NOTES D’ÉTUDES

ET DE RECHERCHE

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June 2005

NER - R # 126

BANQUE DE FRANCE

DIRECTION GÉNÉRALE DES ÉTUDES ET DES RELATIONS INTERNATIONALES

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Technology Shocks and Monetary Policy in an Estimated Sticky Price Model of the Euro Area[1]

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June 10, 2005

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[1] We would like to thank L. Benati, F. Collard, M. Dupaigne, P. Fève, M. Jonsson, H. Le Bihan, J. Linde, J.G. Sahuc, F. Smets, R. Wouters, and workshops participants at the Banque de France and T2M for comments and suggestions on an earlier draft. The remaining errors are ours. The views expressed herein are those of the authors and do not necessarily reflect those of the Banque de France.

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Résumé :

Dans cet article, nous cherchons à caractériser les effets dynamiques des chocs technologiques permanents et la façon dont les autorités monétaires européennes y ont réagi au cours des deux dernières décennies. Pour ce faire, nous développons un modèle d'équilibre général à prix et salaires visqueux que nous estimons en minimisant la distance entre les réponses théoriques des variables d'intérêt et leurs contreparties empiriques issues d'un VAR structutel. Dans une seconde étape, nous conduisons un exercice contre-factuel consistant à comparer ces réponses avec celles qu'implique la politique monétaire optimale. L'exercice débouche sur l'existence d'un écart significatif entre ces réponses. Ceci suggère la possibilité que la réponse des autorités monétaires européennes n'ait pas été optimale sur la période considérée.

Mots-clés : prix et salaires 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 European monetary authorities reacted to these shocks over the past two decades. 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 conduct a counterfactual experiment consisting to compare these responses with the outcome of the optimal monetary policy. A significant discrepancy emerges between these responses, suggesting the European monetary authorities might not have responded optimally to permanent technology shocks.

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

JEL Codes: E31, E32, E58.

Résumé non technique :

A l'aide de restrictions de long-terme mises en oeuvre dans un modèle VAR structurel (VARS) estimé sur les données de la zone euro sur la période 1980(1)-2002(4), nous étudions la dynamique de la croissance du produit, de l'inflation, de l'inflation salariale, et du taux d'intérêt nominal de court terme en réponse à des chocs technologiques permanents, afin de caractériser la façon dont les autorités monétaires européennes ont réagi à ces chocs au cours des deux dernières décennies. Nous propons une explication possible basée sur un modèle d'équilibre général intertemporel stochastique (DSGE) avec prix et salaires visqueux, conçu et estimé de façon à reproduire ces réponses. Armés de cette représentation structurelle des données, et conditionnellement aux paramètres estimés, nous menons à bien un exercice contre-factuel permettant de quantifier dans quelle mesure la réponse systématique historique des autorités monétaires européennes aux chocs technologiques est compatible avec la réponse optimale.

Le modèle DSGE est estimé par minimisation d'une distance pondérée entre les réponses théoriques et celles issues du VARS, conformément à la méthode proposée par Christiano et al. (2001) et Rotemberg et Woodford (1997,1999), entre autres. Comme chez ces auteurs, cette stratégie nous permet d'estimer le modèle en nous concentrant sur un seul choc, évitant de la sorte d'avoir à spécifier toute la structure stochastique de l'économie. Il est à noter que d'après notre modèle VARS, les chocs technologiques sont responsables d'une part significative de la composante cyclique de l'inflation, de la l'inflation salariale et du taux nominal. Il est donc légitime de s'intéresser à ces chocs lorsque l'on analyse la politique monétaire européenne.

Notre cadre d'analyse inclut des prix et des salaires visqueux, des consommations intermédiaires, et prend en compte de nombreux éléments "hybrides", parmis lesquels la formation des habitudes, et l'indexation partielle des prix et des salaires. Il a été montré que tous ces éléments permettent d'améliorer l'adéquation des modèles DSGE aux données. Un aspect important de notre cadre d'analyse est que la prise en compte simultanée de prix et de salaires visqueux permet un problème de politique monétaire non trivial, à l'opposé de celui qui découlerait d'un modèle où seuls les prix seraient visqueux et qui consisterait alors à élmiminer totalement les fluctuations de l'inflation.

A l'aide des paramètres estimés et d'un modèle qui reproduit correctement les réponses issues du VARS, nous calculons la réponse de l'économie aux chocs technologiques sous l'hypothèse que la politique monétaire est optimale. Notre résultat principal est que cette dernière et celle issue du VARS ne coïncident pas sur l'échantillon retenu dans ce papier. En particulier, les réponses historiques du taux nominal et de l'inflation ont été trop timide et trop prononcée, respectivement.

Non-technical summary:

Using standard long-run restrictions in a structural vector autoregression (SVAR) estimated on euro area data over the sample 1980(1)-2002(4), we study the response of output growth, inflation, wage inflation, and the short-term nominal interest rate to permanent technology shocks, so as to characterize the way in which European monetary authorities reacted to these shocks over the past two decades. We then propose a possible rationalization of these responses within a small dynamic stochastic general equilibrium (DSGE) model with sticky prices and wages designed and estimated so as to replicate these responses as closely as possible. Armed with this structural representation of the data, and contingent upon the estimated parameters, we conduct a counterfactual experiment designed to quantify the extent to which the historical systematic response of European monetary authorities to permanent technology shocks differs from the optimal response.[1]

We estimate our DSGE model by resorting to the Minimum Distance Estimation (MDE) technique recently advocated by Christiano et al. (2001) and Rotemberg and Woodford (1997,1999), among others. More precisely, the structural parameters of the DSGE 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. As in Rotemberg and Woodford (1997, 1999) and Christiano et al. (2001), our Minimum Distance strategy allows us to estimate the model by focussing on a single shock, thus avoiding the hassle of fully specifying the stochastic structure of the economy. Importantly, according to our SVAR, technology shocks account for a sizable portion of the business cycle components of of inflation, wage inflation, and

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[1] See Galí et al. (2001) for a related paper on US data.

the nominal interest rate. It is thus legitimate to focus on technology shocks when analyzing European monetary policy.

Our setup incorporates prices and wages both sticky, material goods, and features various hybrid elements, including habit persistence and partial wage and price indexation schemes. All these modelling elements have been shown to be important in terms of empirical fit. An important aspect of our modelling strategy is that by considering prices and wages both sticky, we end up with a non trivial optimal monetary policy, as opposed to a policy consisting to shut down inflation.

Armed with these parameters estimates and a model that does a reasonably good job of reproducing the economy's response to identified technology shocks, we then go on to compute the optimal response to these shocks. Our main result is that European monetary authorities dynamic reaction to a permanent technology shock does not appear to have been optimal over the sample period studied in this paper. In particular, the historical responses of the nominal interest rate and inflation have been too timid and too pronounced, respectively, when compared with the outcome of the optimal monetary policy.

1 Introduction

Using standard long-run restrictions in a structural vector autoregression (SVAR) estimated on euro area data over the sample 1980(1)-2002(4), we study the response of output growth, inflation, wage inflation, and the short-term nominal interest rate to permanent technology shocks. Doing so allows us to characterize the way in which European monetary authorities reacted to these shocks over the past two decades. We then propose a possible rationalization of these responses within a small dynamic stochastic general equilibrium (DSGE) model with sticky prices and wages designed and estimated so as to replicate these responses as closely as possible. Armed with this structural representation of the data, and contingent upon the estimated parameters, we conduct a counterfactual experiment designed to quantify the extent to which the historical systematic response of European monetary authorities to permanent technology shocks differs from the optimal response.[2]

We estimate our DSGE model by resorting to the Minimum Distance Estimation (MDE) technique recently advocated by Christiano et al. (2001) and Rotemberg and Woodford (1997,1999), among others. More precisely, the structural parameters of the DSGE 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.

As in Rotemberg and Woodford (1997, 1999) and Christiano et al. (2001), our Minimum Distance strategy allows us to estimate the model by focussing on a single shock, thus avoiding the hassle of fully specifying the stochastic structure of the economy. As a consequence, if the shock of interest accounts for a small fraction of fluctuations in the business cycle components of the relevant variables, our limited information estimation is of limited interest. As it turns out, however, according to our SVAR, technology shocks account for a sizable portion of the business cycle components of of inflation, wage inflation, and the nominal interest rate, when the latter are defined by means of the band pass filter advocated by Christiano and Fitzgerald (2003). It is thus legitimate to focus on technology shocks when analyzing European monetary policy.

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[2] See Galí et al. (2001) for a related paper on US data.

Our setup incorporates prices and wages both sticky, 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 as well as euro area 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. An important aspect of our modelling strategy is that by considering prices and wages both sticky, we end up with a non trivial optimal monetary policy, as opposed to a policy consisting to shut down inflation.

A possible drawback of our analysis is that we must a priori specify a monetary policy rule before estimating the model. Thus, our answer to the question asked at the beginning of the paper is clearly contingent upon this rule. Yet, it seems at first 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 successfully estimated for a number of countries, including an aggregate of European countries.[3] Within the context of a fully specified, estimated DSGE model, Smets and Wouters (2003) also show that such a parsimonious rule captures the essential features of European monetary policy. An interesting preliminary result is that European monetary authorities' systematic response to technology shocks, as implied by the structural VAR, is very well approximated by a simple Taylor-like rule within the confines of our DSGE model.

Armed with these parameters estimates and a model that does a reasonably good job of reproducing the economy's response to identified technology shocks, we then go on to compute the optimal response to these shocks. To do so, we follow Giannoni and Woodford (2003) and derive the monetary authorities loss function as a second-order approximation to the social utility function. Our main result is that European monetary authorities dynamic reaction to a permanent technology shock does not appear to have been optimal over the sample period studied in this paper. In particular, the historical responses of the nominal interest rate and inflation have been too timid and too pronounced, respectively, when compared with the outcome of the optimal monetary policy. These results should be taken with caution since the model

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[3] See Galí et al., 2001, for example.

abstracts from real-world elements that could eventually modify our conclusions, e.g. transaction frictions, imperfect information. Taking these mechanisms into account is well beyond the scope of the present study, and we leave them as possible tracks for future research.

The remainder is as follows. Section 2 describes our SVAR model and highlights the relative importance of technology shocks in explaining business cycle movements of inflation, wage inflation, and the nominal interest rate over the last two decades. Section 3 describes the theoretical model. Section 4 details the model calibration 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 Supply Shocks and Monetary Policy in a SVAR

In this section, we describe how we identify technology shocks in our SVAR model of the euro area economy. We then discuss our results and emphasize that technology shocks, as defined below, are not a negligible source of fluctuation at business cycle frequencies.

2.1 Structural VAR Estimation

To identify permanent supply shocks, we simply follow the Blanchard and Quah (1989) tradition of assuming that only these shocks can affect the long-run level of output. The data used in our estimation are extracted from the AWM database compiled by Fagan et al. (2001), and consist of real output growth ($\Delta \hat{y}_t$), inflation ($\hat{\pi}_t$), wage inflation ($\hat{\pi}_t^w$), and the short term nominal interest rate ($\hat{\imath}_t$). Our sample period ranges from 1980(Q1) to 2002(Q4). Over this period, inflation, wage inflation, and the nominal interest rate all display a marked and significant downward trend. This phenomenon is due to the process of convergence of member countries.[4]

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[4] The AWM mnemonics are as follows. y_t: YER, π_t: first difference of the log of YED, i_t: STN, π_t^w: first difference of the log of WRN.

Following Coenen and Wieland (2000), we acknowledge that our model is not designed to take account of this process. We thus simply extract quadratic trends from our original dataseries. The transformed data are graphed on figure 1.

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

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

where ℓ is the maximal lag, which we determine by sequential likelihood ratio tests. 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. $\boldsymbol{\varepsilon}_t = \mathbf{S}\boldsymbol{\eta}_t$, 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 output. 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 $\mathbf{S} = \mathbf{B}(1)^{-1}\mathbf{C}(1)$.

A word of caution is in order before proceeding. One might argue that what we identify is a broader set of shocks than technology shocks in the strict sense. Indeed output might respond to a host of other permanent shocks and the latter should not be interpreted as technology shocks. In order to avoid this problem, Galí (1999) proposed to substitute average labor productivity growth for output growth in the SVAR. Unfortunately, this strategy is not an option for us because time series of hours worked per employee are not available for the euro area. Thus our definition of technology shocks is broader than Galí's, but, at the same time, is consistent with that proposed by Hansen and Prescott (1993), i.e. “changes in the production functions or, more generally, the production possibility sets of the profit centers”.[5]

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[5] Other papers that adopt the same interpretation include Ambler et al. (1999), Beaudry and Guay (1996), and Cogley and Nason (1995).

2.2 Results

The dynamics of output growth, 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 95% asymptotic confidence intervals, which we computed numerically.

As the figure makes clear, output growth rises on impact, though not significantly. After a small inflexion in the second quarter, changes in real output gradually reach their steady state value form above. Inflation is irresponsive to a technology shock on impact, though this shock triggers a significantly negative path after one or two quarters. Inflation dynamics have an inverted hump-shape, since inflation continues to decline for two quarters before starting to reach its steady state level. A similar inverted hump-shaped pattern obtains for the short term interest rate. The latter is suggestive of an accommodative behavior of European monetary authorities over our sample. The latter seem to have reacted to technology shocks by a protracted decline in nominal interest rate. Finally, wage inflation also declines after a positive technology shock, though this response is not precisely estimated.

To quantify the importance of technology shocks over the business cycle, we proceed as follows. From the estimated VAR coefficients, we construct the series of output, inflation, wage inflation, and the nominal interest rate that would have obtained absent technology shocks. 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.[6] The filtered series are reported on figure 3.

We obtain that technology shocks account for 29% and 21% of the variance of inflation and wage inflation, respectively, at business cycle frequencies. This proportion, though not dominant, is non negligible. What more, technology shocks explain 86% of business cycle fluctuations of the short term nominal interest rate. In contrast, they only account for 13% of the variance of output at business cycle frequencies. Overall, this variance decomposition exercise suggests that

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[6] 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.

it is legitimate that euro area monetary authorities pay some attention to technology shocks given their relative importance over the business cycle.

3 The Model

The model has six sectors. In the first one, competitive firms combine a set of intermediate goods to produce a homogeneous final consumption good. In the second, competitive firms combine the same set of intermediate goods to produce material goods. In the third sector, monopolistic firms produce these intermediate goods with the inputs of materials goods and an aggregate labor index. In the fourth sector, competitive firms, referred to as labor intermediaries, transform differentiated labor inputs into the above-mentioned aggregate labor index. In the fifth sector, differentiated households sell their specific labor to the labor intermediaries. Households act as monopoly supplier of their differentiated labor input. Additionally they consume and acquire nominal bonds issued by the government. In the last sector, monetary authorities set the nominal interest rate according to a Taylor-like monetary rule.[7]

3.1 Final Goods and Materials Goods

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

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

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

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

Another set of competitive firms produce material goods by combining the same intermediate

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

goods as above. They have access to the CES technology

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

where q_t is the produced quantity of material goods and $q_t\left(\varsigma\right)$ 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 materials goods will be P_t.

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

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

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

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

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

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

where the aggregate nominal wage is defined as

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

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

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

where $g > 1$ is the average, gross growth rate of technical progress, and $\epsilon_t \sim \mathrm{iid}(0, \sigma_\epsilon^2)$.[8] 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.

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.[9] 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, given that monopolistic firms have access to an aggregate labor market.

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

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

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[8] We also experimented with a specification allowing for serial correlation in ϵ_t, but found that the additional parameter was numerically small and not statistically significant.

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

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 $\delta^p_{t,T}$

$$\delta^p_{t,T} = \begin{cases} \prod_{j=t}^{T-1} \pi^{1-\gamma_p} \pi_j{}^{\gamma_p} & \text{if } \ T > t \\ & \\ 1 & \text{otherwise} \end{cases}, \tag{10}$$

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 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

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

where $\mathrm{E}^{\varsigma}_t\{\cdot\}$ is an expectation operator specific to firm ς that integrates over those future states of the world in which firm ς has no reset its price since t. Standard manipulations yield the approximate loglinear relation

$$\hat{\pi}_t - \gamma_p \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1} - \gamma_p \hat{\pi}_t\} + \frac{(1-\beta\alpha_p)(1-\alpha_p)(1-s_m)}{\alpha_p[1+(1-s_m)\omega_p\theta_p]} (\hat{w}_t + \omega_p \hat{y}_t), \tag{11}$$

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,[10] 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.

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

$$\delta^w_{t,T} = \begin{cases} \prod_{j=t}^{T-1} (\pi^w)^{1-\gamma_w} (\pi^w_j)^{\gamma_w} & \text{if } T > t \\ 1 & \text{otherwise} \end{cases}, \tag{12}$$

where π^w is the steady state wage inflation rate and $\gamma_w \in (0,1)$ measures the degree of indexation to the most recently available wage inflation measure. Notice that contrary to Christiano et al. (2001) and Woodford (2003), we let the households index their nominal wage inflation to past wage inflation rather than past inflation alone. 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

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[10] 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}.

claims market, all the households will make the same choices regarding consumption and will only differ by their wage rate and technology of labor. This is directly reflected in our notations.

Household v's goal in life is to maximize

$$\mathbb{W}_t = \mathrm{E}_t \sum_{T=t}^{\infty} \beta^{T-t} [\log(c_T - bc_{T-1}) - \mathbb{V}(h_T(v))], \tag{13}$$

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 $h_t(v)$ is household v's technology of labor. The preferences are characterized by internal habit formation.

The representative agent maximizes (13) subject to the sequence of constraints

$$c_t + b_t/i_t + \xi_t \leq (1+\tau_w)\, w_t(v) h_t(v) + b_{t-1}/\pi_t + \mathrm{div}_t, \tag{14}$$

where div_t denotes profits redistributed by monopolistic firms and $w_t(v) \equiv W_t(v)/P_t$ is the real wage rate earned by type-v labor. Additionally, $b_t \equiv B_t/P_t$, where B_t denotes 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

$$\lambda_t = \frac{1}{c_t - bc_{t-1}} + \beta b \mathrm{E}_t \left\{ \frac{1}{c_{t+1} - bc_t} \right\}, \tag{15}$$

$$\lambda_t = i_t \beta \mathrm{E}_t \left\{ \frac{\lambda_{t+1}}{\pi_{t+1}} \right\}. \tag{16}$$

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

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

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

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

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

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

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

where $\mathrm{E}_t^{\upsilon}\{\cdot\}$ is an expectation operator specific to household υ that integrates over those future states of the world in which household υ has no reset its wage since t. Standard manipulations yield the approximate loglinear relation

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

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 an augmented Taylor rule of the form

$$\hat{\imath}_t = \rho_i \hat{\imath}_{t-1} + (1-\rho_i)\left[a_p \hat{\pi}_t + a_x \hat{x}_{t-1}\right]. \tag{22}$$

This rule incorporates an interest rate smoothing component as well as feedback terms: monetary authorities react to current deviations of inflation as well as to the lagged deviations of the output gap. The latter is defined as the difference between the output and the level of production that would have obtained absent nominal rigidities.

In equilibrium, it must be the case that $\hat{c}_t = \hat{y}_t$. Combined with eq (22), the final linear system can then be summarized as follows

$$\hat{y}_t = \eta \hat{y}_{t-1} + \beta\eta \mathrm{E}_t\{\hat{y}_{t+1}\} - (1 - (1+\beta)\,\eta)\,\hat{\lambda}_t - \eta\epsilon_t, \tag{23}$$

$$\hat{\lambda}_t = \hat{\imath}_t + \mathrm{E}_t\{\hat{\lambda}_{t+1} - \hat{\pi}_{t+1}\}, \tag{24}$$

$$\hat{\pi}^w_t - \gamma_w \hat{\pi}^w_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}^w_{t+1} - \gamma_w \hat{\pi}^w_t\} + \frac{(1-\alpha_w)\,(1-\beta\alpha_w)}{\alpha_w\,(1+\omega_w\theta_w)}(\omega_w\phi\hat{y}_t - \hat{\lambda}_t - \hat{w}_t), \tag{25}$$

$$\hat{\pi}_t - \gamma_p \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1} - \gamma_p \hat{\pi}_t\} + \frac{(1-\beta\alpha_p)(1-\alpha_p)\,(1-s_m)}{\alpha_p[1+(1-s_m)\omega_p\theta_p]}(\hat{w}_t + \omega_p\hat{y}_t), \tag{26}$$

$$\hat{\pi}^w_t = \hat{\pi}_t + \hat{w}_t - \hat{w}_{t-1} + \epsilon_t. \tag{27}$$

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

4 Model Calibration and 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 regroups 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 1.

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 $\phi = 1/.5392$, implying a labor share close of 53.92%, 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. Accordingly, the definition of ω_p implies $\omega_p = \phi - 1$. 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%. This value is consistent with estimates reported by Oliveira Martins and Scaperta (1999). Finally, in line with Smets and Wouters (2003), we set $\theta_w = 5$. Thus, the long-run markup charged by labor suppliers amounts to 25%, reflecting structural rigidities on the European labor markets.

4.2 Structural Parameters Estimation

Recall that we defined the data vector $\mathbf{z}_t = (\Delta\hat{y}_t, \hat{\pi}_t, \hat{\pi}_t^w, \hat{\imath}_t)'$. 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 k-coefficient of $\mathbf{C}\,(L)$. In the sequel, we define $\boldsymbol{\theta}$ as

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

where the vec $(\cdot)$ operator stacks the columns of a matrix.

We regroup the model's structural coefficients which we seek to estimate in the vector $\boldsymbol{\psi}_1 = (\eta, \gamma_w, \gamma_p, \alpha_w, \alpha_p, \omega_w, \rho_i, a_\pi, a_y, \sigma_\epsilon)'$. 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.[11]. 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). The minimization is subject to standard constraints. Letting $\boldsymbol{\psi} = (\boldsymbol{\psi}_0', \boldsymbol{\psi}_1')'$, it is convenient to define

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

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

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 $\mathbf{G}(\boldsymbol{\psi},\boldsymbol{\beta})$ in the neighborhood of the true parameters values. Then let us define

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

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 $\mathbf{G}\left(\boldsymbol{\psi},\boldsymbol{\theta}\right)$ is asymptotically distributed as $\chi^2(\dim(\boldsymbol{\theta})-\dim(\boldsymbol{\psi}_1))$.

4.3 Estimation Results

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 $\rho_i=0$ and $\gamma_w=1$. In a second stage, we enforced these equalities and estimated the remaining parameters. This suggests that the degree of wage indexation to past wage inflation is very high and that European monetary authorities did not particularly smoothed the nominal interest rate. Another interpretation is that the model generates enough endogenous persistence via the feedback effects in eq. (22) that allowing for extra serial correlation in $\hat{\imath}_t$ is not necessary. This interpretation is consistent with the view defended by Rudebusch (2002) on US data.

When it comes to the price setting side of the model, we obtain the following results. First, the probability of no price adjustment is $\alpha_p=0.7186$, implying an average spell of no reoptimization of slightly more than three quarters and a half. This figure is consistent with microeconomic evidence reported by Dhyne et al. (2004) on euro area data. The degree of price indexation to past inflation is significant, with $\gamma_p=0.4599$. This implies that during each quarters, fixed prices incorporate roughly 46% of past inflation. In contrast, the probability of no wage adjustment is $\alpha_w=0.5051$, implying an average spell of no reoptimization of slightly more than two quarters. This result is somewhat surprising, given the conventional view that the European labor market is characterized by a lack of flexibility.

When it comes to preference parameters, we obtain standard results. First, the elasticity of marginal labor disutility is large, with $\omega_w = 2.6975$, but inprecisely estimated. This value is in line with previous estimates reported by Smets and Wouters, though somewhat higher. Second, given $\eta = 0.4975$ and $\beta = 0.99$, we easily deduce that $\bar{b} = 0.8726$. In our sample, we obtain $g = 1.0051$, so that $b = 0.8770$. Thus, the model requires a high degree of habit formation.

When it comes to the remaining monetary policy parameters, we obtain $a_x = 0.2548$, suggesting a modest feedback effect of the output gap. Notice however that this parameter is not estimated very precisely. Second, $a_\pi = 1.5438$, suggesting that over the past two decades, European monetary authorities reacted very sharply to the deviations of inflation, in accordance with the Taylor principle.

The standard error of technology shocks σ_ϵ is close to 0.48%. This value is standard when compared with US estimates. However, it is difficult to compare this value with former studies on the euro area. The reason is that in most of these papers, technology and technology shocks are all assumed to be stationary.

Finally, the global specification test does not allow us to reject the model, with $\mathbf{G}(\boldsymbol{\psi}, \boldsymbol{\theta}) = 33.195$, with a p value of 99.34%. Table 2 reports our estimation results. Additionally, figure 3 plots the theoretical and empirical impulse responses as well as the 95% 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 and hump-shaped declines of inflation, and the nominal interest rate. It does also a good job of reproducing the gradual decline in wage inflation. However, it is less successful at reproducing the initial inflexion of output growth.

5 A Counterfactual Experiment

Having estimated the structural parameters of our model, we are now in a position to conduct the following counterfactual experiment. Following the methodology advocated by Woodford (2003), we start by deriving monetary authorities' appropriate welfare objective and then go

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

on to compute the economy's response to a permanent technology shock under the optimal monetary policy, which we compare with our approximation of the actual responses.

5.1 Optimal Monetary Policy

Standard yet tedious calculations yield the approximate utility-based loss function

$$\mathbb{W}_0 = -\Omega \mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \{\lambda_p(\hat{\pi}_t - \gamma_p \hat{\pi}_{t-1})^2 + \lambda_w(\hat{\pi}_t^w - \gamma_w \hat{\pi}_{t-1}^w)^2 + \lambda_x(\hat{x}_t - \delta \hat{x}_{t-1})^2\} + \text{t.i.p.} + \mathcal{O}\left(||\epsilon||^3\right), \tag{28}$$

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

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

$$\lambda_w = \frac{\theta_w \phi^{-1} \xi_w^{-1}}{\theta_p \xi_p^{-1} + \theta_w \phi^{-1} \xi_w^{-1}}, \qquad \lambda_x = \frac{\varphi \varkappa}{\theta_p \xi_p^{-1} + \theta_w \phi^{-1} \xi_w^{-1}},$$

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

and δ and $\varkappa$ are complicated functions of the structural parameters.[13] The values of λ_p, λ_w, λ_x, and δ are reported in table 3. Notice that this approximate loss function closely resembles 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. Notice also that due to our assumptions regarding wage indexation to past wage inflation, it is the quasi difference $\hat{\pi}_t^w - \gamma_w \hat{\pi}_{t-1}^w$ that appears in the loss function, instead of $\hat{\pi}_t^w - \gamma_w \hat{\pi}_{t-1}$ in Giannoni and Woodford (2003).

The monetary authorities' program consists in maximizing the (approximate) welfare criterion (28), subject to the structural constraints

$$\hat{x}_t = \eta \hat{x}_{t-1} + \beta\eta \mathrm{E}_t\{\hat{x}_{t+1}\} - (1-(1+\beta)\eta)(\hat{\lambda}_t - \hat{\lambda}_t^n), \tag{29}$$

$$\hat{\pi}_t - \gamma_p \hat{\pi}_{t-1} = \beta \mathrm{E}_t\{\hat{\pi}_{t+1} - \gamma_p \hat{\pi}_t\} + \zeta \xi_p[(\hat{w}_t - \hat{w}_t^n) + \omega_p \hat{x}_t], \tag{30}$$

$$\hat{\pi}_t^w - \gamma_w \hat{\pi}_{t-1}^w = \beta \mathrm{E}_t\{\hat{\pi}_{t+1}^w - \gamma_w \hat{\pi}_t^w\} + \xi_w[\omega_w \phi \hat{x}_t - (\hat{\lambda}_t - \hat{\lambda}_t^n) - (\hat{w}_t - \hat{w}_t^n)], \tag{31}$$

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

$$\hat{\pi}_t^w = \hat{\pi}_t + \hat{w}_t - \hat{w}_{t-1} + \epsilon_t, \tag{32}$$

where $\hat{w}_t^n$ and $\hat{\lambda}_t^n$ are stochastic variables beyond the control of monetary authorities,[14] and where we defined the composite parameter

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

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

Having solved the new dynamic system, we can compute the economy's responses to a permanent technology shock under optimal monetary policy. These responses are reported in figure 5. 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.

As is clear from these pictures, it appears that the response of monetary authorities to a permanent technology shock, as summarized by the dynamics of the nominal interest rate, shares little resemblance with the optimal one. The latter implies a much more pronounced decline in the nominal interest rate and a much flatter response of inflation than suggested by either the SVAR or the theoretical model with a Taylor rule. Interestingly, under the optimal monetary policy, wage inflation is hump-shaped. This behavior is consistent with the weight associated with $(\pi_t^w - \gamma_w \pi_{t-1}^w)^2$ in the loss function, i.e. λ_w, which is much smaller than λ_p. Finally, there does not appear any marked difference between the behavior of output growth under optimal monetary policy and that under the Taylor rule, except maybe that the initial impact of a technology shock is higher under the optimal policy. Overall, based on these pictures, we are lead to conclude that the dynamic response of monetary authorities to a permanent technology shock was not optimal over our sample.

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[14] These variables are, respectively, the 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.

The amplitude of the initial decline of nominal interest rate in response to a technology shock 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 no longer be the case if the model included an interest rate smoothing motive in the monetary authorities loss function, resulting for example from transaction frictions.

6 Conclusion

In this paper, we proposed to conduct a counterfactual experiment designed to quantify the extent to which the historical systematic response of European monetary authorities to permanent technology shocks differs from the optimal response. To do so, we have characterized the euro area economy's responses to permanent technology shocks using standard long-run restrictions in a structural vector autoregression (SVAR) over the sample 1980(1)-2002(4) and estimated a DSGE model designed to replicate these responses. Using this small model, we were able to characterize the optimal monetary policy, i.e. the monetary policy that maximizes welfare in an environment where staggered price and wage setting is the only distortion to be corrected by monetary authorities.

Our main conclusions are as follows. First, our estimation results suggest that modelling actual European monetary policy as a forward-looking Taylor rule with a small feedback effect of the output gap captures well the systematic response of the nominal interest rate to a permanent technology shock, as implied by the SVAR. Second, this systematic response of European monetary authorities does not appear to be consistent with the outcome of the optimal monetary policy.

These conclusions call for some words of caution. First, 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. Second, our empirical strategy has abstracted from the convergence process of member countries which resulted in a downward trend in the aggregate inflation and nominal interest rates. Taking these trends into account is an interesting challenge for further research.

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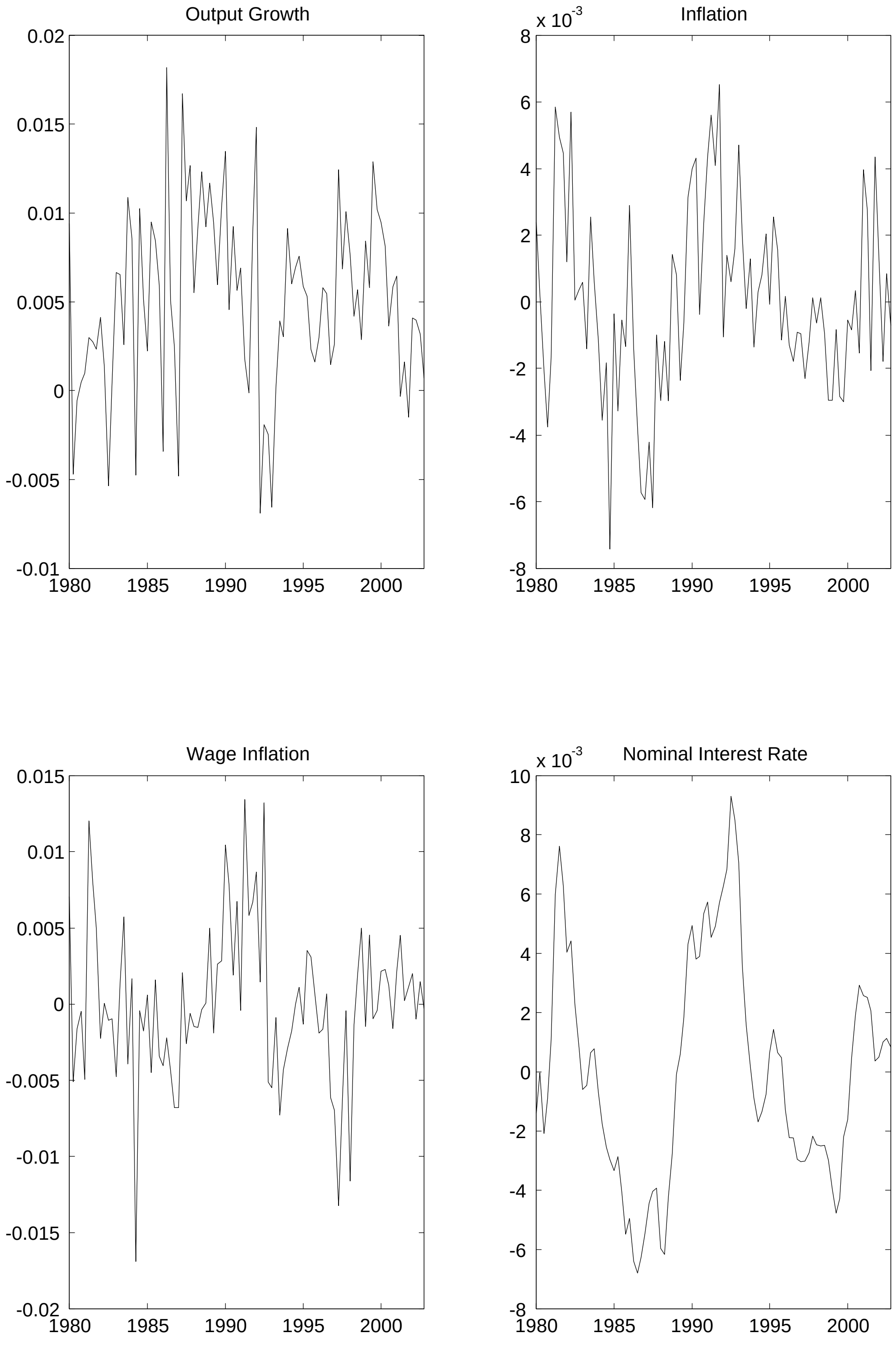

Figure 1: Transformed data, source: AWM database.

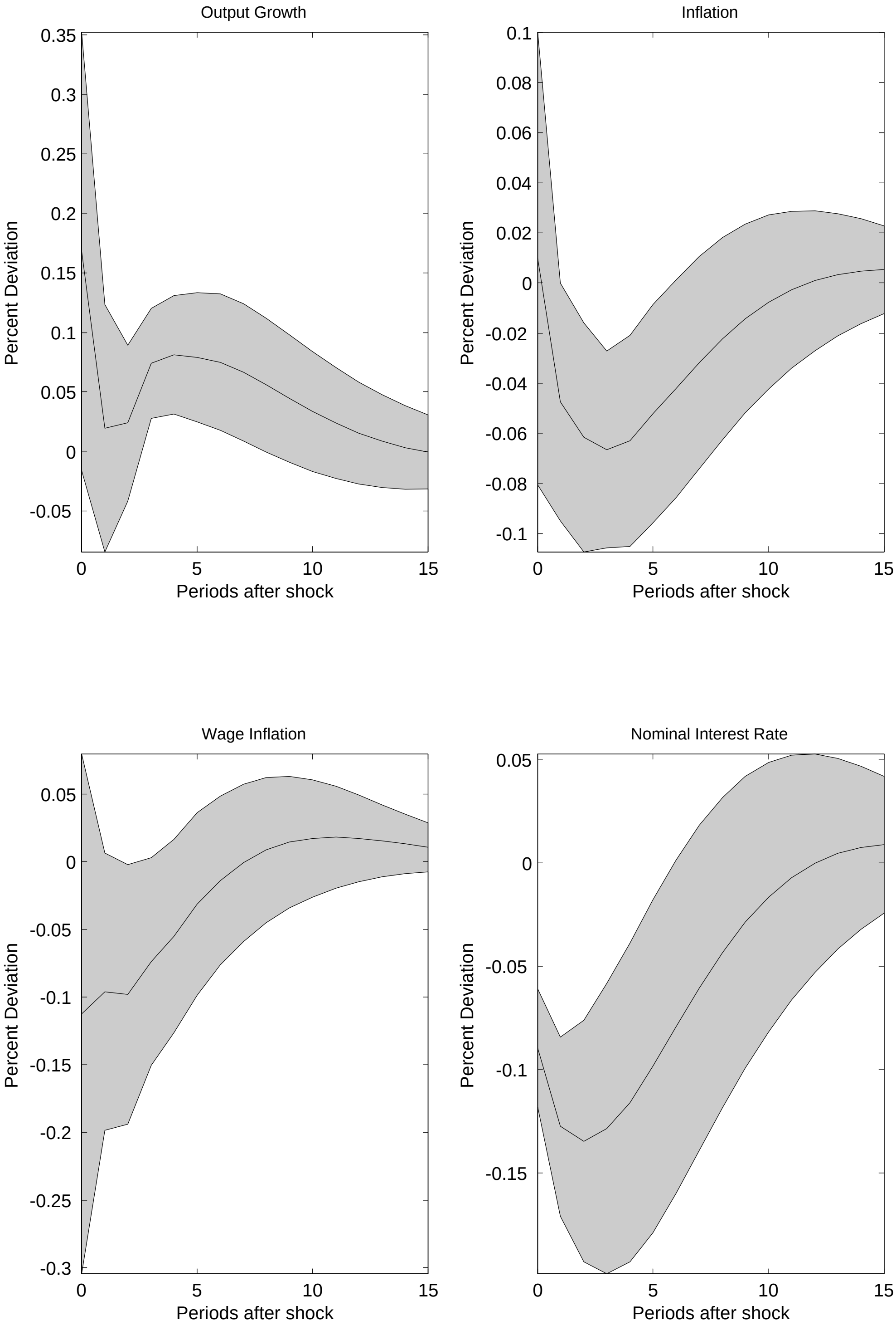

Figure 2: Dynamic responses to a permanent technology shock in the SVAR model. The grey area represents the 95% asymptotic confidence interval of the VAR IRF's.

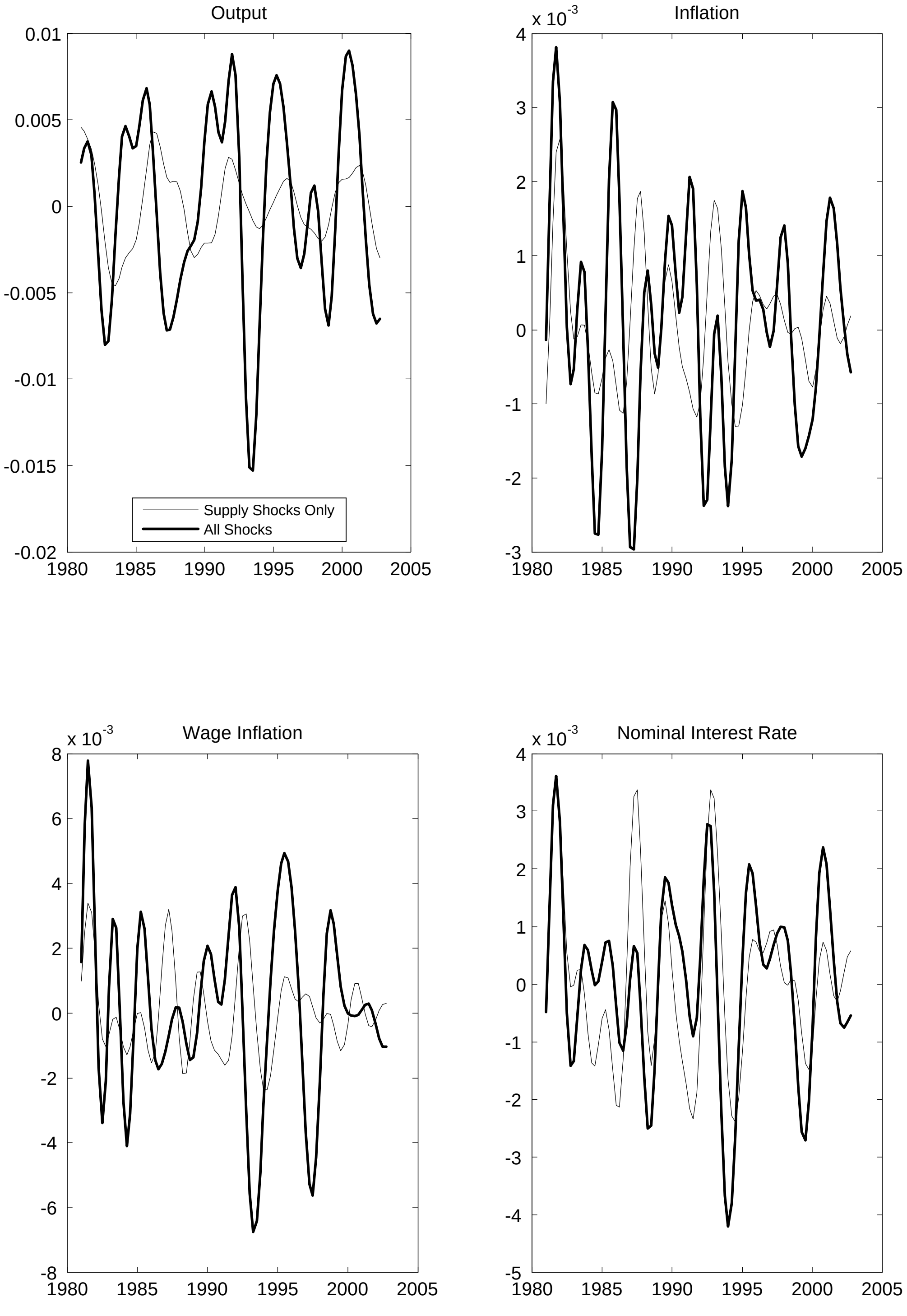

Figure 3: Bandpass(6, 32) filtered series.

Table 1. Calibrated Parameters

Parameters	**Value**	**Interpretation**
β	0.9900	Subjective discount factor
ϕ	1.8546	Inverse elasticity of output wrt labor
s_m	0.5000	Share of material goods in value added
θ_w	5.0000	Price elasticity of labor demand
θ_p	10.0000	Price elasticity of intermediate goods demand
ω_p	0.8546	Elasticity of real marginal cost wrt production

Table 2. Structural Parameters

Parameters	**Value**	**Interpretation**
γ_p	0.4599 [0.1967]	Price indexation parameter
γ_w	1.0000 [*]	Wage indexation parameter
α_p	0.7186 [0.0695]	Probability of no price reoptimization
α_w	0.5051 [0.0687]	Probability of no wage reoptimization
ω_w	2.6975 [1.6709]	Elasticity of marginal disutility of labor
η	0.4975 [0.0069]	Composite habit parameter
ρ_i	0.0000 [*]	Degree of interest rate smoothing
a_p	1.5438 [0.5916]	Interest rate elasticity wrt expected inflation
a_x	0.2548 [0.5104]	Interest rate elasticity wrt output growth
σ_ϵ	0.4816 [0.1662]	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

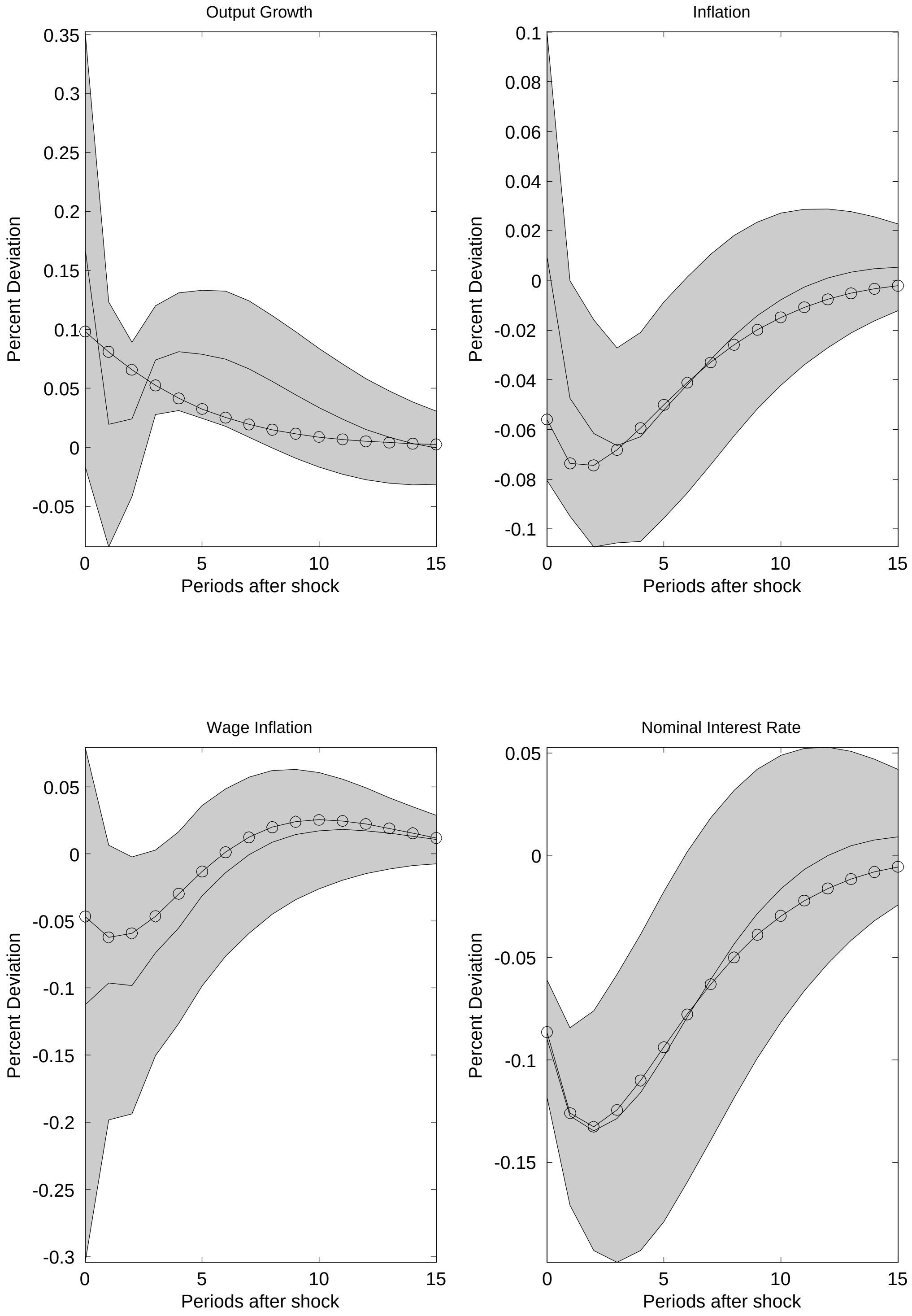

Figure 4: Dynamic responses to a permanent technology shock (plain lines: VAR model, lines with circles: DGE model). The grey area represents the 95% asymptotic confidence interval of the VAR IRF's.

Table 3. Loss Function

λ_p	λ_w	λ_x	δ
0.9138	0.0862	0.0782	0.6956

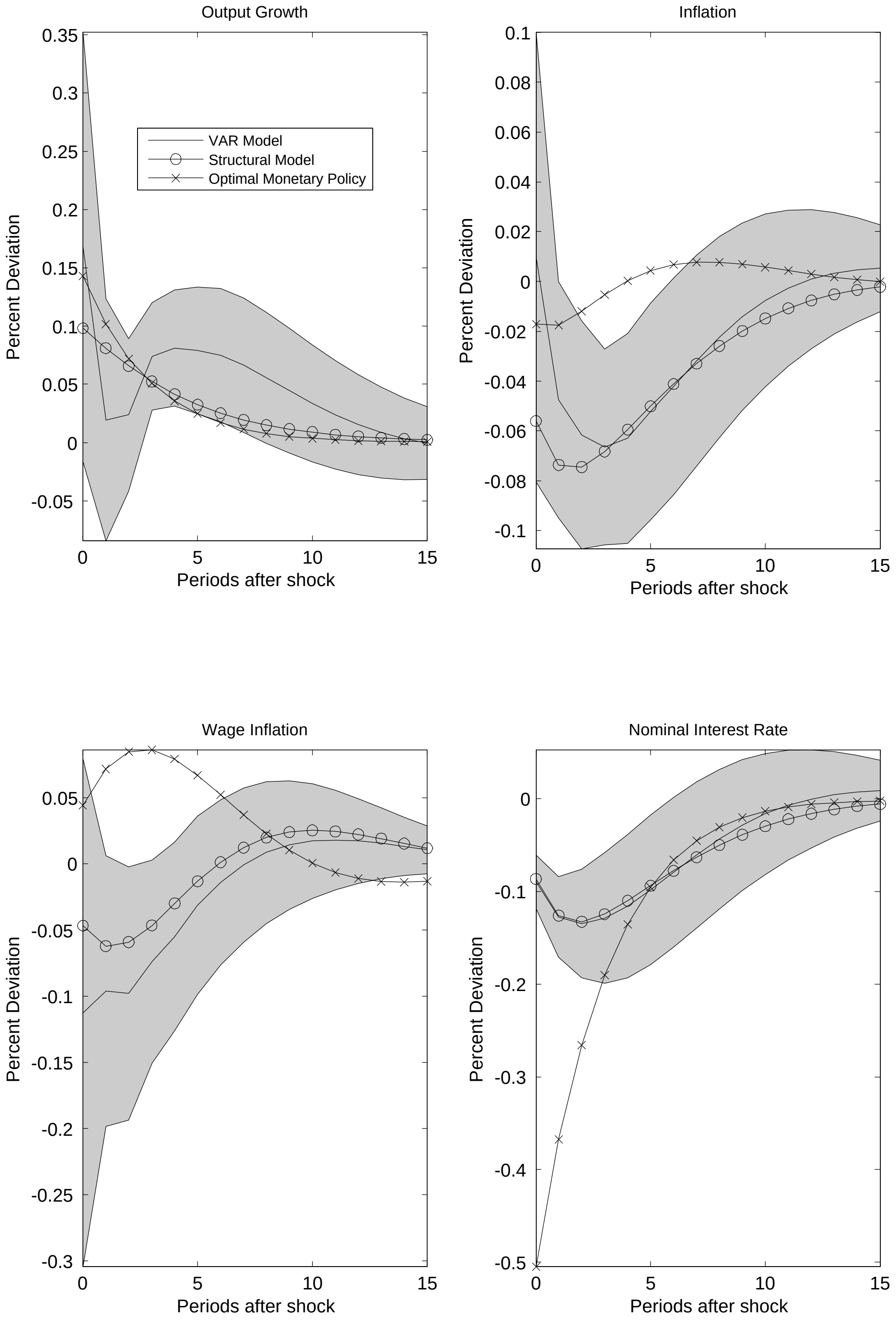

Figure 5: Comparison of the economy's responses to a permanent technology shock in the SVAR, in the structural model, and in the structural model with optimal monetary policy.

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