjustment costs are assumed to be 0 at the steady state, $S(1) = 0$, and are only of second-order at the steady state.

Index households by h and firms by i . Then denote by $N_t(i)$ the labor input of plant i , given by:

$$N_t(i) = \left[\int_0^1 L_t(i, h)^{1/(1+\lambda_t^w)} dh \right]^{1+\lambda_t^w}$$

where $L_t(i, j)$ is the input of labor of type j at plant i . The plant's output is given by equation (4.3).

Aggregate final good output, Y_t is created by (costlessly) combining a continuum of intermediate goods, $Y_t(i)$, indexed by i :

$$Y_t = \left[\int_0^1 Y_t(i)^{1/(1+\lambda_t^p)} di \right]^{1+\lambda_t^p} \quad (4.7)$$

Final goods output is equal to consumption; aggregate investment, I_t ; government spending, G_t ; and capital utilization costs:

$$Y_t = C_t + G_t + I_t + \Psi(U_t)K_{t-1} \quad (4.8)$$

9.1.2 Equilibrium Allocation and Prices In the following, we omit household and plant indices where no confusion will result. The household's budget constraint is standard, and households trade in a complete market to allocate their consumption over time. Let MUC_t denote the marginal utility associated with an incremental increase in consumption in period t , accounting for its effect on period utility in the period $t + 1$:

$$MUC_t = Z_t^b (C_t - \theta C_{t-1})^{-\sigma} - \beta \theta E_t Z_{t+1}^b (C_{t+1} - \theta C_t)^{-\sigma} \quad (4.9)$$

The consumption Euler equation summarizes the representative household's optimal saving behavior:

$$MUC_t = E_t [MUC_{t+1} R_t P_t / P_{t+1}] \quad (4.10)$$

where R_t is the gross nominal interest rate and P_t is the price level.

Households set wages subject to their individual labor demand curves, which arise from the firms' input demands. The evolution of the aggregate nominal wage index is:

$$W_t^{-1/\lambda_t^w} = \xi_w W_{t-1}^{-1/\lambda_t^w} \left(\frac{P_{t-1}}{P_{t-2}} \right)^{-\gamma_w/\lambda_t^w} + (1 - \xi_w) \tilde{w}_t^{-1/\lambda_t^w} \quad (4.11)$$

Here, \tilde{w}_t is the optimal nominal wage chosen by those households that can optimize in the period, which satisfies:

$$\frac{\tilde{w}_t}{P_t} E_t \sum_{i=0}^{\infty} \beta_{t+i}^i \xi_w^i L_{t+i}(h) \varepsilon_{t+i}^b \left[\left(\frac{P_t P_{t+i-1}}{P_{t-1} P_{t+i}} \right)^{\gamma_w} \frac{MUC_{t+i}}{1 + \lambda_{t+i}^w} - Z_t^L (L_{t+i}(h))^{\chi} \right] = 0 \quad (4.12)$$

As is usual in Calvo pricing models, equation (4.12) incorporates forward-looking expectations of future nominal wages but now includes lagged inflation via the partial indexation.

Households own the capital stock, K_t , which they accumulate using the capital accumulation technology and rent to firms at rental rate R_t^k . This leads to three key relationships. First, we let Q_t be the real share value per unit of capital, which is determined by an asset pricing Euler equation from equation (4.10):

$$Q_t = Z_t^q E_t \left[\beta \frac{MUC_{t+1}}{MUC_t} (Q_{t+1}(1 - \delta) + U_{t+1} R_{t+1}^k - \Psi(U_{t+1})) \right] \quad (4.13)$$

where Z_t^q is the i.i.d. external finance premium shock. The optimal investment decision leads to an investment Euler equation:

$$1 - Q_t S' \left(\frac{Z_t^I I_t}{I_{t-1}} \right) \frac{Z_t^I I_t}{I_{t-1}} = E_t \left[\frac{MUC_{t+1}}{MUC_t} Q_{t+1} S' \left(\frac{Z_{t+1}^I I_{t+1}}{I_t} \right) \frac{Z_{t+1}^I I_{t+1}}{I_t} \frac{I_{t+1}}{I_t} \right] \quad (4.14)$$

This equation balances the costs and benefits of investment, with lagged investment and the shocks showing up through the effects of the costs of adjustment. Finally, the first order condition for utilization gives:

$$R_t^k = \Psi'(U_t) \quad (4.15)$$

On the production side, the firms' cost-minimization conditions are symmetric and are given by:

$$\frac{W_t L_t}{R_t^k U_t K_{t-1}} = \frac{1 - \alpha}{\alpha} \quad (4.16)$$

Thus, firms equate the marginal rate of transformation between labor and effective capital ($U_t K_{t-1}$) to the relative factor prices, and the capital-labor ratio is identical across firms. Marginal costs are then given by:

$$MC_t = \frac{W_t^{1-\alpha} (R_t^k)^\alpha}{A_t} \alpha^{-\alpha} (1 - \alpha)^{\alpha-1} \quad (4.17)$$

The evolution of the aggregate nominal price index is:

$$P_t^{-1/\lambda_t^f} = \xi_p P_{t-1}^{-1/\lambda_t^f} \left(\frac{P_{t-1}}{P_{t-2}} \right)^{-\gamma_p/\lambda_t^f} + (1 - \xi_p) \tilde{p}_t^{-1/\lambda_t^f} \quad (4.18)$$

Here, \tilde{p}_t is the optimal price chosen by those firms that can optimize in the period, which satisfies:

$$E_t \sum_{s=0}^{\infty} \beta_{t+s}^s \xi_p^s \lambda_{t+s}^p Y_{t+s}(i) MUC_{t+i} \left[\frac{\tilde{p}_t}{P_t} \left(\frac{P_t P_{t+s-1}}{P_{t-1} P_{t+s}} \right)^{\gamma_p} - (1 + \lambda_{t+s}^p) \frac{MC_{t+s}}{P_{t+s}} \right] = 0 \quad (4.19)$$

Finally, we close the model by specifying an empirical monetary policy reaction function. We specify policy in terms of a generalized Taylor-type rule, where the policy authority sets nominal rates in response to inflation and the output gap. To do this, we define a model-consistent output gap as the difference between actual and potential output, where potential output is defined as what would prevail under flexible prices and wages and in the absence of the three cost-push shocks (Z_t^w, Z_t^p, Z_t^q) that cause variations in wage and price markups and the external finance premium. Thus, the model is supplemented with flexible-price versions of the key equations (4.10) through (4.18), which determine potential output Y_t^* . Then the policy rule is assumed to take the following form:

$$r_t = r_i r_{t-1} + (1 - r_i)(\bar{\pi}_t + r_\pi(\pi_{t-1} - \pi_{t-1}^*) + r_y \log(Y_{t-1}/Y_{t-1}^*)) + r_{\Delta\pi}(\pi_t - \pi_{t-1}) + r_{\Delta y} \{ \log(Y_t/Y_t^*) - \log(Y_{t-1}/Y_{t-1}^*) \} + \eta_t^r \quad (4.20)$$

Here, $r_t = \log R_t$ is the short-term interest rate, $\pi_t = \Delta \ln(P_t/P_{t-1})$ is the inflation rate, π_t^* is an $AR(1)$ shock to the inflation objective, and η_t^R is an i.i.d. policy shock.

9.1.3 The Model with Monetary Frictions In the model with monetary frictions from Section 7.1, the household also has a portfolio allocation decision. The first-order condition is:

$$Z_t^b \varepsilon_t^m (M_t/P_t)^{-\kappa} = (R_t - 1) MUC_t \quad (4.21)$$

The cost-minimization condition [equation (4.16)] now becomes:

$$\frac{R_t W_t L_t}{R_t^k U_t K_{t-1}} = \frac{1 - \alpha}{\alpha} \quad (4.22)$$

In turn, the marginal cost changes from equation (4.17) to:

$$MC_t = \frac{(R_t W_t)^{1-\alpha} (R_t^k)^{\alpha}}{A_t} \alpha^{-\alpha} (1 - \alpha)^{\alpha-1} \quad (4.23)$$

Market clearing in the loan market then implies:

$$W_t L_t = A_t - M_t$$

where A_t represents the level of broad money after the infusion of money via the central bank.

9.1.4 The Model with Staggered Contracts In the model with staggered contracts from Section 7.2, we must make a few alterations to the model. We again allow for partial indexation, so the evolution of an individual household's wage is given by:

$$\begin{aligned} W_{t,j} &= \left(\frac{P_{t-1}}{P_{t-2}} \right)^{\gamma_p} W_{t-1,j-1} && \text{if } j \neq M \\ &= \tilde{w}_t && \text{if } j = M \end{aligned}$$

The aggregate wage index changes from equation (4.11) to:

$$W_t^{-1/\lambda_t^w} = \frac{1}{M} \sum_{j=1}^M W_{t,j}^{-1/\lambda_t^w} \quad (4.24)$$

Finally, the optimal wage choice satisfies:

$$\frac{\tilde{w}_t}{P_t} E_t \sum_{i=0}^{M-1} \beta_{t+i}^i L_{t+i}(h) \left[\left(\frac{P_t P_{t+i-1}}{P_{t-1} P_{t+i}} \right)^{\gamma_w} \frac{MUC_{t+i}}{1 + \lambda_{t+i}^w} - \varepsilon_t^L (L_{t+i}(h))^x \right] = 0 \quad (4.25)$$

9.2 The Linearized Model

9.2.1 Baseline Model For much of the paper, we work with the log-linearized version of the model described above, which we present here. We use lowercase letters to indicate the logarithmic deviations from steady state. In the case of shocks, ε_t^x and η_t^x refer to the shocks normalized to the log-linear equations, with the ε shocks being persistent and the η shocks i.i.d.

To save on notation, we define \bar{R}^k as the mean real rate of return on capital, which is assumed to satisfy $\beta = 1/(1 - \delta + \bar{R}^k)$, and ϕ equals 1 plus the share of fixed costs in production. Furthermore, we denote c_y , g_y , and k_y as the steady-state ratios of consumption, government spending, and capital to output, respectively.

The following ten equations in ten endogenous variables $\{c_t, i_t, q_t, k_t, r_t^k, u_t, l_t, y_t, w_t, \pi_t\}$ are the linearized counterparts to the equations described in Section 9.1 of this appendix:

$$c_t = E_t \frac{1}{1 + \theta + \beta\theta^2} \left\{ \theta c_{t-1} + (1 + \beta\theta^2 + \beta\theta)c_{t+1} - \beta\theta c_{t+2} - \frac{1-\theta}{\sigma} \left((1 - \beta\theta)(r_t - \pi_{t+1}) - \varepsilon_t^b + (1 + \beta\theta)\varepsilon_{t+1}^b - \beta\theta\varepsilon_{t+2}^b \right) \right\} \quad (4.26)$$

$$q_t = -(r_t - E_t \pi_{t+1}) + \frac{1}{1 - \delta + \bar{R}^k} \left\{ (1 - \delta)E_t q_{t+1} + \bar{R}^k E_t r_{t+1}^k \right\} + \eta_t^q \quad (4.27)$$

$$i_t = \frac{1}{1 + \beta} E_t \{ i_{t-1} + \beta i_{t+1} + \zeta q_t + \beta(\varepsilon_{t+1}^i - \varepsilon_t^i) \} \quad (4.28)$$

$$k_t = (1 - \delta)k_{t-1} + \delta i_t \quad (4.29)$$

$$u_t = \psi r_t^k \quad (4.30)$$

$$l_t = -w_t + r_t^k + u_t + k_{t-1} \quad (4.31)$$

$$y_t = c_y c_t + g_y \varepsilon_t^g + \delta k_y i_t + \bar{R}^k k_y u_t \quad (4.32)$$

$$y_t = \phi[\varepsilon_t^a + \alpha(u_t + k_{t-1}) + (1 - \alpha)l_t] \quad (4.33)$$

$$w_t = \frac{1}{1 + \beta} E_t \left\{ \beta w_{t+1} + w_{t-1} + \beta \pi_{t+1} - (1 + \beta \gamma_w) \pi_t + \gamma_w \pi_{t-1} - \frac{\lambda_w (1 - \beta \xi_w) (1 - \xi_w)}{(\lambda_w + (1 + \lambda_w) \chi) \xi_w} \left(w_t - \chi l_t - \varepsilon_t^L + \frac{\beta \theta}{1 - \beta \theta} (\varepsilon_t^b - \varepsilon_{t+1}^b) - \eta_t^w - \frac{\sigma}{(1 - \theta)(1 - \beta \theta)} \left((1 + \beta \theta^2) c_t - \theta c_{t-1} - \beta \theta c_{t+1} \right) \right) \right\} \quad (4.34)$$

$$\pi_t = \frac{1}{1 + \beta \gamma_p} \left\{ \beta E_t \pi_{t+1} + \gamma_p \pi_{t-1} + \frac{(1 - \beta \xi_p)(1 - \xi_p)}{\xi_p} \times (\alpha r_t^k + (1 - \alpha) w_t - \varepsilon_t^a + \eta_t^p) \right\} \quad (4.35)$$

As shown in Onatski and N. Williams (2004), equation (4.32) corrects a slight error in SW due to the capital utilization costs, which enter as the final term.

In addition, there are ten equations for the shock processes, six of which, $\{\varepsilon_t^a, \varepsilon_t^\pi, \varepsilon_t^b, \varepsilon_t^g, \varepsilon_t^l, \varepsilon_t^i\}$, follow AR(1) processes of the form:

$$\varepsilon_t^x = \rho_x \varepsilon_{t-1}^x + v_t^x$$

where v_t^x is a mean zero innovation with variance σ_x^2 . The remaining four shocks, $\{\eta_t^p, \eta_t^q, \eta_t^r, \eta_t^w\}$, are assumed to be i.i.d. with mean zero

and variance σ_x^2 . The innovations are assumed to have zero contemporaneous correlation.

The full model also includes counterparts to equations (4.26) through (4.33) that describe the log-linearized equations for the flexible-price allocation. In these equations, the shocks η_p , η_q , and η_w are set to 0, as is the inflation rate. The nominal interest rate is replaced by the flexible-price real interest rate, r_t^* . This yields nine equations and nine additional variables, $\{c_t^*, i_t^*, y_t^*, w_t^*, l_t^*, q_t^*, r_t^*, r_t^{k*}, k_t^*\}$, where the asterisk superscript denotes the flexible-price value of the variable.

We close the model by including the linearized counterpart to the policy rule:

$$\begin{aligned} r_t = & r_i r_{t-1} + (1 - r_i)(\bar{\pi}_t + r_\pi(\pi_{t-1} - \pi_{t-1}^*) + r_y(y_{t-1} - y_{t-1}^*)) \\ & + r_{\Delta\pi}(\pi_t - \pi_{t-1}) + r_{\Delta y}(y_t - y_t^* - (y_{t-1} - y_{t-1}^*)) + \eta_t^r \end{aligned} \quad (4.36)$$

9.2.2 Model with Monetary Frictions Here, we note the modifications to the expressions above when we consider the model with monetary frictions. Linearizing equation (4.21) gives:

$$\begin{aligned} -\kappa m_t + \varepsilon_t^m = & \frac{\bar{R}}{\bar{R} - 1} r_t + \frac{\sigma}{(1 - \theta)(1 - \beta\theta)} ((1 + \beta\theta^2)c_t - \theta c_{t-1} - \beta\theta E_t c_{t+1}) \\ & - \frac{\beta\theta}{1 - \beta\theta} (\varepsilon_t^b - E_t \varepsilon_{t+1}^b) \end{aligned} \quad (4.37)$$

where m_t is the log-deviation of real cash balances. Here \bar{R} is the steady-state gross nominal rate that satisfies $\bar{R} = 1 + \bar{R}^k - \delta$. Linearizing equation (4.22), we see that we replace equation (4.31) with:

$$l_t = -w_t - r_t + r_t^k + z_t + k_{t-1} \quad (4.38)$$

Linearizing equation (4.23), we see that we replace equation (4.35) with:

$$\begin{aligned} \pi_t = & \frac{1}{1 + \beta\gamma_p} \left\{ \beta E_t \pi_{t+1} + \gamma_p \pi_{t-1} + \frac{(1 - \beta\xi_p)(1 - \xi_p)}{\xi_p} \right. \\ & \left. \times (\alpha r_t^k + (1 - \alpha)(w_t + r_t) - \varepsilon_t^a + \eta_t^p) \right\} \end{aligned}$$

9.3 Estimation Details and Results

9.3.1 Specification of the Priors Table 4.6 reports the details of the specification of the prior for the model.⁶² For the parameters of

Table 4.6
Specification of Priors

Parameter		Distribution	Mean	Standard Deviation
ζ	Investment adjustment costs	Normal	0.5	0.2
σ	Consumption utility	Normal	2	0.5
θ	Consumption habit	Beta	0.7	0.15
χ	Labor utility	Normal	1.2	0.5
$\phi - 1$	Fixed cost-1	Gamma	0.075	0.0125
ψ^{-1}	Capital utilization costs	Log normal	6.4	5
ξ_w	Calvo wages	Beta	0.375	0.1
ξ_p	Calvo prices	Beta	0.375	0.1
γ_w	Wage indexation	Beta	0.5	0.25
γ_p	Price indexation	Beta	0.5	0.25
r_π	Policy, lagged inflation	Normal	2	0.5
$r_{\Delta\pi}$	Policy, change in π	Normal	0.2	0.1
r_i	Policy, lagged interest rate	Normal	1	0.15
r_y	Policy, lagged output gap	Gamma	0.25	0.25
$r_{\Delta y}$	Policy, change in gap	Gamma	0.25	0.25
σ_a	Productivity	Gamma	0.6	0.6
σ_π	Inflation objective	Gamma	0.1	0.1
σ_b	Preference	Gamma	0.3	0.3
σ_g	Government spending	Gamma	0.3	0.3
σ_l	Labor supply	Gamma	3	3
σ_i	Investment	Gamma	0.1	0.1
σ_r	Interest rate	Gamma	0.1	0.1
σ_η	External finance premium	Gamma	5	5
σ_p	Price markup	Gamma	0.2	0.2
σ_w	Wage markup	Gamma	0.2	0.2
ρ_a	Productivity	Beta	0.5	0.25
ρ_π	Inflation objective	Beta	0.85	0.1
ρ_b	Preference	Beta	0.5	0.25
ρ_g	Government spending	Beta	0.5	0.25
ρ_l	Labor supply	Beta	0.5	0.25
ρ_i	Investment	Beta	0.5	0.25

Table 4.7
Estimation Results

Parameter	Posterior Mean	90% Probability Interval
σ_a Productivity	0.5949	0.5441–0.6490
σ_π Inflation objective	0.1153	0.0916–0.1430
σ_b Preference	0.1346	0.0739–0.2171
σ_g Government spending	0.2873	0.2635–0.3134
σ_l Labor supply	2.4625	1.8121–3.2219
σ_i Investment	1.0625	0.8815–1.2570
σ_r Interest rate	0.0001	0.0000–0.0000
σ_q External finance premium	4.0198	2.5531–6.4477
σ_p Price markup	0.2072	0.1812–0.2363
σ_w Wage markup	0.3035	0.2743–0.3351
ρ_a Productivity	0.9639	0.9467–0.9794
ρ_π Inflation objective	0.9950	0.9871–0.9995
ρ_b Preference	0.9397	0.8868–0.9835
ρ_g Government spending	0.9443	0.9147–0.9710
ρ_l Labor supply	0.9833	0.9652–0.9972
ρ_i Investment	0.7170	0.5755–0.8356
r_π Policy, lagged inflation	2.6951	2.1525–3.2813
$r_{\Delta\pi}$ Policy, change in π	0.2637	0.1650–0.3612
r_i Policy, lagged interest rate	0.8392	0.7817–0.8921
r_y Policy, lagged output gap	0.0968	0.0086–0.2417
$r_{\Delta y}$ Policy, change in gap	0.5091	0.4077–0.6386

the shock processes, where we had little guidance from the literature, we set relatively loose priors. For the standard deviations, we used gamma distributions with standard deviations equal to the means. We gauged the relative magnitudes of the shocks from Onatski and N. Williams (2004) and SW. For all but one persistence parameter, we used a wide beta distribution. The exception was the inflation objective shock. Since it and the interest rate shock enter additively in the policy rule of equation (4.37), a tighter prior is necessary to distinguish between them. For the structural parameters, we chose the parameters of the distributions to cover the range of estimates we found in the literature with reasonably high probability.

9.3.2 Computation of the Posterior As in SW, we first look for a parameter vector that maximizes the posterior mode, given our prior and the likelihood based on the data. We took great efforts to explore the

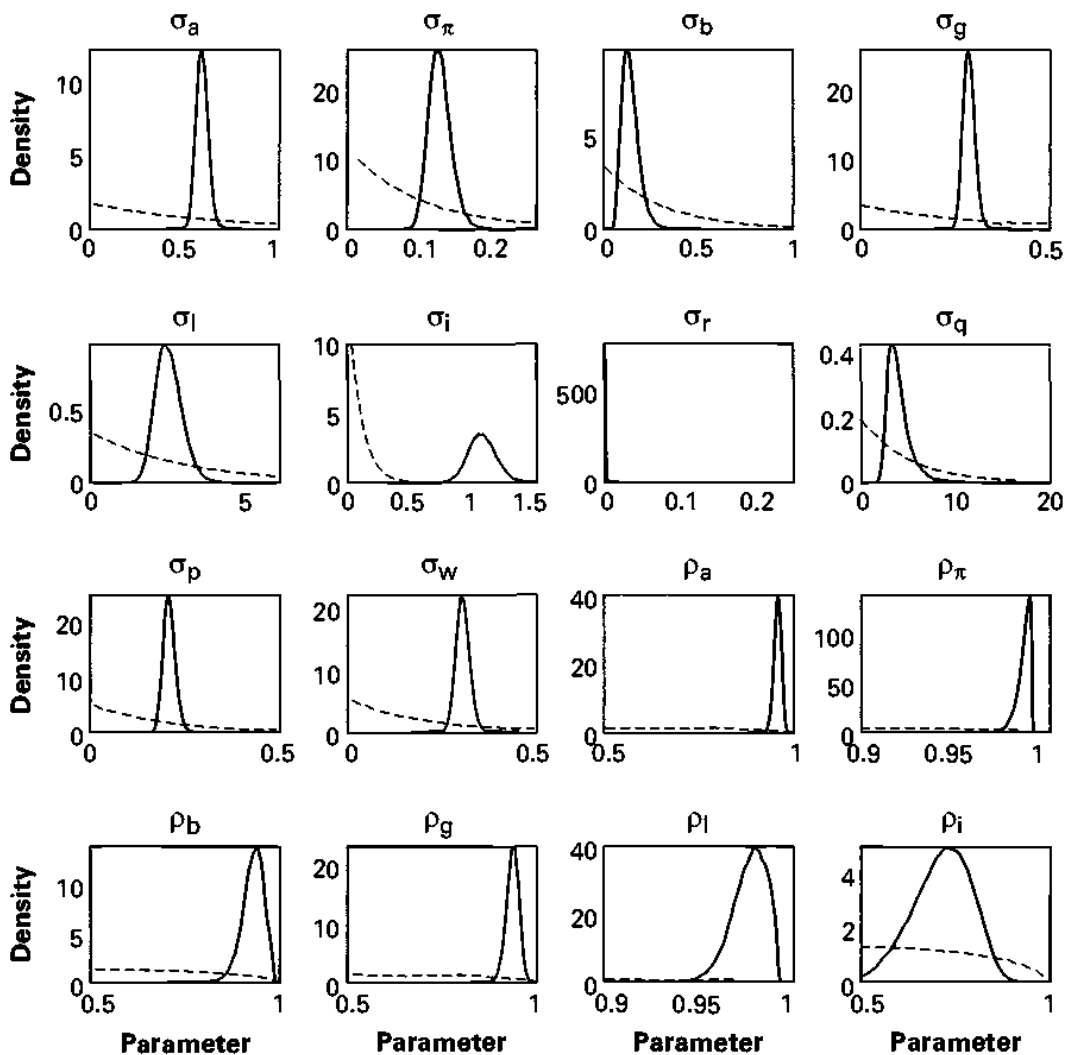


Figure 4.8
 Estimated Posterior Distributions (Solid Lines) and Prior Distributions (Dashed Lines) for the Parameters Describing the Shock Processes

parameter space sufficiently to locate a global maximum. In particular, we sampled 200 values from the prior distribution and used these as starting values for Chris Sims’s optimization algorithms designed to avoid common problems with likelihood functions (these algorithms are available on his web page, <http://www.princeton.edu/~sims>). We reran it in combination with a standard hill-climber algorithm until it settled on the maximal value. We used the resulting mode as the starting point for our MCMC sampling.

We then sample from the posterior distribution using a Metropolis-Hastings Markov chain Monte Carlo (MCMC) algorithm in order to make small sample inferences about the parameters. We sampled ten separate chains for 45,000 periods each, discarding the first 15,000

Table 4.8
 Mode Estimates in the Baseline Specification and Alternative Specification with Monetary Frictions

Parameter	Baseline Specification	Money Frictions
ζ Investment adjustment	0.5487	0.6119
σ Consumption utility	2.0445	2.0433
θ Consumption habit	0.2935	0.3219
χ Labor utility	1.4051	1.6037
κ Money utility	NA	11.3822
ϕ Fixed cost	1.0824	1.0805
ψ Capital utilization	0.1981	0.1769
ζ_w Calvo wages	0.8074	0.8123
ζ_p Calvo prices	0.8240	0.8335
γ_w Wage indexation	0.7734	0.8670
γ_p Price indexation	0.1159	0.1957
σ_a Productivity	0.5942	0.5791
σ_π Inflation objective	0.1067	0.1030
σ_b Preference	0.1205	0.1256
σ_g Government spending	0.2847	0.2878
σ_l Labor supply	2.3217	2.3597
σ_i Investment	1.0349	1.0770
σ_r Interest rate	0.0000	0.0000
σ_q External finance premium	3.6781	3.3857
σ_p Price markup	0.2048	0.1653
σ_w Wage markup	0.2987	0.2931
σ_m Money demand	NA	19.8955
ρ_a Productivity	0.9611	0.9562
ρ_π Inflation objective	0.9944	0.9993
ρ_b Preference	0.9443	0.9392
ρ_g Government spending	0.9418	0.9486
ρ_l Labor supply	0.9803	0.9853
ρ_i Investment	0.7309	0.7221
ρ_m Money demand	NA	0.9877
r_π Policy, lagged inflation	2.7323	2.7974
$r_{\Delta\pi}$ Policy, change in π	0.2847	0.2586
r_i Policy, lagged interest rate	0.8318	0.8412
r_y Policy, lagged output gap	0.0001	0.0001
$r_{\Delta y}$ Policy, change in gap	0.4811	0.5063

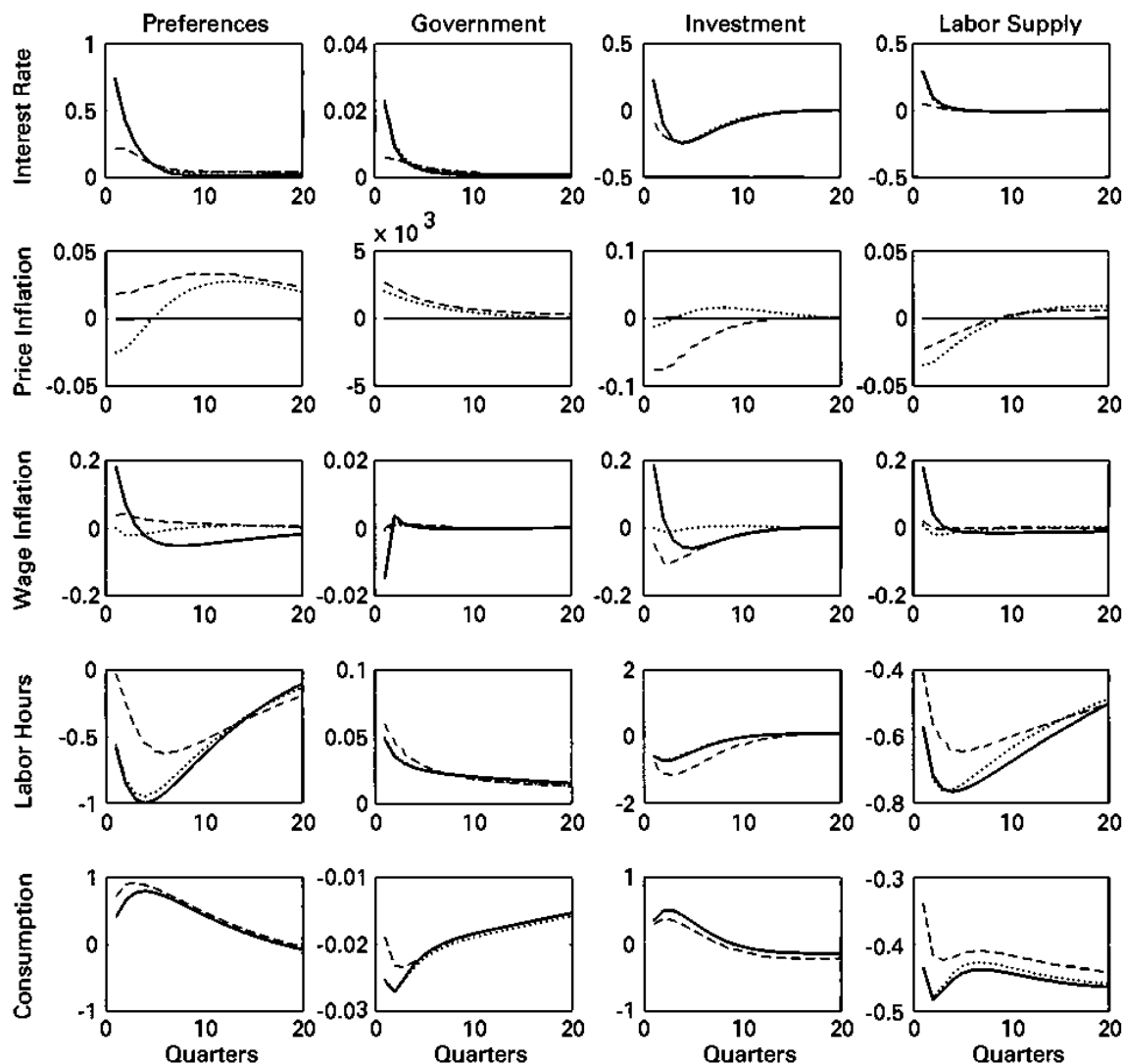


Figure 4.9
 Impulse Responses for One Standard Deviation Shocks: Optimal Policy (Solid Lines),
 Estimated Policy (Dashed Lines), and Flexible-Wage and Flexible-Price Equilibrium
 (Dotted Lines)

periods. Thus, we were left with 300,000 points from the posterior distribution. In order to assess convergence of the Markov chains, we use the potential scale reduction statistic described by Gelman, Carlin, Stern, and Rubin (2004), which gave clear indications of convergence for all the parameters.

9.3.3 Estimation Results for the Shocks and the Monetary Model

The text reports the estimation results for the structural parameters. Table 4.7 reports the estimates of the parameters for the shock processes. Figure 4.8 plots the prior and posterior distributions for the

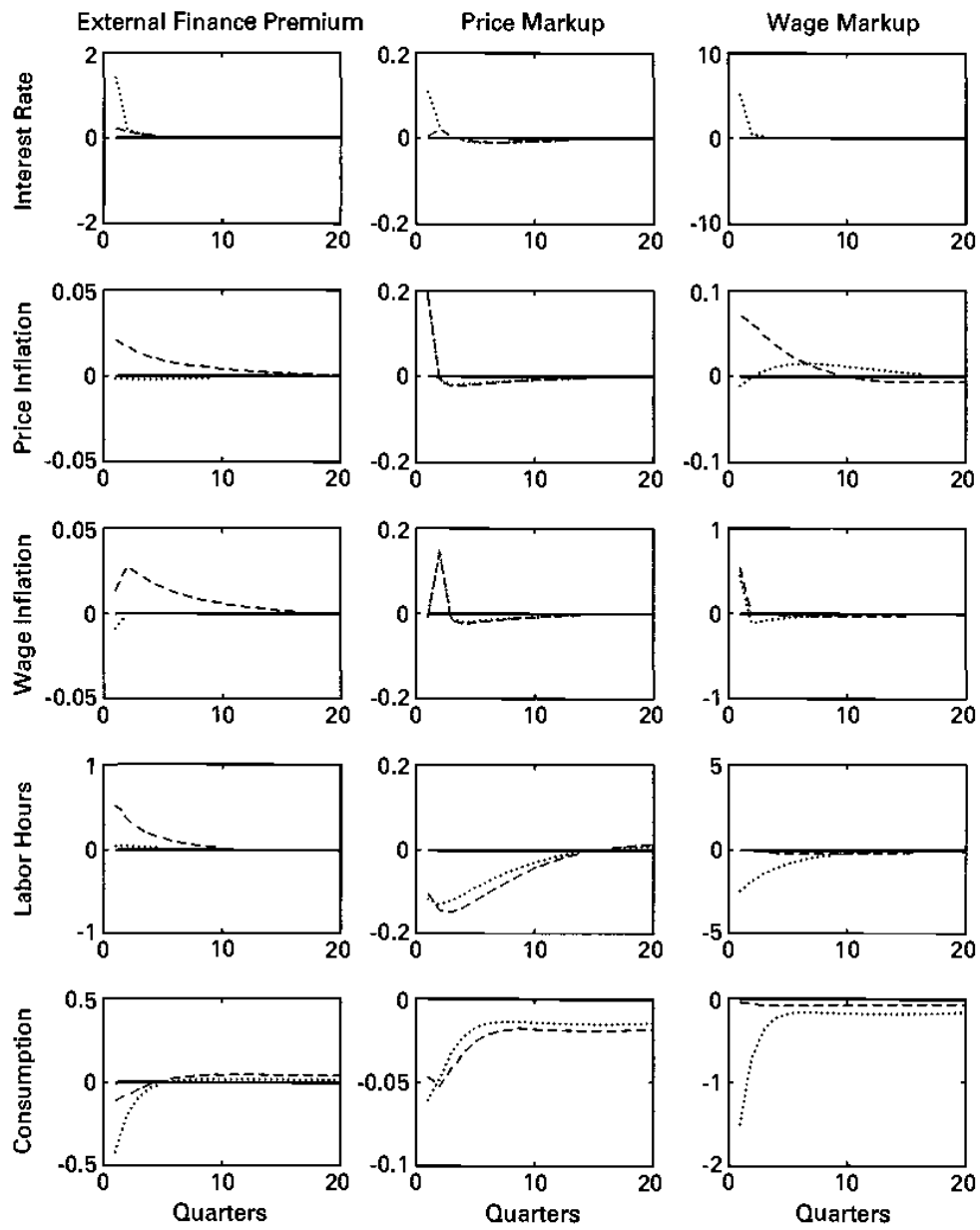


Figure 4.10

Impulse Responses for One Standard Deviation Shocks: Optimal Policy (Solid Lines), Estimated Policy (Dashed Lines), and Flexible-Wage and Flexible-Price Equilibrium (Dotted Lines)

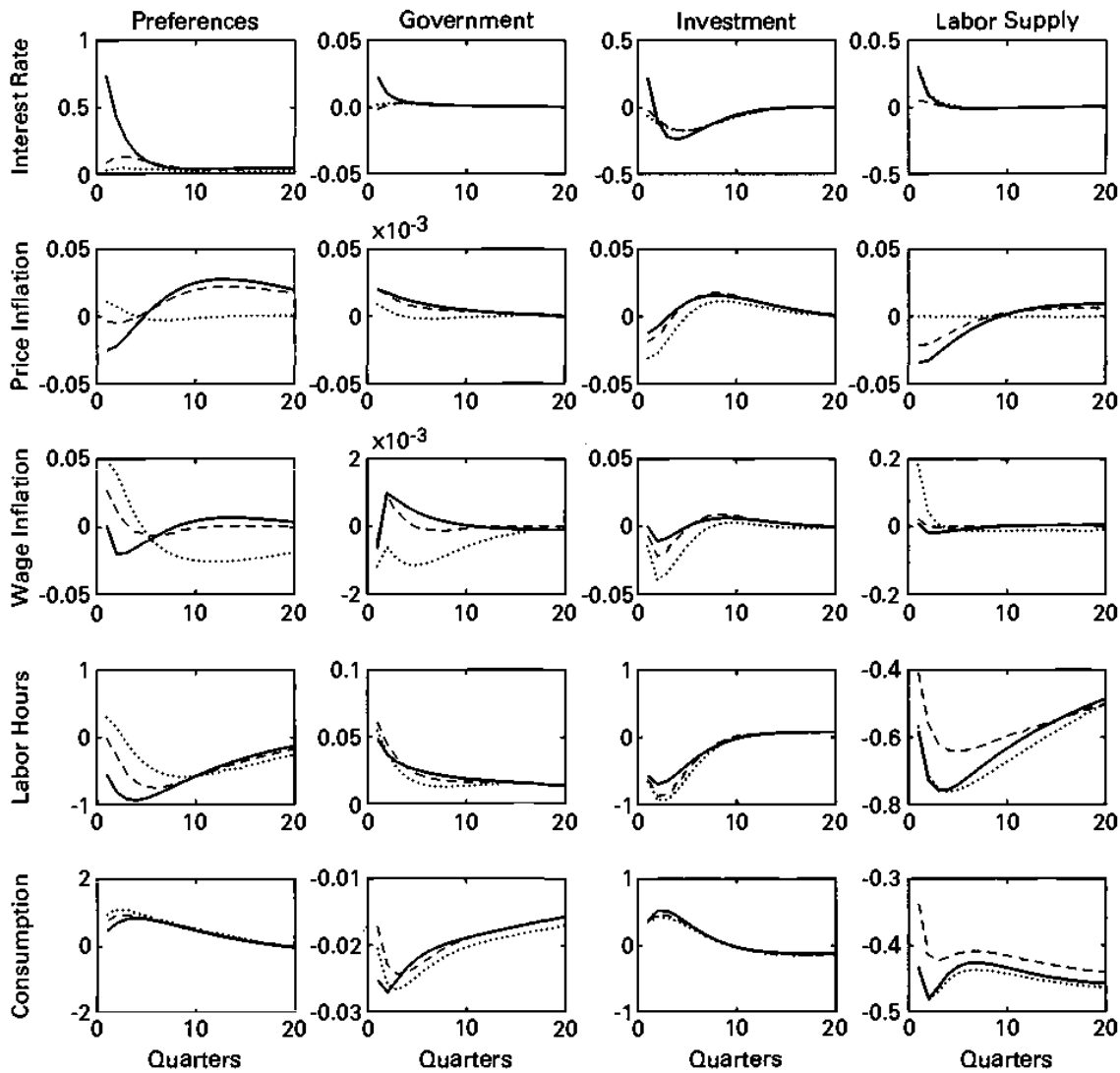


Figure 4.11
 Impulse Responses for One Standard Deviation Shocks: Optimal Policy (Solid Lines), Optimized Wage Inflation Policy Rule (Dashed Lines), and the Optimized Price Inflation Rule (Dotted Lines)

parameters describing the shock processes. Our prior insures that σ_r never hits 0, but its modal value is only 4×10^{-6} . Except for the investment shock, the AR(1) shocks are highly persistent, with the inflation objective shock in particular being nearly a unit root process. Table 4.8 reports the estimates for the specification of the model with monetary frictions from Section 7.1.

9.4 Optimal Policy

Here, we report the impulse responses to other shocks. In response to positive shocks to wages and Tobin’s Q, the optimal policy calls for a

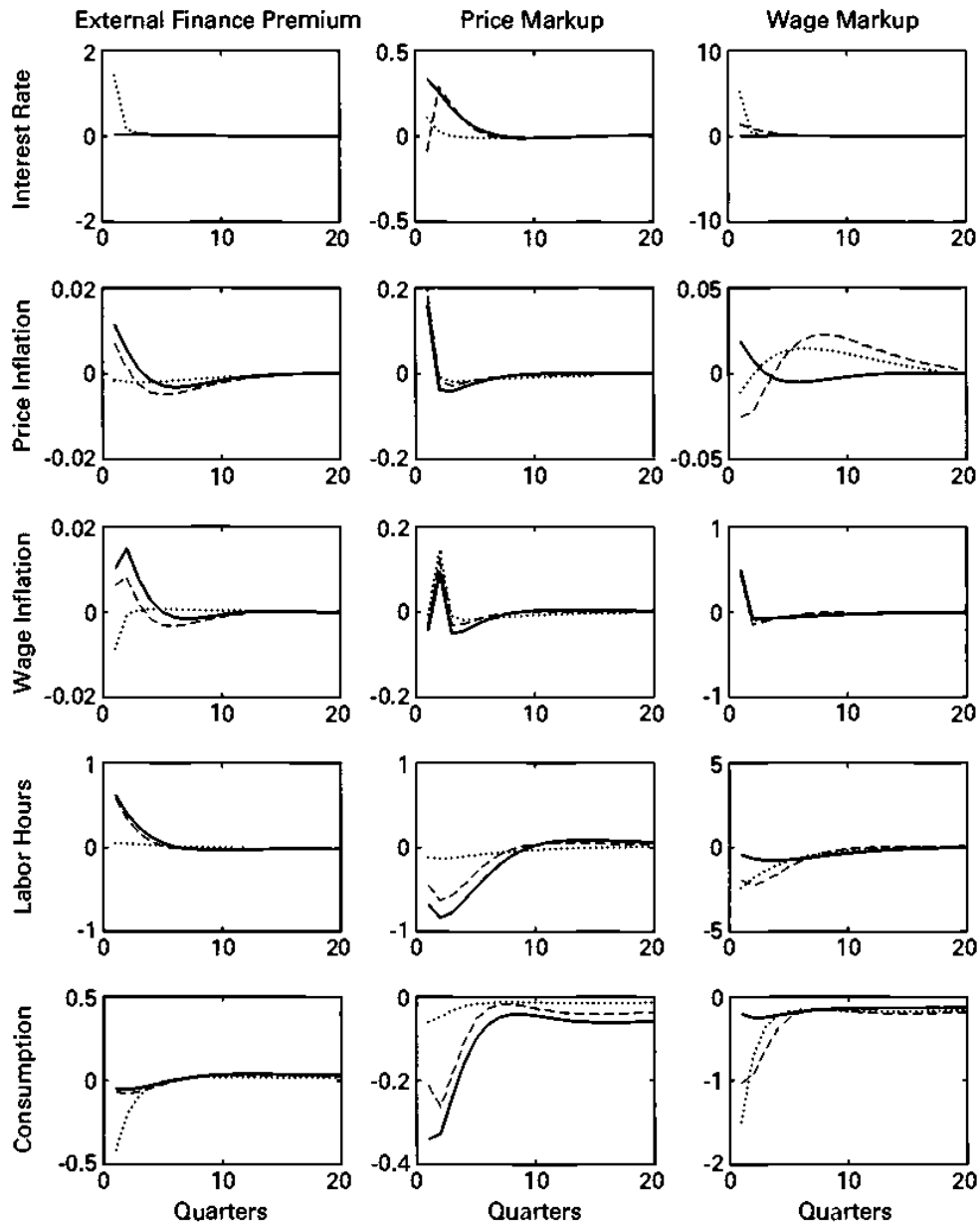


Figure 4.12
 Impulse Responses for One Standard Deviation Shocks: Optimal Policy (Solid Lines), Optimized Wage Inflation Policy Rule (Dashed Lines), and the Optimized Price Inflation Rule (Dotted Lines)

sharp increase in interest rates that causes a large decline in consumption. The contractionary policy response reduces the responses of wages. In contrast, the estimated policy rule accommodates the shocks to a greater degree and allows larger rises in wage inflation. The optimal policy response to a transitory shock to prices, however, is to do almost nothing. The estimated policy rule reacts to the rise in inflation, sending real rates higher and reducing consumption and aggregate labor. See figures 4.9 through 4.12.

Endnotes

The views expressed herein are solely the responsibility of the authors and should not be interpreted as reflecting the views of the Board of Governors of the Federal Reserve System, the management of the Federal Reserve Bank of San Francisco, or anyone else associated with the Federal Reserve System. We appreciate comments and suggestions from the editors, Mark Gertler and Ken Rogoff, and from our two discussants, Giorgio Primiceri and Carl Walsh. This paper has also benefited from conversations with Klaus Adam, Michele Cavallo, Steve Cecchetti, Matt Canzoneri, Richard Dennis, Behzad Diba, John Fernald, John Leahy, David Lopez-Salido, and Lars Svensson.

1. Other early examples include Levin (1989), King and Wolman (1999), McCallum and Nelson (1999), and Rotemberg and Woodford (1999). For a thorough presentation of this approach as well as a comprehensive bibliography, see Woodford (2003).
2. Christiano, Eichenbaum, and Evans (2005) also documented the importance of these structural features in generating a model-implied response to a monetary policy shock consistent with that of an identified vector autoregression (VAR). More recently, Altig, Christiano, Eichenbaum, and Linde (2004) have extended the model to incorporate firm-specific capital accumulation and have analyzed its behavior in response to productivity shocks, while Christiano, Motto, and Rostagno (2004) incorporate a banking system and capital market frictions in their study of the Great Depression.
3. See also Smets and Wouters (2003b) as well as the papers cited in Section 3 below.
4. See McCallum (1988); Craine (1979); Soderstrom (2002); Rudebusch (2001); Taylor (1999a); and Brock, Durlauf, and West (2003). Robust control methods have also been used in investigating monetary policy under uncertainty; see Hansen and Sargent (2003), Onatski and Stock (2002), Onatski (2000), Giannoni (2002), and Tetlow and von zur Muehlen (2002).
5. See Levin and J. Williams (2004), Kimura and Kurozumi (2003), and Walsh (2005).
6. We do not explicitly consider the policy implications of uncertainty about the current state of the economy; for recent analysis of this issue, see Orphanides (2001), Croushore and Stark (2003), Svensson and Woodford (2003), Aoki (2003), Orphanides and Williams (2002), and Orphanides and Williams (2005).
7. The optimal policy regime and optimized simple rules have previously been studied in micro-founded macroeconomic models by Onatski and N. Williams (2004), Levin and Lopez-Salido (2004), Laforte (2003), and Schmitt-Grohé and Uribe (2004).

8. While we focus on simple interest rate rules in this paper, an alternative approach is to specify a simplified objective function for the central bank, as in the literature on flexible inflation targeting; see Svensson and Woodford (2004) and Giannoni and Woodford (2004). Although not reported here, our preliminary analysis suggests that stabilizing a wage inflation objective may also perform well in terms of welfare.
9. See Levin, Wieland, and J. Williams (1999); Levin, Wieland, and John C. Williams (2003); Levin and J. Williams (2003); and Onatski and N. Williams (2003).
10. See Erceg and Levin (2005).
11. We interpret M_t as broad money and assume that households invest the remainder of their assets $A_t - M_t$ with a financial intermediary earning the nominal interest rate R_t .
12. Some authors have considered an alternative specification, referred to as external habit persistence, in which the lagged value of *aggregate* consumption serves as the reference value for each individual household. In the absence of offsetting taxes, this formulation poses an externality that distorts the steady state; thus, given our emphasis on the stabilization role of monetary policy, in this paper we focus exclusively on the internal habit specification given in the text.
13. For example, see the contrast between the conclusions of Fuhrer (2000) and Dynan (2000).
14. See Guvenen (2005) for a recent survey of the literature and an attempt to reconcile the differences in published estimates.
15. See Huang and Liu (2004) for a summary of recent evidence regarding the intertemporal elasticity of labor supply at the intensive and extensive margins.
16. Kimball (1995) proposed a more general form of aggregator function that allows for quasi-kinked demand curves, and several recent empirical studies have analyzed its first-order implications; see Eichenbaum and Fisher (2004); Altig, Christiano, Eichenbaum, and Linde (2004); and Coenen and Levin (2004). However, higher-order approximations of the Kimball specification have not yet been considered and remain well beyond the scope of the present analysis.
17. For empirical analysis of demand elasticities and markups, see Shapiro (1987), Basu (1996), and Basu and Fernald (1997).
18. See Yun (1996) and Woodford (2003) for analysis of the microeconomic underpinnings of the contract structure introduced by Calvo (1983).
19. See Clarida, Gali, and Gertler (1999) and Woodford (2003).
20. For aggregate evidence on the degree of intrinsic inflation persistence, see Gali, Gertler, and Lopez-Salido (2001) and Levin and Piger (2004). For a recent discussion of the microeconomic evidence, see Angeloni, Aucremanne, Ehrmann, Gali, Levin, and Smets (2004).
21. See Bils and Klenow (2004); Klenow and Kryvtsov (2004); and Dhyne et al. (2005).
22. Sveen and Weinke (2004) and Woodford (2005) consider the analytical foundations of firm-specific capital, while empirical studies include Sbordone (2002); Gali, Gertler, and Lopez-Salido (2001); Eichenbaum and Fisher (2004); Altig, Christiano, Eichenbaum, and Linde (2004); and Coenen and Levin (2004).
23. This adjustment cost specification incorporates the basic properties assumed by CEE and SW, who were concerned only with characterizing the steady state and log-linear

properties of the model. By using an explicit definition of the adjustment cost function, we are able to analyze the second-order approximation of the model economy.

24. As with investment adjustment costs, this explicit specification incorporates the basic properties assumed by CEE and SW, while enabling us to analyze the second-order approximation of the model economy.

25. Taylor (1999b) provides an overview of the evidence on nominal wage inertia. For analysis of the elasticity of demand for differentiated labor services, see Griffin (1996a, 1996b).

26. For analysis of optimal policy in economies with steady-state distortions, see Benigno and Woodford (2004) and Schmitt-Grohé and Uribe (this volume).

27. A detailed description of the log-linearized model is provided in Section 9.2 of the appendix.

28. We use the same data set as in Altig, Christiano, Eichenbaum, and Linde (2004), obtained from Martin Eichenbaum's web page, <http://www.faculty.econ.northwestern.edu/faculty/eichenbaum>. The real wage is constructed as nonfarm wage rate adjusted by the GDP price deflator, while total hours are measured for the nonfarm business sector. The inflation rate and interest rate are demeaned and converted to quarterly rates; the other five variables are measured in logarithmic deviations from linear trends, in percentage points.

29. The mean ratio of net exports to GDP was zero to two decimal points over our sample.

30. In specifying these priors, we have drawn heavily on Smets and Wouters (2003a, 2003b); Christiano, Eichenbaum, and Evans (2005); Altig, Christiano, Eichenbaum, and Linde (2004); and Onatski and N. Williams (2004).

31. Since the work of Schorfheide (2000) and especially after the original Smets and Wouters (2003a) paper, there have been a number of papers using Bayesian methods for models similar to ours; examples include Del Negro and Schorfheide (2004); Rabanal and Rubio-Ramirez (2003); Laforte (2003); Onatski and N. Williams (2004); and Del Negro, Schorfheide, Smets, and Wouters (2004).

32. For comparison, Taylor (1993b), using a staggered wage model, estimates an average wage contract duration of about $3\frac{1}{2}$ quarters.

33. See Kydland and Prescott (1980); King and Wolman (1999); and Khan, King, and Wolman (2003).

34. These procedures are available on the Dynare web site or on request from the authors.

35. Judd (1998) provides a general introduction and comparison of methods for solving nonlinear rational expectations models.

36. See Kim and Kim (2003); Kim, Kim, Schaumburg, and Sims (2003); and Woodford (2003).

37. Because perturbation methods provide a local approximation around the steady state, our analysis does not consider the implications of the zero lower bound on nominal interest rates.

38. For this purpose, it is essential to utilize conditional mean-preserving spreads for the exogenous disturbances; see Levin and Lopez-Salido (2004) for further discussion.
39. Impulse responses for other structural shocks are reported in the appendix.
40. For related analysis and results, see Cho, Cooley, and Phaneuf (1997); Canzoneri, Cumby, and Diba (2004); and Paustian (2004).
41. For analysis and discussion of the rationale for simple rules, see Taylor (1993a) and Williams (2003).
42. McCallum (1999) also highlights the role of information lags; thus, while our specification utilizes contemporaneous data, it will be useful to consider this issue further in subsequent research.
43. See Reifschneider and Williams (2000), Eggertsson and Woodford (2003), and others.
44. See also Erceg and Levin (2005) and Mankiw and Reis (2002).
45. We do not, however, vary the parameters associated with the shock processes or the calibrated parameters.
46. In addition, the welfare costs of fluctuations are very sensitive to the assumed degree of substitutability across types of labor and of goods, parameters that we take as fixed in this analysis.
47. Note that we do not impose a relationship between the fixed cost parameter and the markup implied by a zero-profit condition.
48. Thus, we isolate the effects of changing the substitutability of different types of labor on welfare from those on the sensitivity of wages to movements in the marginal rate of substitution.
49. In a previous version of this paper, we estimated an alternative model that included no external finance premium shocks. Estimates of most model parameters were nearly identical to the baseline estimates. Exceptions included the estimate of ζ , which fell, implying significantly *higher* costs of adjusting investment, and the investment adjustment cost shock became more variable and less persistent. The effects on welfare of this specification were modest.
50. Because a shock to preferences affects only welfare and not the production possibilities of the economy, with flexible wages and prices, welfare is nondecreasing to a mean-preserving spread to preferences.
51. For some early analysis of specification uncertainty in structural models, see Becker, Dwolatsky, Karakitsos, and Rustem (1986) and Frankel and Rockett (1988).
52. The money data are available only from 1959 onward, so we shorten the sample by four years. Linearized expressions are given in the appendix.
53. Complete estimation results are reported in Section 9.3 of the appendix.
54. It is still the case that the optimal coefficient on price inflation is 0.
55. Although not considered here, another model of wage and price setting that does not yield dispersion effects on aggregate welfare is the quadratic adjustment costs model of Rotemberg (1982).

56. We estimated a version of the baseline model where wage indexation depends on a combination of past price and wage inflation. We found that the weight is primarily on past price inflation, providing support for the baseline model specification. Nonetheless, one may not be convinced by this finding and remain concerned about uncertainty regarding the form of wage indexation.

57. As explained below, we have not formally estimated this alternative specification. The empirical performance of the model may be sensitive to which type of nominal rigidity is assumed; see Chari, Kehoe, and McGrattan (2000); Kiley (2002); and Guerrieri (2001).

58. We also examined a version of the model with Taylor wage contracts and Calvo prices. The results were very similar to those found when both wages and prices are set by Taylor contracts.

59. The specification of Erceg, Henderson, and Levin (2000) implies a much flatter nominal wage Phillips curve; that is, nominal wage inflation is much less sensitive to the marginal rate of substitution between consumption and leisure. Furthermore, cross-sectional wage dispersion induces differences in labor across households that have substantial effects on social welfare.

60. Erceg and Levin (2003) analyze a DGE model roughly similar to the one in this paper and show that private agents' gradual learning about the Fed's inflation objective is crucial for interpreting the effects of the Volcker disinflation, while Edge, Laubach, and J. Williams (2003) and Erceg, Guerrieri, and Gust (2005) highlight the role of learning in fitting the stylized facts of the U.S. productivity growth boom of the late 1990s.

61. See Beck and Wieland (2002) for analysis of optimal learning and control in a small stylized economy with ongoing structural change.

62. For a brief survey of the literature on specification of priors, see Onatski and N. Williams (2004). This survey includes studies focusing on real models, such as King and Rebelo (1999) and Boldrin, Christiano, and Fisher (2001), as well as papers focusing on monetary policy in smaller models, such as Rotemberg and Woodford (1997), Judd and Rudebusch (1998), and Sack (1998).

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Comment

Giorgio E. Primiceri

Introduction

The 1970s and the 1980s were tough decades for researchers studying the effects of monetary policy and optimal monetary policy responses to exogenous disturbances. In fact, Lucas's (1976) famous critique challenged the usefulness of (or, better, highlighted problems with) econometric models for policy evaluation. Moreover, Lucas's (1987) monograph about the very low cost of business-cycle fluctuations implicitly questioned the relevance of optimal stabilization policy exercises.

Providing convincing responses to Lucas has taken quite some time. Dynamic stochastic general equilibrium (DSGE) modeling should be thought as a (partially) successful effort in that direction. The presence of explicit micro-foundations has made possible the use of these models for policy analysis, and the importance for welfare of heterogeneity, in the form of price and wage dispersion, has made again meaningful the problem of optimal monetary policy.

Exactly in the context of these micro-founded DSGE models, the work of Levin, Onatski, Williams, and Williams (LOWW) is a careful and detailed analysis of optimal monetary policy and the robustness of optimal rules. The model adopted in the paper is a large-scale model of the business cycle with various nominal and real frictions (as in Christiano, Eichenbaum, and Evans 2005) and many exogenous shocks (following along the lines of Smets and Wouters 2003). In order to determine the importance of each friction and each disturbance in the generation of the business cycle, the model is estimated on U.S. quarterly data.

LOWW's analysis delivers four main conclusions. First, the welfare costs of macroeconomic fluctuations are sizable and wage dispersion

is the main source of welfare losses. Second, a simple rule in which the central bank responds only to wage inflation achieves almost the same welfare level of the Ramsey policy. Since the Ramsey policy can have quite complicated representations, finding a simple rule approximating the truly optimal policy is an important contribution. Third, the optimality properties of this simple rule are robust to the uncertainty about many structural parameters of the model. Fourth, exactly because the labor market is very important in the model, the optimal simple rule is not very robust to alternative assumptions about wage rigidity.

For its approach and the interesting results, the paper sets a very high standard for the analysis of optimal monetary policy. Nevertheless, some aspects of the paper deserve further discussion.

I will organize my comments around two points. In the first part, I will argue that the specific rule proposed in the paper cannot be implemented because it implies a very high volatility of the nominal interest rate. I will suggest some alternative rules that are similar to the one recommended by LOWW but are operational. In the second part, I will comment more broadly on the problem of optimal monetary policy in likely misspecified models. In both sections, I will argue that more work is needed in order to provide a compelling reply to Lucas.

Optimal Simple Rules and the Zero Bound

One potential problem with the specific optimal monetary policy rule proposed in the paper is that it implies a very high volatility of the nominal interest rate. Suppose that the LOWW model is augmented with the following class of interest rate rules:

$$R_t = R_{t-1} + \phi_w \Delta W_t \quad (1)$$

where R_t and ΔW_t denote, respectively, the nominal interest rate and wage inflation. Table 4.9 reports the volatility of the annualized nominal interest rate corresponding to several values of ϕ_w , the coefficient of reaction to wage inflation. It is evident that stronger reactions to wage inflation generate a higher volatility of the monetary policy in-

Table 4.9
Volatility of Annualized Nominal Interest Rates (Percentage Points)

ϕ_w	.1	.2	.3	.4	.45	.5	1	1.5	2	3	3.2
$\sigma(R_t)$	1	1.32	1.64	1.88	2	2.16	3.32	4.36	5.4	7.32	7.72

strument. Notice that $\phi_w = 3.2$ is the value recommended by LOWW, and that it corresponds to a volatility of the nominal interest rate of almost 8 percent per year. This number seems too high. In fact, when the inflation target is 0 and the steady-state real rate of interest is 4 percent (as in the paper), this policy rule would imply hit the zero bound of nominal interest rates with approximately a 30 percent chance. This makes the simple rule suggested by LOWW not operational (I borrowed this terminology from McCallum and Nelson 1999).

In some sense, this is not a very surprising result since the problem is common to optimal policy exercises based on linearized models, in which the optimal policy implies a variability of some of the variables for which the linear approximation becomes invalid. Of course, one solution for the monetary authorities would be to replace the policy rule in equation (1) with the following modified version:

$$R_t = \max\{R_{t-1} + \phi_w \Delta W_t; 0\} \tag{2}$$

which does not violate the zero bound constraint. However, this would cause an increase in the variability of output and price and wage inflation which would make equation (2) suboptimal.¹

One alternative solution for the central bank would be to raise its inflation target in order to increase the average of nominal interest rates and thus decrease the probability of hitting the zero bound. Table 4.10 reports the inflation rate that the central bank should target in order to have the average nominal interest rate at least two standard deviations away from 0 (again as a function of ϕ_w).

As should be expected, the inflation target increases with ϕ_w , capturing the idea that the stronger the reaction to wage inflation, the higher the variability of interest rates, and the higher the inflation target necessary to be away from the zero bound with a high probability. In particular, notice that to the optimal value suggested by the authors ($\phi_w = 3.2$) corresponds an inflation target of approximately 11.5 percent, which again seems very high. On the other hand, if the central bank wants to keep an inflation target of 0, the reaction to wage inflation should be reduced to 0.45, a value considerably lower than 3.2.

Table 4.10
Inflation Target Necessary to Avoid the Zero Bound (Percentage Points)

ϕ_w	.45	.5	1	1.5	2	3	3.2
π^*	0	.32	2.64	4.72	6.8	10.64	11.44

To make the wage targeting rule operational, the reaction to wage inflation has to decrease drastically, so one could even question the optimality of the wage targeting rule suggested by LOWW. In particular, one alternative rule that would perform better under the zero-inflation-target and the zero bound constraint² is a rule exhibiting *superinertia*, i.e., a coefficient of reaction to the past level of the interest rate larger than 1. The intuition for the optimality of superinertia is the familiar one: if the central bank credibly commits to an extremely strong reaction to fluctuations in wage inflation, this will affect private agents' expectations formation, resulting in an ex-post lower variability of the interest rates. This allows an increase in the coefficient on wage inflation with respect to the case in which the coefficient on past interest rates is constraint to be 1. Numerical exercises show that the result of the paper, that a mute response to the output gap and price inflation is optimal, continues to be valid.

This simple exercise has a potentially broader interpretation, indicating that the problem of the optimal inflation target and the optimal variability of price and wage inflation are strictly related and probably should not be analyzed separately. Although LOWW work under the assumption that the optimal inflation target is 0, their welfare function could easily be modified in order to consider the possibility of a positive inflation target. The problem of doing so is that the general type of model adopted by LOWW is not completely suitable for analyzing the effects of a positive steady-state inflation. Indeed, the only effect that inflation has on welfare is through price and wage dispersion, and the model abstracts completely from alternative sources of gains and costs, for example, shoe-leather costs, fiscal implications, advantages in terms of flexibility of real wages, etc. All these issues seem to me at least of the same order of magnitude for welfare as the effects due to the variability of inflation examined in the paper.

Optimal Monetary Policy in (Likely Misspecified) DSGE Models

In this section, I will comment more broadly on the problem of optimal monetary policy in models that are "grossly deficient relative to the ideal" (Faust 2005). I want to stress that this section of the discussion should be understood as more related to the entire strand of literature rather than specific to LOWW's paper and that, more than a set of criticisms, my comments should be regarded as suggestions for future developments.

The great achievement of modern DSGE models à la Christiano, Eichenbaum, and Evans (2005) or Smets and Wouters (2003) is being competitive in terms of fit with statistical models like vector autoregressions (VARs).³ However, we should not forget that this improvement in fit comes at the cost of debatable assumptions about the presence of some frictions and some shocks that do not have a clear micro-foundation. Some examples are rule-of-thumb agents, adjustment costs in investment and price and wage indexation. While this point has been made before (see, among others, Faust 2005 and Sims 2003b), it is worthwhile repeating it because one important contribution of LOWW's paper is the sensitivity analysis of optimal interest rate rules to the value of specific structural parameters of the model (capturing specific frictions). This allows us to identify the features of the models that are important for the robustness of optimal rules. Optimal rules seem sensitive exactly to some of the frictions lacking a clear microeconomic interpretation, like adjustment costs in investment or assumptions about the particular kind of wage rigidity.

An Example of Potential Misspecification: Price and Wage Indexation

Notice, however, that there is also a deeper sense in which the model could be misspecified. If this were the case, simply showing the robustness of the policy rule to the uncertainty about the exact level of the coefficients would not be particularly reassuring. I will illustrate this point by focusing on the issue of price and wage indexation, for a reason that will become clear at the end of the section.

In many modern DSGE models with price and wage rigidities, when price- and wage-setters cannot re-optimize, they are assumed to set prices and wages according to a simple indexation rule. The indexation rule is called dynamic when prices and/or wages are indexed to past inflation; it is called static when indexed to long-run or average inflation. Combinations of the two extremes are also possible, like in LOWW's paper.

In a recent study, Schmitt-Grohé and Uribe (2004) emphasize the fact that the particular assumption about indexation plays a key role for the design of optimal rules. When indexation is fully dynamic, the optimal rule does not exhibit inertia; if indexation is less than fully dynamic, the optimal rule has interest rate inertia and sometimes (like in our case) superinertia. Therefore, it could be argued that the best way to proceed would be to determine empirically the right degree of indexation. Notice, however, that finding the degree of indexation that fits the

data best is exactly the same sort of "cavalier treatment of expectations" that Lucas so convincingly criticized in the 1970s. There is no "right" degree of indexation. People probably behave as in a dynamic indexation model in periods in which inflation is highly autocorrelated. On the other hand, static indexation would be more natural when the autocorrelation is low. This is just another way of saying that the degree of indexation is an endogenous object and that any model in which the degree of indexation is exogenous should not be considered a truly structural model.

If this was indeed the case, analyzing the sensitivity of optimal policy rules to the exact degree of price and wage indexation would not be the relevant exercise. This is because the right model would be one without any exogenous indexation but with a completely different expectations formation process for the private agents. Clearly, all these considerations are potentially very important for the design of optimal monetary policy.

Learning, Frictions, and Persistence

Here I am not necessarily trying to argue that the assumptions about price and wage indexation are more important than other features of the model for the design of optimal policy. Instead, the reason why I chose to digress on indexation is simply because it makes a natural link to what I regard as a very promising avenue for future research.

What is strange and puzzling in many modern DSGE models is that in the same economy, there is a group of agents who are so intelligent and with such perfect information that their behavior can be well approximated by rational expectations. At the same time, there is another group of agents behaving not only suboptimally but very incoherently. Both assumptions seem too extreme, and I wonder whether it would not be more desirable to model all agents as rationally bounded in a more systematic way.

Learning has enormous potential in this respect. After all, Sargent (1999); Orphanides (2000); Primiceri (2005); and Sargent, Williams, and Zha (2004), among others, have shown how learning can greatly improve our understanding of policymakers' behavior in the postwar period. More recently, in the context of a small-scale monetary model, Milani (2005) has shown that a model in which private agents learn over time fits the data better than a model in which agents have rational expectations. Moreover and most important, Milani (2005) shows that some of the exogenous frictions, which sometimes are necessary

in a model with rational expectations to improve the fit and generate the persistence observed in the data, become redundant when agents are assumed to learn over time. As argued, for example, in Orphanides and Williams (2004), optimal policy under the assumption of rational expectations can perform quite poorly when agents are actually learning.

More generally, modeling the way people process information and form beliefs in a more complex way than the one implicit in the assumption of rational expectations seems crucial in order to reproduce some of the features of the data in a theoretical model (see, for instance, Sims 2003a or Mackowiak and Wiederholt 2005). Clearly, integrating learning and even more sophisticated assumptions about the formation of agents' beliefs in large-scale models like the one presented in this paper represents a challenge, but it should be considered a priority for future research.

Endnotes

I would like to thank Andrea Tambalotti and Alejandro Justiniano for useful conversations.

1. In the context of the FRB/US model, Reifschneider and Williams (2000) argue that the use of a rule similar to equation (2) would yield only small stabilization costs.
2. Here, again, I follow Rotemberg and Woodford (1998) and Schmitt-Grohé and Uribe (2004) in imposing the nonnegativity constraint by requiring that the nominal interest rate is at least two standard deviations away from the zero bound. This is just a computationally convenient approximation and ideally, one should impose the nonnegativity constraint directly, as in Eggertsson and Woodford (2003).
3. In Smets and Wouters (2003), as well as LOWW, one important shortcoming that makes the model competitive with VARs in terms of fit is detrending and demeaning the data in advance (i.e., ignoring the restrictions implied by the balanced growth path). This is clearly undesirable.

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Comment

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The marriage of micro-founded dynamic stochastic general equilibrium models and nominal rigidities has opened up new possibilities for policy analysis, and in particular for conducting welfare-based analysis using estimated macro models. Andy Levin, Alexsei Onatski, John Williams, and Noah Williams (henceforth LOWW) have exploited these possibilities in an excellent paper, one in which they accomplish three things. First, they specify a second-generation, new Keynesian model and estimate it using Bayesian techniques. Second, they use this model to calculate the welfare costs of fluctuations under alternative policies. Third, they investigate the robustness of policy rules to parameter and model misspecification.

Each of these tasks is carried out in elegant fashion, producing a paper that not only represents the state of the art in modern monetary economics but provides an outstanding example of how to do policy analysis. Because LOWW provide such a carefully and well-specified model, one that includes all the bells and whistles of the latest generation of new Keynesian models, it offers an opportunity for assessing the ability of these models to serve as the workhorse for monetary policy analysis. I will argue that this estimated new Keynesian model fits the data in a very non-Keynesian manner. By this I mean the model attributes most of the actual output fluctuations experienced in the U.S. economy to fluctuations in the flexible-price equilibrium level of output, suggesting that nominal rigidities have contributed little to observed business cycles. The model also implies an interpretation of the early 1980s and the Volcker disinflation that is at odds with the views shared by most new Keynesians. Further, while the authors find that the labor market is critical for the welfare costs of fluctuations, the estimated output gap implied by their model bears little relationship to fluctuations in the unemployment rate.

In my comments, I very briefly describe the model, make a few points about the empirical strategy, and assess the results. Then, after discussing the authors' policy findings, I conclude with some comments on the specification of the labor market.

The Model, Empirical Strategy, and Results

In the model that LOWW specify, wages and prices are sticky, with the adjustment of both governed by the standard Calvo mechanism augmented by Woodford-type partial indexation (Woodford 2003). Intertemporal consumption preferences exhibit internal habit persistence, capital utilization is variable, and there are investment adjustment costs. These modeling choices have become standard in new Keynesian models, particularly when a goal is to take the model to the data (see, for example, Christiano, Eichenbaum, and Evans 2005 and Smets and Wouter 2003). Indexation is included to justify the presence of lagged wage and price inflation in the wage and price adjustment equations, and habit persistence is used to motivate the presence of lagged output in the Euler equation. Variable capital utilization serves to dampen the impact of output movements on marginal cost and therefore on inflation. While there is little micro evidence to justify some of these extensions, they have all become accepted components of the standard model, necessary to capture the persistence typically displayed by the data.

Where LOWW differ from the earlier literature is in the set of economic shocks that their model includes. Some of these are standard, such as serially correlated disturbances to the marginal disutility of work and to the production function. Others are less common; for example, they include serially correlated disturbances to the representative household's subjective rate of time discount, to investment adjustment costs, to the demand elasticity faced by individual firms, to the elasticity of labor demand faced by individual households, and to the asset pricing Euler equation. These last three disturbances are assumed to be i.i.d., while the first three are treated as AR(1). The paper provides little discussion rationalizing these particular modeling choices, yet these choices are important, particularly when the authors need to decide which shocks affect the efficient, flexible-price equilibrium and which do not.

Let me briefly mention four of the authors' choices in taking their theoretical model to the data that may bear further investigation. First,

to close the model, monetary policy is represented by an interest rate rule with a serially correlated stochastic inflation target. This treatment of monetary policy, while standard, is somewhat at odds with the general approach adopted in the paper. The micro-founded specification of the private sector takes as given that decision rules are not primitives—one specifies objective functions and constraints and from these, decision rules are derived. Hence, while LOWW treat private agents in their model as rational optimizers, this is not how they treat their central bank policymaker when they estimate the model. The central bank is assumed to implement a simple instrument rule for the nominal rate of interest. That is, the decision rule of the central bank is treated as a primitive. The debate over representing central bank behavior as a simple rule or recommending that a central bank actually implement a simple rule is an active one. One argument for simple rules is that they provide good policy guidance when the central bank has only limited information about the economy. But LOWW assume the central bank has complete information, letting it respond to an output gap measure whose calculation requires knowledge of the entire model. It might be interesting to assume alternatively that a central bank equipped with complete knowledge of the model would in fact implement the optimal policy rather than rely on a simple (and suboptimal) rule. Dennis (2005) has followed this approach in jointly estimating the structural parameters of a simple new Keynesian model, along with the weights in the central bank's objective function. An interesting exercise would be to see if the empirical parameter estimates are affected when the central bank is treated as an optimizing, rational agent, as the private sector already is.

Second, the model is estimated over the period 1955 to 2001. Given the simple structure of the model and the major changes that have occurred in the U.S. economy over the past half century, one must question whether parameters have remained constant over the entire sample. In addition, previous work (for example, Judd and Rudebusch 1998) shows that Federal Reserve behavior was not constant over this period of time.

Third, consumption, investment, output, hours, and the real wage are all measured as log deviations from linear trends. In a micro-founded model, the choice to separately detrend these variables seems open to question. Theory should tell us something about the common sources of the growth trends in these variables, and this information should be used if possible.

Fourth, government spending is treated as an exogenous disturbance. However, in the actual estimation, the government spending variable is measured by government purchases plus net exports. This is necessary as the theoretical framework corresponds to a closed economy, but the data come from an open economy. The problem is that, while one might be willing to treat government spending as exogenous, this is not a reasonable assumption with respect to net exports.

While the authors discuss the estimation results for individual parameters, they do not evaluate the overall ability of the model to match the data. One means of doing so is to examine the way the model decomposes output into potential output and the output gap. This is done in figure 4.13. The solid line is log, detrended real gross domestic product (GDP), expressed in percentage terms, the authors' measure of output. The dashed line is their estimate of potential output y^* , while the dotted line is the output gap, $y - y^*$. Potential output is defined as the flexible-price equilibrium output level that would occur in the absence of price, wage, and equity cost-push shocks. As the figure reveals, the model attributes almost all of the fluctuations in actual output to fluctuations in potential output. Expressed alterna-

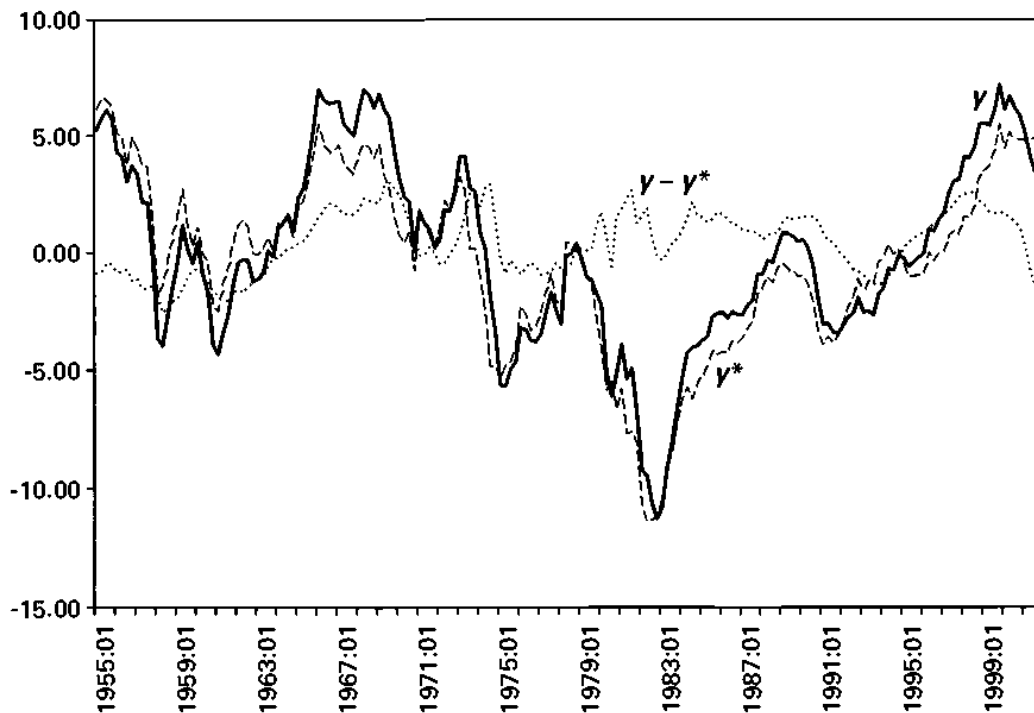


Figure 4.13
Estimated Potential Output y^* (Dashed Line) Tracks Actual Output y (Solid Line) Closely. Also Shown Is the Output Gap $y - y^*$ (Dotted Line)

tively, despite the new Keynesian addition of sticky wages and prices, the estimated model basically delivers a real business-cycle representation of output. And recall that the output series has already been detrended so that the authors' y is itself a measure that is often identified as an output gap in empirical work.

How should this close parallel between output and potential output be interpreted? In versions of the new Keynesian model in which the steady-state is Pareto efficient, the flexible-price equilibrium output level—LOWW's potential output—is also the welfare-maximizing output level. Hence, one interpretation of figure 4.13 is that the Federal Reserve has managed to keep actual output very close to the welfare-maximizing output level. Such an interpretation seems at odds with the model itself, which finds both that the impulse responses to shocks under the estimated policy rule differ significantly from the impulse responses implied by the optimal policy and that the estimated interest rule leads to higher welfare costs than the optimal Ramsey policy.

Another way to assess the model is to focus on a particular historical episode for which most of us have fairly strong priors about the role of monetary policy. The period from late 1979 to 1984 was one in which the United States experienced two back-to-back recessions that almost all economists attribute to the Federal Reserve's actions to bring down inflation. Output declined significantly over this period before recovering. If this decline was the result of monetary policy, potential output should not show a similar decline, and we should expect to see parallel movements of the output gap and actual output. Figure 4.14 shows the decline of y and its subsequent recovery. However, the figure also shows that the model attributes this decline entirely to a decline in potential output y^* . In fact, the model implies that the early 1980s were a period of positive output gaps, with actual output exceeding the flexible-price equilibrium level. Thus, according to the model, far from generating a recession, Volcker failed to allow output to decline as much as y^* fell.¹

Figure 4.14 also shows the unemployment rate (expressed as a deviation from its sample mean). Consistent with the standard interpretation of this period as one of economic recession, the unemployment rate rose in 1980, eventually peaking in the fourth quarter of 1982. This behavior does not seem consistent with a period that, according to the model, was experiencing a positive output gap. I will return to the relationship between the unemployment rate and the estimated output gap series below.

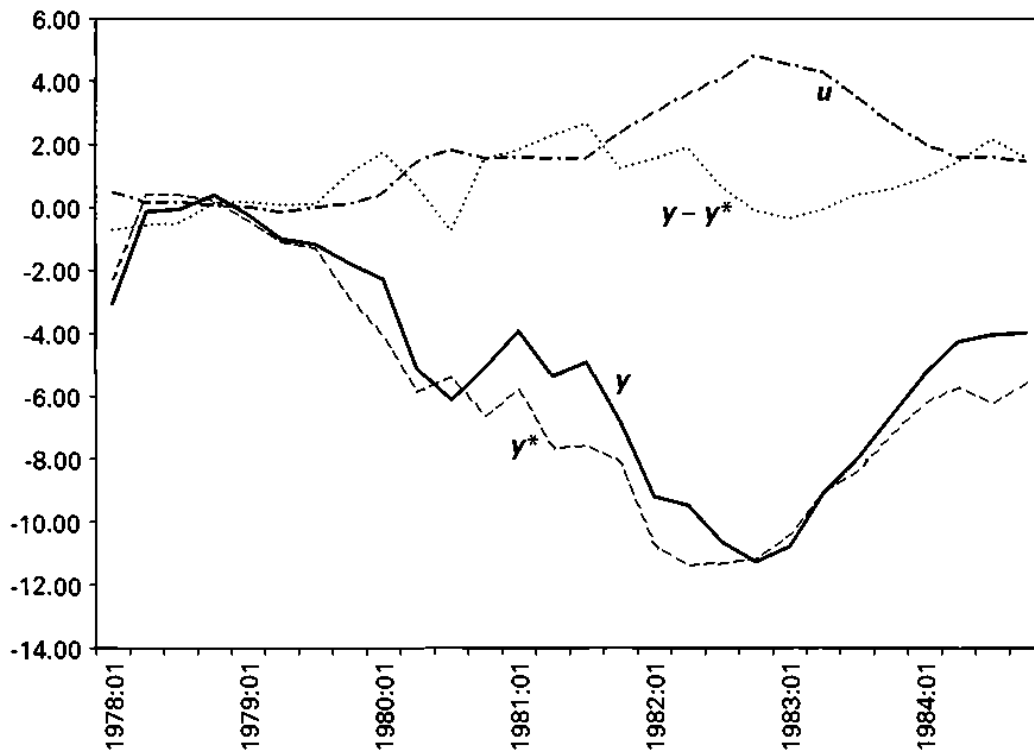


Figure 4.14

During the Early 1980s, the Model Attributes the Decline in Output (Solid Line) to a Parallel Decline in Potential Output (Dashed Line). The Output Gap (Dotted Line) Was Actually Positive. Also Shown Is the Unemployment Rate (Dotted-Dashed Line)

If actual policy has not been fully optimal, two other interpretations of figure 4.13 are perhaps more plausible. The model contains ten stochastic shocks. LOWW assume that seven of these shocks, all but the equity, wage, and price cost-push shocks, cause movements in y^* . The decomposition of output between y^* and $y - y^*$ will depend on which shocks are assumed to be reflected in movements in y^* and which are not. The high correlation between y and y^* suggests, perhaps not surprisingly, that understanding the sources of the exogenous shocks will be critical in assessing whether the fluctuations they induce are efficient or welfare reducing.

A final interpretation is simply that the model is missing some critical aspect that is important for the actual behavior of business cycles. One possibility is that the failure to capture the standard interpretation of the 1980s is due, in part, to the way LOWW specify the monetary policy instrument rule. This instrument rule contains two stochastic elements: one is the inflation target, the other is a shock to the equation as a whole (labeled a policy shock). Given the linear structure, these two can be disentangled only because the policy shock is assumed

to be white noise while the inflation target is allowed to be serially correlated.² The time variation to the inflation target is assumed to be known perfectly by all agents in the model. Thus, I suspect that to fit the data, the estimated inflation target falls in 1980, but because this decline is known and perfectly credible, it has little impact in the model on the output gap. To match the decline in actual output, the model must attribute the recession to a fall in y^* . In contrast, Erceg and Levin (2003) argue that accounting for the imperfect credibility of the Fed's inflation target is important for understanding the economy's behavior during the Volcker disinflation.

Policy Analysis

Household welfare is the metric LOWW employ to evaluate alternative policies, thereby providing a model-consistent means of comparing outcomes under different policies. By assuming the presence of labor and production subsidies that neutralize the distortions arising from imperfect competition, LOWW take the flexible-price equilibrium to be Pareto optimal. Results are reported in terms of consumption equivalents, and they find sizable costs of economic fluctuations, amounting to a 1.4 percent decrease in permanent consumption even under the optimal Ramsey policy. Presenting policy comparisons in terms of consumption equivalents is an excellent idea, one that others should emulate. LOWW's results highlight how policies that lead to similar volatility of inflation and the output gap—the standard metrics for comparing policy outcomes—can actually result in quite different levels of welfare.

Perhaps their most interesting finding, however, is that a simple difference rule, in which the change in the nominal interest rate responds to the rate of wage inflation, does almost as well as the fully optimal Ramsey policy, and it does significantly better than the estimated policy rule. This result is a consequence of the critical role nominal wage rigidity plays in the model. As the authors explain, the welfare costs of fluctuations depend critically on the degree of wage stickiness. And because wage volatility is so critical for generating the costs of fluctuations, optimal policy will place a large weight on stabilizing wage changes. Thus, a simple rule that reacts strongly to wage inflation comes close to replicating outcomes under the fully optimal policy. Also of interest is their finding that a wage inflation rule is robust to several forms of parameter uncertainty and model misspecification.

The Labor Market

Perhaps the most important lesson from LOWW is that the labor market is critical in accounting for the welfare costs of economic fluctuations. These costs are due to the dispersion of hours worked across households that occur when wages are sticky. As LOWW put it, "Overall, our results have emphasized the central importance of the labor market for welfare and policy analysis." This finding is consistent with the work of Galí, Gertler, and Lopez-Salido (2002), who find that the economy's efficiency gap is primarily the result of stochastic fluctuations in the wedge between the households' marginal rate of substitution between leisure and consumption and the real wage. Because of its importance, LOWW consider some alternative specifications of the labor market. However, they limit their focus to alternative models of nominal wage stickiness. This may not be the only aspect of the labor market specification that should be examined. I will mention two others.

In LOWW, the wedge between the households' marginal rate of substitution between leisure and consumption and the real wage arises from stochastic fluctuations in the wage elasticity of labor demand $\lambda_{w,t}$. The relevant real wage for labor supply should be the consumption real wage, but because the model is a closed economy model, the authors use the real product wage in its place. Thus, there is the possibility that what the estimated model attributes to $\lambda_{w,t}$ (and recall, $\lambda_{w,t}$ is assumed to generate inefficient movements in output) is really just the wedge between the real consumption wage that should appear in the wage inflation equation and the real product wage that actually appears. Under this interpretation, $\lambda_{w,t}$ reflects variations in the consumer price index relative to the GDP deflator, variations that are not exogenous but are associated with, for example, exchange rate movements. An interesting extension would incorporate open economy aspects into the model to see if this is, in fact, the source of LOWW's cost-push shock and whether accounting for it affects the estimated welfare costs of fluctuations.³

Since the labor market seems to be critical for the welfare costs of fluctuation, how do unemployment fluctuations relate to the authors' estimated output gap? Okun's law provides a convenient and conventional link between output gap fluctuations and movements in the unemployment rate relative to the natural rate of unemployment. This relationship is shown in the top panel of figure 4.15, in which the unemployment rate is plotted on the horizontal axis, and detrended log

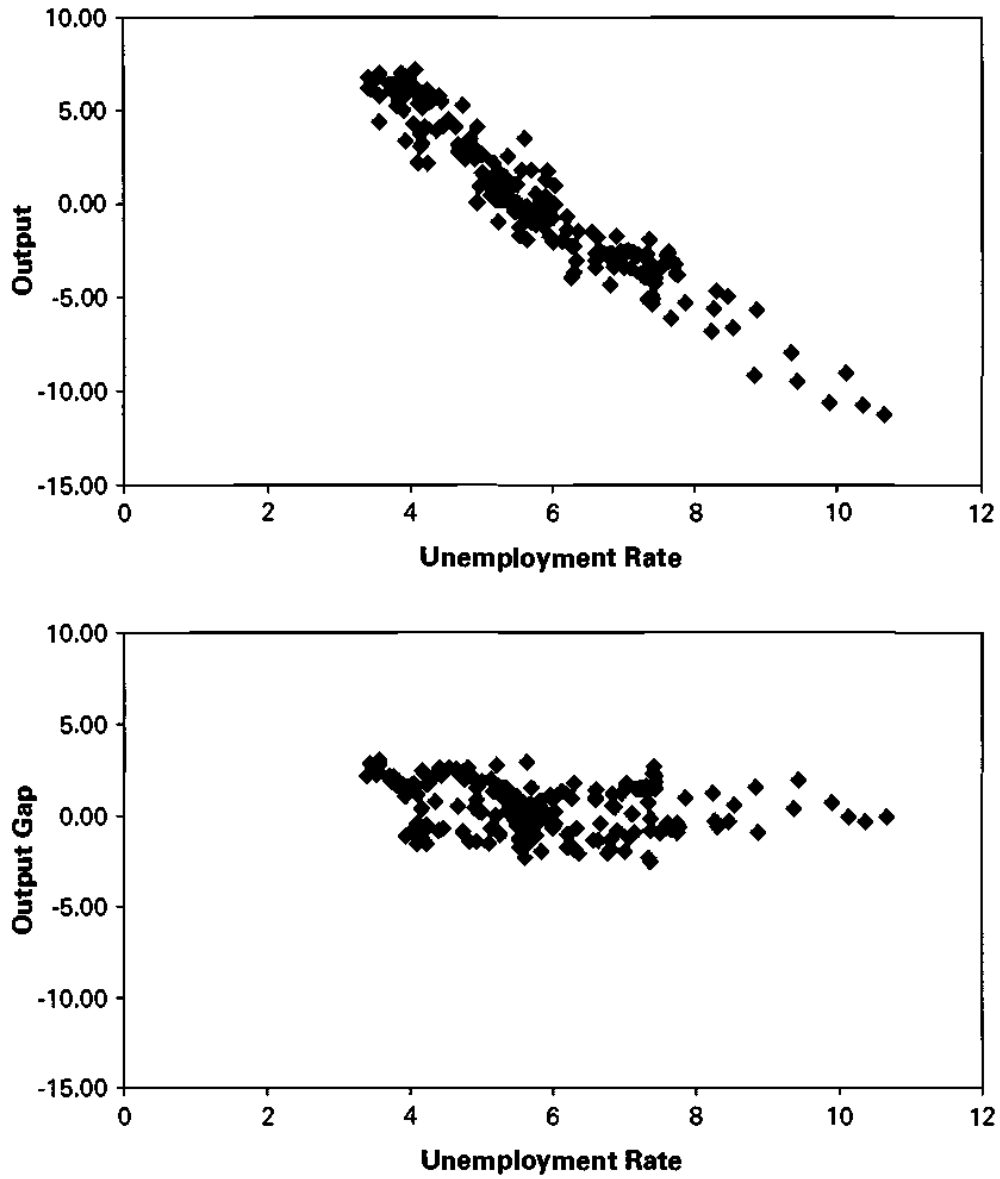


Figure 4.15

The Top Panel Shows the Standard Okun's Law Relationship Between the Unemployment Rate and Detrended Output. The Bottom Panel Shows That LOWW's Estimated Output Gap $y - y^*$ Is Unrelated to the Unemployment Rate

GDP, LOWW's y , is plotted on the vertical axis. The bottom panel shows the relationship between the unemployment rate and LOWW's estimated output gap, $y - y^*$. The model-consistent output gap is essentially unrelated to the unemployment rate. The fluctuations LOWW identify as due to nominal rigidities appear not to be associated with the fluctuations we observe in the unemployment rate, raising the question of whether movements in the rate of unemployment are in fact misleading measures of cyclical inefficiencies or whether the new Keynesian model is providing a distorted view of business cycles.

LOWW employ Bayesian methods to estimate their model; similarly, I interpret figures 4.13, 4.14, and 4.15 from a Bayesian perspective. My prior is that most short-run movements of output and the unemployment rate are not simply a reflection of fluctuations in potential output and the natural rate of unemployment. From that perspective, the failure of the new Keynesian model to uncover a relationship between unemployment and output gaps is troubling.

My hunch is that this failure can be traced to the way labor markets are treated in most new Keynesian models. These models have yet to incorporate what Hall (2005) refers to as the modern theory of unemployment, a theory based on the work of Mortensen and Pissarides (1994). In fact, new Keynesian models such as the one employed by LOWW follow RBC models in emphasizing the intensive margin (variations in hours per worker) rather than the extensive margin (variation in the number of workers employed). Exactly the opposite emphasis, on the extensive rather than the intensive margin, is likely to provide a better match with labor market experiences.

In the Mortensen-Pissarides framework, unemployed workers and firms with vacancies engage in a costly matching process. While most papers employing this framework have assumed flexible prices, a few papers have begun to explore the interactions of nominal rigidities with labor market search (Walsh 2005, Trigari 2004). Given the importance that the labor market plays in policy analysis, at least according to LOWW's findings, incorporating the modern theory of unemployment into the new Keynesian framework must be high on the research agenda.

Conclusions

I believe there is much to be learned from LOWW's paper. It provides a superb illustration of how policy analysis should be conducted, and

it provides new estimates of the costs of economic fluctuations. A key lesson to draw from the paper is that labor markets are critical for understanding the costs of macroeconomic fluctuations. The results also suggest that simple wage inflation policy rules may be close to optimal, at least within the model the authors employ, and that these rules are robust to some aspects of parameter and model uncertainty. However, the fact that the model attributes almost all output fluctuations to fluctuations in the flexible-price equilibrium level of output, even during the Volcker disinflation of the early 1980s, and the fact that the estimated output gap bears little relationship to such standard measures of the business cycles as the unemployment rate call into question the ability of the current generation of new Keynesian models to provide an adequate foundation for monetary policy analysis.

Endnotes

1. The graph of potential output for the Euro area presented in Smets and Wouter (2003) also shows a large drop in potential output from roughly 1979 to 1982, producing a positive and increasing output gap even though actual output was falling over this period.
2. The standard deviation of the policy shock is estimated to be essentially equal to 0.
3. This wedge would also be affected by time variation in taxes, another factor that may be important to incorporate.

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Discussion

Michael Woodford agreed with discussant Giorgio Primaceri that the indexation coefficient in the wage equation is endogenous rather than truly structural; in particular, the indexation coefficient is likely to change under different monetary policy regimes. Woodford suggested that the authors check the robustness of their proposed policy rule (a simple interest rate rule that responds solely to nominal wage inflation and the lagged interest rate). He speculated that their rule would be robust, based on his recent work with Marc Giannoni. This work finds that when no indexation is believed to exist, the optimal policy rule is to stabilize only nominal wage inflation, whereas when indexation is believed to exist, the optimal rule is to stabilize wage inflation minus lagged goods price inflation. Andrew Levin replied that the former case better fit their data; the authors' posterior estimates suggest that there is almost no price indexation, and thus their simple policy rule is quite robust.

Robert Hall called for improvements in the way the paper models labor markets. He considered the key limitation of the paper to be that it builds on the general equilibrium macro model of Kydland and Prescott that ignores unemployment. Hall encouraged the authors to take unemployment seriously rather than just introduce a preference disturbance to make up for its omission. He explained that this specification developed in the 1970s with a model in which workers grant multi-year call options on their services to employers, with a nominal exercise price that is set either periodically, as in Taylor, or randomly, as in Calvo. But Hall cautioned that there are no micro-foundations of this call-option view. According to Hall, work by Pissarides and others has developed a promising new view of the labor market that is truly micro-founded.

Andrew Levin responded to Hall's comment by noting that the assumption of call options is also built into price-setting: people can buy as much as they want of a given good at a given price. In reality, people search and switch suppliers or retail stores. Thus, the modern labor market seems a lot more like the modern product market, with more research needed on both markets. John Williams remarked that the authors would be interested in working a modern version of labor markets into the paper, but Noah Williams noted that at this time, there are no off-the-shelf search models appropriate for this paper.

Mark Gertler was surprised that the authors find unusually large welfare costs relative to other studies, which the authors attribute to wage dispersion. He found this puzzling because the authors do not obtain the same welfare costs for price dispersion. He speculated that different wage structures might be affecting aggregate volatility, which in turn is affecting investment and adjustment costs, which brings about the welfare effects. He advised the authors to try to sort this out.

The remaining comments referred to the model's implications for monetary policy. Frederic Mishkin asked how wage inflation could be sufficient for a policy rule, especially since monetary policymakers use information on many other variables, such as output gaps. John Williams explained that the objective function actually has three variables: the output gap, the quasi-difference in wage inflation, and the quasi-difference in price inflation. However, in this model, the weights on the output gap and price inflation are very small. It is true that optimally responding to all three variables would increase welfare, but the primary driver of welfare is wage inflation.

Ben Friedman raised two questions related to the efficacy of monetary policy. He first questioned whether the cause of the wage inflation—with a policy rule based solely on wage inflation—is important. For example, are wages rising because workers are more productive? If the cause of wage inflation is important, then Friedman speculated that the structure of the productivity disturbances in the model is crucial for the optimality of the rule. Second, he asked for an interpretation of why, as discussed Carl Walsh documented, actual output closely tracks potential output, even during the Volcker disinflation. Is monetary policy not very effective, and thus regardless of mistakes by policymakers, actual and potential output will inevitably

track one another? Or was actual output pushed away from potential output, but the genius of policymakers knew just how to conduct monetary policy to bring actual output back to potential?

And Justin Wolfers wondered about the possibility of monetary policy having long-run effects. Specifically, he noted that if the natural rate of unemployment is itself a function of policy, there could be deep welfare costs.

