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Technology Shocks and Monetary Policy in an Estimated Sticky Price Model of the US Economy*

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Résumé :

Dans ce papier, nous cherchons à caractériser les effets dynamiques des chocs technologiques permanents ainsi que la façon dont les autorités monétaires américaines ont réagi à ces chocs au cours de la période 1955(1)–2002(4). A cette fin, nous développons un modèle augmenté avec prix et salaires visqueux, que nous estimons en minimisant la distance entre la réponse théorique des variables du modèles à leurs contreparties empiriques issues d'un VAR structurel. Dans une seconde étape, nous comparons ces réponses avec celles qui découleraient de la politique monétaire optimale.

Mots-clés : prix et alaires visqueux, règle de Taylor, politique monétaire optimale

Abstract:

In this paper, we, seek to characterize the dynamic effects of permanent technology shocks and the way in which US monetary authorities reacted to these shocks over the sample 1955(1)–2002(4). To do so, we develop an augmented sticky price-sticky wage model of the business cycle, which is estimated by minimizing the distance between theoretical, dynamic responses of key variables to a permanent technology shock and their structural VAR counterparts. In a second step, we compare these responses with the outcome of the optimal monetary policy.

Keywords: Sticky prices and wages, Taylor rule, Optimal monetary policy

JEL Codes: E31, E32, E58.

Résumé non technique :

Ce papier propose de caractériser les effets dynamiques des chocs technologiques permanents ainsi que la façon dont les autorités monétaires américaines y ont réagi au cours de la période 1955(1)–2002(4). Nous commençons notre analyse en estimant un modèle VAR structurel (SVAR) avec contraintes d'identification à long terme. Les variables incluses dans l'analyse sont le taux de croissance de la productivité moyenne du travail, les heures travaillées, l'inflation, l'inflation salariale, et le taux d'intérêt nominal de court terme. Les chocs technologiques sont identifiés comme les seuls chocs pouvant affecter le niveau de la productivité à long terme. Bien que ne constituant pas la source principale des fluctuations aux fréquences du cycles économique, les chocs technologiques ainsi identifiés engendrent une fraction non négligeable des fluctuations des variables d'intérêt. A ce titre, il apparaît donc légitime que les autorités monétaires leur prêtent attention.

Dans une seconde étape, nous développons un modèle d'équilibre général stochastique et dynamique (DSGE) avec prix et salaires visqueux. Le modèle incorpore de nombreux éléments de modélisation, dont des mécanismes d'indexation partielle des prix et des salaires, de la formation des habitudes sur la consommation, et des biens matériels. Le modèle est estimé à l'aide de la technique de "Minimisation de la distance", récemment proposée et mise en oeuvre par Christiano et al. (2001) et Rotemberg and Woodford (1997,1999), entre autres. Plus précisément, les paramètres du modèle théorique sont estimés de façon à minimiser une distance entre les réponses théoriques des variables d'intérêt à un choc technologique et leurs contreparties issues du modèle SVAR. La plupart des paramètres estimés sont significatifs et permettent au modèle DSGE de reproduire les réponses empiriques de façon satisfaisante.

Une récente littérature a mis en avant les difficultés rencontrées par les modèles SVAR à identifier correctement les chocs. Une question préliminaire importante et de savoir si notre modèle SVAR échappe à cette critique. A cette fin, nous simulons le modèle DSGE et ré estimons sur les données simulées le même SVAR que sur les données empiriques. Le résultat de cet exercice montre que le modèle SVAR identifie correctement le "vrai" choc technologique, même s'il existe un biais à la hausse.

A l'aide de ces représentations des données, nous posons la question contrefactuelle: la réponse de l'économie américaine aurait-elle été différente de ce qu'indique le SVAR si la politique monétaire avait été optimale? Pour répondre à cette question, nous suivons Giannoni et Woodford (2003) et dérivons la fonction de perte des autorités monétaires comme l'approximation à l'ordre deux de la fonctionnelle de bien-être social. Nous calculons alors la réponse optimale de l'économie aux chocs technologiques sous le modèle DSGE, et développons un test simple de l'hypothèse d'optimalité basé sur une comparaison de ces réponses avec celles induites par le SVAR. Il faut souligner que ce test en information limité n'exclut pas la possibilité que les autorités monétaires aient mal réagi aux chocs que nous n'avons pas cherché à identifier.

Le résultat principal est que la réponse de l'économie sous la règle monétaire optimale ne diffère apparemment pas de la réponse optimale sur l'échantillon étudié. Ce résultat va à l'encontre des conclusions de Galí et al. (2003). La raison de cet écart provient du fait que nous avons postulé des salaires visqueux. Sous cette hypothèse, la réponse optimale de l'inflation n'est plus identiquement nulle, autorisant ainsi un ensemble plus grand de dynamiques potentielles. De plus, sur la base d'une analyse quantitative simple, cette hypothèse ne semble pas rejetée par les données. Nous complétons cette analyse en séparant l'échantillon en deux sous périodes, avant et après la nomination de Paul Volcker à la tête de la Réserve Fédérale. Bien que nous obtenions des signes de changement structurels dans les coefficients du SVAR, nos conclusions principales sont confirmées.

Non-technical summary:

In this paper, we, seek to characterize the dynamic effects of permanent technology shocks and the way in which US monetary authorities reacted to these shocks over the sample 1955(1)–2002(4). We begin our analysis by estimating a structural VAR (SVAR) with long-run identification constraints. The variables under study are average labor productivity growth, hours worked, inflation, wage inflation, and the Fed Funds rate. Technology shocks are identified as the only shocks that can have a long-run impact on labor productivity. We find that, while maybe not the dominant source of business cycle fluctuations, technology shocks still account for a sizable portion of the fluctuations

in output, hours, inflation, wage inflation, and the nominal interest rate. Thus, if the SVAR does a good job of identifying technology shocks, these results suggest that monetary authorities should pay attention to these shocks.

In a second step, we develop an augmented dynamic stochastic general equilibrium (DSGE) sticky price-sticky wage model of the business cycle, featuring various additional modelling elements, including partial price and wage indexation, habit formation, and material goods. The model is estimated through the Minimum Distance technique recently advocated by Christiano et al. (2001) and Rotemberg and Woodford (1997,1999), among others. More precisely, the structural parameters of our DSGE model are pinned down so as to minimize a weighted distance between theoretical and VAR-based impulse responses of key macroeconomic variables to a permanent technology shock. Most of the associated parameters are found significant and allow the DSGE model to replicate fairly well the economy's response to technology shocks.

Given the recent emphasis on the identification difficulties encountered by SVAR models, an important preliminary investigation is to assess whether our SVAR is able to pin down technology shocks. To this end, we simulate our estimated DSGE and reestimate the SVAR as above on the simulated data. The result indicates that the SVAR is able to catch the true (model) response, though with a small upward bias.

Armed with this SVAR representation of the data and a DSGE model that does a reasonably good job of reproducing the economy's response to identified technology shocks, we ask the counterfactual question: Would the economy's dynamic response have been different from what the SVAR indicates if US monetary authorities systematic response to technology shocks had been optimal? To answer this question, we follow Giannoni and Woodford (2003) and derive the monetary authorities loss function as a second-order approximation to the social utility function. We then compute the optimal response to permanent technology shocks in our DSGE model and develop a simple test of the optimality hypothesis by comparing the outcome of the optimal monetary policy with the SVAR model. It must be noticed that this is a limited information test, in that it does not preclude that monetary policy badly reacted to other shocks that we do not seek to identify in our SVAR.

Our main result is that monetary authorities dynamic reaction to a permanent technology shock does not apparently differ from the optimal response over the sample period studied in this paper. This result contrasts with the conclusions reached by Galí et al. (2003). The major reason for this is our assumption that both prices and wages are sticky. Under this hypothesis, the optimal response of inflation is no longer zero, thus allowing a broader set of potential dynamics. Moreover, based on simple quantitative analyses, we show that allowing for sticky wages in addition to sticky prices is important in terms of empirical fit. We complement our analysis by splitting our sample into two separate samples, one covering the pre-Volcker period and the other covering the post-Volcker period. Though we obtain evidence of structural changes in the SVAR coefficients, our previous conclusions are broadly confirmed.

1 Introduction

Following the provocative contribution by Galí (1999), there has been a renewed interest in technology shocks over the recent years, especially within the theoretical framework of New Keynesian models. Galí et al. (2003) is a prominent example of this renewed interest,[1] focussing on the link between US monetary policy and the economy's response to such shocks. In this paper, the authors first characterize the Fed's systematic response to technology shocks identified by means of a SVAR model where only technology shocks account for the unit-root in average labor productivity. Second, using a small DSGE model with sticky prices calibrated to US data, they evaluate the extent to which the actual, SVAR-based Fed's response to these shocks is consistent with that implied by simple monetary rules. They find strong evidence in favor of the view that US monetary policy was not optimal during the period preceding the appointment of Paul Volcker as the Fed's Chairman.

The present paper contributes to this literature by revisiting the conclusions reached by Galí et al. (2003). In doing so, our study makes two important improvements with respect to the methodology used in the latter paper. First, we explicitly include sticky wages in our analysis of US monetary policy. Taking this modeling element into account is potentially important in such an analysis. Indeed, as shown by Erceg et al. (2001), considering prices and wages both sticky allows for a non trivial monetary policy, as opposed to the environment considered by Galí et al. (2003) where the optimal monetary policy calls for a zero response of inflation to a permanent technology shock. Thus, when comparing impulse responses generated from a DSGE model featuring only sticky prices with their SVAR-based counterparts, one must reject the optimality hypothesis as long as the empirical response of inflation is statistically different from zero. This need not be the case when the DSGE model features sticky wages in addition to sticky prices.

Second, we perform a more systematic evaluation of our DSGE model. To this end, we resort to the Minimum Distance technique recently advocated by Christiano et al. (2001) and Rotemberg and Woodford (1997,1999), among others. More precisely, the structural parameters of our DSGE

[1] See also Altig et al. (2004), Edge et al. (2003), Ireland (2004).

models are pinned down so as to minimize a weighted distance between theoretical and VAR-based impulse responses of key macroeconomic variables to a permanent technology shock. Additionally, we resort to a much more detailed DSGE model than Galí et al. (2003). In addition to sticky prices and wages, our setup incorporates material goods, and features various hybrid elements, including habit persistence and partial wage and price indexation schemes. All these modelling elements have been shown elsewhere in the literature to help New Keynesian DSGE models better fit US data. In this paper, we confirm this conclusion: most of the associated parameters are found significant and allow the DSGE model to replicate fairly well the economy's response to technology shocks.

We start our analysis by characterizing the US economy's response to permanent technology shocks by means of a structural vector autoregression (SVAR) estimated on US data over the sample 1955(1)-2002(4). As in Galí et al. (2003), technology shocks are the only shocks responsible for the unit-root in average labor productivity. We show that, within the confines of our SVAR, technology shocks, while maybe not the dominant source of business cycle, account for a sizable portion of fluctuations in output, hours, inflation, wage inflation, and the nominal interest rate. Thus, if the SVAR does a good job of identifying technology shocks, these results suggest that monetary authorities should pay attention to these shocks.

Armed with this empirical representation of the data and a DSGE model that does a reasonably good job of reproducing the economy's response to identified technology shocks, we ask the counterfactual question: Would the economy's dynamic response have been different from what the SVAR indicates if US monetary authorities systematic response to technology shocks had been optimal? To answer this question, we follow Giannoni and Woodford (2003) and derive the monetary authorities loss function as a second-order approximation to the social utility function. We then compute the optimal response to permanent technology shocks in our DSGE model and develop a simple test of the optimality hypothesis by comparing the outcome of the optimal monetary policy with the SVAR model. It must be noticed that this is a limited information test, in that it does not preclude that monetary policy badly reacted to other shocks that we do not seek to identify in our SVAR.

Our analysis requires that we a priori specify a monetary policy rule before estimating the model. In the present paper, we adopt a specification that closely resembles that advocated by Taylor (1993). Thus, our answer to the question asked at the beginning of the paper is clearly contingent upon this rule. Yet, it seems desirable to resort to a parsimonious rule which allows us to synthesize the complex process of monetary policy with a small number of parameters. Such rules have been shown to depict well actual monetary policy with a number of countries.[2] Within the context of a fully specified, estimated DSGE model, Boivin and Giannoni (2003) also show that such a parsimonious rule captures the essential features of US monetary policy. At the same time, it has been argued that such rules perform well relative to the more complicated optimal rule. Thus, we view our modelling choice as a good compromise between parsimony and goodness of fit.

Our main result is that monetary authorities dynamic reaction to a permanent technology shock does not apparently differ from the optimal response over the sample period studied in this paper. This result contrasts with the conclusions reached by Galí et al. (2003). The major reason for this is our assumption that both prices and wages are sticky. Moreover, based on simple quantitative analyses, we show that allowing for sticky wages in addition to sticky prices is important in terms of empirical fit. We complement our analysis by splitting our sample into two separate samples, one covering the pre-Volcker period and the other covering the post-Volcker period. Though we obtain evidence of structural changes in the SVAR coefficients, our previous conclusions are broadly confirmed.

The remainder is as follows. Section 2 briefly details our structural VAR approach and comments on the obtained results. Section 3 describes the theoretical model. Section 4 details the estimated structural VAR model and expounds the minimum distance estimation technique used to select the structural parameters. Section 5 states the program facing monetary authorities and derives the optimal monetary policy. The economy's dynamic responses to permanent technology shocks under this policy are then compared with those deriving either from the SVAR or from the theoretical model coupled with a Taylor rule. The last section briefly concludes.

[2] See Clarida et al. (1998, 2000).

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 ($\hat{n}_t$). Inflation ($\hat{\pi}_t$) is the growth rate of output's implicit deflator. Wage inflation ($\hat{\pi}_t^w$) is the growth rate of nominal hourly compensation. Finally, the nominal interest rate ($\hat{\imath}_t$) is simply the quarterly Fed Funds rate.[3] The same variables are considered in our DSGE model. We follow Galí and Rabanal (2004) and extract a quadratic trend from hours, to account for structural changes in the labor market that our model is not designed to reproduce.[4] The transformed data are graphed on figure 1.

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

$$\mathbf{z}_t = \mathbf{A}_1\mathbf{z}_{t-1} + \cdots + \mathbf{A}_\ell\mathbf{z}_{t-\ell} + \boldsymbol{\varepsilon}_t, \quad \mathrm{E}\boldsymbol{\varepsilon}_t\boldsymbol{\varepsilon}_t' = \mathbf{\Sigma},$$

where ℓ is the maximal lag, which we determine by minimizing the Hannan-Quinn information criterion. In our analysis, we found that $\ell = 2$. Let us define

$$\mathbf{B}(L) = (\mathbf{I}_m - \mathbf{A}_1 L - \cdots - \mathbf{A}_\ell L^\ell)^{-1},$$

where $\mathbf{I}_m$ is the identity matrix and m is the number of variables in $\mathbf{z}_t$. Now, we assume that the canonical innovations are linear combinations of the structural shocks $\boldsymbol{\eta}_t$, i.e.

$$\boldsymbol{\varepsilon}_t = \mathbf{S}\boldsymbol{\eta}_t,$$

[3] The data are extracted from the Bureau of Labor Statistics website, except for the Fed Funds rate which is obtained from the FREDII database.

[4] See also Galí (2005).

for some non singular matrix $\mathbf{S}$. As usual, we impose an orthogonality assumption on the structural shocks, which combined with a scale normalization implies $\mathrm{E}\boldsymbol{\eta}_t\boldsymbol{\eta}_t' = \mathbf{I}_m$.

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

2.2 Results

The dynamics of output, hours, inflation, wage inflation, and the nominal interest rate in response to a one percent technology shock are reported on figure 2. The grey area represents the 90% asymptotic confidence intervals, which we computed numerically. Notice that output is simply deduced from the combined dynamics of average labor productivity and hours.

Output rises on impact, and then slightly declines. These responses are not found 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 an inverted hump pattern. They decline on impact, continue to decline for two periods, and then start to reach back their steady state level. These results confirm the pattern obtained by 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 and long horizons. This somewhat contradicts result reported by Christiano et al. (2004). The difference arises because *(i)* we used quadratically detrended hours and *(ii)* we do not resort to the same set of covariates in the SVAR in addition to hours and productivity growth.

Inflation and wage inflation share similar patterns. They initially decrease, though not statistically significantly, and then gradually rise toward their steady state value. The transitional paths are significant after a few quarters, and exhibit a substantial amount of persistence. Finally, the nominal interest rate follows an inverted hump pattern qualitatively similar to that of hours. 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 nominal interest rate. Interestingly, the patterns of the responses of output and inflation are consistent with what one could expect from a technology shock.

Before continuing, we must address an important question: Do technology shocks contribute much to fluctuations in our SVAR? This question 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 conduct two complementary exercises.

We start by computing the percentage of variance of the k step ahead forecast error in the elements of $\mathbf{z}_t$ due to technology shocks. These are reported on table 1, at forecast horizons of 0, 4, 8, and 20. Table 1 also contains the associated 90% confidence interval. These confidence interval are obtained based on 1000 bootstrap replications of the estimated SVAR

We obtain that technology shocks account for slightly less than 30% of the forecast error variance of productivity growth, at all the forecast horizons considered. Surprisingly, we obtain similar figures for hours. Such a conclusion contrasts sharply with 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 30% of the forecast error variance of inflation and the Fed funds at forecasts horizons of 4, 8, and 20, and half as much on impact. Finally, their contribution to the forecast error of wage inflation is smaller, comprised between 10% and 25% at forecast horizons of 4, 8, and 20 quarters, and a mere 1% on impact. Notice that the confidence intervals are fairly large. This simply means that these variance decompositions are weakly informative.

Second, we compute the ratio of the variance of the business cycle components of $\mathbf{z}_t$ conditional on technology shocks only to the variance of the business cycle components of $\mathbf{z}_t$ conditional on all five shocks. We proceed as follows. From the estimated VAR coefficients, we construct the series of output, hours, inflation, wage inflation, and the nominal interest rate that would have obtained with technology shocks only. We then filter these series using the band pass filter advocated by Christiano and Fitzgerald (2003). In the implementation of this filter, we retain the traditional definition of the business cycle as those movements between 6 and 32 quarters. The same filter is applied on the original series. We can thus compute the contribution of technology shocks to the variance of the business cycle components of each series.[5] Notice that in this case, we reconstruct output as the cumulated sum of productivity growth plus hours. The filtered series are reported on figure 3. We obtain that technology shocks account for 17.58% of the variance of the business cycle component of output, 43.03% for hours, 27.81% for inflation, 23.68% for wage inflation, and 26.43% for the Fed funds. As a robustness test, we also use the Hodrik and Prescott (1997) filter, with a smoothing parameter set to 1600, as is customary with quarterly data. In this case, technology shocks account for 18.31% of the variance of the business cycle component of output, 37.16% for hours, 23.76% for inflation, 9.63% for wage inflation, and 23.55% for the Fed funds.

Our findings relative to the contribution of technology shocks to the variance of the business cycle component of hours seem at odds with bivariate evidence reported by Galí and Rabanal (2004), who find a much smaller contribution of technology shocks. To make sure that these results are not an artifact of our SVAR, we conduct the following exercises. First, we estimate a SVAR of productivity growth and labor, using the same identification procedure as outlined above. In this case, technology shocks account for roughly 60% of the forecast error for productivity growth at all forecast horizons. When it comes to hours, technology shocks account for 14% of the forecast error variance for $k = 4$ and 11% for $k = 8, 20$. We obtain similar results with BP or HP filtered data. Notice that in this case, the fraction of the variance of output at business cycle frequencies explained by the technology shock is roughly comprised between 2% and 4%. Hence, we find bivariate results broadly consistent with those reported by Galí (1999) and Galí and Rabanal (2004). Second, we estimate a SVAR of productivity growth, labor, and inflation, using again

[5] As recommended by Christiano and Fitzgerald (2003), we drop two years of data at the beginning and end of the sample before computing these variance ratios.

the same identification procedure. In this case, technology shocks account for roughly 35% of the forecast error for productivity growth at all forecast horizons. When it comes to hours, technology shocks account for 25% of the forecast error variance for $k = 4$ and 20% for $k = 8, 20$. Finally, they account for roughly 40% of the forecast error variance of inflation for $k = 4, 8, 20$. We obtain similar results with BP or HP filtered data. Notice that in this case, the fraction of the variance of output at business cycle frequencies explained by the technology shock increases to roughly 13%. Thus, the mere inclusion of inflation as an additional variable in the SVAR substantially modifies the picture that emerges from a simple bivariate analysis. This emphasizes that these variance decomposition exercises should be interpreted with caution because of their high sensitivity to possible misspecification biases such as those arising in the case of omitted variables..

Overall, these results suggest that technology shocks, while maybe not the dominant source of business cycle, still account for a sizable portion of fluctuations in the variables of interest. 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 The Model

We now expound our theoretical framework. The latter contains a large number of modelling elements that should help it to get a convincing fit.[6] The model is similar in spirit to those of Giannoni and Woodford (2003) and Galí and Rabanal (2004).

3.1 Final Goods and Material Goods

Competitive firms produce a homogeneous final good with the inputs of intermediate goods, according to the CES technology

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

[6] A detailed technical appendix is available from the authors upon request.

where y_t is the quantity of final good produced in period t and $y_t(\varsigma)$ 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

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

Another set of competitive firms produce material goods by combining the same intermediate goods as above. They have access to the CES technology

$$q_t = \left(\int_0^1 q_t(\varsigma)^{(\theta_p-1)/\theta_p} \, \mathrm{d}\varsigma \right)^{\theta_p/(\theta_p-1)}, \tag{3}$$

where q_t is the produced quantity of material goods and $q_t(\varsigma)$ denotes the input of intermediate good ς. Notice that the technologies for producing final and material goods share the same substitution elasticity between any two intermediate goods. Accordingly, the price of material goods will be P_t.

Let $d_t(\varsigma)$ denote the overall demand addressed to the producer of intermediate good ς. The above assumptions imply the following relationship

$$d_t(\varsigma) = \left(\frac{P_t(\varsigma)}{P_t} \right)^{-\theta_p} d_t, \quad d_t \equiv y_t + q_t. \tag{4}$$

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

3.2 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

$$h_t = \left(\int_0^1 h_t(\upsilon)^{(\theta_w-1)/\theta_w} \, \mathrm{d}\upsilon \right)^{\theta_w/(\theta_w-1)}, \tag{5}$$

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

$$h_t(\upsilon) = \left(\frac{W_t(\upsilon)}{W_t}\right)^{-\theta_w} h_t, \tag{6}$$

where the aggregate nominal wage is defined as

$$W_t = \left(\int_0^1 W_t(\upsilon)^{1-\theta_w}\,\mathrm{d}\upsilon\right)^{1/(1-\theta_w)}. \tag{7}$$

Notice that eq. (7) is a direct consequence of the combination of eq. (6) and the zero profits condition.

3.3 Intermediate Goods

In the third sector, monopolistic firms produce the intermediate goods. Each firm $\varsigma \in [0,1]$ is the sole producer of intermediate good ς. Given a demand $d_t(\varsigma)$, it faces the following production possibilities

$$\min\left\{\frac{\mathrm{e}^{z_t}F(n_t(\varsigma))}{1-s_m}, \frac{m_t(\varsigma)}{s_m}\right\} \geq d_t(\varsigma), \quad 0 < s_m < 1, \tag{8}$$

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 value added. This specification is borrowed from Rotemberg and Woodford (1995). Finally, z_t is a productivity shock which evolves according to

$$z_t = \log(g) + z_{t-1} + \zeta_t \tag{9}$$

$$\zeta_t = \rho\zeta_{t-1} + \epsilon_t, \tag{10}$$

where $g > 1$ is the average, gross growth rate of technical progress, $\rho \in (0,1)$, and $\epsilon_t \sim \mathrm{iid}(0, \sigma_\epsilon^2)$. The autocorrelation of productivity shocks is meant to capture the effects of gradual technology diffusion[7], such as those rationalized by Rotemberg (2003).

Additionally, we assume that 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.

[7] Altig et al. (2004) and Galí et al. (2003) also consider autocorrelated growth rates of technical progress.

Over the recent past, a number of authors have argued that including material goods in New Keynesian models is important for obtaining a good empirical fit.[8] In the present paper, following suggestions in Woodford (2003), the material goods device plays an important role in strengthening the degree of strategic complementarity in price setting decisions.

Cost minimization ensures that

$$m_t(\varsigma) = s_m d_t(\varsigma),$$

so that the real cost $\mathbb{C}(d_t(\varsigma))$ of producing $d_t(\varsigma)$ units of good ς is

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

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 $P_T(\varsigma) = \delta^p_{t,T} P_t(\varsigma)$, where $\delta^p_{t,T}$

$$\delta^p_{t,T} = \begin{cases} \prod_{j=t}^{T-1} \pi^{1-\gamma_p} \pi_j{}^{\gamma_p} & \text{if } T > t \\ 1 & \text{otherwise} \end{cases}, \tag{11}$$

where $\pi_t \equiv P_t/P_{t-1}$ represents the (gross) 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. This is an extension of the inflation indexation mechanism considered in Woodford (2003). While with the latter a hybrid new Phillips is only valid in the neighborhood of a zero-inflation steady state, the former enables us to consider strictly positive steady state inflation rates.

Since firm ς is a monopoly supplier, it will take the demand function (4) into account when setting its price. Additionally, it takes into account the fact that this price rate will presumably hold for more than one period -except for the automatic revisions. Now, let $P^*_t(\varsigma)$ denote the price chosen in period t, and let $d^*_{t,T}(\varsigma)$ denote the production of good ς in period T if firm ς last reoptimized

[8] See among others Dotsey and King (2001), Matheron and Maury (2004), Woodford (2003).

its price in period t. According to eq. (4), $d^*_{t,T}(\varsigma)$ obeys the relationship

$$d^*_{t,T}(\varsigma) = \left(\frac{\delta^p_{t,T} P^*_t(\varsigma)}{P_T}\right)^{-\theta_p} d_T.$$

Then, $P^*_t(\varsigma)$ is selected so as to maximize

$$\mathrm{E}_t \sum_{T=t}^{\infty} (\beta\alpha_p)^{T-t} \lambda_T \left\{ (1+\tau_p) \frac{\delta^p_{t,T} P^*_t(\varsigma)}{P_T} d^*_{t,T}(\varsigma) - \mathbb{C}(d^*_{t,T}(\varsigma)) \right\}.$$

Standard manipulations yield the approximate loglinearized first order condition

$$\hat{\pi}_t - \gamma_p \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1} - \gamma_p \hat{\pi}_t\} + \frac{(1-\beta\alpha_p)(1-\alpha_p)}{\alpha_p[(1-s_m)^{-1} + \omega_p\theta_p]} (\hat{w}_t + \omega_p \hat{y}_t), \tag{12}$$

where $\hat{\pi}_t$ is the logdeviation of π_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,[9] 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. Letting $\mu_p \equiv \theta_p/(\theta_p - 1)$, notice that it is the term $(1 - s_m)$ rather than $\left(1 - \mu_p s_m\right)$ that appears in eq. (12). This is a direct result of our assumption that there is no monopoly distortion in the deterministic steady state of the model.

3.4 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

[9] Given the presence of a stochastic trend in technical progress, 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}.

according to the simple rule $W_T(\upsilon) = g^{T-t}\delta^w_{t,T}W_t(\upsilon)$, where $\delta^w_{t,T}$

$$\delta^w_{t,T} = \begin{cases} \prod_{j=t}^{T-1} \pi^{1-\gamma_w}\pi_j{}^{\gamma_w} & \text{if } T > t \\ \\ 1 & \text{otherwise} \end{cases}, \tag{13}$$

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 technical progress. In addition to being economically realistic, this assumption contributes to ensuring the existence of a well-behaved deterministic steady state. Finally, we assume that households are subsidized at rate τ_w. Furthermore, we assume that this rate is such that the monopoly distortion is completely eliminated.

In addition, a typical household must select a sequence of consumptions and nominal bonds holdings. As such, the above described problem makes the choices of wealth accumulation contingent upon a particular history of wage rate decisions, thus leading to households heterogeneity. For the sake of tractability, we assume that the momentary utility function is separable across consumption and leisure. Combining this with the assumption of a complete set of contingent claims market, all the households will make the same choices regarding consumption and will only differ by their wage rate and supply of labor. This is directly reflected in our notations.

Household υ's goal in life is to maximize

$$\mathbb{W}_t = \mathrm{E}_t \sum_{T=t}^{\infty} \beta^{T-t}[\log(c_T - bc_{T-1}) - \mathbb{V}(h_T(\upsilon))], \tag{14}$$

where E_t is the expectation operator, conditional on information available as of time t, $\beta \in (0, 1)$ is the subjective discount factor, $\mathbb{V}(\cdot)$ 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 (14) subject to the sequence of constraints

$$c_t + b_t/i_t + \xi_t \leq (1 + \tau_w)\, w_t(\upsilon)h_t(\upsilon) + b_{t-1}/\pi_t + \mathrm{div}_t, \tag{15}$$

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 $t+1$; ξ_t denotes lump-sum taxes; i_t denotes the gross nominal interest rate.

The first order conditions with respect to c_t and b_t are

$$\lambda_t = \frac{1}{c_t - bc_{t-1}} - \beta b \mathrm{E}_t \left\{ \frac{1}{c_{t+1} - bc_t} \right\}, \tag{16}$$

$$\lambda_t = i_t \beta \mathrm{E}_t \left\{ \frac{\lambda_{t+1}}{\pi_{t+1}} \right\}. \tag{17}$$

Let us define $\hat{\imath}_t$ and $\hat{c}_t$ as the logdeviations of 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

$$\hat{c}_t = \eta \hat{c}_{t-1} + \beta\eta \mathrm{E}_t\{\hat{c}_{t+1}\} - (1 - (1+\beta)\eta)\,\hat{\lambda}_t + \beta\eta \mathrm{E}_t\{\zeta_{t+1}\} - \eta\zeta_t, \tag{18}$$

$$\hat{\lambda}_t = \hat{\imath}_t + \mathrm{E}_t\{\hat{\lambda}_{t+1} - \hat{\pi}_{t+1} + \zeta_{t+1}\}. \tag{19}$$

where we defined

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

Let us now consider the wage setting decision confronting a household drawn to reoptimize its nominal wage rate in period t, say household υ. In the sequel, it will be convenient to define wage inflation $\pi_t^w \equiv W_t/W_{t-1}$. Since the household is a monopoly supplier, it will take the demand function (6) into account when setting its wage. Additionally, it takes into account the fact that this wage rate will presumably hold for more than one period -except for the automatic revision. Now, let $W_t^*(\upsilon)$ denote the wage rate chosen in period t, and let $h_{t,T}^*(\upsilon)$ denote the hours worked in period T if household υ last reoptimized its wage in period t. According to eq. (6), $h_{t,T}^*(\upsilon)$ obeys the relationship

$$h_{t,T}^*(\upsilon) = \left(\frac{g^{T-t}\delta_{t,T}^w W_t^*(\upsilon)}{W_T} \right)^{-\theta_w} h_T. \tag{20}$$

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

$$\mathrm{E}_t \sum_{T=t}^{\infty} (\beta\alpha_w)^{T-t} \left\{ \lambda_T (1+\tau_w) \frac{g^{T-t}\delta_{t,T}^w W_t^*(\upsilon)}{P_T} h_{t,T}^*(\upsilon) - \mathbb{V}(h_{t,T}^*(\upsilon)) \right\}. \tag{21}$$

Standard manipulations yield the approximate loglinear relation

$$\hat{\pi}_t^w - \gamma_w \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1}^w - \gamma_w \hat{\pi}_t\} + \frac{(1-\alpha_w)(1-\beta\alpha_w)}{\alpha_w(1+\omega_w\theta_w)}(\omega_w \phi \hat{y}_t - \hat{\lambda}_t - \hat{w}_t), \tag{22}$$

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

$$\omega_w \equiv \frac{\mathbb{V}_{hh}(h)\,h}{\mathbb{V}_h(h)}, \quad \phi \equiv \frac{F(n)}{F'(n)\,n}.$$

3.5 Monetary Policy and Equilibrium

The monetary authority is assumed to obey a Taylor (1993)-like rule of the form

$$\hat{\imath}_t = \rho_i \hat{\imath}_{t-1} + (1-\rho_i)\left[a_p \hat{\pi}_t + a_y \hat{y}_t\right]. \tag{23}$$

This rule incorporates an interest rate smoothing component and the usual feedback terms: monetary authorities react to the deviation of inflation as well as to the deviations of output from its stochastic trend. A large literature has documented that such simple rules perform well relative to the fully optimal rule.

In equilibrium, it must be the case that $\hat{c}_t = \hat{y}_t$. Combined with eq (23), the final linear system can then be summarized as follows

$$\hat{y}_t = \eta \hat{y}_{t-1} + \beta\eta \mathrm{E}_t\{\hat{y}_{t+1}\} - (1-(1+\beta)\eta)\,\hat{\lambda}_t + \beta\eta \mathrm{E}_t\{\zeta_{t+1}\} - \eta\zeta_t, \tag{24}$$

$$\hat{\lambda}_t = \hat{\imath}_t + \mathrm{E}_t\{\hat{\lambda}_{t+1} - \hat{\pi}_{t+1} + \zeta_{t+1}\}, \tag{25}$$

$$\hat{\pi}_t^w - \gamma_w \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1}^w - \gamma_w \hat{\pi}_t\} + \frac{(1-\alpha_w)(1-\beta\alpha_w)}{\alpha_w(1+\omega_w\theta_w)}(\omega_w \phi \hat{y}_t - \hat{\lambda}_t - \hat{w}_t), \tag{26}$$

$$\hat{\pi}_t - \gamma_p \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1} - \gamma_p \hat{\pi}_t\} + \frac{(1-\beta\alpha_p)(1-\alpha_p)}{\alpha_p[(1-s_m)^{-1} + \omega_p\theta_p]}(\hat{w}_t + \omega_p \hat{y}_t), \tag{27}$$

$$\hat{\pi}_t^w = \hat{\pi}_t + \hat{w}_t - \hat{w}_{t-1} + \zeta_t. \tag{28}$$

This system is solved with the AIM package proposed by Anderson and Moore (1985).

4 Model Estimation

In this section, we describe the model calibration and the minimum distance estimation technique. We then, go on to expound our results.

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. Let $\boldsymbol{\psi}_0 = (\beta, \phi, s_m, \theta_w, \theta_p, \omega_p)'$ denote the vector of calibrated parameters. The calibration is summarized in table 2.

We first set $\beta = 0.99$ as is conventional in the literature. Assuming that F is Cobb-Douglas, i.e. $y = n^{1/\phi}$, we set $\phi = 3/2$, implying a labor share close of $2/3$, 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 F 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 value added is 50%. We set $\theta_p = 10$, so that the long-run markup charged by intermediate goods producers amounts to 11%, consistent with the values reported by Basu and Fernald (1997). Symmetrically, we set $\theta_w = 10$.

4.2 Structural Parameters Estimation

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

$$\boldsymbol{\theta}_k = \frac{\partial \mathbf{z}_{t+k}}{\partial \boldsymbol{\eta}_t^s}.$$

Formally, $\boldsymbol{\theta}_k$ is the first column of $\mathbf{C}_k$, where $\mathbf{C}_k$ is the kth coefficient of $\mathbf{C}(L)$. In the sequel, we define $\boldsymbol{\theta}$ as

$$\boldsymbol{\theta} = \text{vec}([\boldsymbol{\theta}_0, \boldsymbol{\theta}_1, \ldots, \boldsymbol{\theta}_k]'),$$

where the vec $(\cdot)$ operator stacks the columns of a matrix. In the vector $\boldsymbol{\theta}$, we replace the response of $\Delta\hat{a}_t$ with that of logged output, which we obtain by comulating the response of $\Delta\hat{a}_t$ and adding that of $\hat{n}_t$ to the result. We regroup the model's structural coefficients which we seek to estimate in the vector $\boldsymbol{\psi}_1 = (\eta, \gamma_w, \gamma_p, \alpha_w, \alpha_p, \omega_w, \rho_i, a_p, a_y, \sigma_\epsilon)'$. These structural coefficients are selected so as to solve

$$\hat{\boldsymbol{\psi}}_1 = \arg\min_{\boldsymbol{\psi}_1 \in \boldsymbol{\Psi}} \left[\boldsymbol{\theta}^m(\boldsymbol{\psi}_0, \boldsymbol{\psi}_1) - \boldsymbol{\theta}\right]' \mathbf{V}^{-1} \left[\boldsymbol{\theta}^m(\boldsymbol{\psi}_0, \boldsymbol{\psi}_1) - \boldsymbol{\theta}\right],$$

where $\boldsymbol{\theta}^m(\boldsymbol{\psi}_0, \boldsymbol{\psi}_1)$ denotes the theoretical counterpart of $\boldsymbol{\theta}$, $\boldsymbol{\Psi}$ is the set of admissible values for the parameters $\boldsymbol{\psi}_1$ and $\mathbf{V}$ is a diagonal matrix containing the asymptotic variances of $\boldsymbol{\theta}$ along its diagonal.[10] As suggested by Christiano et al. (2001), this choice of weighting matrix ensures that $\boldsymbol{\psi}_1$ is selected so that the model-based IRF lie as much as possible in the confidence interval of the SVAR-based IRF. The minimization is subject to standard constraints.[11] Letting $\boldsymbol{\psi} = (\boldsymbol{\psi}_0', \boldsymbol{\psi}_1')'$, it is convenient to define

$$J(\boldsymbol{\psi}, \boldsymbol{\theta}) = \left[\boldsymbol{\theta}^m(\boldsymbol{\psi}_0, \boldsymbol{\psi}_1) - \boldsymbol{\theta}\right]' \mathbf{V}^{-1} \left[\boldsymbol{\theta}^m(\boldsymbol{\psi}_0, \boldsymbol{\psi}_1) - \boldsymbol{\theta}\right].$$

To obtain the parameters standard errors, we resort to the δ-function method. We start by taking a first order Taylor expansion on the first order condition associated with the minimization of $J(\boldsymbol{\psi}, \boldsymbol{\beta})$ in the neighborhood of the true parameters values. Then let us define

$$\mathbf{D} = -\left[\frac{\partial^2 J(\boldsymbol{\psi}, \boldsymbol{\theta})}{\partial \boldsymbol{\psi}_1 \partial \boldsymbol{\psi}_1'}\right]^{-1} \left[\frac{\partial^2 J(\boldsymbol{\psi}, \boldsymbol{\theta})}{\partial \boldsymbol{\psi}_1 \partial \boldsymbol{\theta}'}\right].$$

Applying standard reasoning, we obtain

$$\sqrt{T}(\hat{\boldsymbol{\psi}}_1 - \boldsymbol{\psi}_1) \underset{a}{\sim} \mathrm{N}(\mathbf{0}, \mathbf{D}\boldsymbol{\Sigma}_\theta\mathbf{D}'),$$

where $\boldsymbol{\Sigma}_\theta$ is the variance covariance matrix of $\boldsymbol{\theta}$ and T is the sample size. In practice, all the partial derivatives are computed numerically at the point estimate. Notice finally that $J(\boldsymbol{\psi}, \boldsymbol{\theta})$ is asymptotically distributed as $\chi^2(\dim(\boldsymbol{\theta}) - \dim(\boldsymbol{\psi}_1))$.

[10] This estimation method relates to that of Amato and Laubach (2003), Boivin and Giannoni (2003), Christiano et al. (2001), Giannoni and Woodford (2003), Gilchrist and Williams (2000), and Rotemberg and Woodford (1997, 1999).

[11] The constrained minimization is undertaken with the sequential quadratic programming provided in the MATLAB optimization package.

4.3 Estimation Results

Table 3 reports our estimation results. Additionally, figure 4 plots the theoretical and empirical impulse responses as well as the 90% asymptotic confidence interval of the latter.[12] As is clear from the graph, the model does a good job of reproducing the main features of the empirical responses to a permanent technology shock. In particular, it captures well the protracted declines of inflation, wage inflation, hours, and the nominal interest rate. However, it is less successful at reproducing the initial inflexion of output. In spite of this, the global specification test does not allow us to reject the model. We obtain a J-stat of 28.10, with a p-value of 99.9%. We are nonetheless reluctant to emphasize this result because of the large number of degrees of freedom and the well-documented lack of power of such global specification tests.

During the course of the estimation, we first tried to estimate all the parameters in $\boldsymbol{\psi}_1$. Two parameters were characterized by binding constraints, namely $a_y = 0$ and $\gamma_w = 1$. In a second stage, we enforced these equalities and estimated the remaining parameters.[13] This suggests that the degree of wage indexation to past wage inflation is very high and that monetary authorities did not particularly grant attention to the dynamics of the deviation of output from its stochastic trend. An alternative interpretation concerning a_y is that our sample comprises different monetary policy regimes in which output stabilization did not receive the same attention. In particular, according to Clarida et al. (2000), monetary authorities were maybe reluctant to correctly stabilize output fluctuations is the pre-Volcker period. These differing monetary policy regimes and their consequence might create a tension in our estimation procedure, summarized by a zero feedback effect of detrended output on the policy instrument. We further explore this possibility in the next section.

When it comes to the price setting side of the model, we obtain the following results. First, the probability of no price adjustment is $\alpha_p = 0.78$, implying an average spell of no reoptimization of slightly more than three quarters and a half. Though small compared with other estimates, e.g.

[12] Here, and in the following pictures, the size of the technology shock is normalized to one standard deviation.

[13] Accordingly, we substract 2 to $\dim(\boldsymbol{\psi}_1)$ to obtain the number of degrees of freedom of the χ^2 test.

Galí and Gertler (1999), this figure is higher than what suggest microeconomic evidence reported by Bils and Klenow (2004), even when one takes into account the effects of sampling uncertainty. However, it is broadly consistent with the results obtained by Blinder et al. (1998). The degree of price indexation to past inflation is significant, with $\gamma_p = 0.3982$. This implies that during each quarters, fixed prices incorporate roughly 40% of past inflation. The probability of no wage adjustment is $\alpha_w = 0.8369$, implying an average spell of no reoptimization of slightly more than six quarters. This value is higher than that reported by Christiano et al. (2001).

When it comes to preference parameters, we obtain standard results. First, the elasticity of marginal labor disutility is large, with $\omega_w = 3.2646$, but imprecisely estimated. This value is in line with estimates reported by Prescott (2004), though slightly higher. Second, given $\eta = 0.4997$ and $\beta = 0.99$, we easily deduce that $\bar{b} = 0.9040$. In our sample, average, quarterly labor productivity growth amounts to 0.52%, that is $g = 1.0052$, so that $b = 0.9087$. Thus, the model requires a high degree of habit formation to capture the persistence of output and hours.

When it comes to the remaining monetary policy parameters, we obtain $a_p = 1.2019$, suggesting that over the period 1955-2002, monetary authorities reacted sharply to the deviations of inflation, in accordance with the Taylor principle. This result stands in contrast with the view emphasized by Clarida et al. (2000), who find the pre-Volcker period might be characterized by a failure to fulfill the Taylor principle. However, our conclusion is consistent with experiments reported in Christiano et al. (2001). In particular, they show that with a similar Taylor rule as ours, and a value of a_p close to that estimated, the economy's response to monetary shocks does not differ much from the predictions of a monetary SVAR. We also obtain $\rho_i = 0.7369$, a value close to that retained in the literature. This value suggests that monetary authorities cared about smoothing the nominal interest rate. Another interpretation is that the model does not generate enough endogenous persistence via the feedback effects in eq. (23), so that allowing for extra serial correlation in $\hat{\imath}_t$ is necessary.

The standard error of technology shocks σ_ϵ is close to 0.45%. Notice also that $\rho = 0.56$, suggesting that the model lacks endogenous propagation mechanisms. This implies that the standard of the growth rate of technical progress is about 0.54, a standard value when compared with other US estimates.

We experienced with ρ and constrained this parameter to zero. This resulted in a higher value of σ_ϵ but did not quantitatively affect the other estimates. In this case, the global specification test remained supportive of our model. Allowing for a positive ρ is however essential to capture the inverted-hump-shaped dynamics of hours at short horizons.

4.4 Does the SVAR Really Identify Technology Shocks?

In light of a recent set of papers questioning the ability of SVAR models to identify structural shocks, e.g. Chari et al. (2004), Dupaigne et al. (2005), and Erceg et al. (2004), one may wonder whether ours does a good job of identifying technology shocks. Our DSGE model provides us with a natural environment where to investigate this question quantitatively. This is not done just for the sake of assessing how well our SVAR model captures technology shocks. Indeed, since we estimate our DSGE model so as to replicate SVAR-based impulse response functions (IRF), it seems necessary to investigate whether our estimated parameters are corrupted by a possible poor identification of technology shocks.

In setting up this robustness analysis, we follow Altig et al. (2004) and implement the simulation experiment described below.

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 ρ and σ_ϵ to simulate a series of ζ_t. Let $\mathbf{z}_{\mathrm{m},t}^{(i)}$, $t = 1, \ldots, T$, denote the ith simulated path of $(\Delta\hat{a}_t, \hat{n}_t, \hat{\pi}_t, \hat{\pi}_t^w, \hat{\imath}_t)'$.

2. We draw shocks from the SVAR residuals, eliminate the SVAR-based technology shocks, and compute a sample path for $(\Delta\hat{a}_t, \hat{n}_t, \hat{\pi}_t, \hat{\pi}_t^w, \hat{\imath}_t)'$ according to the SVAR parameters. Let $\mathbf{z}_{\mathrm{v},t}^{(i)}$, $t = 1, ..., T$, denote the ith simulated path from this second step.

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

Steps 1 to 3 are repeated 1000 times ($i = 1, \ldots, 1000$), thus generating a population of IRF. These are sorted in ascending order, and we simply keep the 50th and 950th simulated IRF to form a 90% confidence interval. Notice that implicit in this simulation exercise is the assumption that $\mathbf{z}_{\mathrm{m},t}^{(i)}$ and $\mathbf{z}_{\mathrm{v},t}^{(i)}$ are orthogonal. This assumption is of course consistent with the identifying constraints in the empirical SVAR.

The result of this simulation experiment is reported on figure 5. This figure clearly shows that the empirical SVAR manages to identify the true (i.e. the DSGE model) technology shocks. More precisely, the median responses have the same signs and shapes as the true responses. These conclusion are consistent with simulation results reported by Erceg et al. (2004).

What can we conclude from this exercise? As shown by Chari et al. (2004) and Dupaigne et al. (2005), a misspecified SVAR model can, under certain conditions, produce IRF that are not compatible with the true data generating process.[14] In this case, estimating a DSGE by means of an MDE procedure applied on impulse response can yield severe biases. However, if the data were indeed generated by the sticky price DSGE model, then the previous simulations clearly show that a SVAR similar to that estimated in section 2 would correctly identify the "true" technology shocks.

5 Counterfactual Analysis

Having estimated the structural parameters of our model, we are now in a position to answer the question asked at the beginning of the paper: Would the economy's dynamic response have been different from what the SVAR indicates if US monetary authorities systematic response to technology shocks had been optimal? To answer this question, we follow the methodology advocated by Woodford (2003). We start by deriving the appropriate welfare objective and then go on to compute the economy's response to a permanent technology shock under the optimal monetary

[14] For example, a SVAR can identify technology shocks leading to a decline in hours worked whereas the true data generating process, say an RBC model, implies that hours rise in response to a technology shock.

policy.

5.1 Optimal Monetary Policy

Let us define the natural rate of output $\hat{y}_t^n$ as the level of detrended output that would have prevailed in the absence of nominal rigidities. Define similarly the output gap $\hat{x}_t$ as the difference $\hat{y}_t - \hat{y}_t^n$. Then standard yet tedious calculations yield the approximate utility-based loss function

$$\mathbb{W}_0 = -\Omega \mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \{\lambda_p(\hat{\pi}_t - \gamma_p \hat{\pi}_{t-1})^2 + \lambda_w(\hat{\pi}_t^w - \gamma_w \hat{\pi}_{t-1})^2 + \lambda_x(\hat{x}_t - \delta \hat{x}_{t-1})^2\} + \text{t.i.p.} + \mathcal{O}(||\epsilon||^3), \quad (29)$$

where t.i.p. stands for "terms independent of policy", and

$$\Omega = \frac{\left(1-\beta\bar{b}\right)\left(\theta_p \xi_p^{-1} + \theta_w \phi^{-1} \xi_w^{-1}\right)}{2\left(1-\bar{b}\right)}, \qquad \lambda_p = \frac{\theta_p \xi_p^{-1}}{\theta_p \xi_p^{-1} + \theta_w \phi^{-1} \xi_w^{-1}},$$

$$\lambda_w = \frac{\theta_w \phi^{-1} \xi_w^{-1}}{\theta_p \xi_p^{-1} + \theta_w \phi^{-1} \xi_w^{-1}}, \qquad \lambda_x = \frac{(1-\bar{b})^{-1}\left(1-\beta\bar{b}\right)^{-1} \varkappa}{\theta_p \xi_p^{-1} + \theta_w \phi^{-1} \xi_w^{-1}},$$

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

and δ and $\varkappa$ are complicated functions of the structural parameters.[15] The values of λ_p, λ_w, λ_x, and δ are reported in table 4. Notice that this approximate loss function is exactly similar to that derived by Giannoni and Woodford (2003). This result was not warranted since our model differs from theirs due to the presence of permanent technology shocks and material goods.

The monetary authorities' program consists in maximizing the (approximate) welfare criterion (29), subject to the structural constraints

$$\hat{x}_t = \eta \hat{x}_{t-1} + \beta\eta \mathrm{E}_t\{\hat{x}_{t+1}\} - (1-(1+\beta)\eta)(\hat{\lambda}_t - \hat{\lambda}_t^n), \quad (30)$$

$$\hat{\pi}_t - \gamma_p \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1} - \gamma_p \hat{\pi}_t\} + \varpi \xi_p[(\hat{w}_t - \hat{w}_t^n) + \omega_p \hat{x}_t], \quad (31)$$

$$\hat{\pi}_t^w - \gamma_w \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1}^w - \gamma_w \hat{\pi}_t\} + \xi_w[\omega_w \phi \hat{x}_t - (\hat{\lambda}_t - \hat{\lambda}_t^n) - (\hat{w}_t - \hat{w}_t^n)], \quad (32)$$

$$\hat{\pi}_t^w = \hat{\pi}_t + \hat{w}_t - \hat{w}_{t-1} + \zeta_t, \quad (33)$$

[15] For further details, see Gianonni and Woodford (2003), as well as our technical appendix.

where $\hat{w}_t^n$ and $\hat{\lambda}_t^n$ are stochastic variables beyond the control of monetary authorities,[16] and where we defined the composite parameter

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

Solving the above program results in a system of first order conditions and constraints that we solve, once again, with the AIM algorithm.

5.2 Results and Discussion

Given the parameter vector $\boldsymbol{\psi}$ obtained in the previous section, we obtain values for λ_p, λ_w, λ_x, and δ, which are listed in table 4. Our results stand in contrast with previous estimates derived by Giannoni and Woodford (2003). In particular, our results suggest that the utility-based loss function puts a relatively small weight on $(\hat{\pi}_t - \gamma_p\hat{\pi}_{t-1})^2$, with $\lambda_p = 0.116$. The difference might be explained as follows. First, we use a much longer dataset than Giannoni and Woodford (2003). Second, we estimate our model by focussing on a different shock. The fact that our conclusions differ is perhaps a limitative feature of the limited information strategy adopted in the present paper as well as in Giannoni and Woodford (2003).

Having solved the new dynamic system, we can compute the economy's responses to a permanent technology shock under the optimal monetary policy. These responses are reported in figure 6. For ease of comparison, we also report the responses implied by the structural model with a Taylor rule and those implied by the SVAR. Once again, we include the VAR-based confidence intervals.

Though the dynamics of the nominal interest rate under the simple Taylor rule shares little resemblance with the optimal response of $\hat{\imath}_t$, it is difficult on the basis of our experiment to reject the null hypothesis that the observed dynamics of output, hours, inflation, and wage inflation do not differ from their optimal counterparts. In particular, the dynamics of output under the assumed

[16] These variables are, respectively, the stationarized wage rate and the stationarized Lagrange multiplier on the household's budget constraint, both taken in logdeviation from their steady state values, absent nominal rigidities, i.e. under full price flexibility.

Taylor rule and under the optimal policy are virtually indistinguishable. The negative dynamics of hours is slightly less pronounced under the optimal policy. The same applies for inflation and wage inflation.

We can construct a formal test to investigate the null of no difference by constructing the following Q statistic

$$Q = [\boldsymbol{\theta}^o(\boldsymbol{\psi}_0, \boldsymbol{\psi}_1) - \boldsymbol{\theta}]'\mathbf{V}^{-1}[\boldsymbol{\theta}^o(\boldsymbol{\psi}_0, \boldsymbol{\psi}_1) - \boldsymbol{\theta}],$$

where $\boldsymbol{\theta}^o(\boldsymbol{\psi}_0, \boldsymbol{\psi}_1)$ is $\boldsymbol{\theta}$'s theoretical counterpart under the optimal monetary policy. The Q statistic is distributed as a χ^2 with degrees of freedom equal to $\dim(\boldsymbol{\theta})$. In this exercise, we neglect the possibility of sampling uncertainty on the estimated value of $\boldsymbol{\psi}_1$, consistently with the spirit of our MDE strategy. As it turns out, the null hypothesis is accepted with a p-value well above 90%.

We exclude the dynamic response of $\hat{\imath}_t$ from $\boldsymbol{\theta}$ to conduct this test, because the dynamics of the policy instrument is ultimately irrelevant for our purpose. To see this, notice that under the simple Taylor rule, monetary authorities first select the nominal interest rate and let the economy optimally react to the way in which this variable is selected. In contrast, under the optimal monetary policy, the Central Bank selects directly the inflation rate, the wage inflation rate, and the output gap, and the nominal interest rate is residually deduced from the dynamics of the rest of the economy. Another way of saying this is that under the simple Taylor rule, the nominal interest rate is a relevant state variable which contributes to determining the dynamics of the rest of the economy while it does not belong to the set of state variables under the optimal monetary policy. In this case, the system is augmented with additional state variables, namely the Lagrange multipliers associated with constraints (30)-(32).

Our results substantially differ from those of Galí et al. (2003). The latter find no evidence in support of the view that monetary policy was optimal over the sample period studied in the present paper. The principal reason why we obtain such contrasted results derives from the assumption that prices and wages are both sticky. In an environment where only prices are sticky, it is possible for the Central Bank to completely stabilize inflation and the output gap, simultaneously. Thus, as long as the SVAR-based impulse responses of inflation are statistically different from zero, it is possible that a simple χ^2 test as that proposed above would reject the optimality hypothesis. However, as shown by Erceg et al. (2000), as soon as one assumes that wages are also sticky, the Central Bank can no longer simultaneously stabilize inflation, wage inflation, and the output gap. In this case, it is possible that the optimal response of inflation is different from zero. This is what we obtain in practice in our own exercise.

To verify this intuition, we propose the following exercise. In a first step, we reestimate our DSGE model, assuming flexible wages (this amounts to imposing $\gamma_w = \alpha_w = 0$). During the course of the estimation, we encountered two different problems. As above, the parameter a_y is driven toward 0. Additionally, the parameter γ_p is driven toward 1. We accordingly enforce these equalities. More problematic is our finding that a_p is driven below one. In this case, we encounter the usual indeterminacy problem. Dealing with the latter is beyond the scope of the present paper, so that we simply impose the restriction $a_p = 1.01$. The remaining parameters are estimated, and, while broadly satisfying (with a p-value of 45%), the overall fit of our model is poor, especially when it comes to hours and wage inflation, as shown in figure 7.[17] Second, we recompute the approximate loss function (imposing $\lambda_w = 0$ and $\lambda_p = 1$), and rerun our simple χ^2 test. We obtain a p-value of zero, thus rejecting unambiguously the optimality hypothesis. As is clear from figure 7, the optimal response of inflation is uniformly zero and, thus drives the statistic Q to high values. Additionally the optimal responses of wage inflation and hours somewhat differ from their SVAR-based counterpart. This is all the more penalizing as the confidence interval of the SVAR-based response of is relatively narrow. This exercise demonstrates that the mere inclusion of sticky wages completely overturns the conclusion that one would have reached based on a simple sticky price model.

It must be emphasized that our counterfactual experiment is not a priori biased toward accepting the null hypothesis. In setting up this exercise, we left a priori no chance to the model with an "ad-hoc" Taylor rule to reproduce the economy's dynamics under the optimal monetary policy. In

[17] The remaining parameter values are $\omega_w = 0.949$, $\eta = 0.494$, $\alpha_p = 0.674$, $\sigma_\epsilon = 0.628$, and $\rho = 0.361$. All these parameters were found significant at the usual 95% confidence level.

fact, one may even argue that we a priori hampered the model, in the sense that the "ad-hoc" Taylor rule does not belong to the same parametric class as that of the optimal rule. Thus, one can view our thought experiment as a very conservative (limited information) test of optimality.

The amplitude of the dynamics of the nominal interest rate under optimal monetary policy might seem too large. Thus, care should be taken when interpreting our results. As is well known in the literature, the optimal monetary policy calls for fairly volatile nominal interest rates. On this point, our paper is no exception. This, however, would not necessarily be the case if the model included an interest rate smoothing motive in the monetary authorities loss function, resulting for example from transaction frictions.

5.3 Subsample Analysis

A number of recent papers have argued that US monetary policy experienced a drastic structural break after the appointment of Paul Volcker as Chairman of the Fed. This change in US monetary policy is likely to have sizable consequences on our previous discussion. Following Galí et al. (2003), we investigate this question further and reconduct our analysis over two separate subsamples. The first one, referred to as the pre-Volcker period, ranges from 1955(1) to 1979(3). The second one, referred to as the post-Volcker period, ranges from 1982(4)-2002(4).

We thus reestimate the SVAR of section 2 and reestimate accordingly the structural parameters of our model. In doing so, we allow for all the parameters to change, hereby acknowledging that, if any, structural breaks might have affected other dimensions of the economy than solely monetary policy.[18]

5.3.1 The Pre-Volcker Period

The estimated parameters are reported in the second column of table 3. We encountered similar problems with a_y and γ_w as noted before. Additionally, we were not able to obtain an estimate

[18] See Ahmed et al. (2004) and the references cited herein for a discussion on the apparent reduction of the volatility of real GDP growth and inflation in the US since 1984.

for ω_w. We thus constrained this parameter to its value estimated with the complete sample. Interestingly, we do not obtain parameters that significantly differ from their estimated values with the complete sample. Notice also that γ_p and ρ_i are not estimated precisely. The model-based and SVAR-based IRFs are reported on figure 8. As is clear, the model is less successful at matching the SVAR-based IRF, though the p-value of the overidentification test is still higher than 90%.

We now perform our (limited information) test of optimality. Given the parameters previously estimated, we recompute λ_p, λ_w, λ_x, and δ. The results are reported in the second row of table 4. As can be seen, our previous findings are not qualitatively altered. We then compute the Q statistic defined above and obtain results still supporting the optimality hypothesis, with a p-value of 60.35%. Figure 8 shows that there is a more marked difference between the SVAR-based IRF and the model-based IRF under optimal policy than in the previous exercise. However, our formal statistical test rejects the significance of this difference.

Once again, we reestimate the model under the assumption of perfect wage flexibility. As above, a_y is driven toward 0 and γ_p toward 1. We enforce these equalities. We still obtain that a_p is driven below one. As above, we simply impose the restriction $a_p = 1.01$. The remaining parameters are estimated. The overall fit of our model is good, with a p-value above 90%, as shown in figure 10.[19] Second, we recompute the approximate loss function (still imposing $\lambda_w = 0$ and $\lambda_p = 1$), and rerun our simple χ^2 test. We once again obtain a p-value of zero, thus rejecting unambiguously the optimality hypothesis. As is clear from figure 10, it is the zero response of inflation under the optimal monetary policy that explains this rejection.

Thus, had we neglected the significant presence of wage stickiness, we would have concluded that US monetary policy was not optimal during the pre-Volcker period. To the contrary, our exercise suggests that, at lest when it comes to technology shock, the Fed managed to engineer the correct responses of inflation, wage inflation, and the output gap.

[19]The remaining parameter values are $\omega_w = 1.205$, $\eta = 0.495$, $\alpha_p = 0.661$, $\sigma_\epsilon = 0.633$, and $\rho = 0.319$. All these parameters were found significant at the usual 95% confidence level.

5.3.2 The Post-Volcker Period

The estimated parameters are reported in the last column of table 3. Once again, we encountered similar problems with a_y, ω_w, and γ_w as noted before. We consequently set $a_y = 0$, $\gamma_w = 1$, as before. In the present case, ω_w converged toward zero, thus suggesting a substantial increase in the elasticity of the labor supply. Additionally, we were not able to obtain an estimate for a_p. In a first step, the parameter converged to a value close to one, but due to a possible lack of identification, we obtained very large standard errors for this and other parameters. We thus prefer to constrain it to a small value ($a_p = 1.01$), so as to get sensible results. The remaining parameter estimates are substantially modified compared to the previous sample. In particular, the degree of nominal rigidity in the goods market is much lower.

The model-based and SVAR-based IRFs are reported on figure 9. Notice that in this case, the VAR-based confidence intervals are fairly large. Accordingly, the estimated IRF do not seem to be very informative. This might partly explain the problems described above. However, the model is successful at matching the SVAR-based IRF, and the p-value of the overidentification test is well above 90%.

We now perform our (limited information) test of optimality. Given the parameters previously estimated, we recompute λ_p, λ_w, λ_x, and δ. The results are reported in the last row of table 4. As can be seen, the loss function is highly modified due to the changes in the structural parameters. In particular, the loss function grants more weight to inflation than our previous exercise suggests. We then compute the Q statistic defined above and obtain results that still support the optimality hypothesis, with a p-value well above 90%, as appears on figure 9.

To conclude this exercise, we reestimate the model under the assumption of perfect wage flexibility. Once again, a_y is driven toward 0. The parameter γ_p is now driven toward 0. We thus enforce these equalities. We still obtain that a_p is driven to values very close to one, but with a very large standard error. As above, we simply impose the restriction $a_p = 1.01$. The remaining parameters are estimated. The overall fit of our model is good, with a p-value above 90%, as shown in figure

11.[20] Second, we recompute the approximate loss function (still imposing $\lambda_w = 0$ and $\lambda_p = 1$), and rerun our simple χ^2 test. We now obtain a p-value well above 90%, thus accepting the optimality hypothesis. As is clear from figure 10, the difference between the SVAR-based and the optimal responses is sometimes large, but the SVAR-based responses are not estimated very precisely, so that acknowledging this large sampling uncertainty leads us to accept the null hypothesis.

Of course, this conclusion is consistent with the subsample analysis conducted by Galí et al. (2003). Thus, with or without sticky wages, we fail to reject the null hypothesis that the Fed correctly reacted to permanent technology shocks in the post-Volcker period. However, we insist that this exercise should be interpreted with caution, because of the large sampling uncertainty associated with the estimated SVAR. The latter might yield corrupted structural parameter estimates, and substantially reduces the meaningfulness of our simple χ^2 test.

6 Conclusion

In this paper, we asked the question: Would the economy's dynamic response have been different from what the SVAR indicates if US monetary authorities systematic response to technology shocks had been optimal? To answer this question, we have first characterized the US economy's responses to permanent supply shocks using standard long-run restrictions in a structural vector autoregression (SVAR) over the sample 1955(1)-2002(4). We obtain that technology shocks, while maybe not the dominant source of business cycle fluctuations, still account for a sizable portion of the variance of inflation, hours, and other variables. This in itself 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. Using this small model, we were then able to characterize the optimal monetary policy, i.e. the monetary policy that maximizes welfare in an environment where staggered price and wage setting are the only distortion to be corrected by monetary authorities.

[20] The remaining parameter values are $\omega_w = 3.300$, $\eta = 0.317$, $\alpha_p = 0.321$, $\sigma_\epsilon = 0.524$, and $\rho = 0.174$. With the exception of ω_w and ρ, all these parameters were found significant at the usual 95% confidence level.

Our main conclusions are as follows. First, the economy's responses under actual US monetary policy does not significantly differ from those implied by the outcome of optimal monetary policy. Second, this conclusion still holds when we split the sample into two separate periods, one covering the pre-Volcker era and the other covering the post-Volcker era. However, we do obtain evidence of a change in monetary policy, but the latter seems to originate from changes in the deep parameters rather than solely from changes in the parameters summarizing monetary policy.

Our results stand in contrast with the conclusions reached by Galí et al. (2003). The main reason for this discrepancy is that we assume wage stickiness in addition to price stickiness. In such an environment, the optimal response of inflation to a permanent technology shock need not be uniformly zero, in contrast with a model with only sticky prices, as in Galí et al. (2003). Furthermore, our econometric evaluation of the DSGE model suggests that sticky wages are an important model component in terms of goodness-of-fit.

These conclusions warrant some words of caution. Under the assumed structure of the model, there is no interest rate smoothing motive for a benevolent policy maker desiring to maximize social welfare. As a result, the nominal interest rate exhibits a high volatility under the optimal monetary policy. It is a priori unclear whether including such a motive in the central bank loss function would modify our conclusion. We leave this issue for future research.

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Table 1. Variance Decomposition

Forecast Horizon	**0**	**4**	**8**	**20**
$\Delta\hat{a}_t$	0.28 [0.07,0.68]	0.28 [0.12,0.61]	0.29 [0.14,0.60]	0.29 [0.15,0.60]
$\hat{n}_t$	0.36 [0.05,0.62]	0.31 [0.04,0.57]	0.27 [0.04,0.53]	0.29 [0.06,0.50]
$\hat{\pi}_t$	0.17 [0.00,0.45]	0.38 [0.02,0.64]	0.43 [0.03,0.69]	0.45 [0.03,0.70]
$\hat{\pi}_t^w$	0.01 [0.00,0.21]	0.12 [0.03,0.30]	0.21 [0.05,0.39]	0.24 [0.05,0.44]
$\hat{\imath}_t$	0.17 [0.00,0.44]	0.32 [0.02,0.60]	0.37 [0.02,0.65]	0.41 [0.03,0.67]

Notes: Estimated forecats error variance decomposition from the SVAR. The values in brackets are the confidence intervals based on 1000 bootstrap replications of the estimated VAR.

Table 2. Calibrated Parameters

Parameters	**Value**	**Interpretation**
β	0.9900	Subjective discount factor
ϕ	1.5000	Inverse elasticity of output wrt labor
s_m	0.5000	Share of material goods in value added
θ_w	10.0000	Price elasticity of labor demand
θ_p	10.0000	Price elasticity of intermediate goods demand
ω_p	0.5000	Elasticity of real marginal cost wrt production

Table 3. Structural Parameters

Parameters		**Value**		**Interpretation**
Sample Period	1955(1)–2002(4)	1955(1)–1979(3)	1982(4)–2002(4)	
γ_p	0.3982 [0.1603]	0.3650 [0.2523]	0.4199 [0.5871]	Price indexation parameter
γ_w	1.0000 [*]	1.0000 [*]	1.0000 [*]	Wage indexation parameter
α_p	0.7763 [0.0536]	0.7758 [0.0683]	0.6520 [0.1755]	Proba. of no price reoptimization
α_w	0.8369 [0.0863]	0.7863 [0.1218]	0.8266 [0.0807]	Proba. of no wage reoptimization
ω_w	3.2646 [9.4059]	3.2646 [*]	0.0000 [*]	Elasticity of $\mathbb{V}_h$
η	0.4997 [0.0029]	0.4962 [0.0082]	0.3394 [0.3187]	Composite habit parameter
ρ_i	0.7369 [0.1231]	0.3459 [0.4869]	0.9674 [0.3432]	Interest rate smoothing
a_p	1.2019 [0.3547]	1.0342 [0.1588	1.0100 [*]	Interest rate elasticity wrt $\hat{\pi}_t$
a_y	0.0000 [*]	0.0000 [*]	0.0000 [*]	Interest rate elasticity wrt $\hat{y}_t$
ρ	0.5567 [0.1122]	0.5113 [0.1310]	0.2438 [0.3007]	Autocorr. of technology shocks
σ_ϵ	0.4517 [0.1066]	0.5288 [0.1251]	0.4704 [0.2069]	S.E. of technology shocks

Notes: Estimated and calibrated parameters. The values in brackets are the standard errors computed as indicated in the text. A star refers to a parameter which hit a constraint during the course of the first stage estimation

Table 4. Loss Function

	λ_p	λ_w	λ_x	δ
Full Sample	0.1160	0.8840	0.0162	0.7869
Pre-Volcker	0.1937	0.8063	0.0128	0.6742
Post-Volcker	0.6450	0.3550	0.0066	0.3222

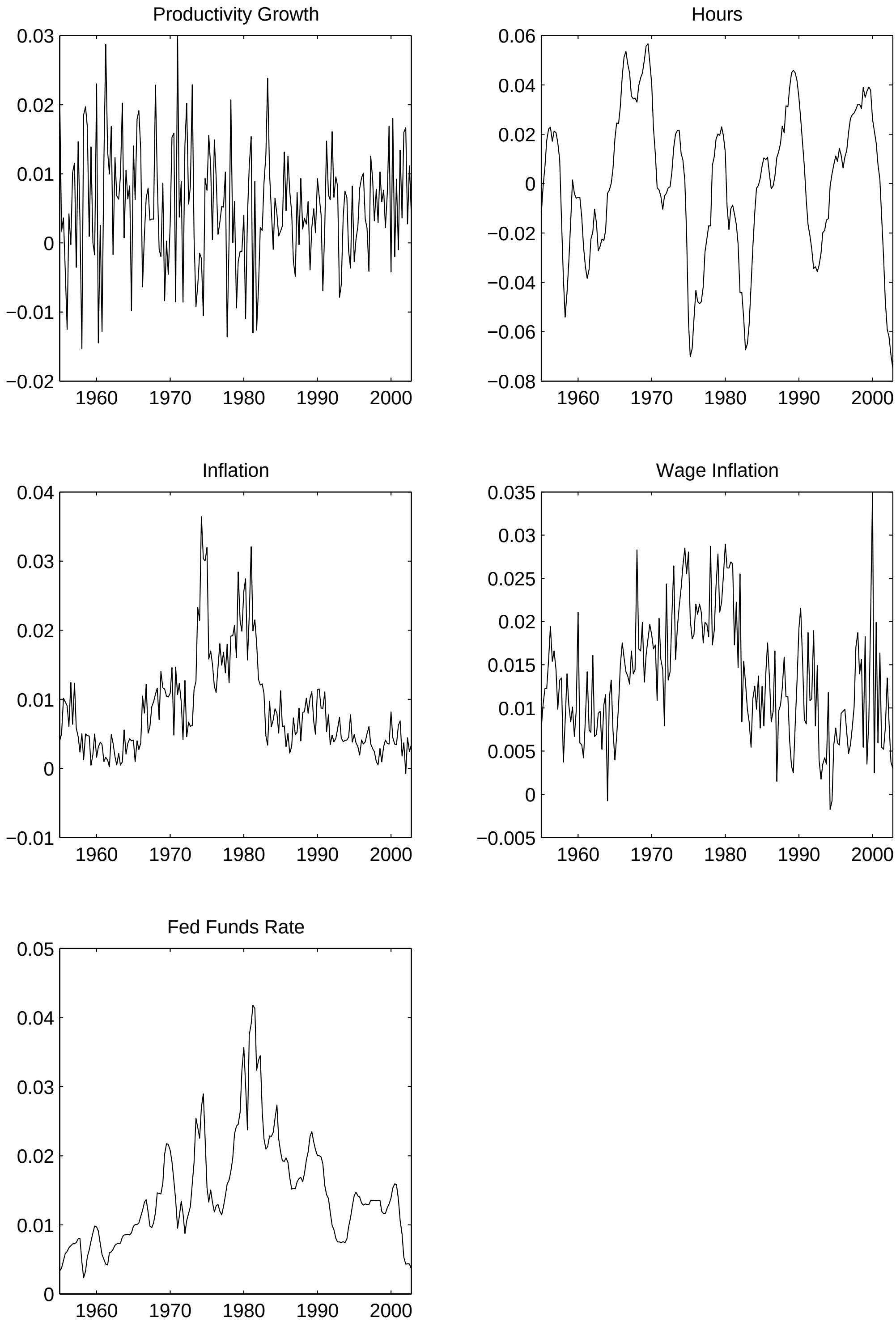

Figure 1: Data used in analysis. Sample period 1955(1)-2002(4).

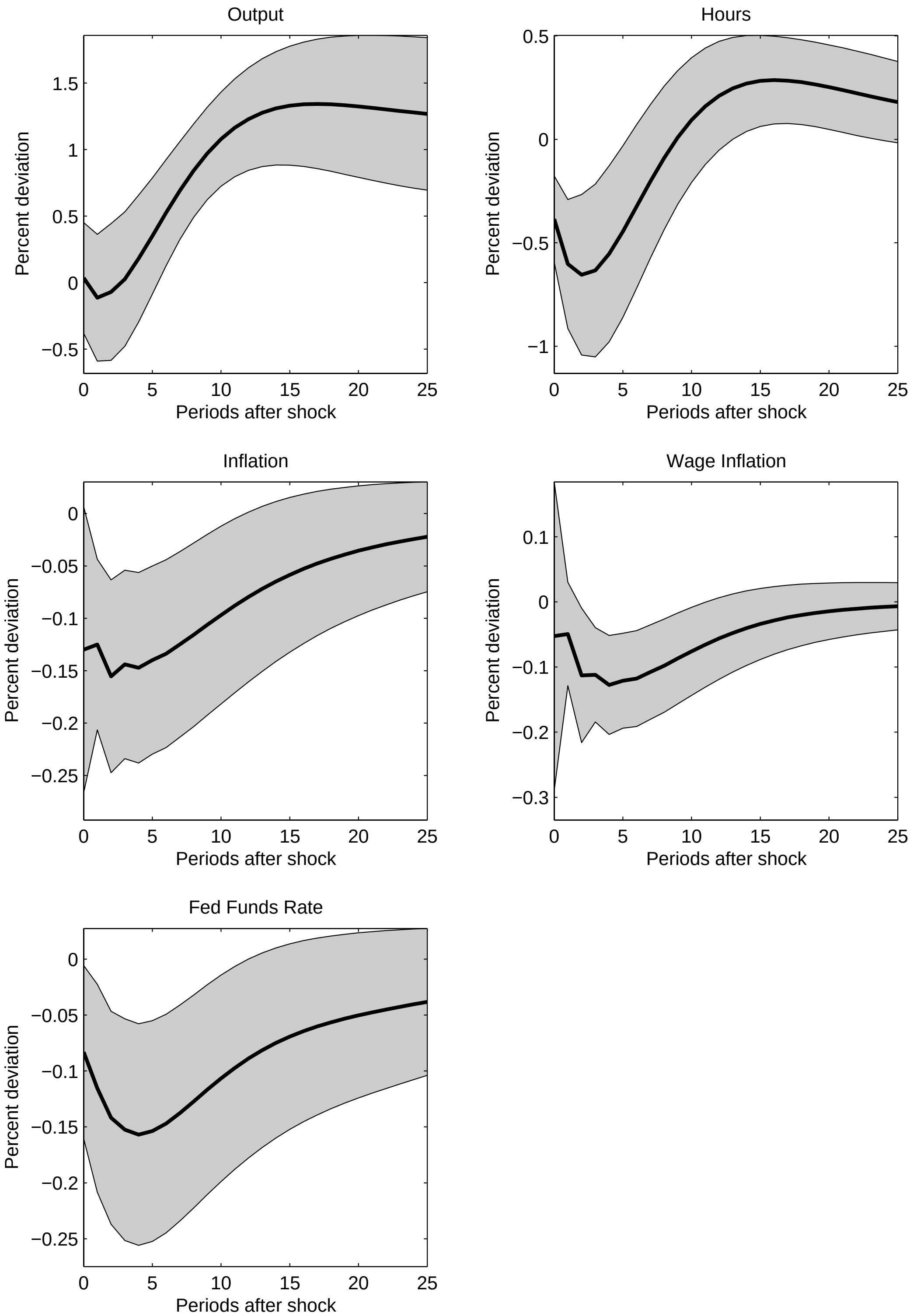

Figure 2: Dynamic responses to a permanent technology shock in the SVAR model. The grey area represents the 90% asymptotic confidence interval of the VAR IRF's.

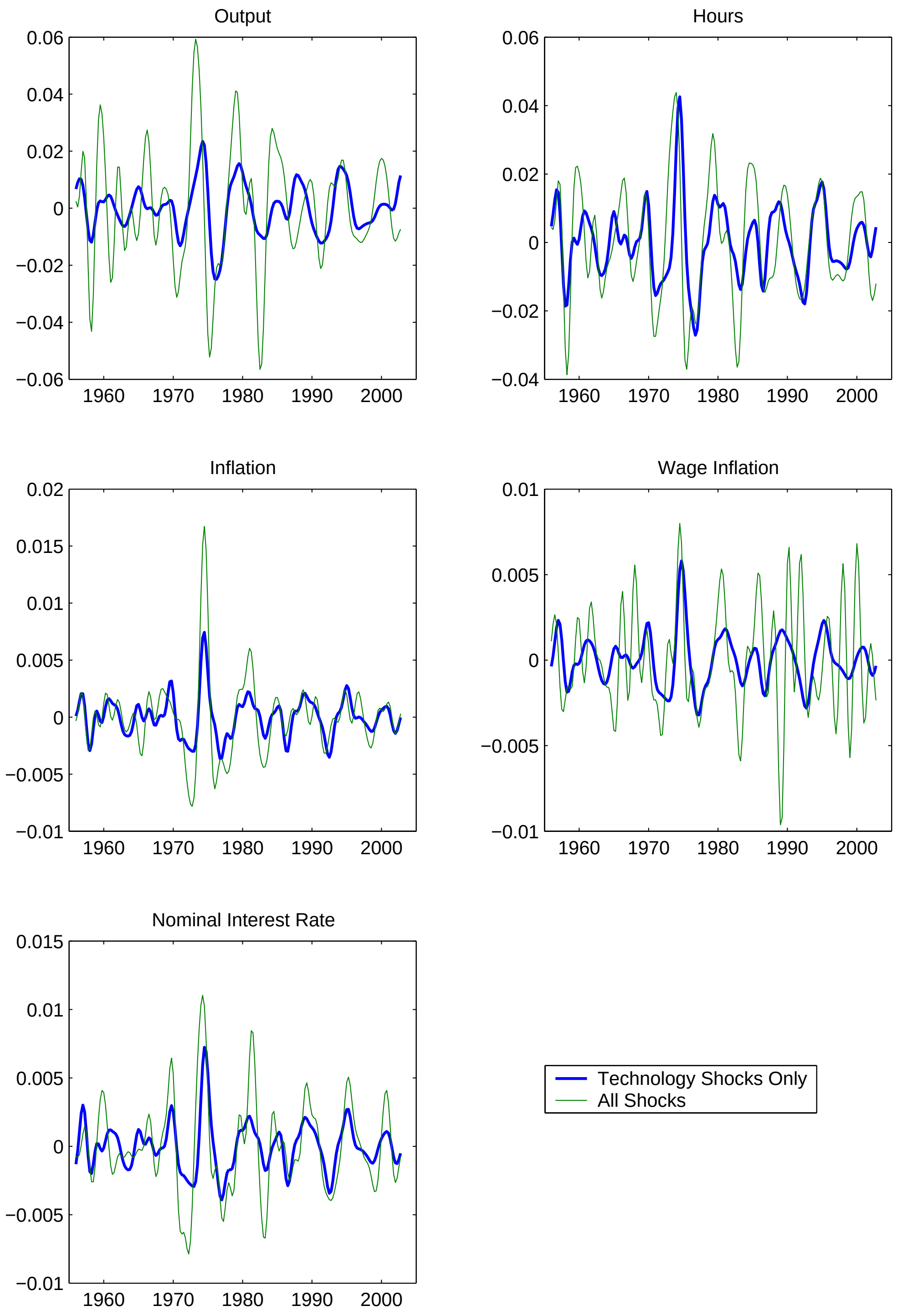

Figure 3: Business cycle components of $\mathbf{z}_t$, obtained by means of the band pass filter advocated by Christiano and Fitzgerald (2003).

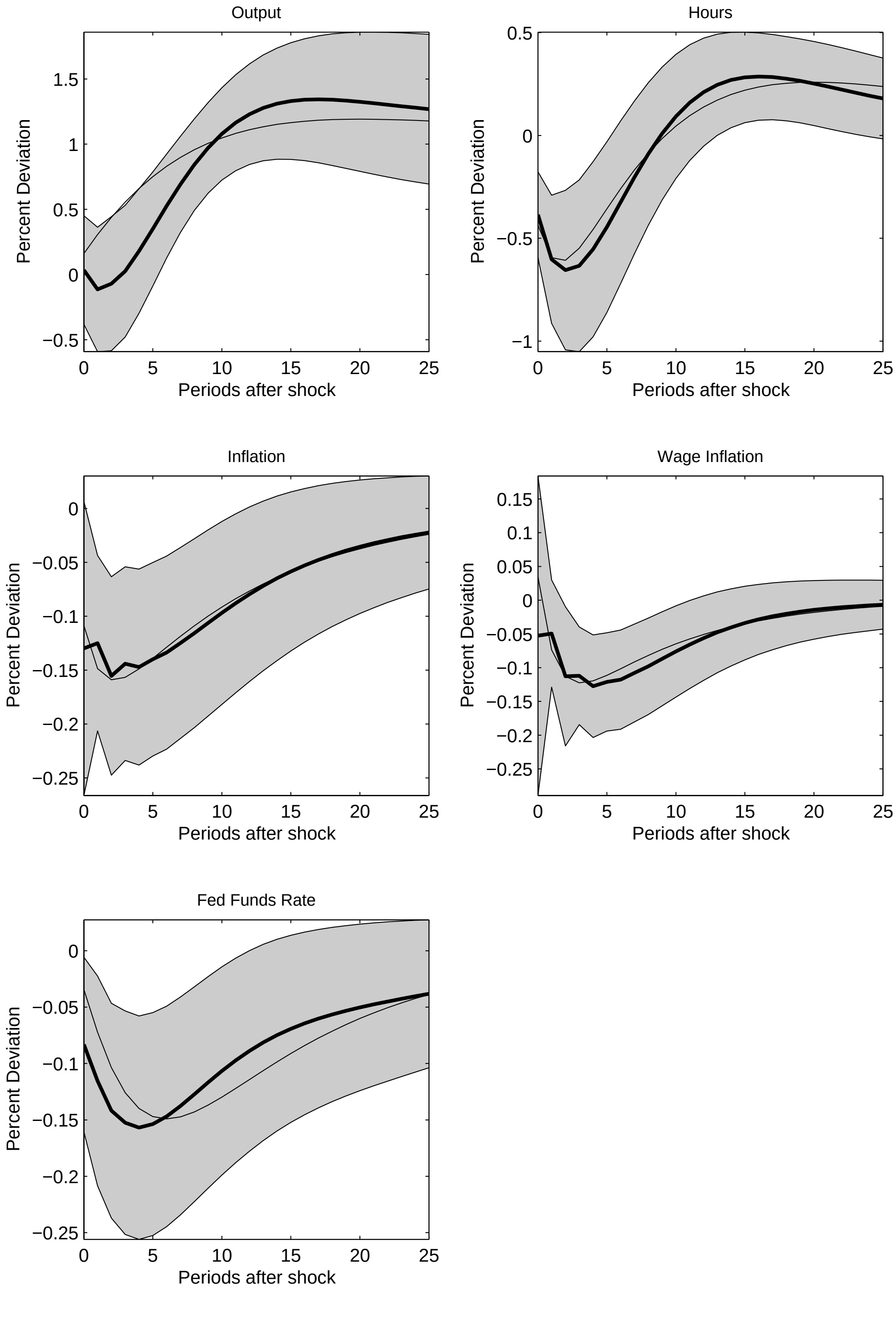

Figure 4: Dynamic responses to a permanent technology shock (thick lines: VAR model, normal lines: DSGE model). The grey area represents the 90% asymptotic confidence interval of the VAR IRF's.

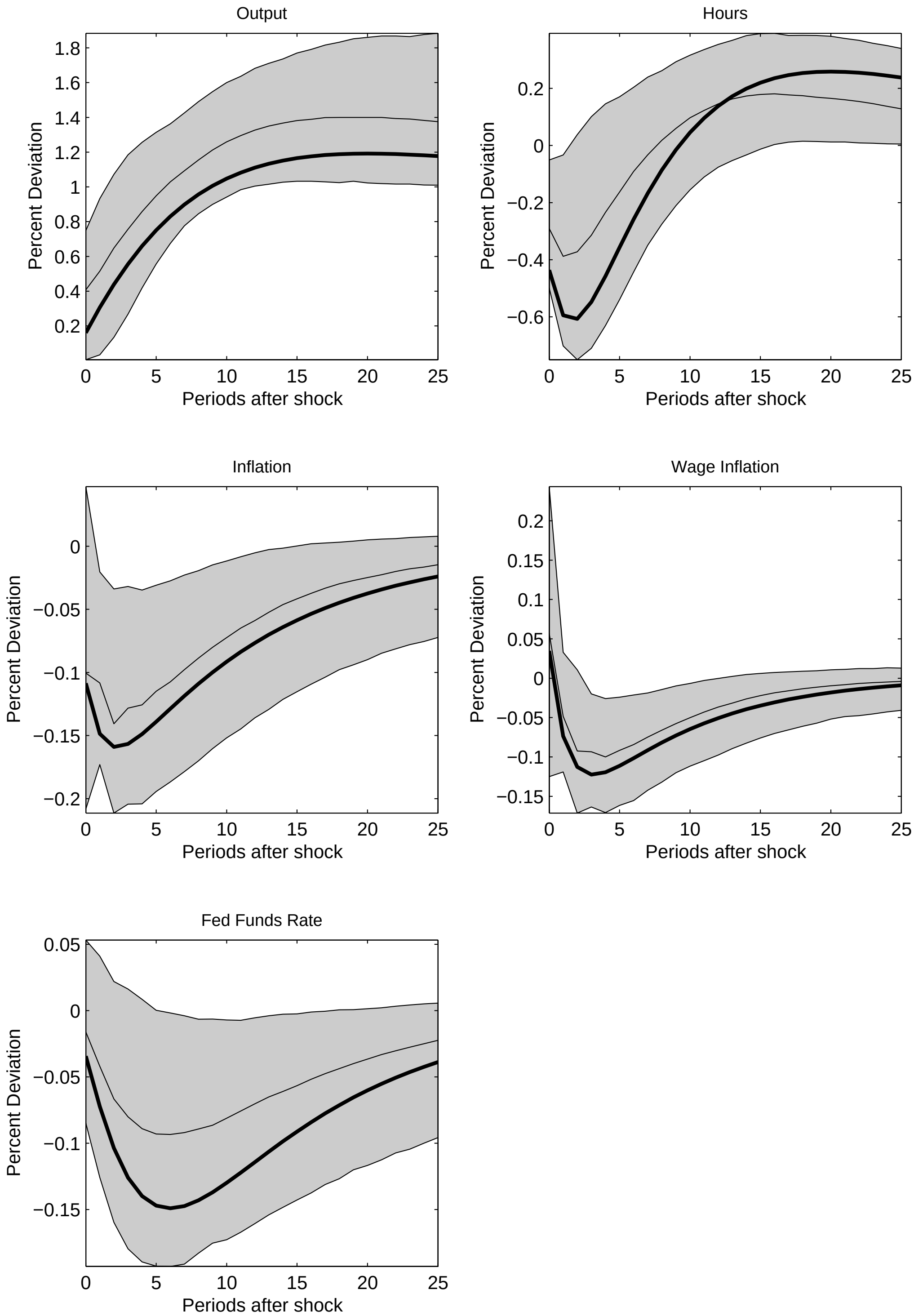

Figure 5: Impulse responses to a technology shock from the DSGE model (thick line) and median of the simulation (thin line) of a SVAR as described in section 4.4. The grey area represents the 90% confidence from the simulation.

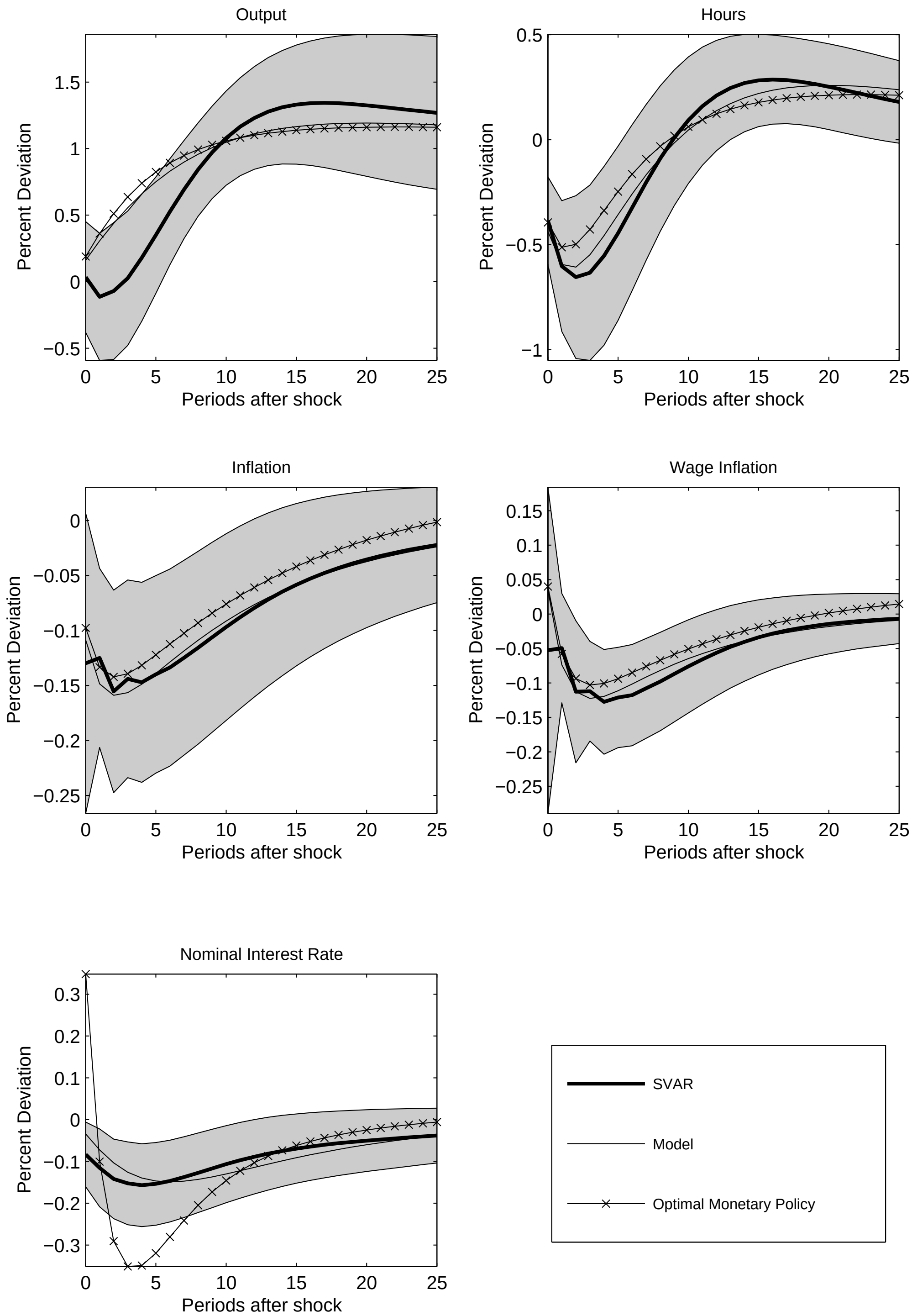

Figure 6: Comparison of the economy's responses to a permanent technology shock in the SVAR, in the structural model, and in the structural model with optimal monetary policy.

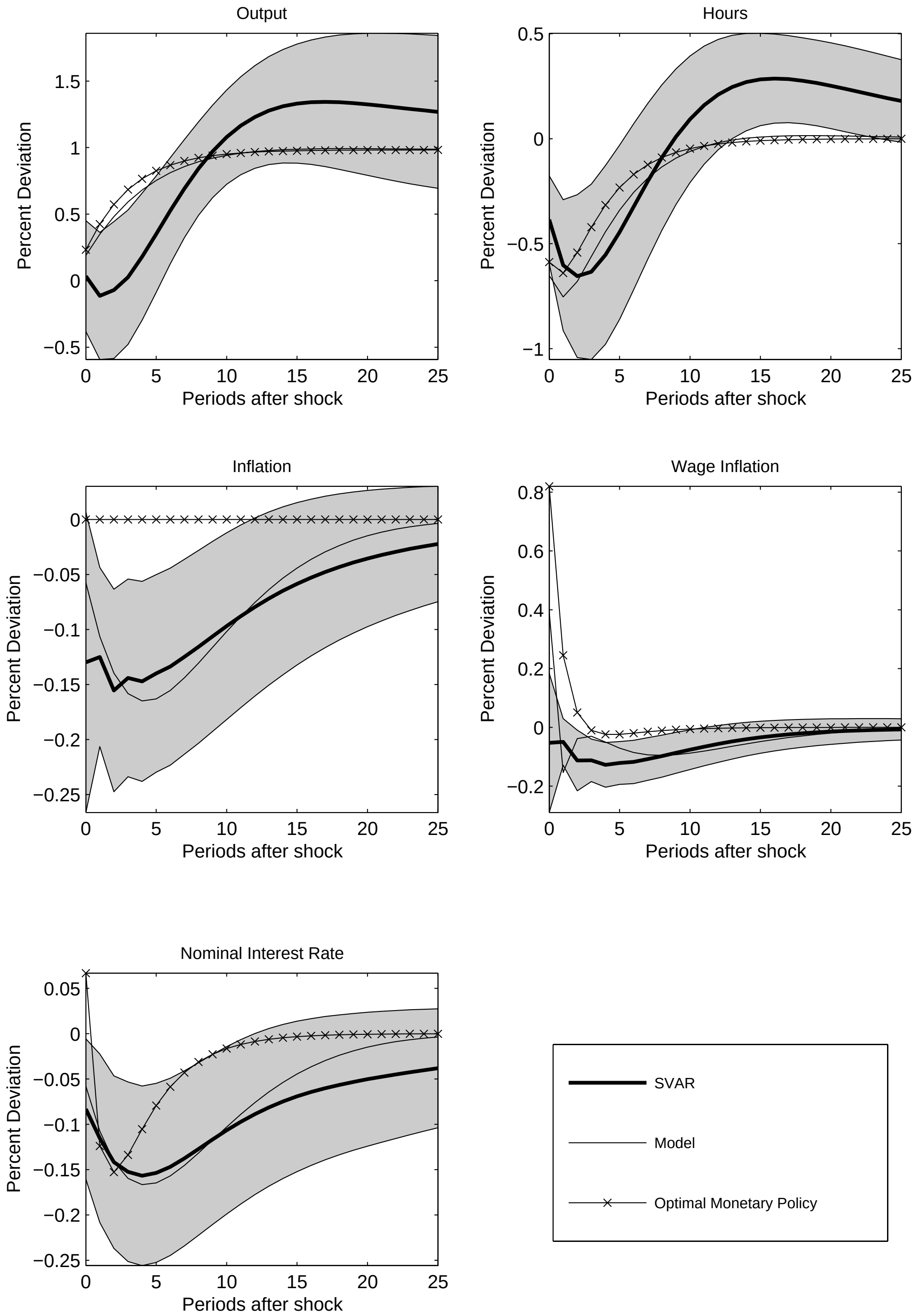

Figure 7: Comparison of the economy's responses to a permanent technology shock in the SVAR, in the structural model, and in the structural model with optimal monetary policy, under the asumption of wage flexibility.

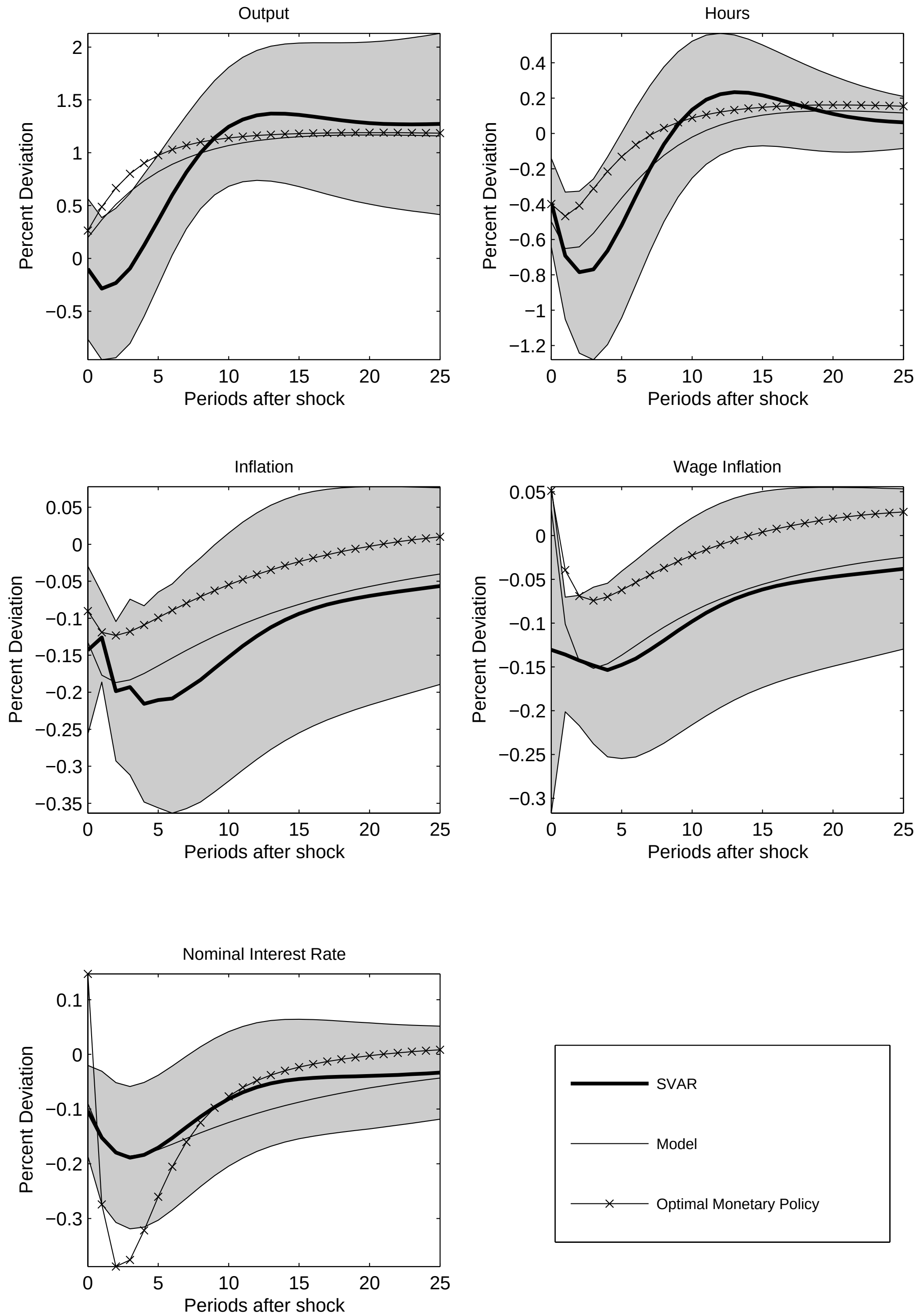

Figure 8: Subsample analysis, 1955(1)–1979(3).

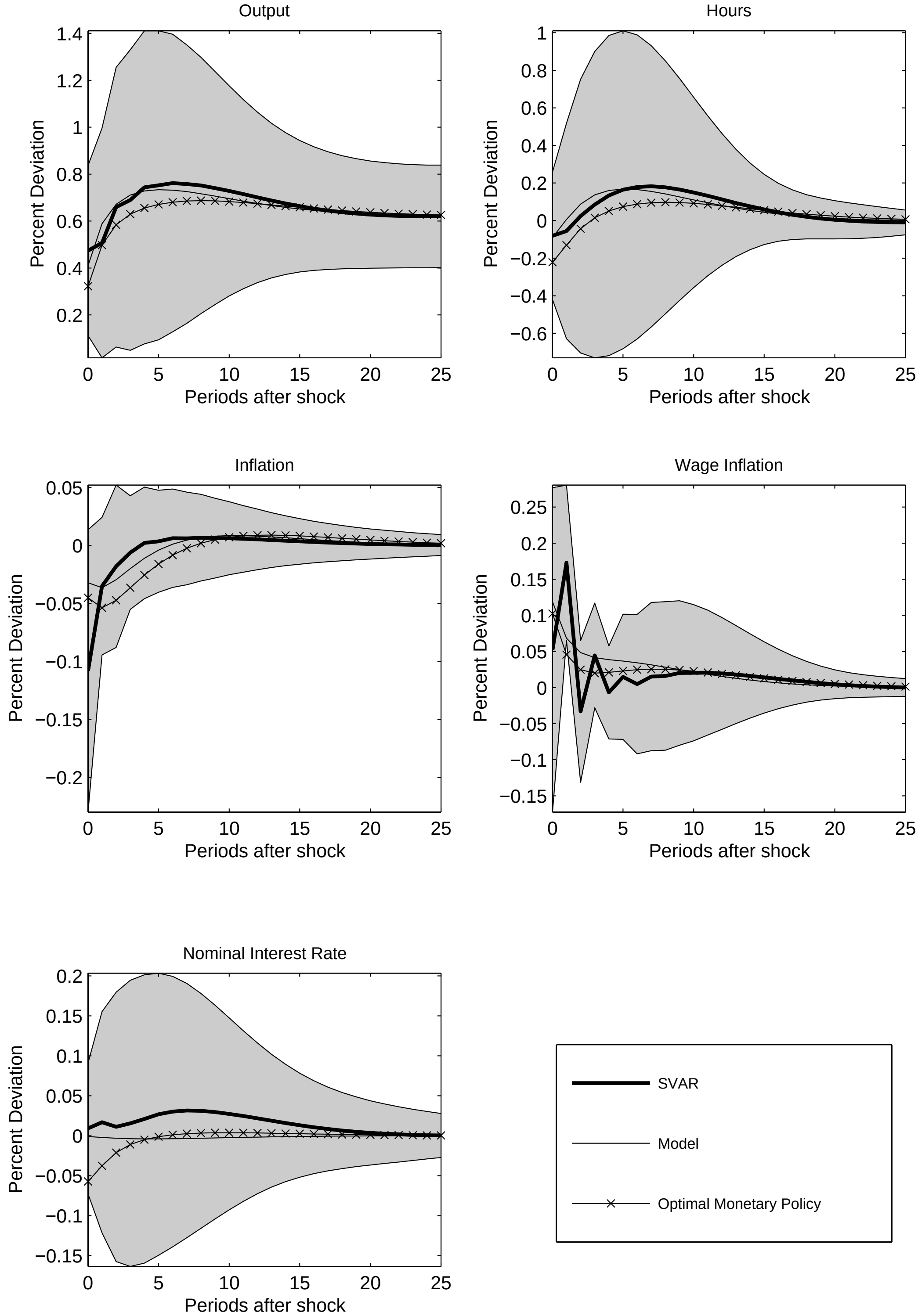

Figure 9: Subsample analysis, 1982(4)–2002(4).

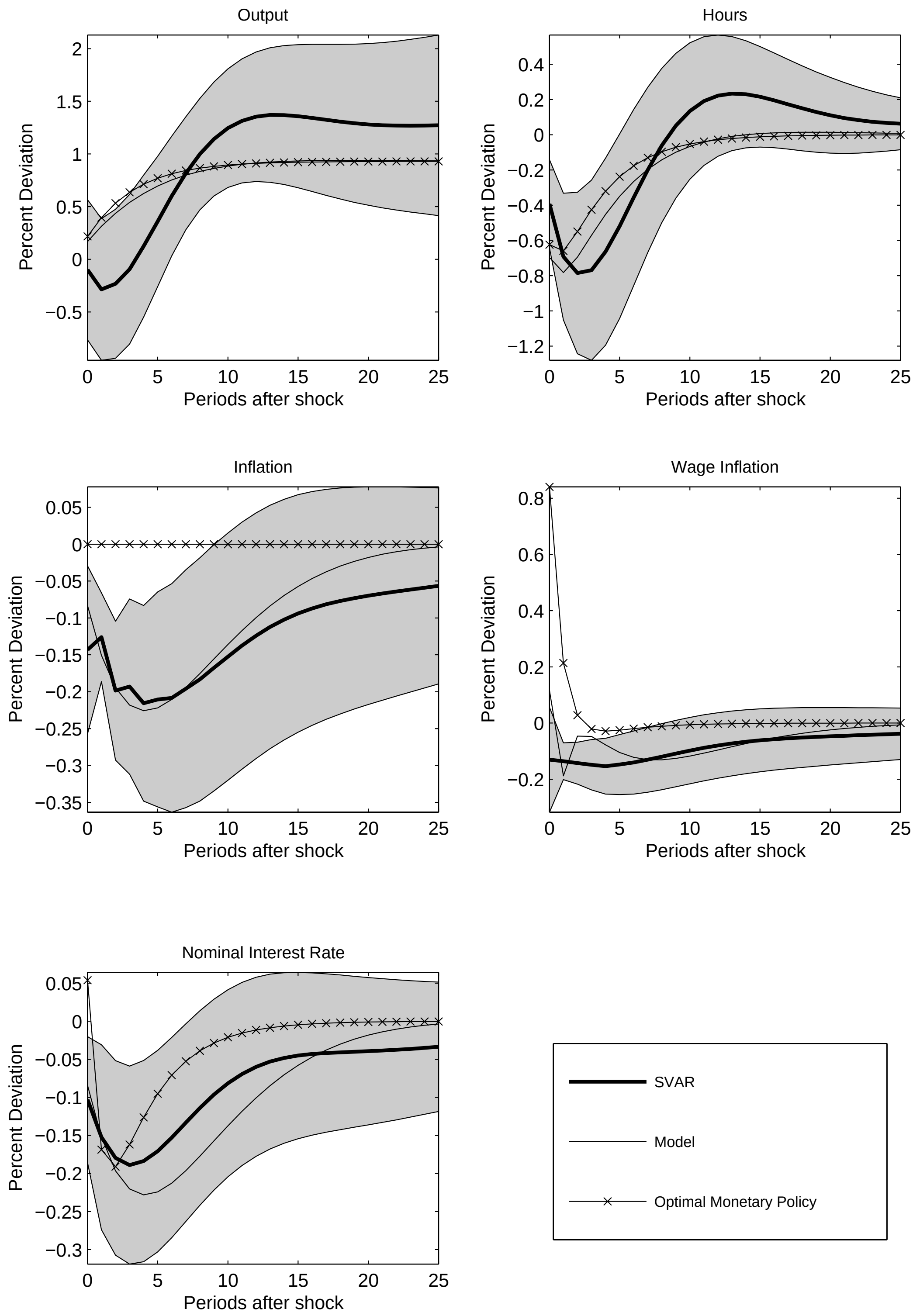

Figure 10: Subsample analysis, 1955(1)–1979(3), under flexible wages.

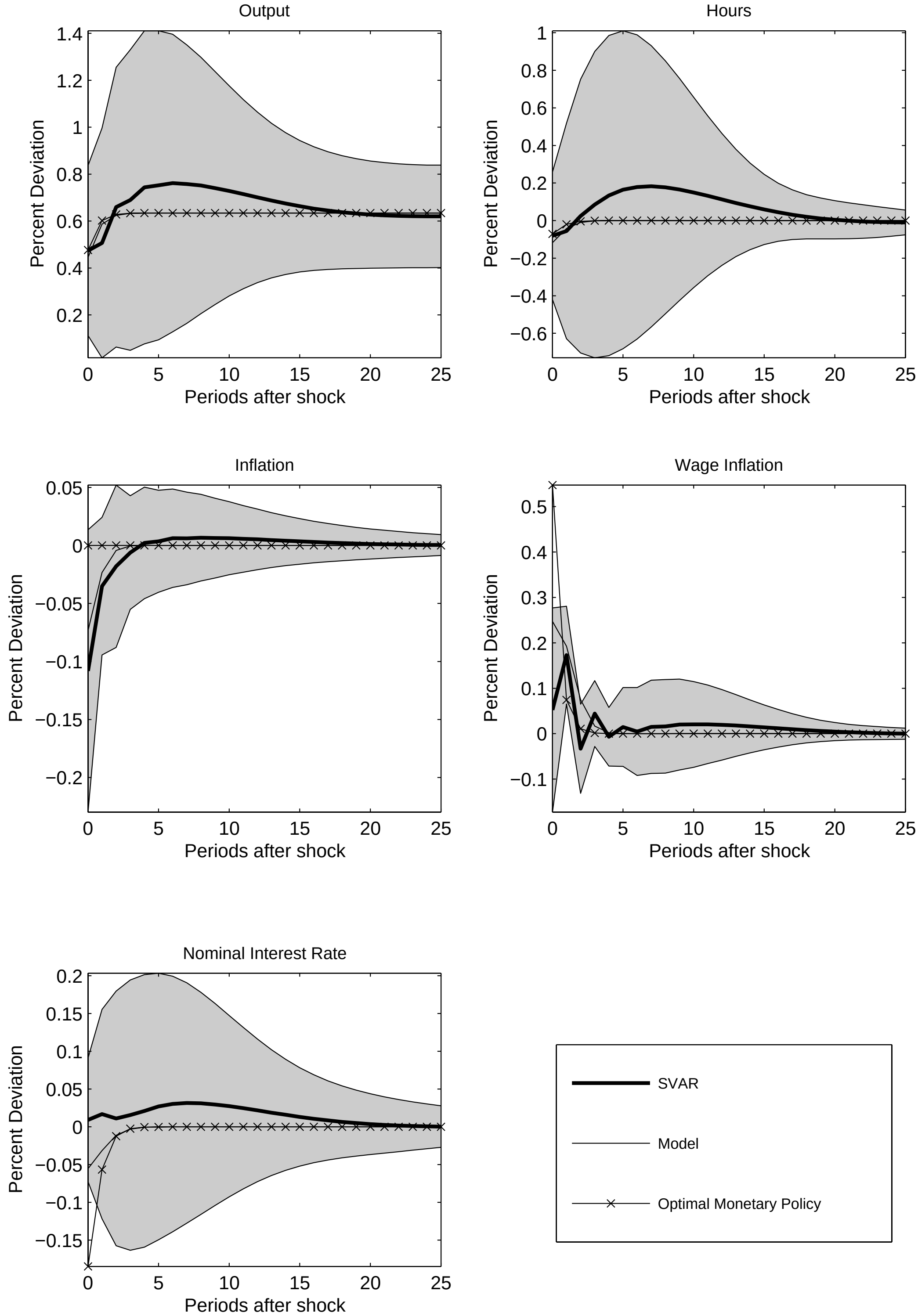

Figure 11: Subsample analysis, 1982(4)–2002(4), under flexible wages.

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