Optimal Monetary Policy and Technology Shocks in the Post–War US Business Cycle

Patrick Fève

TSE (University of Toulouse–GREMAQ), IDEI,

and Banque de France (Service de Recherche en économie et finance)

Julien Matheron

Banque de France (Service de Recherche en économie et finance),

and SDFi–University of Dauphine

Jean-Guillaume Sahuc*

Banque de France (Service de Recherche en économie et finance),

and Audencia School of Management

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Abstract

This paper assesses the optimality of US monetary policy in the face of permanent technology shocks. We first identify these shocks and their effects on aggregate variables through a SVAR model by resorting to long-run restrictions. Second, we consider a standard sticky price–sticky wage model with optimal monetary policy. The DSGE model is estimated and tested on its ability to replicate the responses of key variables to technology shocks as previously identified. Our findings suggest that one cannot reject the hypothesis that US monetary policy has been optimal, either in the Volcker–Greenspan or the pre–Volcker periods.

Keywords: Technology shocks, optimal monetary policy, nominal rigidities.

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*Address: Banque de France, DGEI–DIR–RECFIN, 31 rue Croix des Petits Champs, 75049, Paris Cedex 1. Email: `jean-guillaume.sahuc@banque-france.fr`. We would like to thank F. Collard, M. Dupaigne and F. Portier for helpful discussions. The traditional disclaimer applies. The views expressed herein are those of the authors and do not necessarily reflect those of the Banque de France.

1 Introduction

In the recent empirical macroeconomic literature, technology shocks have received a considerably renewed attention. Based on structural Vector Autoregressions (SVAR) evidence, the dynamic responses of aggregate variables to such shocks has been used to develop and test small scale Dynamic Stochastic General Equilibrium (DSGE) models. In particular, the ability of New Keynesian DSGE models to reproduce these dynamics has been extensively documented (e.g. Galí, 1999, Galí and Rabanal, 2004, Ireland, 2004). In most cases, the models considered above are closed by postulating a Taylor rule that need not implement the optimal monetary policy.

Indeed, to a great extent, New Keynesian DSGE models with optimal monetary policy are often considered as theoretical curiosities, barely consistent with the observed responses to technology shocks. For example, in a simple model with sticky prices, inflation is constant under the optimal monetary policy, as shown by Galí et al. (2003). In more detailed models, featuring sticky wages as an additional source of nominal rigidity, this need not be true but, still, it is not uncomon to obtain an astonishing volatility of the nominal interest rate under such a policy (see, for example, Amato and Laubach, 2003, for a generic diagnostic). Evidently, both features share little resemblance with the data. In spite of these empirical shortcomings, assessing the optimality of monetary policy through the lenses of a DSGE model remains a highly desirable objective, be it from the stand point of central banks or from that of academic research.[1]

In this paper, we argue that a DSGE model with optimal monetary policy can be seriously taken to the data provided it embeds sufficient persistence channels, in the form of nominal and real rigidities and/or indexation schemes. While imposing the optimality hypothesis is cumbersome for several reasons (essentially, doing so requires to impose a large number of restrictions which a researcher might fear are not supported by the data), it presents a key advantage: provided the null hypothesis is supported by the data, the deep parameters can be estimated in a convergent way. More precisely, the restrictions imposed by the null hypothesis are fully exploited in the estimation and testing steps of the analysis.

We illustrate these ideas in the context of the post-War US business cycle through a limited information approach. We start our analysis by characterizing the US economy's response to technology shocks

[1]To date, the literature has addressed these issues in various ways. A first strand reveals the central banker's preferences in semi reduced-form or DSGE models (Favero and Rovelli, 2003, Dennis, 2004, 2006, and Lippi and Neri, 2006). However, this strategy remains silent on the benevolent nature of monetary policy. Another strand of the literature resorts to a counterfactual approach to revealing the social optimality of monetary policy in DSGE models (Rotemberg and Woodford, 1997, Amato and Laubach 2003, and Galí et al. 2003). This approach explicitly tackles the welfare–maximizing monetary policy but does not exploit the implied restrictions on the deep parameters in the estimation stage.

identified through a Structural Vector AutoRegression (SVAR) with long-run restrictions, à la Galí (1999) over the sample 1955(1)-2002(4). These have regained much attention in the recent literature, e.g. Galí et al. (2003), Ireland (2004). An interesting characteristic of these shocks is the trade-off they create for monetary policy. On the one hand, a positive technology shock implies an increase in output which, everything else equal, could trigger an increase in the nominal interest rate under certain circumstances. On the other hand, such a shock generates a decrease in inflation which calls for a decrease in the nominal interest rate. This tension is potentially useful for identification purposes, especially so in the context of optimal monetary policy. Following Galí et al. (2003), we split our sample into two samples, one covering the pre–Volcker period (1955(1)-1979(2)) and the other covering the Volcker–Greenspan period (1982(3)-2002(4)), thus acknowledging a priori the possible presence of a structural break in monetary policy. Overall, we find that these shocks account for a sizeable fraction of the variance of the relevant variables. Thus, if the SVAR does a good job of identifying technology shocks, these results legitimate that monetary authorities pay attention to the latter.

Has US monetary policy responded optimally to these shocks? To answer this question from a quantitative point of view, we consider a standard sticky price–sticky wage model with optimal monetary policy. The structural parameters are pinned down via a minimum distance estimation (MDE) technique à la Rotemberg and Woodford (1997). More precisely, we select the parameters values that minimize a weighted distance between the SVAR-based impulse responses to a technology shock and their theoretical counterparts.[2] Importantly, in the estimation stage, we consider two alternative specifications of monetary policy. In the first one, we stipulate exogenous policy objectives, to borrow Walsh's (2005) terminology, by specifying a loss function with unrestricted weights. In the second, we consider endogenous policy objectives, by making the loss function coincide with the appropriate welfare criterion. The limited–information econometric procedure that is implemented here allows us to formally test the optimality of monetary policy. First, we resort to the information criterion advocated by Hall et al. (2007) to select the horizon of the impulse response functions in the estimation stage. Second, we simulate a centered version of our estimated model in an attempt to compute the appropriate finite sample distribution of our overidentification test statistic.

Our main results are as follows. First, when we impose an unrestricted loss function that belongs to the exact same parametric class as that implied by a second order approximation to the correct welfare

[2]This method has its advantages and its limits. Since it concentrates exclusively on a particular observed phenomenon, it does not specify the whole model' stochastic structure (other shocks and/or mechanisms). At the same time, the method does not pretend that the DSGE model represents the true Data Generating Process of actual data but only a useful approximation for the question under study (see Driddi, Guay and Renault, 2006).

criterion, we do not reject the null hypothesis that the central banker is an optimizing agent. Formally, the model passes an overidentification test that is supportive of this hypothesis.

What more, when we further impose the restrictions on the loss function which make it coincide with the correct (approximate) welfare criterion, the null hypothesis that the central banker is benevolent is even less rejected. Finally, we obtain that an assessment of the optimality of monetary policy critically depends on the proper representation of private agents behavior. In particular, if the model is not rich enough (i.e. does not contain enough propagation channels), the optimality hypothesis is easily rejected. This suggests that the common view holding DSGE models with optimal monetary policy as theoretical curiosities hardly consistent with the data may be due more to a poor modelling of the private sector behavior than to the optimality of monetary policy.

The paper is organized as follows. In section 2, we identify the effects of technology shocks within the framework of a SVAR with long-run restrictions. Section 3 presents the model and the particular details of monetary policy. Section 4 expounds our estimation technique and explains our simulation approach to testing the model's fit. Our empirical results are discussed in section 5. The last section briefly concludes.

2 SVAR Analysis

We start our analysis by characterizing the economy's response to permanent technology shocks. This is done by estimating a SVAR in which technology shocks are identified as the only shocks that can have a permanent effect on the long-run level of productivity. The first subsection details the estimation and identification procedure and the second subsection expounds the empirical results.

2.1 Structural VAR Estimation

We use data from the Non Farm Business (NFB) sector over the sample period 1955(1)-2002(4). We define the log of average labor productivity ($\hat{a}_t$) as the difference between the log of output ($\hat{y}_t$) and the log of hours ($\hat{n}_t$). Quarterly inflation ($\hat{\pi}_t$) is the growth rate of non farm business GDP's implicit deflator. Quarterly wage inflation ($\hat{\pi}_t^w$) is the growth rate of nominal hourly compensation. Finally, the short–run nominal interest rate ($\hat{\imath}_t$) is the quarterly Fed Funds rate.[3] We follow Galí and Rabanal (2004) and extract

[3]Output and hours worked are divided by the civilian population over 16. The Fed Funds rate is expressed at a quarterly rate. The data are extracted from the Bureau of Labor Statistics website, except for the Fed Funds rate which is obtained from the FREDII database.

a linear trend from hours, to account for structural changes in the labor market that our model is not designed to reproduce (see also Galí, 2005).

It has been argued in the literature (Boivin and Giannoni, 2006, Galí et al., 2003) that US monetary policy experienced significant structural changes over the period studied in this paper. We follow Galí et al. (2003) and accordingly split our sample into two subperiods: the first one (pre-Volcker) covers 1955(1)-1979(2) and the second one (Volcker–Greenspan) covers 1982(3)-2002(4). We then estimate our SVAR on each subperiod.[4] As in Galí et al. (2003), the period 1979(3)-1982(2) is excluded, because of its idiosyncrasy (see Bernanke and Mihov, 1998).

Formally, let us consider the data vector $Z_t = (\Delta\hat{a}_t, \hat{n}_t, \hat{\pi}_t, \hat{\pi}_t^w, \hat{\imath}_t)'$. We estimate the canonical VAR

$$Z_t = A_1 Z_{t-1} + \cdots + A_\ell Z_{t-\ell} + u_t, \;\; \mathrm{E}\{u_t u_t'\} = \Sigma,$$

where ℓ is the maximal lag determined by standard information criteria. Let us define $B(L) = (I_m - A_1 L - \cdots - A_\ell L^\ell)^{-1}$, where I_m is the identity matrix and m is the number of variables in Z_t. Now, we assume that the canonical innovations are linear combinations of the structural shocks η_t, i.e. $u_t = S\eta_t$, for some non singular matrix S. As usual, we impose an orthogonality assumption on the structural shocks, which combined with a scale normalization implies $\mathrm{E}\{\eta_t \eta_t'\} = I_m$.

Since we are only identifying a single shock, we need not impose a complete set of restrictions on the matrix S. Let us define $C(L) = B(L)S$. Given the ordering of Z_t, we simply require that $C(1)$ be lower triangular, so that only technology shocks can affect the long-run level of labor productivity. This amounts to imposing that $C(1)$ be the Cholesky factor of $B(1)\Sigma B(1)'$. Given consistent estimates of $B(1)$ and Σ, we easily obtain an estimate for $C(1)$. Retrieving S is then a simple task using the formula $S = B(1)^{-1}C(1)$.

2.2 Results

The dynamics of output, hours, inflation, wage inflation, and the nominal interest rate in response to a positive technology shock are reported on figure 1 for the pre–Volcker period and on figure 2 for the Volcker–Greenspan period. In each case, the grey areas represent the 95% asymptotic confidence intervals, which we computed numerically. Notice that output is simply deduced from the combined dynamics of average labor productivity and hours. The selected lag is $\ell = 3$ and $\ell = 4$ in the first and second subsample, respectively.

[4] In each case, only observations from the relevant subsample are used, especially so for the initial lags.

Over the first subperiod (see figure 1), output slightly declines on impact. However, the very short–run responses are not statistically significant. After a few quarters, output starts to monotonically and significantly reach its new steady state level. These responses are similar to what Galí et al. (2003) obtain. Hours follow a U-shaped pattern in the short–run. They start by declining in the first few periods and then eventually overshoot their long–run level which they asymptotically reach from above. These results are in the line of Galí (1999), Galí and Rabanal (2004), and Galí et al. (2003). Notice additionally that the response of hours is estimated precisely, with a narrow confidence interval at short horizons. Inflation initially decreases, though not statistically significantly, and then gradually rises toward its steady state value. The transitional path is significant after a few quarters, and exhibits a substantial amount of persistence. Wage inflation exhibits a similar pattern as inflation. Finally, the nominal interest rate follows an inverted hump shape. The latter is suggestive of an accommodative behavior of monetary authorities over our sample which seem to have reacted to technology shocks by a protracted decline in the nominal interest rate. Interestingly, the patterns of the responses of output and inflation are consistent with what one could expect from a technology shock.

Over the second subperiod (see figure 2), we generically obtain responses that exhibit much smaller amplitude and persistence. In particular, virtually all the inverted hump dynamics have disappeared. Output now rises on impact, and rapidly reaches its new steady state level. The impact response of hours is still negative, but is much less pronounced than in the pre–Volcker period. In contrast, the impact response of inflation is similar to what obtained in the previous subperiod, but now, inflation reaches back its initial level much faster. This is suggestive of a significant change in inflation persistence. Finally, it should also be noticed that over this subperiod, we obtain very large confidence intervals. When using these moments to estimate our DSGE model, we try to explicitly address this issue.

Before continuing, we must address an important quantitative issue: Do technology shocks contribute much to fluctuations in our SVAR? This issue is of course important, because, ultimately, if these shocks account for a tiny portion of fluctuations, it does not matter much whether monetary authorities correctly reacted to them. To answer this question, we compute the percentage of variance of the k step ahead forecast error in the elements of Z_t due to technology shocks. These are reported in tables 1 and 2, for the first and second subsamples, respectively, at forecast horizons of 0, 4, 8, and 20. The table also contains the associated 90% confidence interval. These confidence intervals are based on 1000 bootstrap replications of the estimated SVAR.

Over the first subsample, we obtain that technology shocks account for roughly 20% of the forecast error variance of productivity growth. These shocks account for more than 30% of the forecast error variance of hours. Such a conclusion contrasts with bivariate results reported by Galí and Rabanal (2004) but seems more in accordance with what Christiano et al. (2004) find. Technology shocks account for more than 50% of the forecast error variance of inflation and the Fed funds at forecasts horizons of 4, 8, and 20 quarters. Finally, their contribution to the forecast error of wage inflation is substantial, comprised between 33% and 44% at forecast horizons of 4, 8, and 20 quarters.

Over the second subperiod, things appear to be somewhat different. Technology shocks now account for slightly more than 45% of the forecast error variance of productivity growth and for roughly 40% of the forecast error variance of inflation. They do not contribute much to the fluctuations of hours (between 1% and 8%), and account only for roughly 4% and 6% of the forecast error variances of the Fed Funds rate and wage inflation, respectively.

Overall, these results suggest that technology shocks account for a sizable portion of fluctuations in the variables of interest, especially so when it comes to the business cycle component of output and inflation. This exercise suggests that it is legitimate that US monetary authorities pay attention to technology shocks given their relative importance over the business cycle.

3 Optimal Monetary Policy in a Sticky Price – Sticky Wage Model

In this section, we briefly describe a standard sticky price–sticky wage model, similar in spirit to those of Giannoni and Woodford (2005) and Galí and Rabanal (2004). We then go on to expound the optimal monetary policy. Model details are provided in appendix A.

3.1 Summary of the Model

To begin with, we assume that the only shock present in the model is a permanent technology shock z_t, which, as in Galí et al. (2003) evolves according to

$$z_t = \log(g) + z_{t-1} + \varphi_t,$$

$$\varphi_t = \rho\varphi_{t-1} + \epsilon_t,$$

where $g > 1$, $\rho \in (-1, 1)$, and $\epsilon_t \sim \mathrm{iid}(0, \sigma_\epsilon^2)$.

The first model equation is the celebrated New Keynesian Phillips curve:

$$\hat{\pi}_t - \gamma_p\hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1} - \gamma_p\hat{\pi}_t\} + \frac{(1-\beta\alpha_p)(1-\alpha_p)}{\alpha_p[(1-s_m)^{-1} + \omega_p\theta_p]}(\hat{w}_t + \omega_p\hat{y}_t), \tag{1}$$

where E_t is the expectation operator, conditional on information available as of time t, $\hat{\pi}_t$ is the logdeviation of inflation, $\hat{y}_t$ and $\hat{w}_t$ are the logdeviations of detrended output and real wage, respectively.[5] The parameter $\beta \in (0,1)$ denotes the subjective discount factor, $\gamma_p \in [0,1]$ is the degree of indexation of prices to the most recently available inflation measure, $\alpha_p \in (0,1)$ is the degree of nominal price rigidity, $s_m \in [0,1)$ denotes the share of material goods in gross output, θ_p is the price elasticity of demand, and ω_p is the real marginal cost elasticity with respect to the level of production.

The second set of equations defines the IS curve

$$\hat{y}_t = \eta\hat{y}_{t-1} + \beta\eta\mathrm{E}_t\{\hat{y}_{t+1}\} - (1-(1+\beta)\eta)\hat{\lambda}_t + \beta\eta\mathrm{E}_t\{\varphi_{t+1}\} - \eta\varphi_t,$$

$$\hat{\lambda}_t = \hat{\imath}_t + \mathrm{E}_t\{\hat{\lambda}_{t+1} - \hat{\pi}_{t+1} + \varphi_{t+1}\}.$$

where $\hat{\imath}_t$ is the logdeviation of the gross nominal interest rate, $\hat{\lambda}_t$ is that of the detrended marginal utility of wealth $\lambda_t \mathrm{e}^{z_t}$. We define $\bar{b} \equiv b/g$, where b is the degree of habit formation, and $\eta \equiv \bar{b}/(1+\beta\bar{b}^2)$.

The wage setting equation is given by

$$\hat{\pi}^w_t - \gamma_w\hat{\pi}_{t-1} = \beta\mathrm{E}_t\{\hat{\pi}^w_{t+1} - \gamma_w\hat{\pi}_t\} + \frac{(1-\alpha_w)(1-\beta\alpha_w)}{\alpha_w(1+\omega_w\theta_w)}(\omega_w\phi\hat{y}_t - \hat{\lambda}_t - \hat{w}_t), \tag{2}$$

where $\hat{\pi}^w_t$ is the logdeviation of gross wage inflation, $\gamma_w \in [0,1]$ is the degree of indexation of wages to the most recently available inflation measure, $\alpha_w \in (0,1)$ is the degree of nominal wage rigidity, θ_w is the wage elasticity of labor demand, ω_w is elasticity of the marginal disutility of labor, and ϕ is the inverse elasticity of output with respect to labor input. Wage inflation and inflation are linked together through the relation

$$\hat{\pi}^w_t = \hat{\pi}_t + \hat{w}_t - \hat{w}_{t-1} + \varphi_t.$$

3.2 Monetary Policy Specification

We assume that monetary authorities set their policy so as to minimize a quadratic loss function of the form

$$\mathscr{L}_0 = \mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \{\lambda_p(\hat{\pi}_t - \gamma_p\hat{\pi}_{t-1})^2 + \lambda_w(\hat{\pi}^w_t - \gamma_w\hat{\pi}_{t-1})^2 + \lambda_x(\hat{x}_t - \delta\hat{x}_{t-1})^2\}, \tag{3}$$

where the output gap $\hat{x}_t$ is defined as $\hat{y}_t - \hat{y}^n_t$, $\hat{y}^n_t$ being the logdeviation of the level of detrended output that would have prevailed absent nominal rigidities. In turn, the natural rate of output ($\hat{y}^n_t$) obeys

$$[1 + (1-\eta(1+\beta))\omega]\hat{y}^n_t = \beta\eta\mathrm{E}_t\{\hat{y}^n_{t+1}\} + \eta\hat{y}^n_{t-1} + \beta\eta\mathrm{E}_t\{\varphi_{t+1}\} - \eta\varphi_t.$$

[5] Given the presence of a stochastic trend in z_t, the above model leads to a deterministic steady state in which consumption, output, and real wages grow at the same rate while labor is constant through time. To obtain a bounded steady state, trending variables dated t are divided through by e^{z_t}.

where $\omega \equiv \omega_w \phi + \omega_p$. We also impose the normalization $\lambda_p + \lambda_w = 1$. The minimization of eq. (3) is subject to the contraints

$$\hat{x}_t = \eta \hat{x}_{t-1} + \beta\eta \mathrm{E}_t\{\hat{x}_{t+1}\} - (1-(1+\beta)\eta)(\hat{\lambda}_t - \hat{\lambda}_t^n), \tag{4}$$

$$\hat{\pi}_t - \gamma_p \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1} - \gamma_p \hat{\pi}_t\} + \varpi \xi_p[(\hat{w}_t - \hat{w}_t^n) + \omega_p \hat{x}_t], \tag{5}$$

$$\hat{\pi}_t^w - \gamma_w \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1}^w - \gamma_w \hat{\pi}_t\} + \xi_w[\omega_w \phi \hat{x}_t - (\hat{\lambda}_t - \hat{\lambda}_t^n) - (\hat{w}_t - \hat{w}_t^n)], \tag{6}$$

$$\hat{\pi}_t^w = \hat{\pi}_t + \hat{w}_t - \hat{w}_{t-1} + \varphi_t, \tag{7}$$

where $\hat{w}_t^n$ and $\hat{\lambda}_t^n$ are stochastic variables beyond the control of monetary authorities,[6] and where we defined the composite parameters

$$\varpi = \frac{(1+\omega_p\theta_p)}{(1-s_m)^{-1} + \omega_p\theta_p}.$$

$$\xi_w = \frac{(1-\alpha_w)(1-\beta\alpha_w)}{(1+\theta_w\omega_w)\alpha_w}, \qquad \xi_p = \frac{(1-\alpha_p)(1-\beta\alpha_p)}{(1+\omega_p\theta_p)\alpha_p}.$$

Notice that the processes governing $\hat{y}_t^n$, $\hat{w}_t^n$, and $\hat{\lambda}_t^n$ are taken into account in the monetary authorities problem. The above program results in a system of first order conditions and constraints, which we solve with the Anderson and Moore (1985) algorithm. Here, we focus on the full–commitment monetary policy.

In the first model version, we follow Dennis (2004) and Lippi and Neri (2006) and assume that the weights λ_p, λ_w, λ_x are exogenously given, thus reflecting the particular preferences of the central banker. In this case, the above loss function need not coincide with the second order approximation to the correct social welfare criterion. In other words, we assume that monetary authorities are not necessarily benevolent from a social point of view but instead have specific preferences which they maximize subject to constraints imposed by the private sector behavior. We will refer to this particular model as the model with *exogenous objectives optimal monetary policy*. Our objective, as in Dennis (2004), is to estimate these weights in an attempt to reveal the central banker's preferences together with the parameters governing the private sector's dynamics.

In the second model version, we assume that monetary authorities act as a benevolent social planner whose objective is to maximize the appropriate welfare objective. We will refer to this alternative model as the one with *endogenous objectives optimal monetary policy*. We follow Woodford (2003) and formulate the (approximate) linear-quadratic problem associated with welfare maximization. Standard yet tedious

[6]These variables are the stochastically detrended real wage rate Lagrange multiplier on the household's budget constraint, respectively, both taken in logdeviation from their steady state values, absent nominal rigidities, i.e. under full price flexibility. Formally $\hat{\lambda}_t^n = \omega \hat{y}_t^n$ and $\hat{w}_t^n = -\omega_p \hat{y}_t^n$.

calculations yield an approximate utility-based loss function of the exact same form as that postulated in eq. (3). Under this assumption, it can be shown that the following restrictions on the weights must hold

$$\lambda_p = \frac{\theta_p \xi_p^{-1}}{\theta_p \xi_p^{-1} + \theta_w \phi^{-1} \xi_w^{-1}}, \quad \lambda_w = \frac{\theta_w \phi^{-1} \xi_w^{-1}}{\theta_p \xi_p^{-1} + \theta_w \phi^{-1} \xi_w^{-1}}, \quad \lambda_x = \frac{[(1-\bar{b})(1-\beta\bar{b})]^{-1} \varkappa}{\theta_p \xi_p^{-1} + \theta_w \phi^{-1} \xi_w^{-1}}. \tag{8}$$

It is easy to verify that $\lambda_p + \lambda_w = 1$. In addition, $\varkappa$ and δ obey the restrictions

$$\delta = \bar{b}/\varkappa, \quad \varkappa = \frac{\beta}{2}\left(\chi + \sqrt{\chi^2 - 4\bar{b}^2\beta^{-1}}\right), \tag{9}$$

where

$$\chi = \frac{\omega(1-\bar{b})(1-\beta\bar{b}) + (1+\beta\bar{b}^2)}{\beta}.$$

Once again, the monetary authorities minimize (3) where the weights are given by (8)-(9), subject to the constraints imposed by the private sector behavior, namely eqs. (4)-(7).

Notice that we restrict the *exogenous objectives optimal monetary policy* to belong to the exact same class as that with *endogenous objectives*, i.e. that consisting in maximizing social welfare. In doing so, we are in a position to formally test whether the central banker's preferences so defined coincide with the appropriate welfare criterion.

4 Calibration, Estimation, and Testing

In this section, we describe the model calibration and the minimum distance estimation and testing technique.

4.1 Structural Parameters Calibration

We partition the model parameters into two groups. The first one collects the parameters which we calibrate prior to estimation. These include parameters that can be given a value based on great ratios, as well as parameters that cannot be separately identified. Let $\xi = (\beta, \phi, \omega_p, s_m, \theta_w, \theta_p)'$ denote the vector of calibrated parameters. The calibration is summarized in table 3. The first four parameters can be calibrated to mimic "great ratios", and the last two raise specific problems.

We first set $\beta = 0.99$ as is conventional in the literature. The average (gross) growth rate of output is $g = 1.005$. Assuming that the production function is Cobb-Douglas, i.e. $y = n^{1/\phi}$, we set $\phi = 1/0.64$, implying a labor share of about 64%, as in the data. Notice that we implicitly assume that profits are redistributed proportionately to factors income, so that $1/\phi$ is indeed the steady state labor share, as in

Chari et al. (2000). Given that the production function is Cobb-Douglas, the definition of ω_p implies $\omega_p = \phi - 1$. Following Basu (1995), we set $s_m = 0.5$, implying that the share of material goods in gross output is 50%.

Finally, notice that θ_p and θ_w cannot be identified as long as we want to estimate the probabilities of price and wage fixity, namely α_p and α_w. The reason why is simple: α_p and θ_p (resp. α_w and θ_w) always appear together, either in eq. (1) (resp. eq. (2)) or in the weights definitions (8). Fundamentally, the data allow us only to estimate the partial elasticity of inflation (resp. wage inflation) with respect to the real marginal cost (resp. labor disutility wedge), and many combinations of α_p and θ_p (resp. α_w and θ_w) are compatible with a given estimate of this partial elasticity, as explained by Rotemberg and Woodford (1997), Amato and Laubach (2003), and Eichenbaum and Fisher (2004). Thus, α_p and θ_p (resp. α_w and θ_w) are not separately identified. Here, we chose to estimate α_p and α_w, which requires that θ_p and θ_w be calibrated prior to estimation. We set $\theta_p = 11$, so that the long-run markup charged by intermediate goods producers amounts to 10%, consistent with the values reported by Basu and Fernald (1997). Finally, we set $\theta_w = 21$, as in Christiano et al. (2005).

4.2 Structural Parameters Estimation and Testing

Recall that we defined the data vector $Z_t = (\Delta\hat{a}_t, \hat{n}_t, \hat{\pi}_t, \hat{\pi}_t^w, \hat{\imath}_t)'$. Now, for $k \geq 0$, let us define the vector collecting the dynamic responses of the components of Z_{t+k} to a technology shock η_t^s

$$\zeta_k = \frac{\partial Z_{t+k}}{\partial \eta_t^s}.$$

Formally, ζ_k is the first column of C_k, where C_k is the kth coefficient of $C(L)$. In the sequel, we define θ as

$$\theta = \text{vec}([\zeta_0, \zeta_1, \ldots, \zeta_k]'),$$

where the vec$(\cdot)$ operator stacks the columns of a matrix. The vector θ regroups the set of moments that we ask our DSGE model to match. It is worth noting that the moments selection is based on Impulse Response Functions (IRFs) of variables in Z_t from impact to horizon $k \geq 0$. In the vector θ, we replace the response of $\Delta\hat{a}_t$ with that of logged output, which we obtain by adding the responses of hours to the cumulated response of $\Delta\hat{a}_t$. We regroup the model's structural coefficients which we seek to estimate in the vector ψ.

In the model with *exogenous objectives optimal monetary policy*, we have

$$\psi = (\lambda_w, \lambda_x, \delta, b, \omega_w, \gamma_w, \gamma_p, \alpha_w, \alpha_p, \rho, \sigma_\epsilon)'.$$

Notice that λ_p does not enter ψ since we use the constraint $\lambda_p + \lambda_w = 1$.

In the model with *endogenous objectives optimal monetary policy*, the first three parameters are function of the remaining parameters. Accordingly, in this case, we have

$$\psi = (b, \omega_w, \gamma_w, \gamma_p, \alpha_w, \alpha_p, \rho, \sigma_\epsilon)'.$$

Finally, $h(\psi)$ denotes the theoretical counterpart of θ and we define $g(\psi, \theta) \equiv h(\psi) - \theta$.[7] Our structural parameters estimates are defined by the relation

$$\hat{\psi}_T = \arg\min_{\psi \in \Psi} J(\psi), \quad J(\psi) \equiv [g(\psi, \theta)]' V [g(\psi, \theta)],$$

where Ψ is the set of admissible values for the parameters ψ, T is the sample size, and V is a weighting matrix.[8]

Up to now, the horizon k of IRFs has been taken as given. This is an important issue because our results potentially depend heavily on the horizon k selected for the impulse response fonctions. Hall et al. (2007) address this problem and propose a new information criterion for selecting the appropriate impulse response functions horizon in SVAR–based minimum distance estimation. As argued by Hall et al. (2007), a key advantage of their procedure is that it allows us to select the most informative horizon, therefore reducing the bias and improving the efficiency of the parameters estimates. Formally, the selected horizon $\hat{k}_T$ minimizes the following criterion

$$\log(\det(\hat{\Sigma}_{\psi,T}(k))) + k \frac{\log(\sqrt{T})}{\sqrt{T}},$$

where $\hat{\Sigma}_{\psi,T}(k)$ is the estimated covariance matrix of the structural parameters ψ, which of course depend on the matrix V and on k. Interestingly, this procedure is valid irrespective of the particular choice of weighting matrix.

Ideally, the weighting matrix V should be equal to the inverse of the covariance matrix of the IRFs θ. In practice however, this choice is not feasible. Indeed, θ contains, at most, as many free elements as the vector of VAR parameters. In our empirical applications, θ can be larger than the latter (this is true only for the first subsample). This is so because what turns out to be important for estimating the economic model is the persistence embedded in the IRFs, which leads us to include a large number of moments in θ. In addition, our own experimentation reveals that the rank of the covariance matrix of θ is more closely

[7] Though this is not directly reflected in our notations, h also depends on ξ.

[8] This estimation method relates to that of Amato and Laubach (2003), Boivin and Giannoni (2006), Christiano et al. (2005), Giannoni and Woodford (2005), and Rotemberg and Woodford (1997, 1999).

related to the number of variables in our VAR than to the number of free parameters in the latter. This is even more stringent than the previous limitations, because it allows us to focus only on a very small number of IRFs.

To eschew this econometric difficulty, the weighting matrix V is set equal to a matrix containing the inverse of the asymptotic variances of the elements of θ along its diagonal and zeros elsewhere. As suggested by Christiano et al. (2005), this choice of weighting matrix ensures that ψ is selected so that the model-based IRFs lie as much as possible in the confidence interval of the SVAR-based IRFs. While this approach allows us to sidestep the stochastic singularity issues discussed above, this entails a cost. Since V is not the optimal weighting matrix, we should not expect the statistic $J(\hat{\psi}_T)$ to be asymptotically distributed as a χ^2 with $\dim(\theta) - \dim(\psi)$ degrees of freedom under the null hypothesis that the model is true. However, we are utlimately interested in testing the fit of our model. Thus it is important that we know how the statistic $J(\hat{\psi}_T)$ is distributed. To do so, we adapt the bootstrap techniques advocated by Hall and Horowitz (1996) to our particular framework.

We start by bootstrapping the relevant IRFs from the estimated SVAR model. For each replication, we reestimate the two DSGE model versions from a centered version of the bootstrap analog of the moments conditions for each subsample. As a result, for each replication, we obtain the J statistic as well as bootstrap analog of t-statistics of parameter significance. Repeating this a large number of times, we obtain populations of statistics from which we can compute critical and P-values. The P-values associated with the J test of overidentification can be used to assess the model's fit.

5 Assessing the Monetary Policy Performance

The results are reported in tables 4 and 5, for the first and second subsamples, respectively. In each table, the first column of results pertains to the model with *exogenous objectives optimal monetary policy* and the second column corresponds to the model with *endogenous objectives optimal monetary policy*. The tables report the parameters estimates together with P-values of their t-statistic, in brackets. The tables also include the estimated or implied monetary policy parameters, with the associated P-values. Finally, they report the statistic $J(\hat{\psi}_T)$ and the associated P-value. These P-values are based on 100 bootstrap replications and are obtained from a Gaussian kernel fitted to the population of relevant statistics.[9]

[9]For a given confidence level, say 5%, a parameter is found to be significantly different from zero when the reported P-value is below 5%. Similarly the model passes the overidentification test provided that the P-value is higher than 5%.

5.1 Practical Issues

In the process of estimating the model, we encountered four problems. First in the *exogenous objectives optimal policy* case, we encountered numerical precision problems that undermine our horizon selection procedure. To settle this question, we adopt in this case the same horizon as that selected by our criterion in the *endogenous objectives optimal policy* case. Given our emphasis on optimal monetary policy, this is a minor restriction. In the pre-Volcker sample, we select $\hat{k}_T = 12$ and in the Volcker–Greenspan sample, we obtain $\hat{k}_T = 14$. Second, the parameter γ_w invariably converges to its upper bound of unity. This is reminiscent of results found elsewhere in the literature (e.g. Giannoni and Woodford, 2005, Christiano et al., 2005). To avoid possible numerical problems raised by this, we subsequently impose the constraint $\gamma_w = 1$. Third, we encountered several convergence problems when δ is freely estimated (i.e. in the model with *exogenous objectives optimal monetary policy*). In an attempt to avoid these problems, we imposed the same relation between b and δ as in eq. (9). Notice that for the purpose of the present paper, this parameter is not central for characterizing the central banker's preferences. What turns out to be really essential are the weights λ's in the loss function eq. (3). Finally, in some instances, the parameter ω_w turned out to be difficult to estimate. For the sake of comparability, we imposed the same value for ω_w as that obtained in the first subsample with *endogenous objectives optimal monetary policy*. The remaining parameters are freely estimated.

Before proceeding, we must address an important issue for our purpose: Does the SVAR really identify technology shock? This question is legitimate in light of a recent set of papers challenging the ability of SVAR models to properly identify structural shocks, e.g. Chari et al. (2005) and Erceg et al. (2005). Thus, one may wonder whether ours does a good job of identifying technology shocks. The proposed DSGE model offers a natural environment where to investigate this question quantitatively. To do so, we follow Altig et al. (2005) and implement the following experiment:

1. We start by drawing technology shocks from a normal distribution and feed them into our DSGE model. In this first step, we use the estimated values of ψ to simulate paths for $\{Z_t\}_{t=0}^{T}$. Let $Z_t^{\mathrm{m}}(i)$, $t = 1, \ldots, T$, denote the ith simulated path of Z_t.

2. We draw shocks from the SVAR residuals, eliminate the SVAR-based technology shocks, and compute a sample path for Z_t according to the SVAR parameters. Let $Z_t^{\mathrm{v}}(i)$, $t = 1, ..., T$, denote the ith simulated path from this second step.

3. We form $Z_t(i) = Z_t^{\mathrm{m}}(i) + Z_t^{\mathrm{v}}(i)$, and estimate the same SVAR as that described in section 2 on $\{Z_t(i)\}_{t=1}^{T}$. The IRFs of $Z_t(i)$ to a technology shock are then computed and stored.

In step 1, we also discard 200 initial points so as to make sure that the simulation does not depend on initial conditions. Steps 1 to 3 are repeated 1000 times ($i = 1, \ldots, 1000$), thus generating a population of IRFs. We keep the 25th and 975th simulated IRFs to form a 95% confidence interval.

The results of these simulation experiments are reported on figure 5 for the pre–Volcker period. In each panel, the solid line corresponds to the IRF obtained under the DSGE model with *endogenous objectives optimal monetary policy* while the dashed line is the SVAR-based median IRF obtained from the simulation. The grey area is the 95% confidence interval. The figure clearly shows that the empirical SVAR model manages to identify the true (i.e. the DSGE model) technology shocks, in spite of a small upper bias. More precisely, the median responses have the same signs and shapes as the true responses. These conclusions are consistent with simulation results reported by Erceg et al. (2005). Incidentally, this reinforces our confidence in the procedure used to identify technology shocks. Thus, if the data were indeed generated by the DSGE model, then the simulation clearly shows that a SVAR model similar to that estimated in section 2 would correctly identify the "true" technology shocks.[10]

5.2 The Pre–Volcker Period

We first consider the model version where the weights in the loss function are treated as free parameters. Recall that we referred to this specification as the model with *exogenous objectives optimal monetary policy*. To begin with, notice that the estimated statistic $J(\hat{\psi}_T)$ is equal to 28.85 with an associated P-value of 15.22%. Thus, the model with *exogenous objectives optimal monetary policy* is supported by the data according to our overidentification test. Figure 3 visually confirms this test and reports the IRFs obtained under the SVAR model (solid lines) and under the model with *exogenous objectives optimal monetary policy* (circles). The grey area represents the 95% asymptotic confidence interval. As the figure makes clear, the model does a pretty good job of replicating the empirical responses of output, hours, inflation, wage inflation, and the nominal interest rate to a permanent technology shock. First, all theoretical responses are well within the SVAR–based confidence bands. Second, the model is able to capture the short-run behavior of the nominal interest rate, even in the absence of a desire to smooth the nominal interest rate in the loss function. The latter result runs counter conventional wisdom which holds optimal monetary policy as generating too much nominal interest rate volatility (Amato and Laubach, 2003, Rotemberg and Woodford, 1997). Thus a central banker concerned only with fluctuations

[10] We obtain comparable results with *exogenous objectives optimal monetary policy*. We also repeated this experiment with the Volcker–Greenspan sample, but the confidence intervals of the estimated responses are so large that this exercise is not informative.

in inflation, wage inflation and in the output gap is not incompatible with the smooth observed response of the nominal interest rate. Obviously, our estimation procedure selects the parameters that guarantee a good fit on this dimension. At the same time, if the model were unable to reproduce the nominal interest rate response, it would be rejected by the overidentification test. This illustrates that (i) our DSGE framework embeds sufficient inertial forces to match this response and (ii) features a trade-off between stabilizing inflation and output, as explained by Erceg et al. (2000).

Our estimation procedure delivers the following parameter estimates. The estimated habit persistence in consumption is roughly equal to 0.90. The parameter is very precisely estimated, since it is significantly different from zero at the one percent level. Our finding is an additional piece of evidence in favor of a substantial degree of intertemporal complementarities in consumption decisions. We obtain a moderate degree of price indexation, with $\gamma_p = 0.58$. The latter is significant at conventional levels. This implies that current prices roughly incorporate 60% of past inflation. Notice that our estimate is substantially lower than previously reported in the literature (e.g. Boivin and Giannoni, 2006, Giannoni and Woodford, 2005). The degree of nominal price rigidity α_p is not estimated precisely, with an associated P-value of 18%. This value implies an average duration of no price reoptimization of slightly more than three quarters, in between those reported by Bils and Klenow (2004) and Nakamura and Steinsson (2007). The probability of not reoptimizing nominal wages α_w is estimated precisely. The estimate implies an average non-reoptimization duration of 9 quarters. This value is higher than previous estimated or calibrated values (e.g. Amato and Laubach, 2003, Christiano et al., 2005). Finally, the growth rate of technology shock is not found to be persistent ($\rho = 0.07$, not significantly different from zero), with a standard error roughly equal 0.6, close to standard estimates in the literature.

As in Dennis (2004, 2006), our model with *exogenous objectives optimal monetary policy* allows us to reveal the US central banker's preferences. Two striking results emerge from our estimation. First, US monetary authorities seem to essentially pay attention to wage inflation, since $\lambda_w = 0.94$, with an associated P-value of 0.56%. Thus, within the confines of this model, the data support a representation of monetary policy that clearly favors wage inflation stabilization. Second, we obtain that λ_x is essentially zero. Thus, no weight at all is given to stabilizing the output gap. Taken together, these results run counter the conventional view that pre-Volcker monetary policy paid too much attention to real activity and not enough to nominal fluctuations (e.g. Clarida et al., 2000).

Overall, the data are supportive of the optimality hypothesis, at least in the sense that one cannot reject the null hypothesis that a model in which the central banker minimizes a specific loss function appropriately reproduces the actual economy's dynamics triggered by a permanent technology shock.

However, this is not sufficient to conclude that actual monetary policy was optimal in a welfare-maximizing sense in response to these particular shocks. Indeed, for the moment we do not know whether the estimated λ's coincide with the values that would otherwise have been reached in an estimated model with a loss function corresponding to a second order approximation to the correct welfare criterion. In other words, it remains to be seen whether the data are also supportive of a benevolent view of policy. The second column of results from table 4 provides an answer to this question.

One can see from table 4 that the model with *endogenous objectives optimal monetary policy* fares particularly well. The statistic $J(\hat{\psi}_T)$ is slightly higher than its unconstrained counterpart, has a higher P-value, and the estimated parameters are very similar to what obtained before, be it for the deep parameters or the implied policy parameters. Notice however that in almost all instances, our estimates are more precise. This is important because it allows us to provide a sharper assessment of the policy objective. In addition, inspecting the IRFs in figure 3 reveals that the *endogenous objectives optimal monetary policy* (dashed lines) induces dynamic responses that almost coincide with those of the model with *exogenous objectives optimal monetary policy* (circles). This is of course a direct consequence of the great similitude between the estimated structural parameters in both model versions.

Our findings are in contradiction with the results obtained by Galí et al. (2003). These authors conclude that monetary policy was not optimal (in a welfare-maximizing sense) in the pre–Volcker period. They base this conclusion on a comparison between the IRFs obtained from a similar SVAR model as ours and the responses implied by a calibrated sticky price model with weak internal persistence channels. In this case, the optimality hypothesis is rejected essentially for two reasons: (i) since they only consider sticky prices, the *endogenous objectives optimal monetary policy* implies a zero response of inflation, which is obviously at odds with the data; (ii) under this policy, the nominal interest rate is too volatile compared with the data. As explained above, in our theoretical setup, none of these defficiencies is present.

This leads us to argue that one does not test for the optimality hypothesis *per se* but within a particular model. If the latter poorly fits the data, one should not be surprised to reject the optimality hypothesis. To illustrate this, first, consider the implication of shutting down price and wage indexation, i.e. setting $\gamma_p = \gamma_w = 0$. Since, in our case, a high γ_w is essential to fit the data, the model is strongly rejected by the over-identification test. The model is not supported by the data because it drammatically fails to mimic the dynamics of inflation and wage inflation. This would lead us to reject the optimality hypothesis in a sticky price–sticky wage model with no price and wage indexation. Second, consider the implications of shutting down the habit persistence in consumption, $b = 0$. So as to hamper the model, we also set $\rho = 0$. The latter constraint prevents the estimation procedure to select a higher degree of serial correlation in the exogenous shock to account for aggregate persistence. Once again, the model is rejected by the data. This is a direct consequence of the model's inability (in this particular configuration) to match the gradual adjustments of output and the dynamics of hours. Under this configuration, output immediately shifts up while hours are almost unresponsive, pretty much as in a flexible price model. These results suggest that a proper characterization of optimal monetary policy dramatically hinges on the persistence channels embedded in the specification of the private sector's behavior.

To sum up, these exercises suggest that, from a quantitative point of view, imposing the restriction that the central banker is a benevolent social planner provides higher confidence in the estimated model and more precise parameters estimates.

5.3 Volcker–Greenspan Period

We now turn our attention to the second subsample. The estimation results are reported in table 5. From a general point of view, our conclusions are unchanged when it comes to the model's fit. The two model versions satisfactorily match the data, since the P-values associated with the $J(\hat{\psi}_T)$ statistics are large. These results are in the line of those reported by Galí et al. (2003) when it comes to the Volcker–Greenspan period.

We obtain two broad conclusions in either model versions. First of all, the persistence channels have been drammatically reduced. Now, the habit parameter b is found to be much lower (less than 0.5) and the degree of price indexation is either almost zero or statistically insignificant. This suggests that two important sources of stickiness have been shut down in the recent period. Second, we obtain a standard error for the technology shock half as small as that obtained in the pre-Volcker sample. This is reminiscent of the so-called "Great Moderation" that our model allows us to interpret in terms of structural parameters. This moderation can originate from (i) a reduction in the volatility of shocks, (ii) changes in the private sector behavior, or (iii) an improvement in policy. Our DSGE model with optimal monetary policy suggests that, when it comes to technology shocks, this moderation in aggregate volatility is essentially due to (i) and (ii). In particular, as shown in figure 4, the quick observed upswing of output in response to a technology shock can be explained by a substantial reduction in the degree of habit formation. Similarly, the low persistence of inflation might be interpreted as smaller indexation rules.

Additionally, in the second subsample, we obtain a stark difference between the estimated and implied policy parameters in both model versions. In the model with *exogenous objectives optimal monetary* *policy*, we obtain that λ_p is much higher than λ_w. In the model version with *endogenous objectives optimal monetary policy*, we obtain the reverse configuration. More troubling, both version seem to fit equally well the data, as is clear from figure 4. However, we are reluctant to insist on this result since the policy parameters are not precisely estimated. This is a direct consequence of the large confidence bands of IRFs obtained from the SVAR. Notice though that, given our moment selection procedure, we made sure that all the relevant information has been fully exploited in the estimation stage.

6 Concluding Remarks

In this paper, we asked whether a DSGE model with nominal rigidities and optimal monetary policy can successfully reproduce the US economy's dynamics after a permanent technology shock. To answer this question, we have first characterized the US economy's responses to such shocks using standard long-run restrictions in a structural vector autoregression (SVAR) over the sample 1955(1)-2002(4). Acknowledging the possible presence of a structural change in monetary policy over this period, we split our sample into two separate subsamples, the first one covering the pre-Volcker period and the second one covering the Volcker-Greenspan period. In each case, technology shocks account for a sizable portion of the variance of aggegate variables. This suggests that it is legitimate that US monetary authorities pay attention to these shocks. Second, we estimated a DSGE model designed to replicate these responses. An important part of this procedure consists in imposing during the estimation stage that monetary policy is conducted in an optimal (possibly welfare-maximizing) way. Our main finding is that, even in the pre–Volcker period, we fail to reject the null hypothesis that monetary policy has been optimal. Importantly, even though the central banker, with either *exogenous* or *endogenous* objectives, has no explicit interest rate smoothing concern, both model versions are capable of matching very well the dynamic responses of the short–run nominal interest rate. This result prominently hinges on the private sector specification. Had the model abstracted from important real and nominal frictions, it would have failed to mimic the nominal interest rate, as well as other aggregate variables.

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A Model Details

A.1 Final Goods and Material Goods

Competitive firms produce a homogeneous final good with the inputs of intermediate goods. The latter can be either consumed (c_t) or used as a material input in the production of intermediate goods (m_t). The final good is produced according to the CES technology

$$d_t = \left(\int_0^1 d_t(\varsigma)^{(\theta_p - 1)/\theta_p} \mathrm{d}\varsigma \right)^{\theta_p/(\theta_p - 1)}, \tag{A.1}$$

where d_t is the quantity of final good produced in period t and $d_t(\varsigma)$ is the input of intermediate good ς. Intermediate goods are imperfectly substitutable, with substitution elasticity $\theta_p > 1$. The zero profit condition for final good producers implies that the aggregate price index obeys the relationship

$$P_t = \left(\int_0^1 P_t(\varsigma)^{1-\theta_p} \mathrm{d}\varsigma \right)^{1/(1-\theta_p)}. \tag{A.2}$$

The above assumptions imply the following demand function

$$d_t\left(\varsigma\right) = \left(\frac{P_t\left(\varsigma\right)}{P_t} \right)^{-\theta_p} d_t. \tag{A.3}$$

This is the demand function that monopolist ς will take into account when solving her program.

A.2 Aggregate Labor Index

Following Erceg et al. (2000), we assume for convenience that a set of differentiated labor inputs, indexed on $[0, 1]$, are aggregated into a single labor index h_t by competitive firms, which will be referred to as labor intermediaries in the sequel. They produce the aggregate labor input according to the following CES technology

$$h_t = \left(\int_0^1 h_t\left(\upsilon\right)^{(\theta_w - 1)/\theta_w} \mathrm{d}\upsilon \right)^{\theta_w/(\theta_w - 1)}, \tag{A.4}$$

where $\theta_w > 1$ is the elasticity of substitution between any two labor types and $h_t\left(\upsilon\right)$ denotes the input of labor of type υ. Let $W_t\left(\upsilon\right)$ denote the nominal wage rate associated to type-υ labor, which labor intermediaries take as given. The first order conditions are

$$h_t\left(\upsilon\right) = \left(\frac{W_t\left(\upsilon\right)}{W_t} \right)^{-\theta_w} h_t, \tag{A.5}$$

where the aggregate nominal wage is defined as

$$W_t = \left(\int_0^1 W_t\left(\upsilon\right)^{1-\theta_w} \mathrm{d}\upsilon \right)^{1/(1-\theta_w)}. \tag{A.6}$$

Notice that eq. (A.6) is a direct consequence of the combination of eq. (A.5) and the zero profits condition.

A.3 Intermediate Goods

In the third sector, monopolistic firms produce the intermediate goods. Each firm ς is the sole producer of intermediate good ς. Given a demand $d_t(\varsigma)$, it faces the following production possibilities

$$\min\left\{\frac{\mathrm{e}^{z_t}F\left(n_t\left(\varsigma\right)\right)}{1-s_m},\frac{m_t\left(\varsigma\right)}{s_m}\right\}\geq d_t\left(\varsigma\right),\quad 0<s_m<1, \tag{A.7}$$

where $F(\cdot)$ is an increasing and concave production function, $n_t(\varsigma)$ is the input of aggregate labor, $m_t(\varsigma)$ denotes the input of material goods, and s_m is the share of material goods in gross output. This specification is borrowed from Rotemberg and Woodford (1995).[11] We interpret the case $s_m = 0$ as implying a production function of the form $d_t(\varsigma) = \mathrm{e}^{z_t}F(n_t(\varsigma))$. Finally, z_t is a technology shock which evolves according to

$$z_t = \log\left(g\right) + z_{t-1} + \varphi_t, \tag{A.8}$$

$$\varphi_t = \rho\varphi_{t-1} + \epsilon_t, \tag{A.9}$$

where $g > 1$, $\rho \in [0, 1)$, and $\epsilon_t \sim \mathrm{iid}(0, \sigma_\epsilon^2)$. Additionally, monopolistic producers of intermediate goods are subsidized at rate τ_p. Furthermore, we assume that this rate is such that the monopoly distortion is completely eliminated.

Cost minimization ensures that $m_t(\varsigma) = s_m d_t(\varsigma)$, so that the real cost $\mathscr{C}(d_t(\varsigma))$ of producing $d_t(\varsigma)$ units of good ς is

$$\mathscr{C}(d_t(\varsigma)) = w_t F^{-1}((1-s_m)\mathrm{e}^{-z_t}d_t(\varsigma)) + s_m d_t(\varsigma).$$

Following Calvo (1983), we assume that in each period of time, a monopolistic firm can reoptimize its price with probability $1-\alpha_p$, irrespective of the elapsed time since it last revised its price. The remaining firms simply rescale their price according to the simple rule $P_T(\varsigma) = (1+\delta_{t,T}^p)P_t(\varsigma)$, where

$$1+\delta_{t,T}^p = \begin{cases} \prod_{j=t}^{T-1}(1+\pi)^{1-\gamma_p}(1+\pi_j)^{\gamma_p} & \text{if } \ T>t \\ 1 & \text{otherwise} \end{cases}, \tag{A.10}$$

where $\pi_t \equiv P_t/P_{t-1} - 1$ represents the inflation rate, π is the steady state inflation rate, and $\gamma_p \in [0, 1]$ measures the degree of indexation to the most recently available inflation measure.

Let $P_t^\star(\varsigma)$ denote the price chosen in period t if firm ς is drawn to reoptimize, and let $d_{t,T}^\star(\varsigma)$ denote the production of good ς in period T if firm ς last reoptimized its price in period t. According to eq. (A.3),

[11] See also among others Dotsey and King (2001) and Woodford (2003).

$d^{\star}_{t,T}(\varsigma)$ obeys the relationship

$$d^{\star}_{t,T}(\varsigma) = \left(\frac{(1+\delta^{p}_{t,T}) P^{\star}_{t}(\varsigma)}{P_T} \right)^{-\theta_p} d_T. \tag{A.11}$$

Then, $P^{\star}_{t}(\varsigma)$ is selected so as to maximize

$$\mathrm{E}_t \sum_{T=t}^{\infty} (\beta\alpha_p)^{T-t} \lambda_T \left\{ (1+\tau_p) \frac{(1+\delta^{p}_{t,T}) P^{\star}_{t}(\varsigma)}{P_T} d^{\star}_{t,T}(\varsigma) - \mathscr{C}(d^{\star}_{t,T}(\varsigma)) \right\}, \tag{A.12}$$

where E_t is the expectation operator, conditional on information available as of time t. In addition, λ_t is the marginal utility of wealth. Standard manipulations yield the approximate loglinearized first order condition

$$\hat{\pi}_t - \gamma_p \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1} - \gamma_p \hat{\pi}_t\} + \frac{(1-\beta\alpha_p)(1-\alpha_p)}{\alpha_p[(1-s_m)^{-1} + \omega_p \theta_p]} (\hat{w}_t + \omega_p \hat{y}_t), \tag{A.13}$$

where $\hat{\pi}_t$ is the logdeviation of $1+\pi_t$, $\hat{y}_t$ and $\hat{w}_t$ are the logdeviations of $y_t \mathrm{e}^{-z_t}$ and $w_t \mathrm{e}^{-z_t}$, respectively, and where we defined the composite parameter

$$\omega_p \equiv - \frac{F''(n)\, n}{F'(n)} \frac{F(n)}{F'(n)\, n}.$$

Here, $F(n)$, $F'(n)$, and $F''(n)$ denote the values of F and its first and second derivatives, evaluated at the steady state value of n, and $\beta \in (0,1)$ is the household's subjective discount factor.

A.4 Households

The economy is inhabited by differentiated households, indexed on $[0,1]$. A typical household υ acts as a monopoly supplier of type-υ labor. It is assumed that at each point in time only a fraction $1-\alpha_w$ of the households can set a new wage, which will remain fixed until the next time period the household is allowed to reset its wage. The remaining households simply revise their wages according to the simple rule $W_T(\upsilon) = g^{T-t}(1+\delta^{w}_{t,T}) W_t(\upsilon)$, where

$$1+\delta^{w}_{t,T} = \begin{cases} \prod_{j=t}^{T-1} (1+\pi)^{1-\gamma_w} (1+\pi_j)^{\gamma_w} & \text{if } T>t \\ 1 & \text{otherwise} \end{cases}, \tag{A.14}$$

where $\gamma_w \in [0,1]$ measures the degree of indexation to the most recently available inflation measure. Notice that we let the households index their nominal wage to past inflation as well as to the average growth rate of z_t. This ensures the existence of a well-behaved deterministic steady state. Finally, households are subsidized at rate τ_w. Furthermore, we assume that this rate is such that the monopoly distortion is completely eliminated.

Household υ's goal in life is to maximize

$$\mathrm{E}_t \sum_{T=t}^{\infty} \beta^{T-t} [\log(c_T - bc_{T-1}) - V(h_T(\upsilon))], \tag{A.15}$$

where $V(\cdot)$ is a well-behaved utility functions, and $b \in [0, 1)$. The variable c_t represents consumption and $h_t(\upsilon)$ is household υ's supply of labor. The preferences are characterized by internal habit formation.

The representative agent maximizes (A.15) subject to the sequence of constraints

$$c_t + b_t/(1 + i_t) + \mathrm{tax}_t \leq (1 + \tau_w) w_t(\upsilon) h_t(\upsilon) + b_{t-1}/(1 + \pi_t) + \mathrm{div}_t, \tag{A.16}$$

where div_t denotes profits redistributed by monopolistic firms, $w_t(\upsilon) \equiv W_t(\upsilon)/P_t$ is the real wage rate earned by type-υ labor. Additionally, $b_t \equiv B_t/P_t$, where B_t denotes the nominal bonds acquired in period t and maturing in period $t+1$; tax_t denotes lump-sum taxes; i_t denotes the nominal interest rate.

Let us define $\hat{\imath}_t$ and $\hat{c}_t$ as the logdeviations of $1 + i_t$ and $c_t \mathrm{e}^{-z_t}$, respectively, and $\hat{\lambda}_t$ as that of $\lambda_t \mathrm{e}^{z_t}$. Additionally, let us define $\bar{b} = b/g$. We thus obtain the approximate loglinear first order conditions

$$\hat{c}_t = \eta \hat{c}_{t-1} + \beta \eta \mathrm{E}_t\{\hat{c}_{t+1}\} - (1 - (1 + \beta)\eta) \hat{\lambda}_t + \beta \eta \mathrm{E}_t\{\varphi_{t+1}\} - \eta \varphi_t, \tag{A.17}$$

$$\hat{\lambda}_t = \hat{\imath}_t + \mathrm{E}_t\{\hat{\lambda}_{t+1} - \hat{\pi}_{t+1} + \varphi_{t+1}\}. \tag{A.18}$$

where we defined

$$\eta \equiv \frac{\bar{b}}{1 + \beta \bar{b}^2}.$$

Let $W_t^\star(\upsilon)$ denote the wage rate chosen in period t bu household υ if drawn to reoptimize, and let $h_{t,T}^\star(\upsilon)$ denote the hours worked in period T if household υ last reoptimized its wage in period t. According to eq. (A.5), $h_{t,T}^\star(\upsilon)$ obeys the relationship

$$h_{t,T}^\star(\upsilon) = \left(\frac{g^{T-t}(1 + \delta_{t,T}^w) W_t^\star(\upsilon)}{W_T} \right)^{-\theta_w} h_T. \tag{A.19}$$

Then, $W_t^\star(\upsilon)$ is selected to maximize

$$\mathrm{E}_t \sum_{T=t}^{\infty} (\beta \alpha_w)^{T-t} \left\{ \lambda_T (1 + \tau_w) \frac{g^{T-t}(1 + \delta_{t,T}^w) W_t^\star(\upsilon)}{P_T} h_{t,T}^\star(\upsilon) - V(h_{t,T}^\star(\upsilon)) \right\}. \tag{A.20}$$

Standard manipulations yield the approximate loglinear relation

$$\hat{\pi}_t^w - \gamma_w \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1}^w - \gamma_w \hat{\pi}_t\} + \frac{(1 - \alpha_w)(1 - \beta \alpha_w)}{\alpha_w (1 + \omega_w \theta_w)} (\omega_w \phi \hat{y}_t - \hat{\lambda}_t - \hat{w}_t), \tag{A.21}$$

where $\hat{\pi}_t^w$ and $\hat{w}_t$ are the logdeviations of gross wage inflation and $w_t \mathrm{e}^{-z_t}$, respectively, and where we defined the parameters

$$\omega_w \equiv \frac{V_{hh}(h) h}{V_h(h)}, \quad \phi \equiv \frac{F(n)}{F'(n) n}.$$

Table 1. Variance Decomposition in the Pre-Volcker Period

	0	4	8	12	20	60
Productivity Growth	12.31	20.23	20.28	20.29	20.36	20.37
	[3.75, 24.46]	[12.73, 31.36]	[13.00, 31.24]	[13.01, 31.25]	[13.05, 31.33]	[13.06, 31.34]
Hours	31.90	39.33	33.50	33.68	34.92	35.87
	[19.43, 47.43]	[27.04, 53.60]	[22.53, 47.44]	[23.13, 47.22]	[24.97, 47.83]	[26.17, 48.59]
Inflation	6.95	50.36	58.07	57.98	57.34	56.71
	[0.32, 18.86]	[39.94, 60.71]	[48.18, 68.08]	[47.97, 68.18]	[47.43, 67.77]	[46.74, 67.41]
Wage Inflation	18.11	37.76	45.87	47.57	48.14	48.11
	[8.50, 28.96]	[27.37, 49.03]	[35.06, 56.93]	[36.86, 58.72]	[37.34, 59.41]	[37.31, 59.44]
Fed Funds Rate	33.20	60.75	55.98	54.44	53.74	53.50
	[18.35, 49.89]	[50.86, 72.37]	[45.45, 68.54]	[43.98, 67.32]	[43.17, 66.68]	[42.93, 66.54]

Notes: The figures in brackets correspond to the 90% confidence interval, obtained by standard bootstrap techniques.

Table 2. Variance Decomposition in the Volcker–Greenspan Period

	0	4	8	12	20	60
Productivity Growth	59.93	46.91	45.80	45.59	45.20	45.03
	[50.72, 70.08]	[39.02, 57.84]	[37.99, 56.63]	[37.79, 56.36]	[37.45, 56.01]	[37.35, 55.80]
Hours	8.26	1.24	1.95	3.99	6.51	7.12
	[0.69, 26.32]	[0.90, 9.61]	[1.18, 9.81]	[1.61, 13.97]	[2.15, 18.10]	[2.32, 18.84]
Inflation	54.27	43.35	40.63	39.42	37.03	34.96
	[39.99, 68.04]	[31.07, 57.57]	[28.14, 55.43]	[27.04, 54.28]	[25.02, 51.53]	[23.11, 49.53]
Wage Inflation	0.18	6.01	6.02	5.84	5.86	5.91
	[0.01, 8.50]	[4.61, 14.92]	[4.69, 14.79]	[4.59, 14.49]	[4.67, 14.18]	[4.75, 14.18]
Fed Funds Rate	1.67	4.30	3.28	2.81	2.79	4.08
	[0.03, 10.64]	[0.37, 16.17]	[0.44, 14.26]	[0.75, 12.95]	[0.94, 12.54]	[1.90, 12.35]

Notes: The figures in brackets correspond to the 90% confidence interval, obtained by standard bootstrap techniques.

Table 3. Calibrated Parameters

Parameters	Value	Interpretation
β	0.9900	Subjective discount factor
g	1.0050	Technology growth
ϕ	1.5625	Inverse elasticity of output wrt labor
ω_p	0.5625	Elasticity of real marginal cost wrt production
s_m	0.5000	Share of material goods in gross output
θ_w	21.0000	Price elasticity of labor demand
θ_p	11.0000	Price elasticity of intermediate goods demand

Table 4. Estimation Results, Pre–Volcker Period

		Exogenous Objectives	Endogenous Objectives
ω_w	Labor supply elasticity	0.567 [N/A]	0.567 [9.715]
b	Habit parameter	0.904 [0.469]	0.887 [3.683]
γ_p	Price indexation	0.575 [1.553]	0.604 [5.875]
γ_w	Wage indexation	1.000 [N/A]	1.000 [N/A]
α_p	Price rigidity	0.691 [17.852]	0.694 [0.538]
α_w	Wage rigidity	0.890 [0.000]	0.870 [4.891]
ρ	Persistence of technology shocks	0.068 [18.923]	0.042 [19.539]
σ_ϵ	S.E. of technology shocks	0.574 [0.014]	0.609 [0.233]
		Estimated Policy	Implied Policy
λ_p	Weight on inflation	0.057 [36.328]	0.064 [2.151]
λ_w	Weight on wage inflation	0.943 [0.556]	0.936 [2.151]
λ_x	Weight on output gap	0.025 [63.863]	0.009 [17.590]
δ	"Policy habit"	0.852 [4.992]	0.827 [27.535]
$J(\hat{\psi}_T)$		28.852	29.848
$\mathscr{P}(J \geq J(\hat{\psi}_T))$		15.224%	10.266%

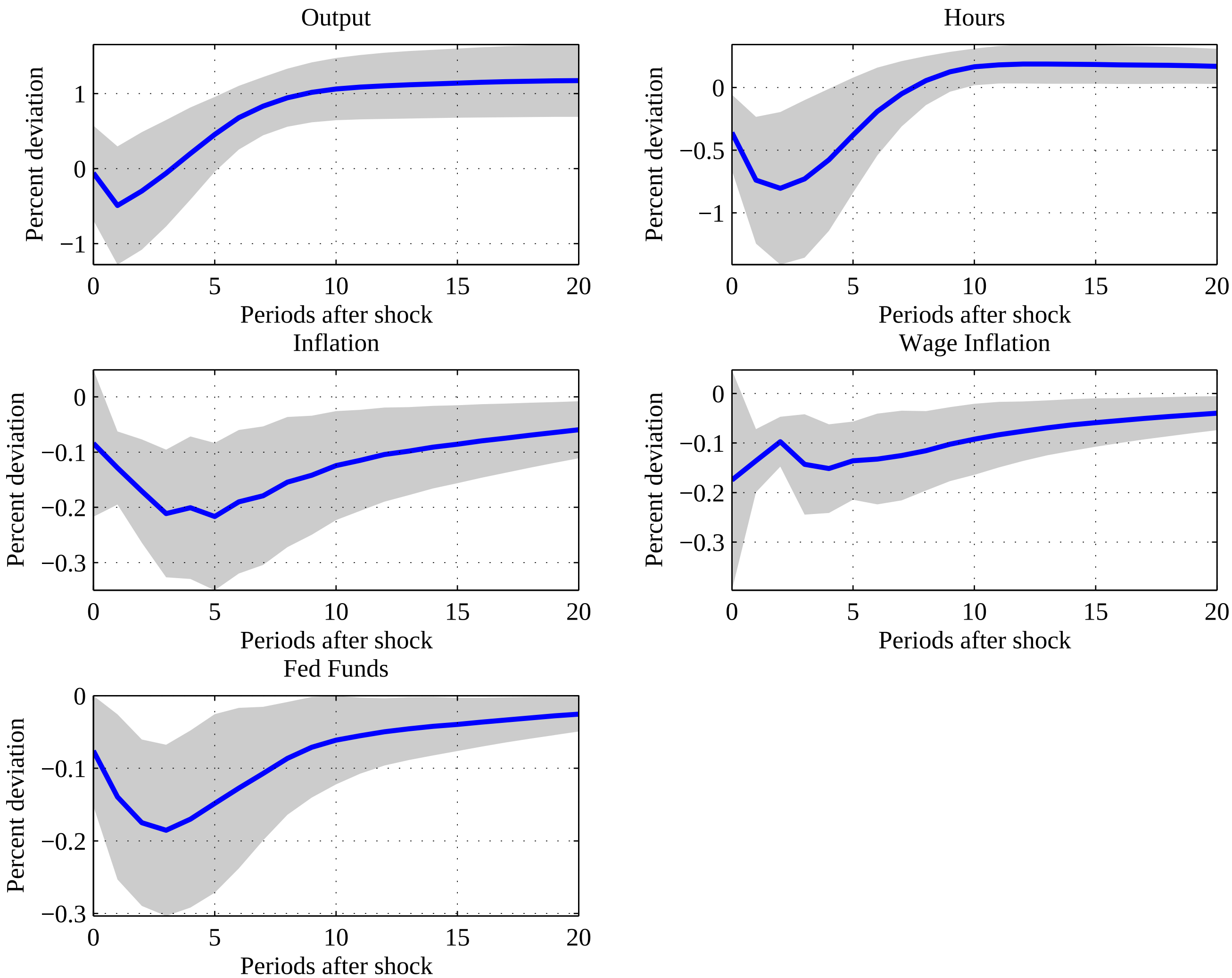
Notes: The values in brackets are the P-values of the bootstrap analog of a t-test of parameters significance (in percentage). The selected horizon according to the Hall et al. (2007) information criterion is $\hat{k}_T = 12$.

Table 5. Estimation Results, Volcker–Greenspan Period

		Exogenous Objectives	Endogenous Objectives
ω_w	Labor supply elasticity	0.567 [N/A]	0.567 [N/A]
b	Habit parameter	0.454 [14.733]	0.423 [18.979]
γ_p	Price indexation	0.326 [9.677]	0.088 [8.333]
γ_w	Wage indexation	1.000 [N/A]	1.000 [N/A]
α_p	Price rigidity	0.752 [0.036]	0.729 [0.005]
α_w	Wage rigidity	0.880 [0.009]	0.829 [0.007]
ρ	Persistence of technology shocks	0.214 [6.364]	0.227 [6.610]
σ_ϵ	S.E. of technology shocks	0.323 [0.006]	0.336 [0.021]
		Estimated Policy	Implied Policy
λ_p	Weight on inflation	0.990 [5.808]	0.140 [30.247]
λ_w	Weight on wage inflation	0.010 [75.106]	0.860 [12.248]
λ_x	Weight on output gap	0.025 [30.003]	0.001 [18.872]
δ	"Policy habit"	0.273 [41.711]	0.329 [42.175]
$J(\hat{\psi}_T)$		8.416	8.788
$\mathscr{P}(J \geq J(\hat{\psi}_T))$		36.855%	35.252%

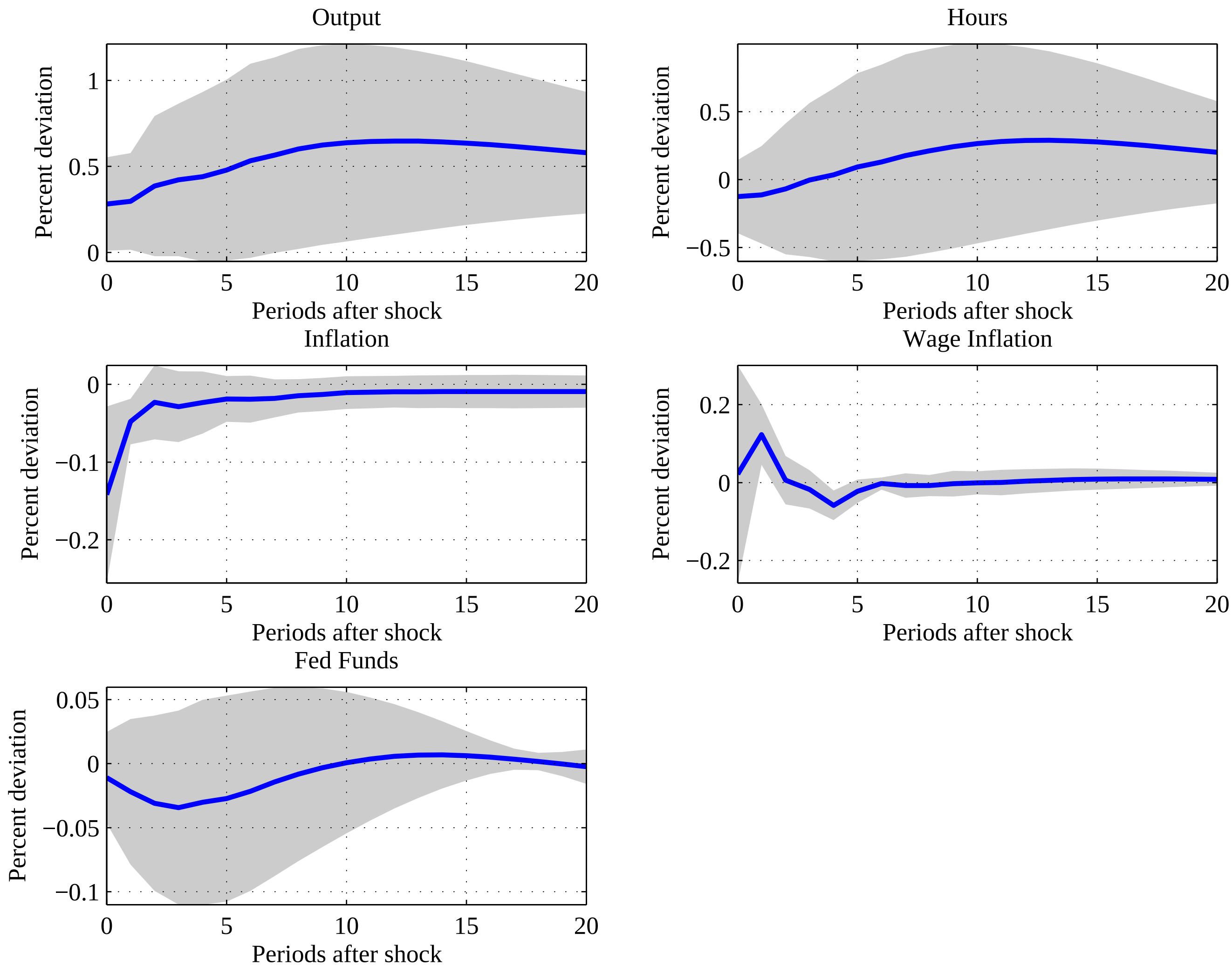
Notes: The values in brackets are the P-values of the bootstrap analog of a t-test of parameters significance (in percentage). The selected horizon according to the Hall et al. (2007) information criterion is $\hat{k}_T = 14$.

Figure 1: Impulse Response Functions – Pre–Volcker Period



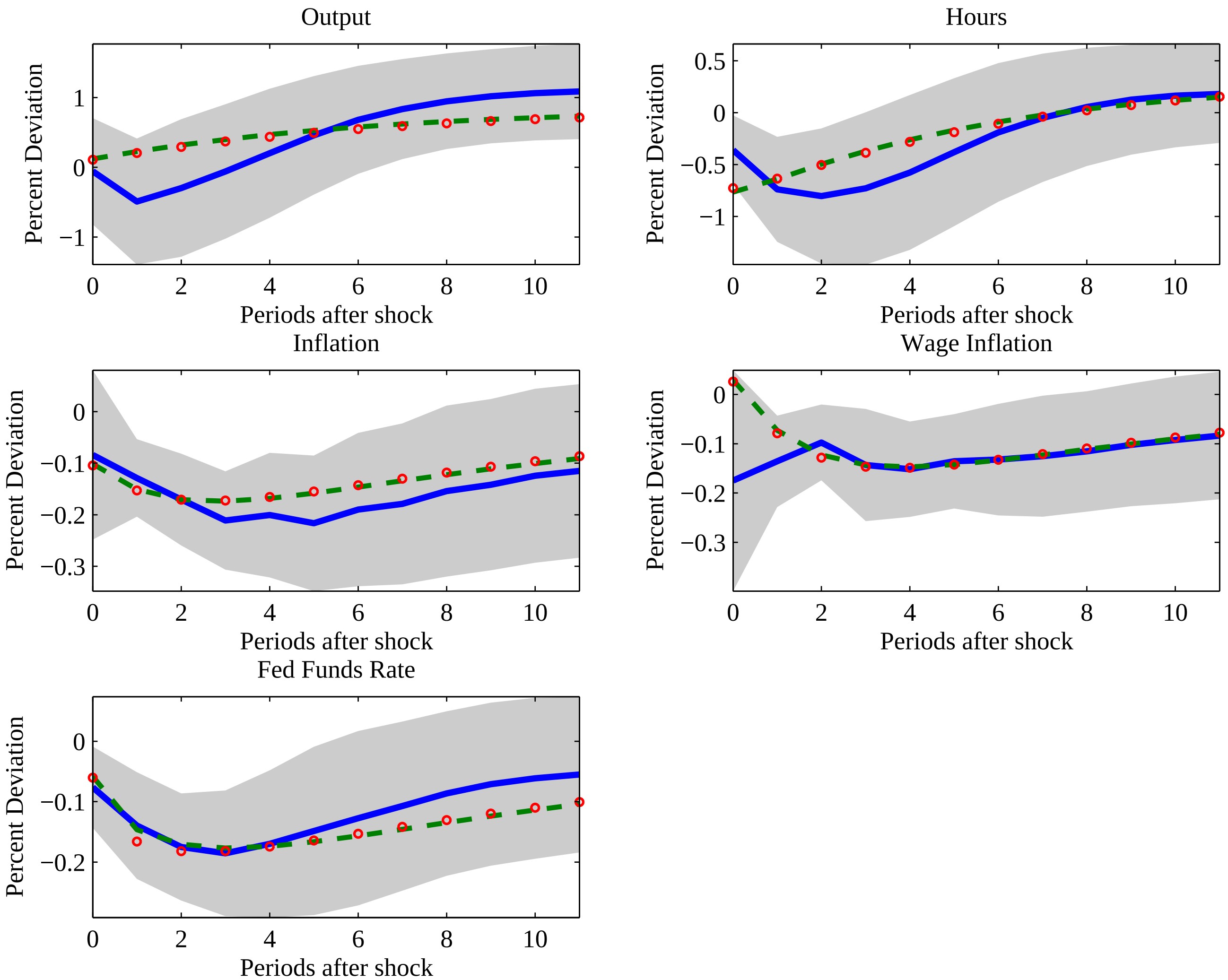
Notes: SVAR-based IRF and grey area corresponding to the 95% asymptotic confidence interval.

Figure 2: Impulse Response Functions – Post–Volcker Period



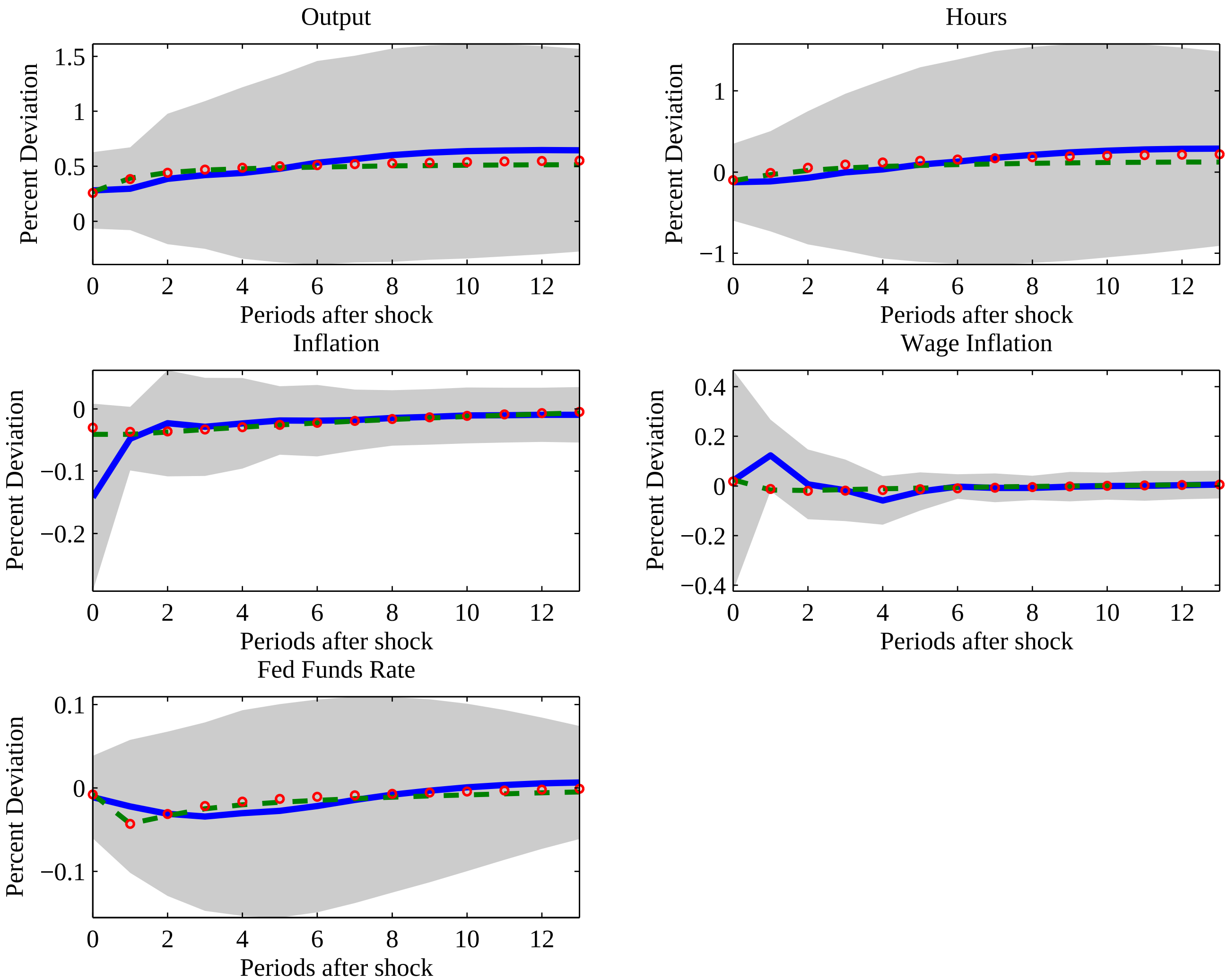
Notes: SVAR-based IRF and grey area corresponding to the 95% asymptotic confidence interval.

Figure 3: DSGE–based IRFs – Pre–Volcker Period



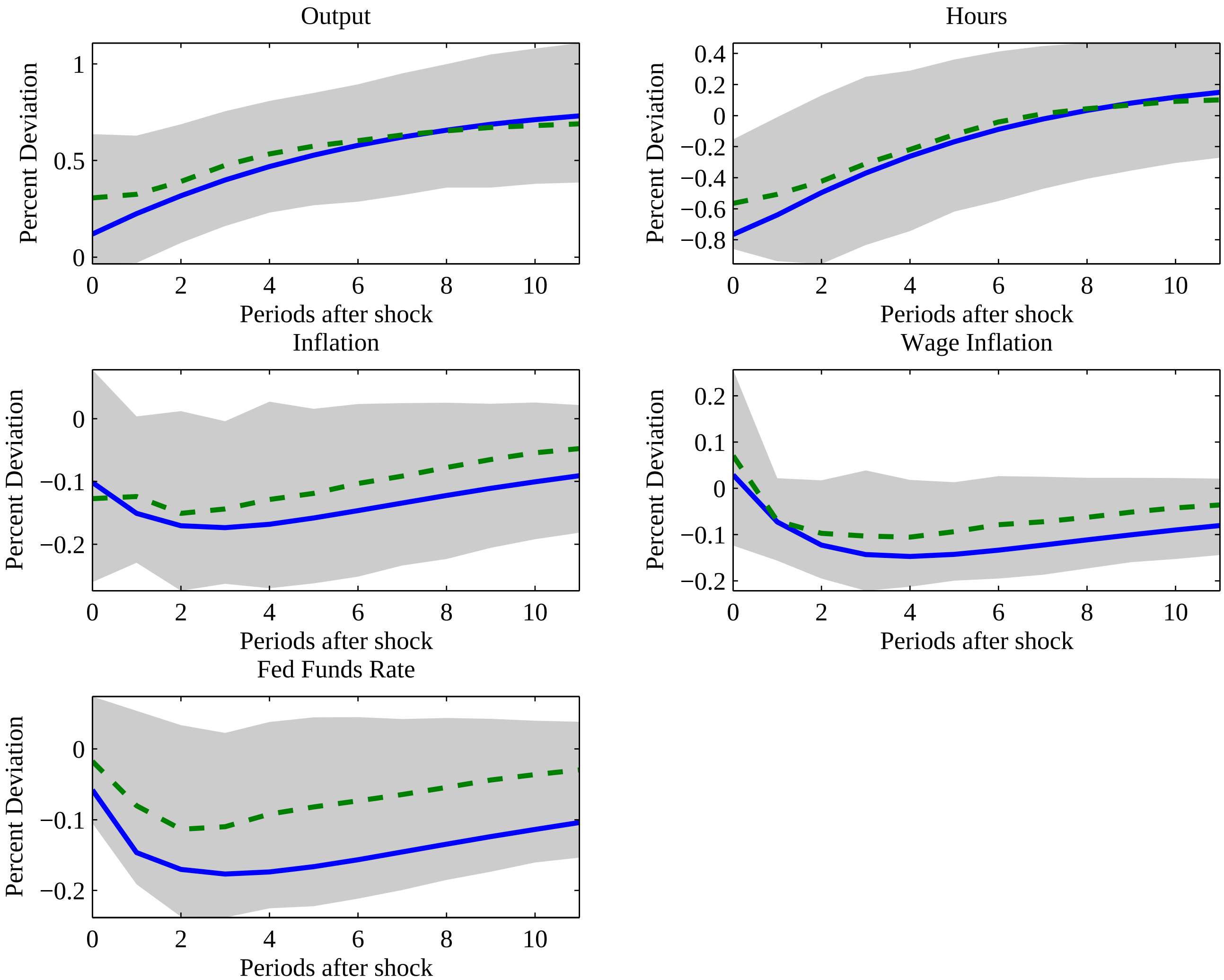
Notes: Solid line: SVAR-based IRF; circles: DSGE-based IRF subject to *exogenous objectives optimal monetary policy*; dashed line: DSGE-based IRF subject to *endogenous objectives optimal monetary policy with.* The grey area corresponds to the 95% asymptotic confidence interval. The selected horizon according to the Hall et al. (2007) information criterion is $\hat{k}_T = 12$.

Figure 4: DSGE–based IRFs – Volcker–Greenspan Period



Notes: Solid line: SVAR-based IRF; circles: DSGE-based IRF subject to *exogenous objectives optimal monetary policy*; dashed line: DSGE-based IRF subject to *endogenous objectives optimal monetary policy.* The grey area corresponds to the 95% asymptotic confidence interval. The selected horizon according to the Hall et al. (2007) information criterion is $\hat{k}_T = 14$.

Figure 5: Simulation of the SVAR Model: Pre–Volcker Period



Notes: Dashed line: SVAR-based IRF on model's data (median response); solid line: DSGE-based IRF (under endogenous objectives optimal monetary policy). The grey area corresponds to the 95% confidence interval of the simulation. The selected horizon according to the Hall et al. (2007) information criterion is $\hat{k}_T = 12$.