Putting the New Keynesian Model to a Test*

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Abstract

In recent years, New Keynesian dynamic stochastic general equilibrium (NK DSGE) models have become increasingly popular in the academic literature and in policy analysis. However, it is still disputed how successful these models are in reproducing the dynamic behavior of an economy following structural shocks. This paper is an attempt to shed some light on this issue. We use a VAR with sign restrictions that are robust to model and parameter uncertainty to estimate the effects of monetary policy, preference, government spending, investment, price markup, technology and labor supply shocks on macroeconomic variables in the United States and the euro area. In contrast to the NK DSGE models, the empirical results indicate that technology shocks have a positive effect on hours worked, and investment and preference shocks have a positive impact on consumption and investment, respectively. While the former is in line with the predictions of Real Business Cycle (RBC) models, the latter indicates the relevance of accelerator effects, as described in the earlier Keynesian literature. Furthermore, we show that NK DSGE models might overemphasize the role of cost-push shocks in business cycle fluctuations, while in the same time underestimating the importance of other shocks such as changes in technology and investment adjustment costs.

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1 Introduction

Dynamic stochastic general equilibrium (DSGE) models have become increasingly popular in macroeconomics. In addition to being the focus of a growing academic literature, they have been utilized for policy analysis in institution such as the International Monetary Fund, the Federal Reserve and the European Central Bank.[1] These new-generation DSGE models, often labelled New Keynesian (NK), are generally equipped with nominal rigidities and other frictions, including sticky prices, habit formation, capital adjustment costs and variable capacity utilization rates, which is useful to capture the underlying dynamics in macroeconomic data. While these features make NK DSGE models an attractive tool for forecasting and quantitative policy analysis, it is disputed how successful these models are in reproducing the dynamic behavior of an economy following structural shocks. This paper is an attempt to shed some light on this issue.

We construct a VAR, identified with a limited number of sign restrictions[2] obtained from a DSGE model that are (i) robust to variations in structural parameters and (ii) to the a priori choice of the model, to estimate the effects of monetary policy, preference, government spending, investment, price markup, technology and labor supply shocks on macroeconomic variables in the United States and the euro area. Some of these shocks, such as exogenous variations to preferences, investment adjustment costs and price markups have not been identified in a VAR framework before.

The advantage of our approach is the possibility to identify a large set of structural shocks at a fairly disaggregated level without the need to impose a number of zero restrictions on the immediate or long-run impact of shocks. If the VAR is estimated for a large set of variables, the implementation of zero restrictions can be very arbitrary and could be misleading. That is why a majority of empirical studies focus on the identification of a single shock, such as monetary or fiscal policy shocks. In the latter case, the identification procedure requires only assumptions about the underlying monetary or fiscal policy rule. Even if additional shocks

[1] For example, the GEM model of the International Monetary Fund, the SIGMA model of the Federal Reserve, the TOTEM model of the Bank of Canada and the NAWM of the European Central Bank are all NK DSGE type of models.

[2] The sign restrictions methodology has been applied intitially by Faust (1998), Uhlig (2005) and Canova and de Nicoló (2002) to identify monetary policy shocks. The methodology has been extended by Peersman (2005) for the joint identification of oil price, aggregate supply, aggregate demand and monetary policy shocks.

are identified, this is still at a relative aggregate level. Examples are aggregate demand and aggregate supply shocks. If economic theory, however, provides sufficient information about the qualitative response of variables, sign restrictions are much more general and easier to implement than traditional identification procedures.

In order to avoid that our test is biased against or in favor of the NK DSGE model, we have to implement sign restrictions that are not only in line with existing empirical evidence, but also robust to model and parameter uncertainty. To highlight some of the controversies in the theoretical literature, notice that standard RBC models predict in contrast to NK models a positive impact of technology shocks on employment. Also, some empirical studies, for example Blanchard and Perotti (2002), Fatás and Mihov (2001) and Galí et. al. (2004), find that a government spending shock has a positive impact on private consumption in the data; a result that is at odds with standard DSGE models.

We address the underlying model and parameter uncertainty by deriving a minimum set of general sign constraints, which are consistent with a broader class of models, for a wide range of structural parameter values, and with the existing empirical evidence. The data can then provide further information about the validity of the unconstrained responses of the model. This way, we are able to put the disputed impulse responses of the NK DSGE model to a test. To avoid some controversial identifying restrictions, a number of constraints on the relative responses of variables are included. For instance, instead of imposing a restriction on output and investment following a structural shock, we show how to implement a restriction on the investment-output ratio. As we will demonstrate in what follows, relative restrictions are helpful, since they are less controversial in the chosen set up.

The results indicate that most of empirical impulse responses remain consistent with the NK DSGE model, including the disputed negative impact of government spending shocks on private consumption and investment. Some interesting differences, however, emerge. Specifically, we find a positive effect of technology shocks on hours worked, and a positive impact of preference and investment shocks on investment and consumption, respectively. While the former is in line with the prediction of Real Business Cycle (RBC) models, the latter indicates the relevance of accelerator effects, as described by earlier Keynesian models. Furthermore, we analyze the likelihood of generating impulse responses that are in line with *all sign restrictions* of the NK DSGE model, compared to the previous case which takes model uncertainty into account. We

also compare the corresponding impulse response functions and forecast error variance decompositions under both scenarios. The results show that, if we impose all restrictions from the NK DSGE model on the VAR, the impact of investment and technology shocks on output are underestimated, while the effects of price markup shocks and also, but to a lesser extent, of monetary policy and labor supply shock on output are more pronounced. Similarly, the VAR with all NK DSGE sign restrictions overestimates the contribution of price markup shocks to the forecast error variance of output, while in the same time underestimating the importance of investment and technology shocks.

This paper relates to previous studies examining the empirical fit of NK DSGE models. Prototype closed economy versions of large-scale NK DSGE models are presented e.g. in the papers by Christiano et. al. (2005) and Smets and Wouters (2003).[3] While Christiano et al. (2005) convincingly demonstrates that NK DSGE models are able to fit the dynamic responses in the data following monetary policy shocks, the paper by Smets and Wouters (2003) has garnered much attention because it shows, using Bayesian estimation, that NK DSGE models are able to fit the *unconditional moments* in the data as well as conventional atheoretical VARs; as long as there are sufficient number of structural shocks incorporated into the model. In particular, Smets and Wouters (2003) allows for ten orthogonal structural shocks in the model, including exogenous shocks to monetary policy, preference, government spending, investment, price markup, technology and labor supply. As the NK DSGE model is estimated directly, shocks are identified using all restrictions imposed by the model. Consequently, the reaction of the impulse response functions are constrained by the New Keynesian model. In this paper, however, we let the data to speak for itself. Using a minimum set of robust sign restrictions for identification, we examine how successful NK DSGE models are in reproducing the dynamic behavior of the U.S. and the euro area economy, respectively.

Structural VARs are frequently used to evaluate theoretical models. Galí (1992), for example, tests whether the IS-LM model is able to fit postwar US data. Blanchard and Perotti (2002) and Fatás and Mihov (2001) analyze the effects of fiscal policy shocks in a VAR and compare it to the outcome generated by traditional Keynesian and Real Business Cycle (RBC) models. Galí (1999) estimates the effects of technology shocks on hours worked to discriminate between sticky price and flexible price models, while Canova (2002) evaluates the impulse responses of a limited participation model and a sticky price model following monetary policy shocks using

[3] See also Goodfriend and King (1997) and Clarida et.al.(1999).

VAR analysis.

The remainder of the paper is organized as follows. In Section 2, we present the equilibrium conditions and discuss the conditional moments of a standard medium-scale NK DSGE model. We also discuss the properties of a set of more general sign conditions, which are consistent with a broader class of models and for a wide range of structural parameter values, that can be used for the empirical analysis. Section 3 presents the estimation results and compares the properties of the VAR for the United States and euro area under both scenarios. Section 4 concludes.

2 A model-based identification method

In what follows, we present a New Keynesian DSGE model as described e.g. in Christiano et. al. (2005) and Smets and Wouters (2003). These type of models exhibit in general both sticky prices and wages, price and wage indexation, habit formation in consumption, investment adjustment costs and variable capital utilization. Additionally, several structural shocks can be introduced and estimated within the model framework. These features make them sufficiently rich to capture the stochastics and dynamics in the data and a valuable tool for policy analysis in an empirically plausible set-up. In the next section we will focus on the log-linearized version of the model. For the description of the full non-linear model and derivation of the equilibrium conditions, the interested reader is referred to the papers cited above. The conditional moments from the model are discussed in Section 2.2. A minimum set of more general constraints are proposed in Section 2.3.

2.1 Description of the model

The model consists of a continuum of households who value consumption, subject to external habit persistence, and leisure over an infinite life horizon. The utility function is subject to two exogenous shocks, one is labeled as a preference shock, the other as a labor supply shock. Households trade bonds in a complete market, which allows them to share risk over time and guarantees that individual income is equalized within households despite imperfect competition and staggered wage setting à la Calvo (1983) in the labor market. Households rent capital services to firms and decide how much capital to accumulate given certain capital adjustment costs. As the rental price of capital goes up, utilization of capital changes according to a cost

schedule à la King and Rebelo (2000). Firms produce differentiated goods, decide on labor and capital inputs and set prices according to the Calvo model. The model is closed by a Taylor (1993) type of monetary policy rule. In the following we will describe the equilibrium conditions of the log-linearized model in some detail.

First, the equation governing the evolution of consumption can be summarized by:

$$c_t = \frac{\gamma_c}{1+\gamma_c} c_{t-1} + \frac{1}{1+\gamma_c} E_t c_{t+1} - \frac{1-\gamma_c}{(1+\gamma_c)\sigma}(r_t - E_t \pi_{t+1}) + \frac{1-\gamma_c}{(1+\gamma_c)\sigma}(\varepsilon_t^b - E_t \varepsilon_{t+1}^b) \quad (1)$$

where c_t is consumption, γ_c is the parameter determining the degree of habit persistence, σ is the degree of risk aversion, r_t is the nominal interest rate, π_t is the inflation rate defined as the the first difference of the aggregate price level p_t, and ε_t^b is an AR(1) shock to the intertemporal elasticity of substitution. As describe before, households have market power and act as wage setters in the labor market. Furthermore, households face nominal wage rigidity à la Calvo (1983) and are only able to reset wages with probability $(1-\xi_w)$. If they are not able to re-optimize, the nominal wage will grow at a rate equal partially to the nominal price inflation. As a result, the optimal wage setting of households leads to the following real wage equation:

$$\begin{aligned} w_t \quad = \quad & \frac{\beta}{(1+\beta)} w_{t+1} + \frac{1}{(1+\beta)} w_{t-1} + \frac{\beta}{(1+\beta)} \pi_{t+1} - \frac{(1+\beta\gamma_w)}{(1+\beta))} \pi_t - \frac{\gamma_w}{(1+\beta))} \pi_{t-1} \quad (2) \\ & - \frac{1}{(1+\beta)} \frac{(1-\beta\xi_w)(1-\xi_w)}{(\xi_w(1+\frac{1+\lambda_w}{\lambda_w}\zeta))} (w_t - \xi_w n_t + \lambda_t + \varepsilon_t^n) \end{aligned}$$

where w_t is the real wage, β is the discount factor, λ_w is a parameter driving the degree of monopolistic competition in the labor market, γ_w determines the degree of partial wage indexation, ζ drives the disutility of labor in the utility function while ε_t^n stand for an AR(1) shock to labor supply.

Households own capital and rent to firms at rental rate r_t^k. Capital used in production can be modified by either changing the utilization rate or through investment. Adjusting both generates adjustment costs which are incurred by the households. Adjustment costs are only of second order and are assumed to be zero in steady state. Also, adjustment costs are subject to a stochastic AR(1) shock ε_t^i, henceforth labelled as an investment shock. As a results the optimal investment i_t is determined by:

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

while the linearized capital accumulation is given by:

$$k_t = (1-\delta) k_{t-1} + \delta i_t \quad (3)$$

where Υ is the inverse of the capital adjustment costs in the steady state, δ is the capital depreciation rate and q_t is the real value of capital and follows:

$$q_t = (1-\delta)\beta q_{t+1} + \beta R^k E_t r^k_{t+1} - (r_t - \pi_{t+1}) \tag{4}$$

Notice that R^k stands for the steady state level of the real rate of capital which depends on the time preference rate β and the depreciation rate of capital.

There is a continuum of intermediate goods producers facing imperfect competition. Cost minimization of firms leads to the following equilibrium conditions, determining the evolution of the capital-labor ratio and the marginal cost function mc_t:

$$n_t = w_t + k_{t-1} + (1+\Psi)\, r^k_t \tag{5}$$

$$mc_t = \alpha r^k_t + (1-\alpha) w_t - \varepsilon^a_t \tag{6}$$

where n_t is hours worked and Ψ is the inverse of the elasticity of the capital utilization cost function and α is a parameter determining the evolution of the log-linearized Cobb-Douglas production function:

$$y_t = \phi(\alpha k_{t-1} + \alpha z_t + (1+\alpha) n_t + \varepsilon^a_t) \tag{7}$$

ϕ is 1 plus the share of fixed costs in steady state output, ε^a_t is an AR(1) technology shock common to all firms and z_t is the degree of capacity utilization. Firms face Calvo-type of nominal price rigidity with partial indexation and the degree of competition is subject to the AR(1) shock ε^p_t. This leads to the following generalized New Keynesian Phillipscurve:

$$\pi_t = \frac{\beta}{(1+\beta\gamma_p)}\pi_{t+1} + \frac{\gamma_p}{(1+\beta\gamma_p)}\pi_{t-1} + \frac{(1-\beta\xi_p)(1-\xi_p)}{(1+\beta\gamma_p)\,\xi_p}(mc_t + \varepsilon^p_t) \tag{8}$$

where γ_p is the degree of price indexation and $(1-\xi_p)$ is the probability to reset prices in the actual period. We assume that fiscal policy is Ricardian and variations in government spending-output share g_t are governed by an AR (1) process. As a result, equilibrium in the goods market is determined by the following equation:

$$y_t = \frac{C}{Y} c_t + \frac{I}{Y} i_t + g_t + R^K \frac{K}{Y} \Psi r^k_t \tag{9}$$

$\frac{C}{Y}, \frac{I}{Y}, \frac{K}{Y}$ are the corresponding steady state ratios of consumption, investment and capital to output.

Finally, the model is closed by a generalized Taylor-rule, where $\bar{\pi}$ is the inflation target (which is implicitly assumed to be zero in the following) and η_t^r an i.i.d. policy shock.

$$\begin{aligned} r_t &= \phi_r r_{t-1} + (1-\phi_r)\left(\phi_\pi(\pi_{t-1}-\bar{\pi}) + \phi_y(y_t - y_t^*)\right) \\ &\quad + \phi_{\Delta\pi}(\pi_t - \pi_{t-1}) + \phi_{\Delta y}(y_t - y_t^* - (y_{t-1} - y_{t-1}^*)) + \eta_t^r, \end{aligned} \tag{10}$$

The output gap is calculated, consistently with New Keynesian type of DSGE models, as a difference between actual output and the level of output that would prevail under flexible prices and wages and in the absence of cost-push shocks. The parameter ϕ_r is the degree of interest rate smoothing, while ϕ_π, ϕ_y, $\phi_{\Delta\pi}$, $\phi_{\Delta y}$ are the elasticity of interest rate to inflation, output gap, inflation growth and the change in the output gap respectively. In the following section, we discuss the impulse response functions of the model.

2.2 Impulse response functions

In this section we present the impulse response functions of the model, from which a limit set is used later as sign restrictions in the VAR analysis, following a monetary policy, preference, government spending, investment, price markup, technology and labor supply shock. To test for robustness, we simulate the impulse responses of the model for a range of sensible parameter values. To delimit the range for the parameter values, we conducted a brief survey of the related empirical literature.[4] For example, the papers by Smets and Wouters (2003 and 2004) estimate the posteriore distribution of the structural parameters of a NK DSGE model for the euro area and United States. Similar models by using alternative estimation techniques have been analyzed by Christiano et. al. (2005), Altig et. al. (2002), Onatski and Williams (2004) and Coenen and Straub (2005). We use the range of parameter values estimated in these papers as a benchmark. To choose the interval for the parameters governing investment adjustment cost, habit persistence, capacity utilization costs, we also consulted studies that focus on real models as King and Rebelo (2000) and Boldrin et. al. (2001).

To calibrate the monetary policy rule, we took into account the confidence interval for the Taylor rule coefficients estimated in the papers by Judd and Rudebusch (1998), Sack (1998), Clarida et. al. (1998) and Rotemberg and Woodford (1998). With regards to the persistence of the shock processes, we cover a wider range for the AR(1) coefficients than the 90 percent

[4] See also Onatski and Williams (2004) for a similar discussion.

interval of the posteriore distribution of the Smets and Wouters (2003) estimates. Particularly, in contrast to Smets and Wouters (2003, 2004), we did not restrict the price markup shock to follow an i.i.d. process and included the entire range of possible values.[5] We follow Smets and Wouters (2003) by setting some of the structural parameters to a fixed value from the start. In particular, we set $\alpha = 0.3$, the subjective discount rate $\beta = 0.99$, the wage markup parameter $\lambda_w = 0.5$ and the depreciation rate $\delta = 0.025$. The intervals for all other parameter values are reported in Table 1.[6]

Table 1: Structural Parameters

β	0.99	ξ_p	$[0.4 - 0.95]$
σ	$[1 - 4]$	ξ_w	$[0.4 - 0.95]$
γ_c	$[0 - 0.9]$	γ_p	$[0 - 0.99]$
ζ	$[1 - 3]$	γ_w	$[0 - 0.99]$
α	0.3	ϕ_r	$[0.6 - 0.99]$
ϕ	$[1 - 1.8]$	ϕ_y	$[0 - 0.8]$
λ_w	0.5	ϕ_π	$[1 - 4]$
δ	0.025	$\phi_{\Delta y}$	$[0 - 0.2]$
Υ	$[0.12 - 0.28]$	$\phi_{\Delta\pi}$	$[0 - 1]$
Ψ	$[2.8 - 10]$	ρ^{shock}	$[0.6 - 0.99]$

After defining the range of sensible parameter values, we proceed with a simulation exercise. First, we assume that the parameters are uniformly distributed over the selected parameter range. Second, we draw a random value for each parameter from the presented intervals and calculate the corresponding impulse response functions of the model. This exercise is repeated for 100,000 simulations. The median, 16th and 84th percentiles of all conditional responses are shown in Figure 1. The corresponding signs are reported in Table 2.

Not surprisingly, the impulse response functions of the model are broadly in line with the results reported so far in the literature. An expansionary[7] monetary policy shock, reflected

[5] In Smets and Wouters (2003), the price markup shock was restricted to follow an i.i.d. process in order to separate it from the AR(1) productivity shock in the Bayesian estimation.

[6] Notice that ρ^{shock} is the range of AR(1) coefficients used in the exercise for all the shocks but price markup shock for which we use the interval $[0 - 0.99]$

[7] In the following, expansionary shocks are defined to have a positive impact on output. Notice also, that while we assume that expansionary supply side shocks have a negative effect on prices, we define demand shocks to induce a positive correlation between output and prices.

by an exogenous decrease in the nominal interest rate results in an increase in consumption, investment, output, prices, hours and real wages. Expansionary preference, government spending and investment shocks all have a positive effect on output, prices and the nominal interest rate.[8] A shift in preferences toward consumption today crowds out investment, but has a positive impact on consumption and output. In contrast, an expansionary investment shock, generated by a temporary reduction in the cost of installing capital, induces a negative correlation between output and consumption. An increase in non-productive government spending implies a negative wealth effect and a corresponding fall in consumption and investment; the well-known crowding-out effect of exogenous government spending. The latter has a positive impact on both labor supply and labor demand resulting in an increase of hours worked and an undetermined effect on real wages. Most of impulse responses generated by the NK DSGE model turn out to be insensitive to variations in parameter values. The reaction of real wages following a preference, government spending and investment shock depends, however, on the chosen parameterization. Specifically, for some values, the DSGE model predicts a positive and for others a negative response.[9]

Table 2: All sign restrictions derived from the NK DSGE model

	y	p	r	n	w	c	i
monetary policy	$\uparrow$	$\uparrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
preference	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow\downarrow$	$\uparrow$	$\downarrow$
government spending	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow\downarrow$	$\downarrow$	$\downarrow$
investment	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow\downarrow$	$\downarrow$	$\uparrow$
price markup	$\uparrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
technology	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$
labor supply	$\uparrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\uparrow$	$\uparrow$

Expansionary supply side shocks, such as the exogenous variation in technology, price markup and labor supply, have a positive impact on output, consumption and investment, whilst the effect on prices and interest rates is negative. Notice that Calvo-type of price stickiness allows

[8] Note that the response of the nominal interest rate to an investment shock is only consistently positive after two quarters for a sensible range of parameter values. This will be taken into account in the empirical analysis.

[9] Smets and Wouters (2003, 2004) find a significant positive reaction of real wages to these three shocks. Notice, however, that we apply a uniform distribution and allow for a larger range of permissible parameter values in our simulation exercise as in their estimated posteriore distribution.

only for a restricted share of firms to adjust prices downwards in the short run. As a result, aggregate demand will initially rise less than aggregate supply following an increase in productivity so that hours worked needs to decrease in equilibrium. Notwithstanding its negative initial effect on marginal costs, a positive technology shock has a positive impact on real wages. The wealth effects induced by the increase in productivity and the corresponding labor supply shift in combination with wage stickiness dominates the negative impact of labor demand effects. On the other hand, an exogenous increase in labor supply has naturally a favorable impact on equilibrium hours worked, but a negative effect on the equilibrium real wage.[10] Finally, and in contrast to technology and labor supply shocks, expansionary price markup shocks generate a positive correlation between real wages and hours worked.[11]

Theoretically, the presented signs are sufficient to uniquely disentangle all seven shocks in an empirical VAR with sign restrictions. Specifically, for each shock the sign of the response of at least one variable is different from the sign of the response to another shock. If one fully believes in the derived restrictions from the New Keynesian model, the results of the SVAR estimations can be used to evaluate the magnitudes of the impulse responses and analyze variance and historical decompositions.

Although the previous exercise took into account the uncertainty surrounding the structural parameters of the model, the presented results are still conditional on the a priori choice of the model. For example, the response of hours worked is generally negative in the NK model following a technology shock. In contrast, RBC models predict a positive effect of technology shocks, also confirmed by empirical results presented in Christiano et. al. (2004), Uhlig (2004) and Peersman and Straub (2004) among others. But the empirical literature is not unanimous (see for example Galí and Rabanal, 2004). The crowding-out of private consumption and investment following a government spending shock is similarly controversial. The majority of the empirical literature predicts a positive or insignificant impact of government spending on private consumption and investment. See the work by Blanchard and Perotti (2002), Fatás and Mihov (2001), Galí et. al. (2004) and Mountford and Uhlig (2005).[12] Finally, the lack of VAR evidence

[10] See Peersman and Straub (2004), for a more detailed discussion on the effects of labor supply and technology shocks in a NK DSGE model.

[11] Except the response of real wages to preference, government spending and investment shocks, which appears to be undetermined in our exercise; the signs of the conditional responses are all consistent with the estimation results of Smets and Wouters (2003).

[12] On the basis of this evidence, Galí et. al. (2004) extend the standard New Keynesian model to allow for

on the dynamic behavior of an economy following preference and investment adjustment cost shocks, give rise to caution in implementing the full set of sign restrictions derived from the NK DSGE model. We therefore propose a much general and less stringent approach to identify the shocks in the next subsection.

2.3 Relaxed sign restrictions

In a first step, we exclude those restrictions of the NK DSGE model that are not necessary to uniquely disentangle the structural shocks. Accordingly, we can already significantly reduce the number of restrictions and still identify all shocks. This does, however, not mean that all controversial restrictions are avoided. For instance, the only restriction to differentiate a price markup shock from a technology shock is the opposite sign of the reaction of hours worked. The latter is, however, exactly at the core of the debate between NK and RBC adherents.

In order to solve this problem, we avoid the use of controversial dynamic responses of the NK DSGE model in the identification procedure by tracking down commonly accepted and therefore more robust sign restrictions. In particular, we use restrictions on the signs of relative responses that are less stringent and less questionable than sign restrictions on the responses of the variables themselves. The signs of the latter can then be estimated. All restrictions used in

the presence of non-Ricardian, rule-of-thumb households and show that the interaction of the latter with sticky prices and deficit financing can account for the existing empirical evidence. However, as discussed in Bilbiie and Straub (2004), the result relies on a sharp response of real wages following government spending shocks which stands in contrast with the observed a-cyclical pattern of real wages in the data. Coenen and Straub (2005) argue, utilizing an estimated DSGE model with non-Ricardian agents for the euro area, that the presence of non-Ricardian households is in general conducive to raising the level of private aggregate consumption in response to government spending shocks; as a practical matter, however, there is only a fairly low probability for this to happen. The results show that the estimated share of non-Ricardian households is quite low, but also that the large negative wealth effect induced by the highly persistent nature of the estimated government spending shocks crowds out consumption of the Ricardian agents significantly.

the estimations described in Section 3 are presented in Table 3.

Table 3: Relaxed restrictions

	y	p	r	n	w	c	i	$y^N - w$	$c - y$	$i - y$
monetary policy	$\uparrow$	$\uparrow$	$\downarrow$							
preference	$\uparrow$	$\uparrow$	$\uparrow$						$\uparrow$	
govern. spending	$\uparrow$	$\uparrow$	$\uparrow$						$\downarrow$	$\downarrow$
investment	$\uparrow$	$\uparrow$	$\uparrow$						$\downarrow$	$\uparrow$
price markup	$\uparrow$	$\downarrow$			$\uparrow$			$\downarrow$		
technology	$\uparrow$	$\downarrow$			$\uparrow$			$\uparrow$		
labor supply	$\uparrow$	$\downarrow$			$\downarrow$					

An expansionary monetary policy shock is identified as a shock that has a negative effect on interest rates and a positive effect on output and prices. These restrictions are commonly accepted and sufficient to uniquely disentangle the shock from all other shocks. The data can then determine whether all other responses are still consistent with the DSGE model. Demand shocks, such as preference, government spending and investment shock are assumed to have a positive impact on output, prices and the nominal interest rate. To differentiate them using the standard responses of the NK DSGE variables, we need to restrict the signs of the impulse response functions of consumption and investment. Specifically, the model predicts that a preference shock has a positive impact on consumption and a negative effect on investment. The opposite is true for an investment shock. On the other hand, both impulse responses are predicted to decrease following a government spending shock. However, the described responses, in particular those following government spending shocks, are disputed in the literature.[13]

Although RBC models also predict a negative impact of government spending on private consumption and investment, a majority of the empirical literature rejects this. Blanchard and Perotti (2002), Fatás and Mihov (2001) and Galí et. al. (2004) find an increase in private consumption following an expansionary government spending shock, but confirm the crowding-out effects on investment. Edelberg et. al. (1999) find that government spending crowds-in investment, while Perotti (2002) provides evidence using data on industrial economies that the impact of fiscal shocks on consumption and investment is insignificant in many countries and

[13] We are not aware of theoretical or empirical papers questioning the mentioned effects of preference and investment shocks. Smets and Wouters (2003, p 1156) do, however, describe the negative conditional responses as a potential problem in their underlying model.

even negative in the post-1980 period for the United States. From the theoretical point of view, Galí et. al. (2004) show that an extended NK DSGE model with rule-of-thumb consumers can account for a positive effect of government spending on consumption in specific circumstances. Consequently, to avoid these controversial restrictions, we introduce in what follows some less stringent constraints on the responses of the consumption-output ratio and investment-output ratio. The theoretical responses of these ratios, obtained from the DSGE model simulations, are shown in the second and third column of Figure 2.

Consider a positive shock to preferences. Since the model predicts a rise in consumption and a fall in all other components of output, the reaction of the consumption-output ratio must be positive. On the other hand, for the same reason, the reaction of the latter to a government spending and investment shock will be negative (not surprisingly because the model predicts for both shocks a rise in output and fall in consumption). More generally, preference shocks, that is a shift in preferences towards consumption today, will cause in most of the commonly accepted models a stronger response of consumption than output. Consequently, we restrict the reaction of the consumption-output ratio to be positive following a preference shock and negative after a shock to government spending and investment adjustment costs. Notice, however, that we still allow this way for a positive reaction of investment after a shock to preferences and a positive effect on private consumption following a government spending and investment shock, as long as the impact is smaller than the effect on total output.[14] We use the same reasoning to discriminate between the investment and government spending shock; we assume that the investment-output ratio increases after the former and falls after the latter in the short-run. These restrictions are still consistent with a standard DSGE model, but are much more general and less stringent. The data will finally determine the exact signs of consumption and investment.

At the supply side (shocks with a negative correlation between output and prices), a labor supply shock is identified as a shock with a negative effect on real wages whilst this effect is assumed to be positive, in accordance with the model, for a technology and price markup shock. Peersman and Straub (2004) illustrate this for a large class of DSGE models, including RBC models. Moreover, Francis and Ramey (2002) and Fleischmann (1999) report a positive effect of technology shocks and a negative effect of labor supply shocks on real wages using an identification strategy in the spirit of Galí (1999).

[14] Note that these restrictions are only introduced the first four lags after a shock in our empirical analysis. Accordingly, it is perfectly possible to have a different sign in the long run.

Finally, the separation of price markup shocks from technology shocks appears to be difficult. The impulse response functions of the two shocks differ only with respect to the reaction of hours worked. Unfortunately, the true causal impact of technology shocks on hours worked is an area of controversy between RBC and sticky price models. The former expects a positive impact whilst the latter predicts a negative effect. Also the empirical evidence is mixed. Galí (1999), Shea (1998), Basu et. al. (1999), Francis and Ramey (2002), and Francis et. al. (2003) find a negative effect and Christiano et. al. (2004), Peersman and Straub (2004), Uhlig (2004), Dedola and Neri (2004) and Canova and Gambetti (2004) find a positive impact. To discriminate between the two shocks, we follow Dedola and Neri (2004) and simulate the impact of both shocks on the difference between labor productivity, defined as y^N, and real wages. As shown in the first column of Figure 2, the reaction is clearly negative following a price markup shock and positive after a technology shock for the range of permissible parameter values.[15] Accordingly, we assume that the impact of technology shocks on labor productivity is stronger than the one on real wages. In contrast, a negative shock to the price markup will have, through the corresponding fall in prices, a stronger effect on real wages than on labor productivity. No other restrictions are required and the data can determine the signs of all unconstrained responses.

3 An SVAR-model with DSGE sign restrictions

In this section, we present the results of the SVAR-model using quarterly data for the United States and the euro area. Time series that are used for the estimations are described in the data appendix. Because a seven-variables VAR is estimated, we use the longest possible sample period. For the US, this is 1955-2004, and for the euro area 1982-2003. The latter is determined by the availability of the hours worked series. All results presented below are, however, robust with respect to alternative sample periods and data series (see appendix for a brief discussion). We first describe the specification and identification strategy of the SVAR in Section 3.1. The results are presented in Section 3.2. The sensitivity of the results when more restrictions from the DSGE model are implemented is discussed in Section 3.3.

[15] The results are insensitive to the existence of nominal rigidities in the model.

3.1 Methodology

Consider the following specification for a vector of endogenous variables Y_t:

$$Y_t = c + \sum_{i=1}^{n} A_i Y_{t-i} + B\varepsilon_t \tag{11}$$

where c is a matrix of constants, A_i is an $(n \times n)$ matrix of autoregressive coefficients and ε_t is a vector of structural disturbances. The endogenous variables, Y_t, that we include in the VAR are real GDP (y_t), the GDP deflator (p_t), short-term nominal interest rate (r_t), hours (n_t), real wages (w_t), consumption (c_t) and investment (i_t). All variables are logs, except the interest rate which is in percentages. We estimate the VAR-model in levels with three lags.

Within the VAR, we identify seven types of shocks derived from the presented NK model: a monetary policy, preference, government spending, investment, price markup, technology and labor supply shock respectively. In order to identify these shocks, we use the sign restrictions as shown in Table 3. The restrictions are sufficient to uniquely disentangle all seven shocks. Specifically, for each shock the sign of the response of at least one variable is different from the sign of the response to another shock. For the implementation of these restrictions, we refer to Peersman (2005). All restrictions are imposed as $\leqslant$ or $\geqslant$. For all variables, the time period over which the sign constraints are binding is set equal to four quarters.[16] Following Uhlig (2005) and Peersman (2005), we use a Bayesian approach for estimation and inference. Our prior and posterior belong to the Normal-Wishart family used in the RATS manual for drawing error bands. Because there are an infinite number of admissible decompositions for each draw from the posterior when using sign restrictions, we use the following procedure. To draw the "candidate truths" from the posterior, we take a joint draw from the posterior for the usual unrestricted Normal-Wishart posterior for the VAR parameters as well as a uniform distribution for the rotation matrices. We then construct impulse response functions. If all the imposed conditions on the responses are satisfied, we keep the draw. If the decomposition does not match the criteria, the draw is rejected. This means that these draws receive zero prior weight. Based on the draws left, we calculate statistics and report the median responses, together with 84th and 16th percentiles error bands. We do not require the restrictions of all shocks to hold simultaneously. Specifically, if the impulse responses to an individual shock are consistent with the imposed conditions for this shock, the results for the specific shock are accepted. This

[16] Note that since the response of the interest rate to an investment shock is only significant at lag 2 in our theoretical analysis, we only introduce this restriction from the second lag onwards after the investment shock.

implies that even if some restrictions for a certain shock are debatable, this has no effect on the estimation of the other shocks.[17] Impulse responses and error bands are computed with a minimum of 1000 solutions for each shock.

3.2 Results

Impulse response functions to all seven shocks are shown in Figures 3 and 4 for the United States and the euro area, respectively. The results are remarkably consistent across both areas. The effects of an exogenous change in monetary policy are in line with the results of the DSGE model. There is a hump-shaped response of output and the reaction of prices is persistent following a temporary rise in the short-term interest rate.[18] Also consumption and investment fall after a monetary policy tightening. The reactions of hours and real wages are not significant. The responses to a government spending shock are also very comparable with the results of the benchmark DSGE model. The signs of output, prices and the interest rate are restricted according to the model's impulse responses for the first four quarters. The reactions of real wages and hours worked are negative but not significant in both areas. Noticeable is that we still find the crowding-out effects of fiscal policy, that is there is a fall in investment and private consumption following an expansionary government spending shock. Both reactions were unconstrained in the estimations. Our finding is in contrast to many other studies using VAR-methods such as Blanchard and Perotti (2002), Fatás and Mihov (2001) and Galí et. al. (2004).

The conditional responses following preference and investment shocks are also conform with the predictions of the NK DSGE model for output, prices, interest rates, hours and real wages respectively. We do find, however, a substantial difference in the response of investment and consumption following a shock to preferences and investment adjustment costs. A shift in preferences towards consumption today, that is a positive preference shock, has a significant positive impact on investment. Similarly, an exogenous fall in investment adjustment costs has a positive effect on private consumption. Crowding-in effects of both shocks seems to be more

[17] This also saves a lot of computational time. If we want to identify all seven shocks in one draw, we need more than 1 million draws to find one solution that match all restrictions from the seven shocks simultaneously. In addition, our approach enables us to evaluate for each individual shock how easy it is to find an admissible decomposition in the data, that is to calculate an acceptance rate for each shock. See Section 3.3.

[18] Note that we show impulse response functions for a restrictive monetary policy shock, which is standard in the VAR literature.

accepted by the data which is at odds with the predictions of theoretical NK DSGE models. The described results are concurrently present in the data for both the United States and the euro area.

Concerning supply side shocks, the impulse responses following price markup and labor supply shocks do concur with the predictions of the DSGE model. Both shocks have a significant positive effect on consumption, investment and hours worked. The latter three responses were unconstrained in our estimations. The reaction of the nominal interest rate is mostly insignificant. For a technology shock, we do find discrepancies between the conditional moments of the data and the model. In particular, we find a positive effect on hours worked following an expansionary technology shock, while the corresponding response is predicted to be negative in standard NK models. As discussed in section 2, our results following technology shocks support the RBC hypothesis. Positive effects on hours worked following a technology shock are also found by Christiano et. al. (2004), Uhlig (2004), Peersman and Straub (2004) and Canova and Gambetti (2004).

3.3 Does the data support the New Keynesian hypothesis?

In this section, we analyze the likelihood and consequences of generating impulse responses that are in line with all sign conditions of the NK DSGE model. The results will give us further indication whether the data supports the hypothesis of the NK model and how likely it is that the economy follows a dynamic path predicted by the NK DSGE model.[19] In the previous section, we have only implemented a set of very general sign restrictions from the NK DSGE model; therefore it is still possible that at least some of the accepted draws are also conform with all the conditional moments of the NK DSGE model, as described in Table 2. Furthermore, we evaluate whether variance decompositions of output and the magnitude of the impulse responses are sensitive to the inclusion of the additional restrictions.

The results are mixed. While imposing all sign restrictions from the DSGE model, we do find solutions for each shock indicating that the predictions of the NK DSGE model are not diametrically opposed by the data. However, for some shocks it is very difficult to find admissible solutions, attesting that the probability of a realization of the corresponding responses is very

[19] For each restriction, we take the most likely outcome predicted by the DSGE model, that is the sign of the median response of the theoretical simulations. These signs are also consistent with the empirical results of Smets and Wouters (2003).

low. Because the signs of all impulse responses are consistent with the theoretical model by construction, we do not report them. Table 4 contains the acceptance rates for all shocks. More specifically, the first column shows for each shock the average number of draws required to find a decomposition that match all the imposed sign conditions for our baseline identification strategy discussed in Section 3.2 (using relaxed, more general sign restrictions).[20] For the United States, the number varies between 1.98 for an investment shock to 37.61 for a shock to preferences. For most of the shocks, it is relatively easy to reconcile the sign conditions with the conditional moments in the data. It appears to be somewhat difficult, however, to find a technology shock in the euro area (361 draws are required) using the general identification scheme.

Table 4: Acceptance rates for all shocks

	Relaxed restrictions	All restrictions	Relative acceptance (%)
United States			
monetary policy	13.89	349.95	3.97
preference	37.61	17141.24	0.20
government spending	25.32	3911.39	0.64
investment	1.98	230.48	0.86
price markup	2.58	45.61	5.66
technology	2.08	78.92	2.64
labor supply	2.41	55.05	4.38
euro area			
monetary policy	3.89	22.59	17.21
preference	20.92	7572392.0	0.00
government spending	17.22	36419.33	0.00
investment	3.57	1164.36	0.31
price markup	12.13	82.15	14.77
technology	361.20	46969.31	0.77
labor supply	3.17	17.51	18.10

Using all sign restrictions from the NK DSGE model makes the estimation procedure ex-

[20] Remind that we take a joint draw from the posterior for the usual unrestricted parameters as well as a uniform distribution for the rotation matrices and then construct impulse response functions. If all imposed conditions on the responses are satisfied, we keep the draw. If the decomposition does not match the criteria, the draw receives zero prior weight. See also Section 3.1.

tremely difficult. For preference, government spending, investment and technology shocks, it is very difficult to find admissible solutions in the data. The latter is also confirmed by the presented relative acceptance rates in the last column of Table 4. The relative acceptance rate is the percentage of accepted draws with more general restrictions that are also accepted using all sign constraints from the DSGE model. In the euro area, the ratio is below 1 percent for preference, government spending, investment and technology shocks. In the United States, we get similar results for all, but technology shocks.[21]

In the next step, we evaluate the sensitivity of the variance decompositions and the impulse response functions of output to the inclusion of the additional restrictions. Figure 5 shows the impulse responses of output to all shocks in the US and euro area. Black lines are median responses obtained from our baseline VAR with the relaxed restrictions, together with 16th and 84th percentiles error bands (dotted lines), as already reported in Figures 3 and 4. The grey lines are the median responses of output when *all* NK DSGE sign restrictions are imposed. For some shocks, the choice of the restrictions affects the magnitude of the output response. Introducing all restrictions from the NK DSGE model, the VAR underestimates the impact of investment and technology shocks on output in both areas, while preference and government spending shocks engender a subdued response of output only in the VAR using euro area data.[22] On the other hand, the reaction of output is rather overestimated after a price markup and, but less pronounced, following a monetary policy and labor supply shock.

The previous results are confirmed by the forecast error variance decompositions of output. Figures are reported in Table 5 for the horizons of 0, 4 and 28 quarters. In the baseline with relaxed constraints, the forecast variance decomposition for the United States indicates that investment and technology shocks are the two most important shocks, explaining 31 and 36 percent of the output variance in the short-run. In the long-run, the number even increases to 56 percent for a technology shock. When all restrictions from the NK DSGE model are imposed, the relative importance of both shocks are only 13 and 18 percent, respectively, while

[21] Note that in the case of a government spending shock, although the controversial conditional properties are consistent with the data, the low acceptance rate is mainly the result of the responses of hours and real wages. Both variables are expected to react positively to a government spending shock in the DSGE model whilst the reaction is rather (insignificantly) negative in the data when no restrictions are imposed.

[22] We have to be careful when interpreting the median response of a preferences shock in the euro area with all DSGE restrictions because the function is only based on a very limited number of observations given the very low acceptance rate.

price markup shocks, in the same time, account for 40 percent of output fluctuations within one quarter. With the relaxed constraints, the contribution of price markup shocks to output fluctuations are reduced to around 12 percent. Similar conclusions are obtained for the euro area. Interestingly, however, preference shocks appear to play a much more important role in business cycle fluctuations than in the United States. Within one quarter, 16 percent of output fluctuations are explained by shocks to preferences in the baseline case.

Table 5: Forecast error variance decomposition of output

	Relaxed restrictions			All restrictions		
	0Q	4Q	28Q	0Q	4Q	28Q
United States						
monetary policy	2.3	6.1	9.1	7.4	15.1	7.9
preference	1.3	3.2	1.4	1.1	2.1	0.8
government spending	5.3	1.7	0.5	4.7	1.1	0.4
investment	30.5	21.1	5.8	12.5	3.9	5.5
price markup	11.7	14.6	14.7	40.4	44.8	38.2
technology	35.7	41.5	55.9	18.0	13.9	29.6
labor supply	13.2	12.0	12.7	15.8	19.0	17.6
euro area						
monetary policy	5.9	15.4	26.3	27.1	33.3	31.4
preference	16.1	9.0	6.9	0.4	1.8	0.5
government spending	7.1	9.3	7.4	2.6	4.1	3.3
investment	24.2	28.6	13.4	6.2	5.4	4.8
price markup	8.6	6.2	12.8	17.5	15.5	24.9
technology	29.7	20.9	21.3	20.9	8.7	10.4
labor supply	8.4	10.6	11.9	25.3	31.2	24.7

Note: Figures are based on the median of the posterior distribution

4 Conclusions

In this paper, we tested how successful NK DSGE models are in reproducing the dynamic behavior of the economy following structural shocks. First, we showed how DSGE models can be used to derive sign restrictions for the identification of a large set of structural shocks in a VAR

for the United States and the euro area. For a sensible range of underlying parameter values, DSGE models can deliver sufficient number of sign restrictions to uniquely identify respectively monetary policy, preference, government spending, investment, price markup, technology and labor supply shocks. Some of the conditional responses generated by the NK DSGE model are, however, not consistent with alternative theoretical models and existing empirical evidence. We therefore proposed a set of minimum constraints, which are still consistent with the presented theoretical model, but also robust to model and parameter uncertainty. As a result, the data provided us with more information about the validity of unconstrained impulse responses. As such, we put the New Keynesian model to a test.

Empirical results for the United States and euro area showed that a majority of the responses remain consistent with the NK DSGE model, including the controversial negative effects of government spending shocks on private consumption and investment. We did find, however, some interesting differences. In contrast to the NK model, we found a positive impact of technology shocks on hours worked; a result in line with the predictions of the RBC model. In addition, we estimated a positive impact of expansionary preference and investment shocks on private consumption and investment, respectively. The latter indicates the existence of accelerator effects, as described by earlier Keynesian models.

We demonstrated that the estimated impact of technology, preference and investment shocks on output is much smaller when all constraints derived from the NK DSGE model are imposed on the data. In contrast, price markup shocks become much more important also picking up the effects of the three other shocks, in particular technology shocks. The previous results indicate that NK DSGE models might overemphasize the role of cost-push shocks such as price markup shocks in business cycle fluctuations, while in the same time underestimating the importance of other shocks such as changes in technology and investment adjustment costs.

A Data appendix

For the US; GDP, investment and consumption are taken from the Bureau of Economic Analysis (Department of Commerce). Output is expressed in billions of chained 2000 dollars. The price level is the log of the implicit price deflator of GDP. Investment and consumption are respectively real gross private domestic investment and real personal consumption expenditures. Results are, however, robust when we use the consumer price index (Bureau of Labour Statistics) instead of

GDP deflator or when we deflate nominal investment and consumption with the overall GDP deflator (the latter is done by Altig et. al., 2002). All series are seasonally adjusted and the interest rate is the Federal Funds Rate. The results are also robust when aggregate real variables are expressed per capita. Because we do not have population data for the euro area (see below), we report the results non-adjusted for population.

Hours and wages (hourly compensation) are for the non-farm business sector and are taken from the Bureau of Labour Statistics. In order to correct hours for the global economy, the index of average hours for the NFB sector is multiplied with total employment. Results are again robust if we take total employment instead of hours.

For the euro area, all data are taken from the Area Wide Model from the ECB (Fagan et. al., 2001). The price level is the GDP deflator (results are not affected if HICP index is used as an alternative). Hours worked is a series constructed by the ECB Economics Department. The latter is only available from 1981 onwards, which determines our sample period (see also Peersman and Straub, 2004). Replacing this series by total employment does also not alter the results.

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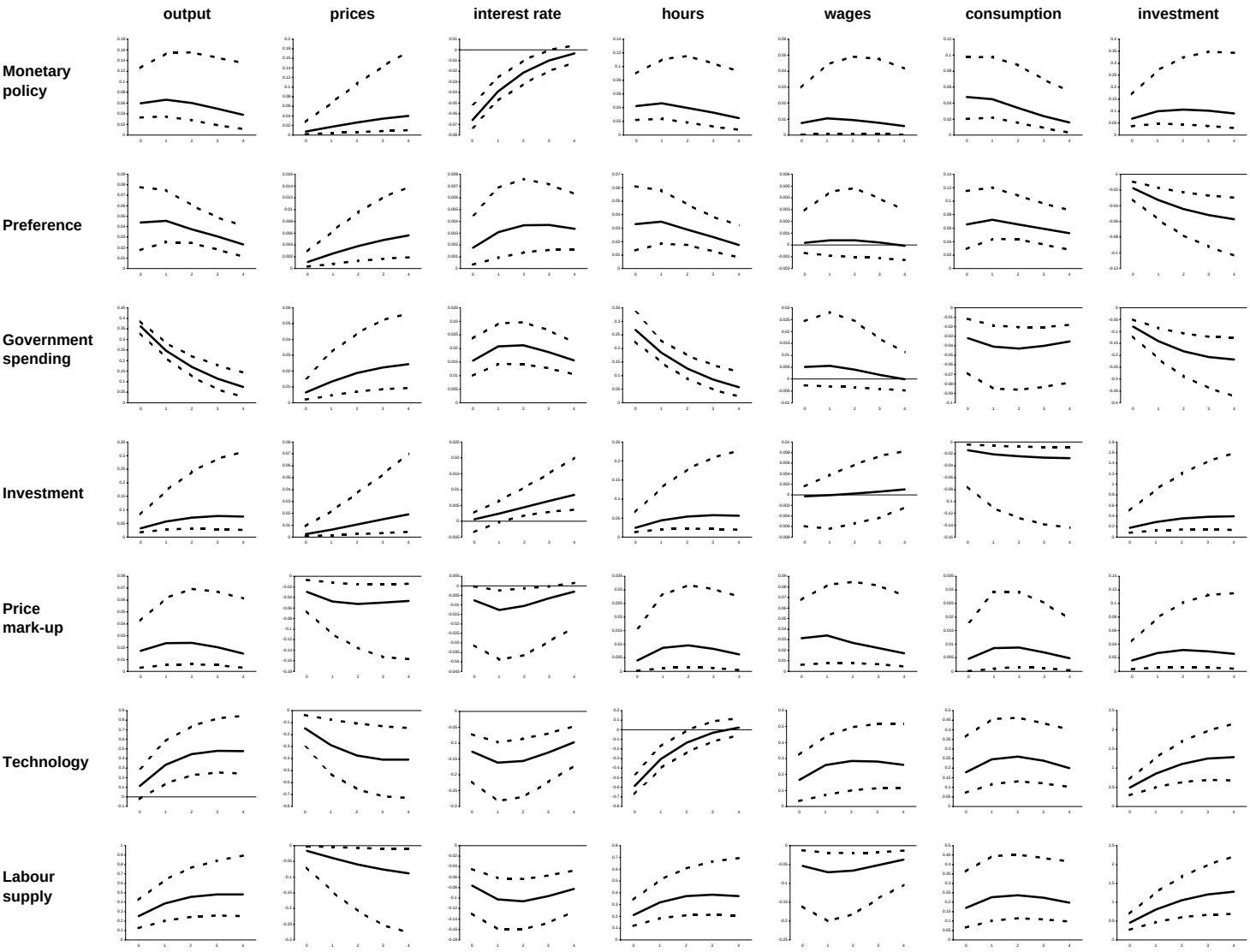
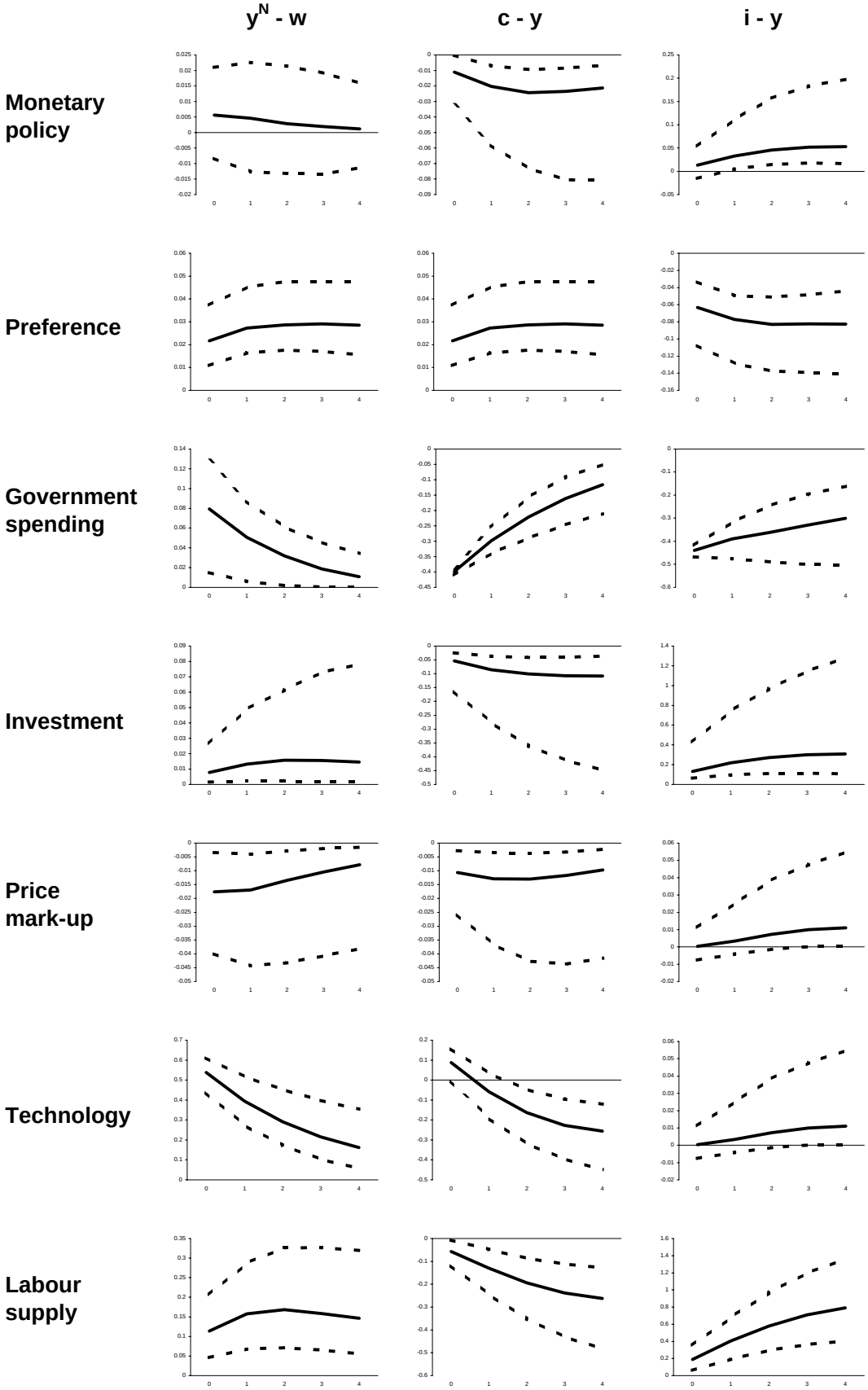
Figure 1 - Theoretical impulse responses of DSGE model



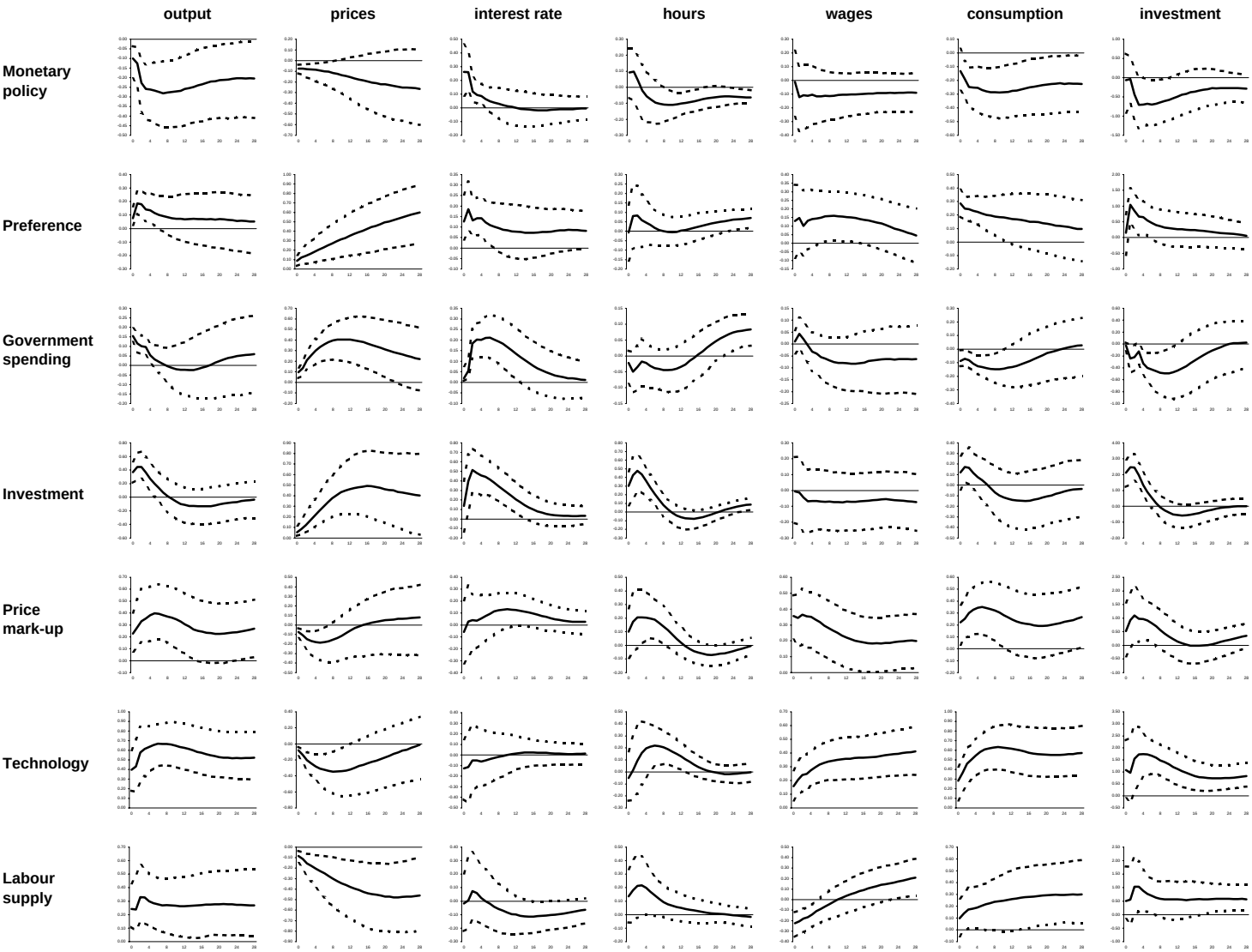
Note: Median impulse response functions together with 16th and 84th percentiles

Figure 2 - Extended theoretical impulse responses of DSGE model



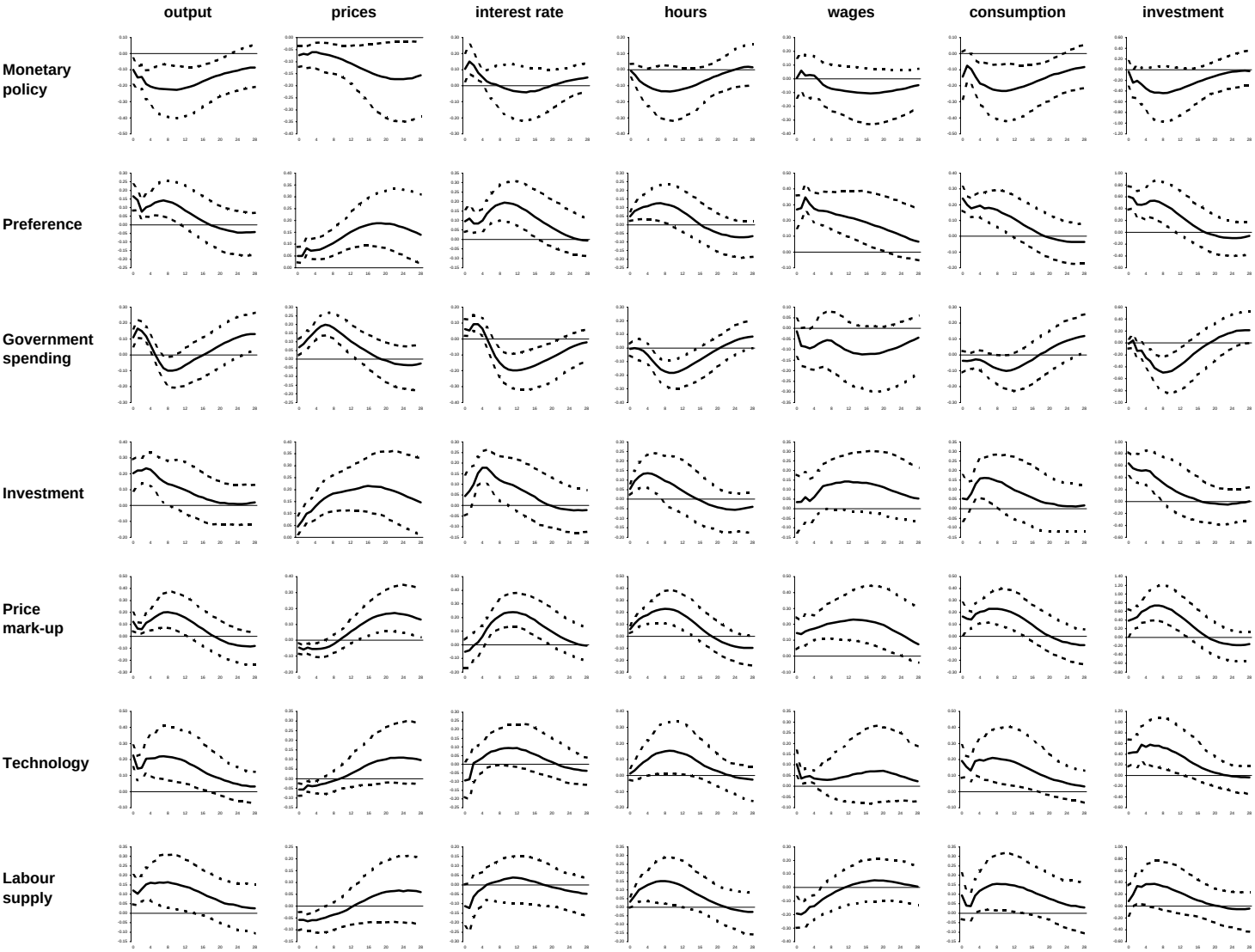
Note: Median impulse response functions together with 16th and 84th percentiles

Figure 3 - United States - Impulse responses of VAR with DSGE sign restrictions



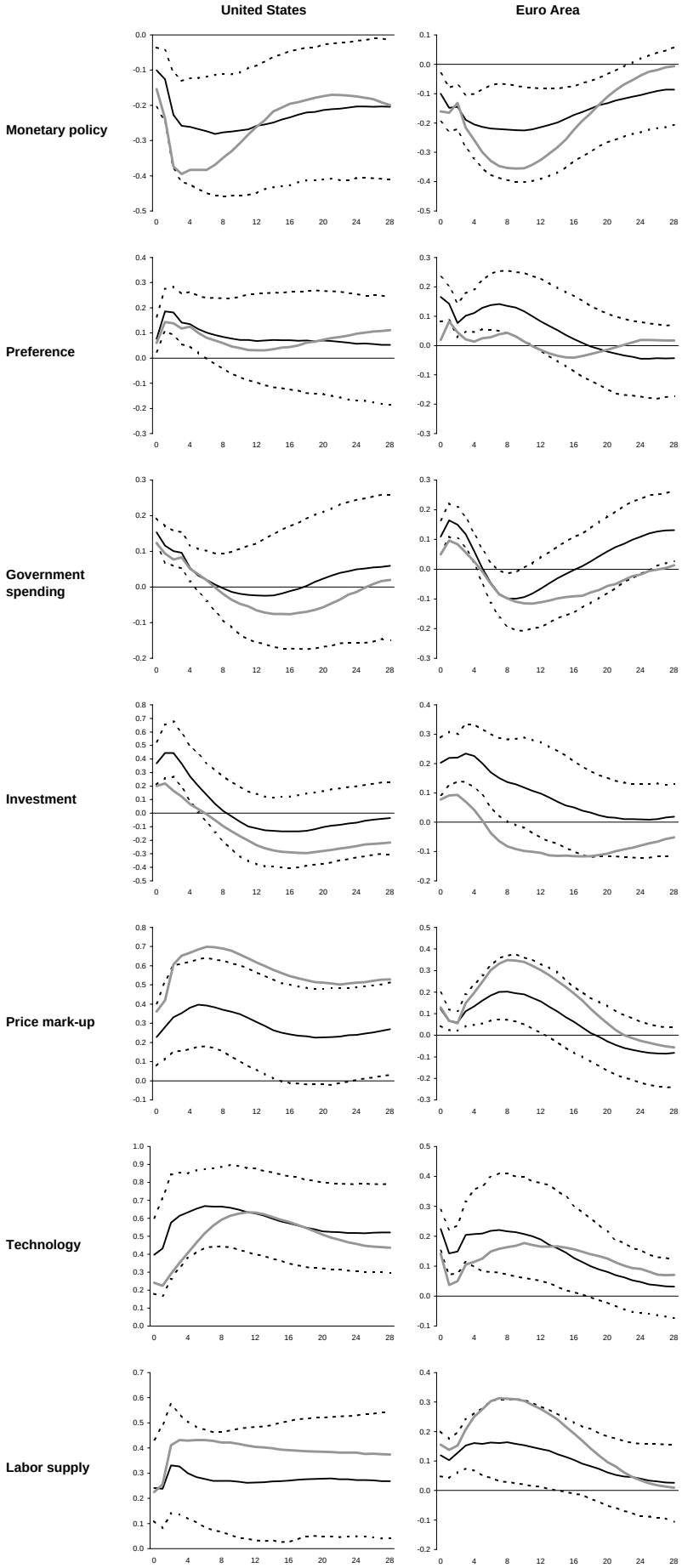
Note: median impulse responses with 84th and 16th percentiles error bands based on Monte Carlo integration, horizon is quarterly

Figure 4 - Euro area - Impulse responses of VAR with DSGE sign restrictions



Note: median impulse responses with 84th and 16th percentiles error bands based on Monte Carlo integration, horizon is quarterly

Figure 5 - Impulse responses of output



Note: Black lines are median impulse response functions together with 16th and 84th percentiles obtained from VAR with relaxed DSGE restrictions
Grey lines are median impulse response functions obtained from VAR with all DSGE restrictions