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WHY ARE THE 2000s SO DIFFERENT FROM THE 1970s?
A STRUCTURAL INTERPRETATION OF CHANGES
IN THE MACROECONOMIC EFFECTS OF OIL PRICES IN THE US

by Olivier J. Blanchard* and Marianna Riggi+

Abstract

In the 1970s, large increases in the price of oil were associated with sharp decreases in output and large increases in inflation. In the 2000s, even larger increases in the price of oil were associated with much milder movements in output and inflation. Using a structural VAR approach, Blanchard and Gali (2009) argued that this reflected a change in the causal relation from the price of oil to output and inflation. They then argued that this change could be due to a combination of three factors, namely, a smaller share of oil in production and consumption, lower real wage rigidity and better monetary policy. Their argument, based on simulations of a simple new-Keynesian model, was informal. Our purpose in this paper is to take the next step, and to estimate the explanatory power and contribution of each of these factors. To do so, we use a minimum distance estimator that minimizes, over the set of structural parameters and for each of two samples (pre- and post-1984), the distance between the empirical SVAR-based impulse response functions and those implied by a new-Keynesian model. Our empirical results point to an important role for all three factors.

JEL Classification: E20, E32, E52.
Keywords: oil prices, wage rigidities, monetary policy credibility.

Contents

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Introduction[1]

In the 1970s, large increases in the price of oil were associated with sharp decreases in output and large increases in inflation. In the 2000s, even larger increases in the price of oil were associated with much milder movements in output and inflation.[2] Our goal in this paper is to explore what can be learned from these changes about shifts in the underlying structure of the economy.

Using a structural VAR approach, Blanchard and Gali (2009) (BG in what follows) estimated impulse response functions (IRFs) for the United States, both for the pre-1984 and the post-1984 periods, and concluded that the post-1984 effects of the price of oil on either output or the price level were roughly equal to one third of those for the pre-1984 period.

They then explored informally the potential role of three factors in accounting for the change: a smaller share of oil in production and consumption, lower real wage rigidity and better monetary policy. Using a calibrated new-Keynesian model, they concluded that, in combination, these factors could potentially explain the change. They did not, however, estimate the model, nor, except for documenting the decrease in the share of oil in production and consumption, did they estimate the change in the relevant parameters. This is the natural next step and this is what we do in this paper.

We first re-estimate the BG VAR, extended to include the nominal interest rate, an important variable if we are to look at the role of monetary policy. We maintain the same identification assumptions and thus interpret the IRFs from the estimated model as causal, from the oil price to other variables. We then write down a standard new-Keynesian model, extended to allow for imported oil used both in production and consumption, for real wage rigidities and for imperfect credibility of monetary policy. Finally, we use a minimum distance estimator that minimizes, over the set of structural parameters and for each of the two samples, the distance between the empirical IRFs and those implied by the model.

Like BG, we document the decrease in the share of oil in production and consumption,

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[2] While the large increase in the price of oil in 2008 may have played a role in the current crisis, it is clear that the sharp drop in output since then is due primarily to factors other than oil. Using data for 2008 on would give an unduly large role to the price of oil in decreasing output. For this reason, we terminate our sample at the end of 2007.

and use this information directly to calibrate the relevant parameters of the models. Turning to estimated parameters, we find a central role for both vanishing real wage rigidities and improved credibility of monetary policy.

The paper is organized as follows. Section 1 gives the empirical IRFs. Section 2 presents the model. Section 3 discusses the results of estimation. Section 4 explores a number of extensions. Section 5 concludes.

1 Impulse responses

We follow BG in the specification of the structural VAR. We look at the joint behaviour of GDP, employment, the nominal wage, the GDP deflator, the CPI and the real price of oil, to which we add, however, given the focus on the potential role of monetary policy, the federal funds rate. The VAR is estimated using quarterly data, over two different samples, 1960:1-1983:4 for the first, and 1984:1-2007:4 for the second. We refer the reader to Appendix A for additional estimation details. We simply note here that by estimating a linear model we implicitly ignore the potentially asymmetric effects of oil price increases and decreases explored by, for example, Mork (1989) or Hamilton (1996) and (2003).

We maintain BG's identification assumption that unexpected changes in the price of oil are exogenous relative to contemporaneous movements in the other variables in the VAR. (Unlike BG, and to align the VAR with the theoretical model, we take oil price shocks to be the unexpected changes in the real price of oil, that is the nominal price divided by the GDP deflator, rather unexpected changes in the dollar price; this makes little difference to the results, however). Like any identification assumption, this one can be and has been challenged (for example, see Barsky and Kilian 2001, Kilian 2009, Lippi and Nobili 2011). While we refer the reader to the discussion in BG, we give two arguments in its defence. The first is that the shape of the estimated IRFs is mostly determined by the dynamic effects of the large shocks of the 1970s and the 2000s. There is wide agreement that the large increases of the 1970s were due to shifts in the supply of oil (Bruno and Sachs 1985 and Hamilton 1983, 1985, 2003). There is also wide agreement that the large increases of the 2000s were due to shifts in the demand from emerging market countries, especially China. While these shocks may have affected the United States through other channels than the oil price (for example, high Chinese growth leading both to an increase in the world oil price and an increase in Chinese imports from the United States), we also find the assumption plausible that the direct effects of the oil price dominated these other channels.

The IRFs for each of the two samples are shown in Figure 1. They are shown for the first twenty quarters. The centred lines in each case give the estimated impulse responses of each variable, in levels, to a positive shock to a price of oil of 10 per cent. The upper and lower lines give one-standard deviation bands, obtained through Monte Carlo simulations. In both samples, the real price of oil shows a near-random walk response, i.e. it jumps on impact and then stays around a new plateau.

We see the IRFs as having the following main characteristics, which one would like a model to fit.

There are slowly building and long-lasting effects on activity and price variables in the two samples. The responses of GDP and employment are considerably more muted in the second than in the first sample (roughly 1/3). Similarly, the effect on the GDP deflator and the CPI is much smaller in the second than in the first sample (roughly 1/3). No significant effect is detected on nominal wages in the second sample, compared with a strong and significant effect in the first sample. Finally, the strength of the response of the federal funds rate has not changed much across sample periods and, in both samples, the response is hump-shaped, positive and significant for the first four quarters.

2 A model

The model we develop to interpret these IRFs and recover structural parameters is a standard new-Keynesian model, except for four extensions, each needed for our purposes.

First, we allow for the use of oil as an input in both production and consumption. We assume that the country is an oil importer, and takes the real price of oil (in terms of domestic goods) as exogenous. Second, we allow for habit formation in consumption. This is done in order to capture the first characteristic of the data listed in the previous section, namely the slow adjustment of output and employment over time. In the model, output is determined by demand and equal to consumption, and habit formation leads to a slow adjustment of consumption. Third, we allow for real wage rigidity, one of the potential factors emphasized by BG. We formalize it as a slow adjustment of the real wage at which workers are willing to work to their marginal rate of substitution. Fourth, to capture the notion of policy credibility, we allow agents' inflation expectations to depend partly on model consistent expectations and partly on current inflation. The smaller the dependence on current inflation, the better anchored are inflation expectations and the more favorable is the trade-off between inflation and output.

The rest of the section presents only the implied log-linearized equations, leaving the full derivation to the appendix. Lower case letters represent deviations from steady state, lower case letters with a hat are proportional deviations from steady state.

2.1 Oil in production and in consumption

Production is characterized by a Cobb-Douglas production function in labour and oil:

$$\widehat{q}_t = \alpha_n \ \widehat{n}_t + \alpha_m \ \widehat{m}_t \tag{1}$$

where $\widehat{q}_t$ is (gross) domestic product, $\widehat{n}_t$ is labour, $\widehat{m}_t$ is the quantity of imported oil used in production, $\alpha_n + \alpha_m \leq 1$. Technological progress does not affect the IRF to oil and can thus be ignored here.

Consumption is characterized by a Cobb-Douglas consumption function in output and oil:

$$\widehat{c}_t = (1-\chi)\widehat{c}_{q,t} + \chi\widehat{c}_{m,t} \tag{2}$$

where $\widehat{c}_t$ is consumption, $\widehat{c}_{q,t}$ is consumption of the domestically produced good, $\widehat{c}_{m,t}$ is consumption of imported oil.

In this environment, it is important to distinguish between two prices, the price of domestic output $\widehat{p}_{q,t}$ and the price of consumption $\widehat{p}_{c,t}$. Let $\widehat{p}_{m,t}$ be the price of oil and $\widehat{s}_t \equiv \widehat{p}_{m,t} - \widehat{p}_{q,t}$ be the real price of oil, which is assumed to follow a first-order autoregressive process, where ρ_s is the autoregressive parameter. From the definition of consumption, the relation between the consumption price and the domestic output price is given by:

$$\widehat{p}_{c,t} = \widehat{p}_{q,t} + \chi \ \widehat{s}_t \tag{3}$$

The important parameters for our purposes are α_m and χ, the shares of oil in production and in consumption.

2.2 Households

The behaviour of households is characterized by two equations. The first one characterizes consumption:

$$\widehat{c}_t = \frac{h}{1+h}\widehat{c}_{t-1} + \frac{1}{1+h}E_t\widehat{c}_{t+1} - \frac{(1-h)}{(1+h)\,\sigma}\left(i_t - \widehat{\pi}^e_{c,t+1} + \log\beta\right) \tag{4}$$

Consumption depends on itself lagged, itself expected, and on the real interest rate in terms of consumption. The parameter σ is the household risk aversion coefficient; together with h, it determines the response of consumption to the real interest rate. The parameter $h \in [0, 1)$ captures habit formation (the utility of consumption depends on $C - hC(-1)$, where C is current consumption, and $C(-1)$ is lagged aggregate consumption). The higher the value of h, the slower the adjustment of the consumption; when $h = 0$, the relation reduces to the usual Euler equation.

The second equation characterizes labour supply, or equivalently, the real consumption wage at which workers are willing to work (the "supply wage"):

$$\widehat{w}_t - \widehat{p}_{c,t} = \gamma\left(\widehat{w}_{t-1} - \widehat{p}_{c,t-1}\right) + (1-\gamma)\left\{\phi\widehat{n}_t + \frac{\sigma}{1-h}\left[\widehat{c}_t - h\widehat{c}_{t-1}\right]\right\} \tag{5}$$

where $\widehat{w}_t$ denotes the nominal wage. The supply wage depends on itself lagged and on the marginal rate of substitution. The marginal rate of substitution depends in turn on employment, with elasticity ϕ, where ϕ is the inverse of the Frisch elasticity, and on $\widehat{c}_t - h\widehat{c}_{t-1}$, with elasticity $\sigma/(1-h)$. The parameter $\gamma \in [0, 1)$ captures the extent of real wage rigidity, which is needed in order to generate a meaningful trade-off between stabilization of inflation and stabilization of the welfare relevant output gap (Blanchard and Gali, 2007).[3] When $\gamma = 0$, the supply wage is equal to the marginal rate of substitution. The higher the value of γ, the higher the degree of real wage rigidity.

2.3 Firms

Domestic goods are imperfect substitutes in consumption and firms are thus monopolistic competitors. Given the production function, cost minimization implies that the firms' demand for oil is given by:

$$\widehat{m}_t = -\widehat{\mu}_t - \widehat{s}_t + \widehat{q}_t \tag{6}$$

where $\widehat{\mu}_t$ is the log deviation of the price mark-up, $\mathcal{M}_t$. Using this expression to eliminate m_t in the production function gives a reduced-form production function:

$$\widehat{q}_t = \frac{1}{1-\alpha_m}\left(\alpha_n\widehat{n}_t - \alpha_m\widehat{s}_t - \alpha_m\widehat{\mu}_t\right) \tag{7}$$

[3] When the degree of real wage rigidities is positive, the wedge between the efficient and the natural level of output (where the latter is defined as the level obtained absent nominal rigidities) fluctuates in response to the oil shock and the central bank faces a trade-off between stabilizing inflation and the welfare relevant output gap.

Given employment, output is a decreasing function of the real price of oil.

Combining the cost minimization conditions for oil and for labour with the aggregate production function yields the following factor price frontier:

$$(1-\alpha_m)\ (\widehat{w}_t - \widehat{p}_{c,t}) + (\alpha_m + (1-\alpha_m)\chi)\ \widehat{s}_t + (1-\alpha_n-\alpha_m)\ \widehat{n}_t + \widehat{\mu}_t = 0 \qquad (8)$$

Given productivity, an increase in the real price of oil must lead to one or more of the following adjustments: (i) a lower consumption wage, (ii) lower employment, or (iii) a lower mark-up.

This equation defines, for a given mark-up, the real consumption wage consistent with a given level of employment; we can think of it as giving us the "demand wage" as a function of employment. This will be useful below.

Firms are assumed to set prices à la Calvo (1983), an assumption which yields the following log-linearized equation for domestic output price inflation (domestic inflation for short):

$$\widehat{\pi}_{q,t} = \beta \widehat{\pi}^e_{q,t+1} - \lambda_p\ \widehat{\mu}_t \qquad (9)$$

where $\lambda_p \equiv [(1-\theta)(1-\beta\theta)/\theta][(\alpha_m+\alpha_n)/(1+(1-\alpha_m-\alpha_n)(\epsilon-1))]$, θ denotes the fraction of firms that leave prices unchanged during a given period, β is the discount factor of households and ϵ is the elasticity of substitution between domestic goods in consumption. A low mark-up leads firms to want to increase prices and leads to more inflation, given expected future inflation.

2.4 Consumption, output, employment and GDP

The condition that trade be balanced (as oil is imported) gives us a relation between consumption and output:

$$\widehat{c}_t = \widehat{q}_t - \chi \widehat{s}_t - \eta \widehat{\mu}_t \qquad (10)$$

where $\eta \equiv \alpha_m/(\mathcal{M} - \alpha_m)$.

Using the reduced-form production function (7) gives a relation between consumption and employment:

$$\widehat{c}_t = \frac{\alpha_n}{1-\alpha_m}\widehat{n}_t - \left(\chi + \frac{\alpha_m}{1-\alpha_m}\right)\ \widehat{s}_t + \left(\eta - \frac{\alpha_m}{1-\alpha_m}\right)\ \widehat{\mu}_t \qquad (11)$$

The characterization of the equilibrium does not require us to introduce either value added or the value added deflator. But these are needed to compare the implications of the model to the data.

The value added deflator $p_{y,t}$ is implicitly defined by $\widehat{p}_{q,t} = (1-\alpha_m)\widehat{p}_{y,t} + \alpha_m \ \widehat{p}_{m,t}$. Rearranging terms gives:

$$\widehat{p}_{y,t} = \widehat{p}_{q,t} - \frac{\alpha_m}{1-\alpha_m} \ \widehat{s}_t \tag{12}$$

thus implying a negative effect of the real price of oil on the GDP deflator, given domestic output prices.

The definition of value added, combined with the demand for oil, yields the following relation between GDP and gross output:

$$\widehat{y}_t = \widehat{q}_t + \frac{\alpha_m}{1-\alpha_m} \ \widehat{s}_t + \eta \ \widehat{\mu}_t \tag{13}$$

2.5 Monetary policy

Monetary policy is characterized by a Taylor rule in which the interest rate responds to the deviation of the core CPI inflation from a zero target inflation and to the welfare relevant output gap ($\widehat{x}^f$), defined as the wedge between the actual and the efficient level of output[4] (see Appendix C for derivation):

$$i_t = \rho_i i_{t-1} + (1-\rho_i)\left(-\log\beta + \phi_\pi \widehat{\pi}_{q,t} + \phi_x \widehat{x}_t^f\right) \tag{14}$$

where the intercept $-\log\beta$ makes the rule consistent with a zero inflation steady state and the parameter $\rho_i \in [0,1)$ captures the degree of smoothing of the interest rate by the central bank.

To analyse the potential role of credibility, we allow expectations of agents to depend directly on current inflation:

$$\widehat{\pi}^e_{q,t+1} = (1-\lambda)\,\widehat{\pi}_{q,t} + \lambda E_t \widehat{\pi}_{q,t+1} \tag{15}$$

We interpret the parameter $\lambda \in [0,1]$ as capturing the credibility of monetary policy. The lower λ, the less credible is monetary policy, the worse the anchoring of inflation expectations and the worse the implied trade-off between inflation and output. Equation (15) captures the idea that, when credibility is low, the central bank is unable to establish

[4] In a model with real wage rigidities, the natural level of output may move a lot with respect to oil price changes. The welfare relevant level of output moves much less, looks like a smooth time trend and appears to be (and should be) what the Fed looks at.

an anchor for inflation expectations, which thus turn out to be strongly connected with actual inflation dynamics.

The shortcut aims at conveying the intuition that when credibility is low, inflation expectations may increase more than the model-consistent ones because of the destabilizing effect through current headline inflation.[5]

Agents understand the static relationship between $\widehat{p}_{c,t}$ and $\widehat{p}_{q,t}$, given by equation (3). Accordingly we have:

$$\widehat{\pi}^{e}_{c,t+1} = \widehat{\pi}^{e}_{q,t+1} + \chi E_t \left(\widehat{s}_{t+1} - \widehat{s}_t\right) \tag{16}$$

2.6 Equilibrium absent nominal rigidities

Absent nominal rigidities, the firms' mark-up would be constant, and the evolution of the economy would be characterized by the condition that the supply wage, implied by equations (5) and (11), be equal to the demand wage, implied by equation (8) with $\widehat{\mu}_t \equiv 0$. That condition would determine employment and, in turn, output, consumption, and GDP:

$$\widehat{n}_t = \Gamma_1 \widehat{s}_t + \Gamma_2 \widehat{s}_{t-1} + \Gamma_3 \widehat{n}_{t-1} \tag{17}$$

where

$$\Gamma_1 \equiv \frac{\left[\sigma\left(1-\gamma\right) - \left(1-h\right)\right]\left[\alpha_m + \chi\left(1-\alpha_m\right)\right]}{\phi(1-\gamma)(1-h)(1-\alpha_m) + \sigma\alpha_n\left(1-\gamma\right) + \left(1-h\right)\left(1-\alpha_m-\alpha_n\right)}$$

$$\Gamma_2 \equiv \frac{\left[(1-h)\gamma - \sigma h\left(1-\gamma\right)\right]\left[\alpha_m + \chi\left(1-\alpha_m\right)\right]}{\phi(1-\gamma)(1-h)(1-\alpha_m) + \sigma\alpha_n\left(1-\gamma\right) + \left(1-h\right)\left(1-\alpha_m-\alpha_n\right)}$$

$$\Gamma_3 \equiv \frac{\gamma\left(1-\alpha_m-\alpha_n\right)\left(1-h\right) + \sigma h\alpha_n\left(1-\gamma\right)}{\phi(1-\gamma)(1-h)(1-\alpha_m) + \sigma\alpha_n\left(1-\gamma\right) + \left(1-h\right)\left(1-\alpha_m-\alpha_n\right)}$$

Two results will be useful for the interpretation of the estimation results below. First,

[5] Others have used this modelling device. Gurkaynak, Sack, and Swanson (2005) use a new-Keynesian model in which the long-term inflation expectations exhibit some degree of loading on the recent history of inflation. They show that the model is consistent with the sensitivity of forward rates to economic news observed in data, a sensitivity which is too large to be consistent with the standard assumption of perfectly anchored long-run inflation expectations. Gurkaynak, Levin and Swanson (2010) take the sensitivity of inflation expectations to incoming economic news as a measure of the central bank's (in)ability to anchor private sector expectations.

the sign of the long-run effects of an increase in the price of oil on employment depends on whether σ is less or greater than one. The reason is the same as in the familiar case of technological progress. A higher price of oil implies a lower real consumption wage and thus a decrease in labour supply. It also implies a decrease in consumption, thus a negative wealth effect, and an increase in labour supply. For $\sigma = 1$, the substitution and wealth effects cancel and employment is constant. If $\sigma < 1$, then the substitution effect dominates and employment decreases. If $\sigma > 1$, then employment increases. As the model implies that the economy returns over time to its equilibrium absent nominal rigidities, the fact that the IRFs show long-lasting effects will lead to estimated values of σ smaller than one.

Second, the sign of the short-run effects of an increase in the price of oil on employment depends on the sign of $(1-h)/\left[\sigma(1-\gamma)\right]-1$. If, for example, $\sigma = 1$ so there is no long-run effect, the sign depends on $h-\gamma$. The higher the degree of real wage rigidity, the more likely employment is to decrease in the short run; the higher the degree of habit formation, the stronger the wealth effect and the more likely employment is to increase in the short run.

2.7 Equilibrium with nominal rigidities

In the presence of nominal rigidities, aggregate demand (here consumption demand), equation (4), determines output and employment. The supply wage, given by equations (5) and (11), together with the factor price frontier, equation (8), determine the mark-up of firms. The mark-up then determines inflation through equation (9).

Monetary policy, given by equation (14), determines the interest rate and thus affects consumption, output and employment. If monetary policy maintains a level of employment equal to that which is obtained absent nominal rigidities, inflation, measured using the output price, is constant. If it tries to maintain higher employment, then inflation is higher.[6]

The coefficients associated with nominal rigidities and with monetary policy play the following role. A lower value of θ (i.e. lower nominal rigidity) leads to a stronger effect of a given decrease in the mark-up on inflation. Thus, for a given policy rule, it leads to a larger initial increase in inflation and a larger initial decline in output. A lower value of λ (i.e. lower credibility) leads to a worse trade-off between stabilization of quantities and stabilization of prices in response to oil price shocks. Credibility gains, captured by

[6]In Appendix D we derive the representation of inflation dynamics in terms of the gap between actual and natural output.

a higher λ, improve the trade-off facing policy-makers and make it possible to have a smaller impact of a given oil price increase on both inflation and output. A higher value of ϕ_π leads to a smaller increase in inflation, but at the expense of a larger decrease in output. Conversely, a higher value of ϕ_x captures a more accommodative monetary policy and leads to a lower drop in output, but at the expense of a larger increase in inflation. A higher value of ρ_i (i.e. more interest rate inertia) attenuates or amplifies the economy's response to the oil shock, depending on the degree of central bank credibility λ. When credibility is high (high λ), small variations in the interest rate which are expected to be followed by further changes in the same direction have a strong effect on demand and output (Woodford 2003a). When credibility is low, a large contemporaneous response of the policy rate is more effective at stabilizing the economy than highly persistent low-amplitude variations. Figure 2 shows the effects of a higher degree of interest rate smoothing ρ_i under the two limiting cases of $\lambda = 0$ (Figure 2a) and $\lambda = 1$ (Figure 2b), for a given calibration of the other parameters.

3 Estimation of the benchmark

Call X the vector composed of the 15 parameters of the model. Let $\Psi(X)$ be the set of impulse responses of $\widehat{p}_{c,t}$, $\widehat{p}_{y,t}$, $\widehat{w}_t$, $\widehat{y}_t$, $\widehat{n}_t$ and i_t over the first 20 quarters to an increase in the price of oil implied by X and let $\widehat{\Psi}$ be the estimated IRFs presented in Figure 1. The minimum distance estimator of X we use is given by[7]

$$X = \text{argmin}[\widehat{\Psi} - \Psi(X)]' D^{-1} [\widehat{\Psi} - \Psi(X)] \tag{18}$$

where D is a diagonal matrix, with the sample variances of the $\widehat{\Psi}$ along the diagonal (so that the more tightly estimated IRFs get more weight in estimation)[8] and X is given by $X \equiv (\alpha_n, \alpha_m, \beta, \chi, \phi, \sigma, \epsilon, h, \gamma, \theta, \phi_\pi, \phi_x, \lambda, \rho_i, \rho_s)$. We estimate X separately for each of the two samples, 1960:1 to 1983:4, and 1984:1 to 2007:3.

[7] This is the same estimator as used for example by Christiano at al. (2005), Boivin and Giannoni (2006) and Kuester (2010) in the context of monetary policy.

[8] While the parallel to the efficient GMM estimation would suggest using the complete impulse responses' variance-covariance matrix, the use of the diagonal matrix with impulse response's variance on the main diagonal has become standard in the literature on impulse response matching (e.g. Christiano at al. 2005, Boivin and Giannoni 2006, Kuester 2010 and Pagan 2007 for the motivations). The diagonal matrix accounts for the fact that some points of the impulse response functions are less precisely estimated than others, giving higher priority to those point estimates that have smaller standard deviations. However, because impulse responses are correlated across horizons, this set-up over-represents the amount of information present in the data to identify the model's deep parameters.

The rationale for using a limited information method, in this case a subset of IRFs implied by the model, is that we have more confidence in the estimated IRFs to oil shocks than, say, to unobservable taste shocks. The rationale for not using a Bayesian prior is to make clear what is learned from the data. Estimating all 15 parameters, however, would be asking too much of the data. Thus, a number of coefficients are chosen a priori, rather than estimated.

The coefficients capturing the role of oil in production and in consumption, α_m and χ, can be constructed directly by using IO tables. Following the computations in BG, we choose $\alpha_m = 1.5$ per cent and $\chi = 2.3$ per cent for the first sample, $\alpha_m = 1.2$ per cent and $\chi = 1.7$ per cent for the second sample. The way in which these shares affect the outcome is through the expression $\alpha_m + (1 - \alpha_m)\chi$ (as can be seen by looking at the term in $\widehat{s}$ in the factor price frontier, (8)). So these numbers imply that, other things equal, the effect of a given increase in the price of oil in the second sample is only 3/4 of the effect in first sample. We assume that, in the short run, firms have enough capital capacity that they operate under constant returns to labour and oil, so $\alpha_n = 1 - \alpha_m$. We calibrate the autoregressive parameter of the oil shock $\rho_s = 0.999$ in order to have the price of oil very close to random walk, as it is in the data, while retaining stationarity. With respect to preferences, we assume $\beta = 0.99$, $\epsilon = 6.0$ (so that the desired mark-up of firms over marginal cost is 20 per cent), the (inverse of the) Frisch elasticity $\phi = 1.0$ and $h = 0.8$, which is consistent with the estimates by Primiceri et al. (2006) and Gertler et al. (2008) (among many others). Given the long-lasting effects of the price of oil in the IRFs, we do not impose long-run neutrality ($\sigma = 1$) and allow for σ to be estimated.

This leaves seven parameters to be estimated, σ for preferences, γ for real wage rigidity, θ for nominal price rigidity and ϕ_π, ϕ_x ρ_i and λ for monetary policy. We restrict these parameters to lie within the bounds implied by the theory, $[0, 1]$ for γ, λ, θ and ρ_i, $[0, +\infty)$ for the others.

3.1 Benchmark parameters

The results of estimation of the benchmark are shown in Table 1. The last row gives the minimized value of the distance function. The implied and actual IRFs are shown in Figure 3. Standard errors are reported in parentheses.[9]

[9] In order to pick out the global, rather than local, minimum the algorithm is implemented by starting the chain from different initial points. Note that when parameters are on the boundary of the parameter space, the asymptotic delta function method cannot be computed as it requires a Taylor series expansion, which is inappropriate at the boundary. Some authors adopt a pragmatic approach by reporting standard deviations only for parameters which do not hit the boundary of the parameter space (e.g. Boivin and

Table 1
Benchmark estimated parameters

	Pre-1984	Post-1984
σ Risk aversion	0.39 (0.15)	0.26 (0.04)
γ Real wage rigidity	0.97 (0.05)	0.00* (0.17)
θ Price stickiness	0.96 (0.05)	0.59 (0.09)
ϕ_π Taylor coefficient on inflation	1.33 (1.02)	1.08 (0.48)
ϕ_x Taylor coefficient on output gap	0.00* (0.25)	0.00* (2.14)
ρ_i Policy inertia	0.49 (0.17)	0.54 (0.18)
λ Central bank credibility	0.00* (0.32)	1.00* (0.18)
Distance function	118.89	83.81

Notes: Standard errors in parentheses. Stars indicate that the estimated coefficient is equal to one of the bounds.

The model provides a good fit of the impulse responses in both samples, capturing the main characteristics listed in Section 1. The implied IRFs are typically within the one-standard deviation bands.[10] A number of estimated coefficients are constrained by natural bounds. The fact that we hit a number of bounds may suggest that the model is misspecified and that ignoring the bounds would result in very different parameters. In order to explore this possibility, Figure 4 shows the shape of the (negative of the) distance function in the neighbourhood of the vector of estimated parameters by varying two crucial parameters at a time within the range in the horizontal axes, keeping the others at their "true" values.[11] The objective function displays enough curvature in all dimensions, excluding weak identification, and is typically fairly flat when hitting the bounds, suggesting that the bounds do not do violence to the fit of the model. We draw the following conclusions.

Giannoni 2006). We compute standard deviations by bootstrapping. Despite Andrews (2000) warning that, for parameters at the boundary of the parameter space, the bootstrapped standard deviations are not asymptotically correct, we report them for completeness.

[10] The distribution of the distance function is unknown. Thus, in order to assess the goodness of fit, we use a bootstrap methodology to compute the empirical probability density function. The null hypothesis that the value attained by the distance function is statistically equal to zero is accepted at the 5 per cent significance level.

[11] This is one of the diagnostic tests proposed by Canova and Sala (2009).

The low estimate of σ in both samples implies a negative long-run effect of an increase in the price of oil on employment. And given the value of $h = 0.8$, it implies a short run consumption's semi-elasticity to the real interest rate $(1-h)/[(1+h)\sigma]$ equal to 0.28 in the pre-1984 sample and 0.43 in the post-1984 sample.

The estimate of the degree of real wage rigidity γ decreases from 0.97 in the pre-1984 sample to 0 (the lower bound) in the post-1984 sample. Using the terminology often used by central banks, this can be described as strong "second-round" effects pre-1984, and weak or non-existent ones post-1984. Faced with similar initial increases in the CPI (the "first round" effects), and for given employment, workers in the 1970s asked for and obtained increases in nominal wages, which then led to higher prices, confronting the central bank with a worse trade-off between activity and inflation. In the 2000s, the same initial increases in the CPI did not lead to increases in nominal wages and thus did not lead to further increases in prices. The strong decrease in real wage rigidities implies a strong decrease in inflation persistence,[12] in line with the empirical evidence detected by Stock and Watson (2007), Benati and Surico (2008) and Cogley, Primiceri and Sargent (2010).

The estimate of λ, which captures the credibility of monetary policy, increases from the lower bound, 0, in the pre-1984 sample to the upper bound, 1, in the post-1984 sample, suggesting a strong increase in central bank credibility, a strong improvement in the anchoring of inflation expectations and a much more favourable short-run trade-off between inflation and activity.

The interest rate appears to respond to inflation, not to activity. The coefficient on the welfare relevant output-gap ϕ_x is equal to its lower bound, 0, in both samples. The coefficient on inflation ϕ_π is equal to 1.33 in the pre-1984 sample and to 1.08 in the post-1984 sample.[13] While the strength of the response of the nominal interest rate has not changed much across sample periods, the weaker response of expected inflation due to enhanced credibility implies, however, that the response of the real interest rate to an oil price shock has become much stronger over time. Figure 5 shows that in the 1970s

[12] As shown by Blanchard and Gali (2007) real wage rigidities imply an inertial behaviour of inflation, as any change in the marginal rate of substitution affects the real wage and hence inflation only gradually. The Phillips curve can be rewritten as in equation (47) in Appendix D, where, taking into account that $\eta(1-\alpha_m)-\alpha_m \simeq 0$, the coefficient on the lagged level of inflation is positive conditional on having $\gamma > 0$.

[13] We have explored the robustness of our results when monetary policy reacts to the cyclical component of output constructed as the log deviation from steady state, rather than to the welfare relevant output gap. For pre-1984 we get the same set of parameters shown in Table 1. For post-1984 we get: $\sigma = 0.21$, $\gamma = 0$, $\theta = 0.56$, $\phi_\pi = 1.39$, $\lambda = 1$, $\phi_y = 0.02$, $\rho_i = 0.72$, yielding a value of the distance function of 76.07.

the real interest rate declined remarkably on impact,[14] while it has increased in the more recent decades.

The estimate of ρ_i is equal to 0.49 in the pre-1984 sample. It increases to 0.54 in the post-1984 subsample. As we argued earlier, such an increase interacts with increased credibility to lead to a more favourable policy trade-off.

The estimate of the degree of nominal price rigidity θ decreases over time (from 0.96 to 0.59). This is the one change that runs against our (and we expect, most economists') priors. First, as inflation has decreased over time, one would expect price setters to change prices less often. Second, a number of recent papers find a flatter Phillips curve characterizing the Great Moderation, which suggests a slower price adjustment in the post-1984 period. Indeed, if present, the lower degree of nominal price rigidities may come as a consequence of the higher competition, forcing firms to adjust prices more often.

In short, the estimated coefficients point to both lower real wage rigidity and better anchoring of inflation expectations as the main two factors behind the change in the response of the economy to oil shocks. The other factor appears to be a lower nominal price rigidity.

While we focus on the effect of credibility on λ, it may well be that higher credibility also affects other coefficients. For example, the lower degree of real wage rigidities may have been driven in part by the better anchoring of inflation expectations. The fall in inflation persistence, predicted in the model by the drop in real wage rigidities, may have come, in turn, as a result of the higher credibility.[15]

[14] The drop in the real rate prior to 1984 is consistent with the direct evidence provided by BG, using a bivariate rolling VAR. This result is also in line with the unconditional evidence in Clarida et. al (2000), who show that pre-1979 the real rate declines as inflation rises. Note that in estimation we impose that the Blanchard and Kahn (1980) conditions hold, so we exclude the possibility of indeterminacy, a route that has been explored by others. However, in the presence of policy inertia, determinacy does not rule out a negative response on impact of the real rate, as long as the *eventual* increase in the nominal interest rate, as a result of a sustained increase in the inflation rate, is more than one for one (Woodford 2003b).

[15] Erceg and Levin (2003) explore the link between imperfect monetary policy credibility and inflation persistence and show that the lack of policy credibility, modelled as private agents' limited information about the central bank's objectives, may lead to a strong degree of inflation persistence.

4 Robustness and extensions

4.1 Leontief technology

The Cobb-Douglas production function implies a unit elasticity between oil and labour, that surely overestimates this elasticity in the short run. For this reason, we explore a model with a Leontief production, where labour and oil are combined in fixed proportions. The production function is given by:

$$\widehat{q}_t = \widehat{n}_t = \widehat{m}_t \tag{19}$$

Consumption is still characterized by the Cobb-Douglas function in output and oil (2) and the relation between the consumption price and the domestic output price is still given by equation (3). The Euler equation (4) and the supply wage (5) therefore continue to characterize the behaviour of households. Real marginal cost is given by:

$$\widehat{mc}_t = \alpha_n \left(\widehat{w}_t - \widehat{p}_{q,t}\right) + \alpha_m \widehat{s}_t \tag{20}$$

As before, we follow the formalism proposed in Calvo (1983) and assume that in each period a measure $(1-\theta)$ of firms reset their prices. This yields the following equation for domestic inflation:

$$\widehat{\pi}_{q,t} = \beta \widehat{\pi}^e_{q,t+1} + \frac{(1-\theta)(1-\beta\theta)}{\theta} \widehat{mc}_t \tag{21}$$

With balanced trade the following relation must hold:

$$\widehat{c}_t = \widehat{q}_t - \left(\chi + \frac{\alpha_m}{\mathcal{M} - \alpha_m}\right) \widehat{s}_t \tag{22}$$

The specification of technology implies a relation between value added and gross output:

$$\widehat{y}_t = \widehat{q}_t \tag{23}$$

while the value added deflator is given by:

$$\widehat{p}_{y,t} = \widehat{w}_t \tag{24}$$

Inflation expectations are still given by (15) and (16) and monetary policy is still described by (14).[16]

Table 2 reports the estimated parameters. Results are robust to the change in the specification of technology: vanishing real wage rigidities and the improvement in the anchoring of expectations remain the driving forces behind the drop in macroeconomic volatility after the oil shock. As before, nominal price rigidity is estimated to have decreased over time. Figure 6 displays estimated and implied IRFs.

Table 2
Estimated parameters under a leontief technology

	Pre-1984	Post-1984
σ Risk aversion	0.42 (0.18)	0.36 (0.05)
γ Real wage Rigidity	0.97 (0.01)	0.00 * (0.25)
θ Price stickiness	0.96 (0.05)	0.71 (0.08)
ϕ_π Taylor coefficient on inflation	1.33 (1.08)	1.58 (0.93)
ϕ_x Taylor coefficient on output gap	0.00 * (0.24)	0.00 * (1.39)
ρ_i Policy inertia	0.53 (0.17)	0.36 (0.29)
λ Central bank credibility	0.00 * (0.37)	1.00 * (0.35)
Distance function	117.68	70.82

Notes: Standard errors in parentheses. Stars indicate that the estimated coefficient is equal to one of the bounds.

4.2 Variable desired mark-ups

Rotemberg and Woodford (1996) argued that another effect was at work behind the size of the observed effects of oil price shocks in the 1970s, namely, an endogenous increase in the firms' mark-ups leading to a larger decrease in output. We capture this idea by specifying the desired mark-up as a function of the real price of oil s. As shown in Appendix E, this assumption modifies domestic inflation (9), which now contains an additive cost push shock:

$$\widehat{\pi}_{q,t} = \beta \widehat{\pi}^e_{q,t+1} - \lambda_p \widehat{\mu}_t + \lambda_p \frac{\phi_\varepsilon}{\varepsilon - 1} \widehat{s}_t \tag{25}$$

[16]The derivation of the welfare relevant output gap under the Leontief technology is presented in Appendix C.

where $\phi_\varepsilon \in [0, 1)$ is a measure of the sensitivity of the desired mark-up to changes in the real price of oil. Table 3 reports the results and points to a value of ϕ_ε that is positive and in the neighbourhood of 0.4 in the first sample and 0.1 in the second. (To give a sense of magnitude, if $\phi_\varepsilon = 0.4$, an increase in the price of oil of 10 per cent leads to an increase in the desired mark-up of 0.8 percentage points).

The model now explains the difference between the two samples through a decrease in the response of the mark-up rather than through an increase in the credibility of the central bank. The other conclusions are unchanged. In the pre-1984 sample the effects of the oil shocks were amplified by the high degree of real wage rigidities. As in the benchmark, nominal price rigidities are lower in the post-1984 sample.

Table 3
Variable desired mark-ups

	Pre-1984	Post-1984
ϕ_e Sensitivity of the desired mark-up to changes in the price of oil	0.36 (0.24)	0.06 (0.11)
σ Risk aversion	1.01 (1.21)	0.33 (0.83)
γ Real wage rigidity	0.96 (0.23)	0.00* (0.25)
θ Price stickiness	0.94 (0.06)	0.64 (0.14)
ϕ_π Taylor coefficient on inflation	1.23 (1.46)	1.33 (0.99)
ϕ_x Taylor coefficient on output gap	0.00* (0.79)	0.03 (0.71)
ρ_i Policy inertia	0.51 (0.09)	0.71 (0.17)
λ Central bank credibility	1.00* (0.24)	1.00* (0.34)
Distance function	114.96	70.60

Notes: Standard errors in parentheses. Stars indicate that the estimated coefficient is equal to one of the bounds.

5 Concluding remarks

Our main conclusion is that two major changes have taken place in the US economy since the 1970s. The first is a large decrease, indeed the apparent disappearance, of real wage rigidities. The second is a substantial increase in the credibility of monetary policy and the anchoring of inflation expectations.

If these conclusions are correct, they have implications both for the effects of other shocks and for the conduct of policy. For example, lower real wage rigidities, higher credibility of policy and - another result from the estimation - lower nominal rigidities, all imply a much more favourable policy trade-off with respect to demand shocks and thus provide a potential explanation for the period known as the Great Moderation.

As an illustration, Figure 7 shows the effects of a monetary policy shock - defined as a 1 per cent increase in the policy rate, decaying at rate 0.5 over time - implied by our estimates for each of the two samples. The implications appear largely consistent with the conclusions from studies that have focused directly on the response to such shocks (Gertler and Lown 1999, Barth and Ramey 2001, Boivin and Giannoni 2002, and especially Boivin and Giannoni 2006, who follow an approach largely similar to ours, but focused on the IRF to a monetary, rather than an oil, shock), namely, a large decrease in the effect of the shock on output and employment. Extending the estimation to integrate the information from the two IRFs is obviously the natural next step on the research agenda.[17]

[17] This is subject to our earlier caveat and our justification for focusing only on the IRF to an oil price in this paper. We believe that oil price shocks are more easily identified than demand shocks. At the same time, different shocks are likely to be more or less helpful in identifying different parts of the parameter space. Studying the effects of an oil price shock may be more revealing about real wage rigidities. Studying the effects of a demand shock may be more revealing about the interest rate rule used by the central bank.

Appendix A

Our VAR makes use of data on the real price of oil, three inflation measures (CPI, GDP deflator and wages), two quantities (GDP and employment) and the federal funds rate. Variables enter in rates of change, measured as quarter to quarter, in quarterly terms. The estimated responses are accumulated and shown in levels in Figure 1. The federal funds rate is taken from the Board of Governors of the Federal System. The other data are drawn from the USECON database. Wage refers to non-farm business compensation per hour.

As in BG, the break date chosen corresponds roughly to the onset of the Great Moderation in the US as identified by several authors (e.g. McConnell and Perez-Quiros 2000).[18] Each subsample contains two large oil price shock episodes, starting in 1973, 1979, 1999 and 2002.

Each equation in our VAR includes four lags of the seven variables above, a constant term and a quadratic trend fitted measure of productivity growth.

As stressed by BG, the large changes in the price of oil are likely to lead to *small sample bias when estimating the oil price equation: the best OLS fit is achieved by reducing the size of these particular residuals, thus by spuriously linking these very large realizations to movements in current or past values of the other variables in the regression. This in turn overstates the endogenous component of the price of oil, and understates the size of the true residuals* (BG, page 390). As in BG, in order to deal with this issue we exclude oil price changes larger than three standard deviation when estimating the oil price equation.

Table 4 sheds light on the importance of oil shocks in accounting for the observed fluctuations in the US. The estimated standard deviations of the oil-driven component of the different variables show that the relevance of oil shocks as a source of fluctuations has diminished considerably, except for the real price of oil itself.

The ratio of the conditional to the unconditional standard deviation documents that the percentage contribution of oil shocks to the volatility of quantity variables and of the federal funds rate has remained roughly unchanged over time. The relative contribution of oil shocks to movements in the GDP deflator and nominal wage has declined, whereas the relative contribution to fluctuations in the CPI has increased. As highlighted by BG, the latter result is consistent with a relatively stable core CPI, with oil price changes being passed through to the energy component of the CPI.

[18] Nakov and Pescatori (2010) explore the coincidence in time between the break in the oil price-business cycle relationship and the beginning of the Great Moderation and find that oil related effects explain around a third of the reduced macroeconomic volatility.

Table 4.
The contribution of oil Shocks to economic fluctuations

	Conditional standard deviation			$\frac{\text{Conditional SD}}{\text{Unconditional SD}}$	
	1960:1-1983:4	1984:1-2007:4	Ratio	1960:1-1983:4	1984:1-2007:4
Oil price (real)	12.62	14.85	1.18	0.80	0.85
CPI	0.56	0.34	0.61	0.33	0.55
GDP deflator	0.49	0.09	0.18	0.46	0.23
Nominal wage	0.47	0.22	0.47	0.44	0.21
GDP	0.41	0.23	0.56	0.24	0.25
Employment	0.61	0.41	0.67	0.33	0.28
Federal funds rate	0.11	0.08	0.73	0.23	0.28

Appendix B

We assume a continuum of infinitely-lived households, indexed by j. They seek to maximize:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left\{ U\left(C_t\left(j\right), C_{t-1}\right) - V\left(N_t\left(j\right)\right) \right\} \tag{26}$$

where $C_t \equiv \chi^{-\chi}\left(1-\chi\right)^{-(1-\chi)} C_{m,t}^{\chi} C_{q,t}^{1-\chi}$ and where $C_{m,t}$ denotes consumption of (imported) oil, $C_{q,t}$ is a CES index of domestic goods, N_t denotes employment or hours worked and χ is the equilibrium share of oil in consumption. Households are concerned with "catching up with the Joneses": there is a certain degree of external habit persistence, indexed by the parameter $h \in [0,1)$; C_{t-1} is the aggregate consumption level in period t-1. We assume:

$$U\left(C_t\left(j\right), C_{t-1}\right) \equiv \frac{\left(C_t\left(j\right) - hC_{t-1}\right)^{1-\sigma}}{1-\sigma} \tag{27}$$

$$V\left(N_t\left(j\right)\right) \equiv \frac{N_t^{1+\phi}(j)}{1+\phi} \tag{28}$$

The period budget constraint is given by:

$$P_{q,t}C_{q,t}\left(j\right) + P_{m,t}C_{m,t}\left(j\right) + Q_t^B B_t\left(j\right) = B_{t-1}\left(j\right) + W_t N_t(j) + \Pi_t \tag{29}$$

where $P_{q,t} \equiv \left(\int_0^1 P_{q,t}\left(i\right)^{1-\epsilon} di\right)^{\frac{1}{1-\epsilon}}$ is a price index for domestic goods, $P_{m,t}$ is the price of oil (in domestic currency), W_t is the nominal wage and Π_t are profits. Q_t^B is the price of a one-period nominally riskless domestic bond, paying one unit of domestic currency. B_t denotes the quantity of that bond purchased in period t. The optimal allocation of expenditures between imported and domestically produced good implies:

$$P_{q,t}C_{q,t} = (1-\chi)\, P_{c,t}C_t \tag{30}$$

$$P_{m,t}C_{m,t} = \chi P_{c,t}C_t \tag{31}$$

where $P_{c,t} \equiv P_{m,t}^{\chi} P_{q,t}^{1-\chi}$ is the CPI index. The first order conditions associated with the household problem are:

$$(C_t - hC_{t-1})^{-\sigma} = \beta E_t \left\{ \frac{P_{c,t}}{Q_t^B P_{c,t+1}} (C_{t+1} - hC_t)^{-\sigma} \right\} \tag{32}$$

$$\frac{W_t}{P_{c,t}} = N_t^{\phi} \left[C_t - hC_{t-1}\right]^{\sigma} \tag{33}$$

Log-linearizing equation 32 yields equation 4. Log-linearizing equation 33 and assuming a slow adjustment of wages to labour market conditions yields equation 5.

Appendix C

Derivation of the welfare relevant output gap under the Cobb Douglas technology

We derive the efficient allocation by assuming perfect competition in goods and labour markets. In this case we have, on the firms' side:

$$(1-\alpha_m)\,(\widehat{w}_t - \widehat{p}_{c,t}) + (\alpha_m + (1-\alpha_m)\chi)\,\widehat{s}_t + (1-\alpha_n-\alpha_m)\,\widehat{n}_t = 0 \tag{34}$$

and on the consumer-workers' side:

$$\widehat{w}_t - \widehat{p}_{c,t} = \phi\widehat{n}_t + \frac{\sigma}{1-h}\left[\widehat{c}_t - h\widehat{c}_{t-1}\right] \tag{35}$$

After substituting the aggregate resource constraint $\widehat{c}_t = \widehat{q}_t - \chi\widehat{s}_t$, we combine both equations:

$$\begin{gathered}(1-\alpha_m)\,\left\{\phi\widehat{n}_t + \tfrac{\sigma}{1-h}\left[\widehat{q}_t - \chi\widehat{s}_t - h\widehat{q}_{t-1} + \chi h\widehat{s}_{t-1}\right]\right\} + \\ +(\alpha_m + (1-\alpha_m)\chi)\,\widehat{s}_t + (1-\alpha_n-\alpha_m)\,\widehat{n}_t = 0\end{gathered} \tag{36}$$

Using the reduced-form production function $\widehat{q}_t = \frac{1}{1-\alpha_m}\,(\alpha_n\widehat{n}_t - \alpha_m\widehat{s}_t)$ and after rearranging terms one yields the following expression for the first-best employment $\widehat{n}_t^f$:

$$\begin{array}{rl} \widehat{n}_t^f = & \frac{\alpha_n \sigma \frac{h}{1-h}}{\phi(1-\alpha_m)+\ \alpha_n \frac{\sigma}{1-h}+(1-\alpha_n-\alpha_m)} \widehat{n}_{t-1}^f + \\ & -\frac{[\alpha_m+(1-\alpha_m)\chi]\left(1-\frac{\sigma}{1-h}\right)}{\phi(1-\alpha_m)+\ \alpha_n \frac{\sigma}{1-h}+(1-\alpha_n-\alpha_m)} \widehat{s}_t - \frac{\sigma \frac{h}{1-h}[\alpha_m+\chi(1-\alpha_m)]}{\phi(1-\alpha_m)+\ \alpha_n \frac{\sigma}{1-h}+(1-\alpha_n-\alpha_m)} \widehat{s}_{t-1} \end{array} \tag{37}$$

Given first-best employment, first-best value added, denoted by $\widehat{y}_t^f$, is given by:

$$\widehat{y}_t^f = \frac{\alpha_n}{1-\alpha_m}\ \widehat{n}_t^f \tag{38}$$

Thus we can write the welfare relevant output gap as follows:

$$\begin{array}{c} \widehat{x}_t^f = \widehat{y}_t - \frac{\alpha_n \sigma \frac{h}{1-h}}{\phi(1-\alpha_m)+\ \alpha_n \frac{\sigma}{1-h}+(1-\alpha_n-\alpha_m)} \widehat{y}_{t-1}^f + \\ + \frac{[\alpha_m+(1-\alpha_m)\chi]\left(1-\frac{\sigma}{1-h}\right)}{\phi(1-\alpha_m)+\ \alpha_n \frac{\sigma}{1-h}+(1-\alpha_n-\alpha_m)} \frac{\alpha_n}{1-\alpha_m} \widehat{s}_t + \frac{\sigma \frac{h}{1-h}[\alpha_m+\chi(1-\alpha_m)]}{\phi(1-\alpha_m)+\ \alpha_n \frac{\sigma}{1-h}+(1-\alpha_n-\alpha_m)} \frac{\alpha_n}{1-\alpha_m} \widehat{s}_{t-1} \end{array} \tag{39}$$

Derivation of the welfare relevant output gap under the Leontief technology

When production is characterized by a Leontief technology in labour and oil, on the firms' side we have:

$$\alpha_n \left(\widehat{w}_t - \widehat{p}_{c,t}\right) + \left(\chi \alpha_n + \alpha_m\right)\ \widehat{s}_t = 0 \tag{40}$$

where we have used (3) to substitute for $\widehat{p}_{c,t}$. Labour supply is still given by (35). Using the aggregate resource constraint $\widehat{c}_t = \widehat{q}_t - \left(\chi + \frac{\alpha_m}{\mathcal{M}-\alpha_m}\right) \widehat{s}_t$ and taking into account that the Leontief specification of technology implies $\widehat{q}_t = \widehat{n}_t = \widehat{y}_t$, we can rewrite the supply wage as follows:

$$\begin{array}{c} \widehat{w}_t - \widehat{p}_{c,t} = \left(\phi + \frac{\sigma}{1-h}\right) \widehat{y}_t - \left(\chi + \frac{\alpha_m}{\mathcal{M}-\alpha_m}\right) \frac{\sigma}{1-h} \widehat{s}_t + \\ -h \frac{\sigma}{1-h} \widehat{y}_{t-1} + h \frac{\sigma}{1-h} \left(\chi + \frac{\alpha_m}{\mathcal{M}-\alpha_m}\right) \widehat{s}_{t-1} \end{array} \tag{41}$$

Combining the previous equation with (40) we get that the first-best value added is given by:

$$\widehat{y}_t^f = -\frac{(\chi \alpha_n + \alpha_m) - \left(\chi + \frac{\alpha_m}{\mathcal{M}-\alpha_m}\right) \frac{\sigma}{1-h} \alpha_n}{\left(\phi + \frac{\sigma}{1-h}\right) \alpha_n} \widehat{s}_t + \frac{\sigma \alpha_n \frac{h}{1-h}}{\left(\phi + \frac{\sigma}{1-h}\right) \alpha_n} \widehat{y}_{t-1}^f - \frac{\alpha_n \sigma \frac{h}{1-h} \left(\chi + \frac{\alpha_m}{\mathcal{M}-\alpha_m}\right)}{\left(\phi + \frac{\sigma}{1-h}\right) \alpha_n} \widehat{s}_{t-1}$$

and we can write the welfare relevant output gap as follows:

$$\widehat{x}_t^f = \widehat{y}_t - \frac{\sigma\alpha_n\frac{h}{1-h}}{\left(\phi+\frac{\sigma}{1-h}\right)\alpha_n}\widehat{y}_{t-1}^f + $$
$$+\frac{(\chi\alpha_n+\alpha_m)-\left(\chi+\frac{\alpha_m}{\mathcal{M}-\alpha_m}\right)\frac{\sigma}{1-h}\alpha_n}{\left(\phi+\frac{\sigma}{1-h}\right)\alpha_n}\widehat{s}_t + \frac{\alpha_n\sigma\frac{h}{1-h}\left(\chi+\frac{\alpha_m}{\mathcal{M}-\alpha_m}\right)}{\left(\phi+\frac{\sigma}{1-h}\right)\alpha_n}\widehat{s}_{t-1}$$

Appendix D
Derivation of the Phillips Curve representation in terms of the gap between actual and natural level of output

Combining the wage schedule with the efficient price frontier we get:

$$-\widehat{\mu}_t + \gamma\widehat{\mu}_{t-1} = (1-\alpha_m)(1-\gamma)\left\{\phi\widehat{n}_t + \tfrac{\sigma}{1-h}\left[\widehat{c}_t - h\widehat{c}_{t-1}\right]\right\} +$$
$$+(\alpha_m + (1-\alpha_m)\chi)\widehat{s}_t - \gamma(\alpha_m + (1-\alpha_m)\chi)\widehat{s}_{t-1} + (1-\alpha_n-\alpha_m)\widehat{n}_t - \gamma(1-\alpha_n-\alpha_m)\widehat{n}_{t-1} \tag{42}$$

which can be combined with the aggregate resource constraint to yield:

$$-\widehat{\mu}_t = -\Gamma_q\widehat{\mu}_{t-1} + \Gamma_x\widehat{n}_t - \Gamma_{xl}\widehat{n}_{t-1} + \Gamma_s\widehat{s}_t + \Gamma_{sl}\widehat{s}_{t-1} \tag{43}$$

where we have defined $\Gamma_q \equiv \frac{[\gamma(1-h)+h(1-\gamma)\sigma(\eta(1-\alpha_m)-\alpha_m)]}{[(1-h)+(1-\gamma)\sigma(\eta(1-\alpha_m)-\alpha_m)]}$,
$\Gamma_x \equiv \frac{[(1-\alpha_n-\alpha_m)(1-h)+\phi(1-\alpha_m)(1-\gamma)(1-h)+(1-\gamma)\sigma\alpha_n]}{[1-h+(1-\gamma)\sigma(\eta(1-\alpha_m)-\alpha_m)]}$, $\Gamma_{xl} \equiv \frac{\{\gamma(1-\alpha_n-\alpha_m)(1-h)+h(1-\gamma)\sigma\alpha_n\}}{[1-h+(1-\gamma)\sigma(\eta(1-\alpha_m)-\alpha_m)]}$,
$\Gamma_s \equiv \frac{[(\alpha_m+(1-\alpha_m)\chi)(1-h-(1-\gamma)\sigma)]}{[1-h+(1-\gamma)\sigma(\eta(1-\alpha_m)-\alpha_m)]}$, $\Gamma_{sl} \equiv \frac{\{h(1-\gamma)\sigma[\chi(1-\alpha_m)+\alpha_m]-\gamma(1-h)(\alpha_m+(1-\alpha_m)\chi)\}}{[1-h+(1-\gamma)\sigma(\eta(1-\alpha_m)-\alpha_m)]}$.

The natural level of employment is defined as the level which is obtained in the absence of nominal rigidities. Accordingly, we can write:

$$\widehat{n}_t^{natural} = \frac{\Gamma_{xl}}{\Gamma_x}\widehat{n}_{t-1}^{natural} - \frac{\Gamma_s}{\Gamma_x}\widehat{s}_t - \frac{\Gamma_{sl}}{\Gamma_x}\widehat{s}_{t-1} \tag{44}$$

Note that equation (44) corresponds to equation (17) in the main text. Indeed, $\Gamma_1 = -\frac{\Gamma_s}{\Gamma_x}$, $\Gamma_2 = -\frac{\Gamma_{sl}}{\Gamma_x}$, $\Gamma_3 = \frac{\Gamma_{xl}}{\Gamma_x}$.

We define the output gap as the wedge between the actual and the natural level of output:

$$\widehat{x}_t^n \equiv \widehat{y}_t - \widehat{y}_t^{natural} = \frac{\alpha_n}{1-\alpha_m}\left(\widehat{n}_t - \widehat{n}_t^{natural}\right) \tag{45}$$

By plugging (43) into equation (9), we get:

$$\widehat{\pi}_{q,t}\left[1-\Gamma_q L\right] = \beta\left[1-\Gamma_q L\right]\widehat{\pi}_{q,t+1}^e + \lambda_p\left\{\Gamma_x\widehat{n}_t - \Gamma_{xl}\widehat{n}_{t-1} + \Gamma_s\widehat{s}_t + \Gamma_{sl}\widehat{s}_{t-1}\right\} \tag{46}$$

Finally, we combine the previous equation for domestic inflation with the equation for expected inflation (15) and we use (44) and (45) to rewrite the Phillips curve in terms of the output gap:

$$\begin{array}{c}\widehat{\pi}_{q,t}=\Gamma_q\widehat{\pi}_{q,t-1}+\frac{\lambda\beta}{[1-(1-\lambda)\beta]}\left[E_t\widehat{\pi}_{q,t+1}-\Gamma_qE_{t-1}\widehat{\pi}_{q,t}\right]\\ +\frac{\lambda_p}{[1-(1-\lambda)\beta]}\frac{\alpha_n}{1-\alpha_m}\left\{\Gamma_x\widehat{x}_t^n-\Gamma_{xl}\widehat{x}_{t-1}^n\right\}\end{array} \tag{47}$$

Appendix E

Derivation of the Phillips Curve with variable desired mark-ups

A firm re-optimizing in period t will choose the price $P^*_{q,t}$ solving the following problem:

$$\max_{P^*_{q,t}}\sum_{k=0}^{\infty}\theta^kE_t\left\{\Lambda_{t,t+k}\left[P^*_{q,t}Q_{t+k/t}-\Psi_{t+k}\left(Q_{t+k/t}\right)\right]\right\}$$

subject to the sequence of demand constraints

$$Q_{t+k/t}=\left(\frac{P^*_{q,t}}{P_{q,t+k}}\right)^{-\varepsilon_{t+k}}C^q_{t+k}$$

where $\Lambda_{t,t+k}\equiv\beta^k\left(\frac{C^q_{t+k}-hC^q_{t+k-1}}{C^q_t-hC^q_{t-1}}\right)^{-\sigma}\left(\frac{P_{q,t}}{P_{q,t+k}}\right)$ is the stochastic discount factor; $\Psi_t(\cdot)$ is the cost function; $Q_{t+k/t}$ is the level of output in period $t+k$ for a firm whose price was last set in period t; ε_{t+k} is a stochastic parameter which determines the variable desired markup in the goods market.

We obtain the first order condition:

$$\sum_{k=0}^{\infty}\theta^kE_t\Lambda_{t,t+k}\left[(1-\varepsilon_{t+k})\frac{C^q_{t+k}}{P^{-\varepsilon_{t+k}}_{q,t+k}}\left(P^*_{q,t}\right)^{-\varepsilon_{t+k}}+\varepsilon_{t+k}\psi_{t+k/t}\frac{C^q_{t+k}}{P^{-\varepsilon_{t+k}}_{q,t+k}}\left(P^*_{q,t}\right)^{-\varepsilon_{t+k}-1}\right]=0 \tag{48}$$

or equivalently:

$$\sum_{k=0}^{\infty}\theta^kE_t\Lambda_{t,t+k}Q_{t+k/t}\left[(\varepsilon_{t+k}-1)P^*_{q,t}-\varepsilon_{t+k}MC_{t+k/t}P_{q,t+k}\right]=0 \tag{49}$$

where $\psi_{t+k/t}\equiv\Psi'_{t+k}\left(Q_{t+k/t}\right)$ and $MC_{t+k/t}\equiv\frac{\psi_{t+k/t}}{P_{q,t+k}}$ are respectively the nominal and the real marginal cost in period $t+k$ for a firm that last reset its price in period t. Log-linearizing around a zero inflation steady state yields:

$$\widehat{p}^{*}_{q,t} = (1-\theta\beta)\sum_{k=0}^{\infty}\theta^{k}\beta^{k}\left[\widehat{p}_{q,t+k} - \frac{\widehat{\varepsilon}_{t+k}}{\varepsilon-1} + \widehat{mc}_{t+k/t}\right] \tag{50}$$

Taking into account the aggregate price index:

$$P_{q,t}^{1-\varepsilon_t} = \theta P_{q,t-1}^{1-\varepsilon_t} + (1-\theta)\left(P^{*}_{q,t}\right)^{1-\varepsilon_t} \tag{51}$$

we get the following domestic inflation, where the variable desired mark-up operates as a cost push shock:

$$\widehat{\pi}_{q,t} = \beta\ E_t\{\widehat{\pi}_{q,t+1}\} - \lambda_p\left(\widehat{\mu}_t + \frac{1}{\varepsilon-1}\widehat{\varepsilon}_t\right) \tag{52}$$

Assuming that $\widehat{\varepsilon}_t = -\phi_{\varepsilon}\widehat{s}_t$ yields equation 25.

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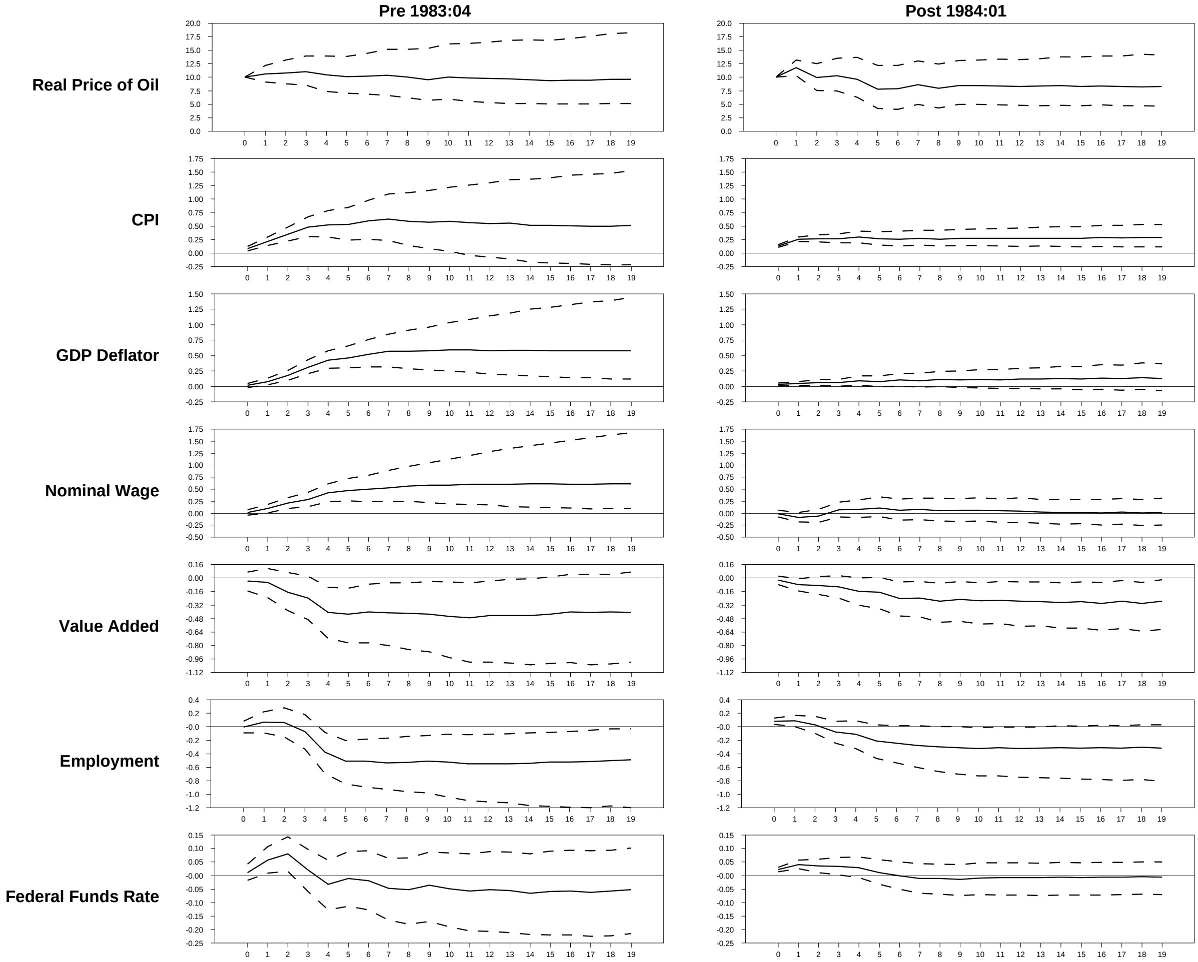
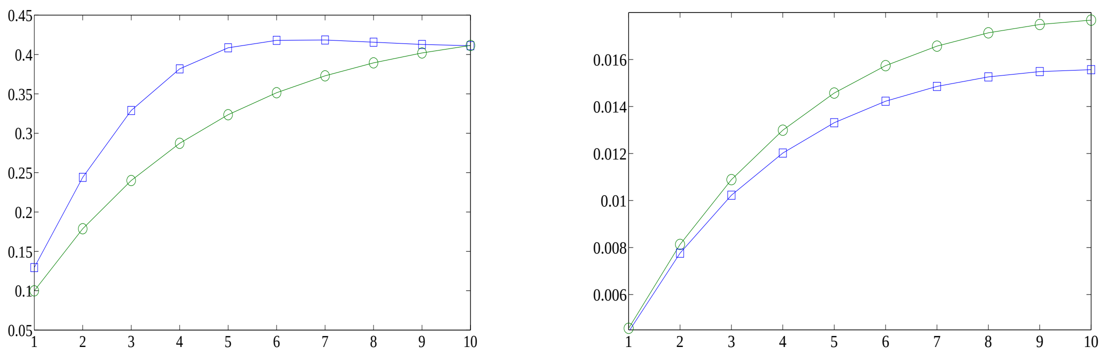
Figure 1. Impulse responses to a 10 per cent oil price shock



Notes: The VAR is estimated using quarterly data on GDP, employment, the nominal wage, the GDP deflator, the CPI and the real price of oil and the federal funds rate, over two different samples, 1960:1-1983:4 for the first and 1984:1-2007:4 for the second. The upper and lower lines give one-standard deviation bands, obtained through Monte Carlo simulations. The interest rate is expressed on a quarterly basis, corresponding with its appearance in the model.

Figure 2. Interest rate smoothing and central bank credibility

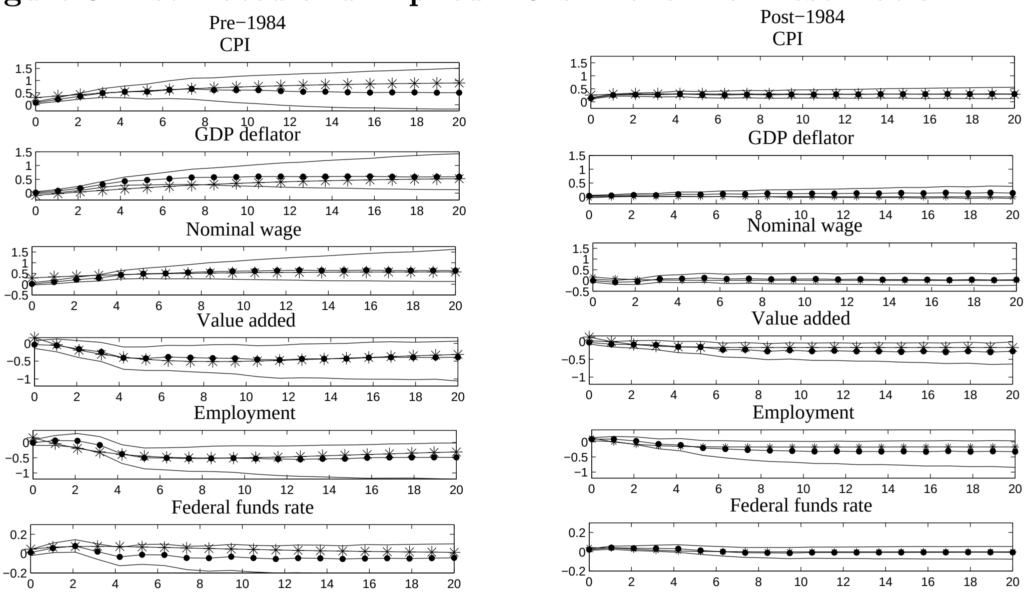
2a. Model based IRF of the core CPI when λ=0 2b. Model based IRF of the core CPI when λ=1



$-\bigcirc-\ \rho_i = 0.0 \qquad -\boxdot-\ \rho_i = 0.8$

Notes: The remaining parameters are calibrated as follows $\beta = 0.99$, $\alpha_n = 0.985$, $\alpha_m = 0.015$, $\chi = 0.023$, $\phi = 1$, $\rho_s = 0.999$, $\sigma = 0.1$, $\epsilon = 6$, $h = 0.8$, $\gamma = 0.8$, $\theta = 0.95$, $\phi_\pi = 1.2$, $\phi_x = 0.5$.

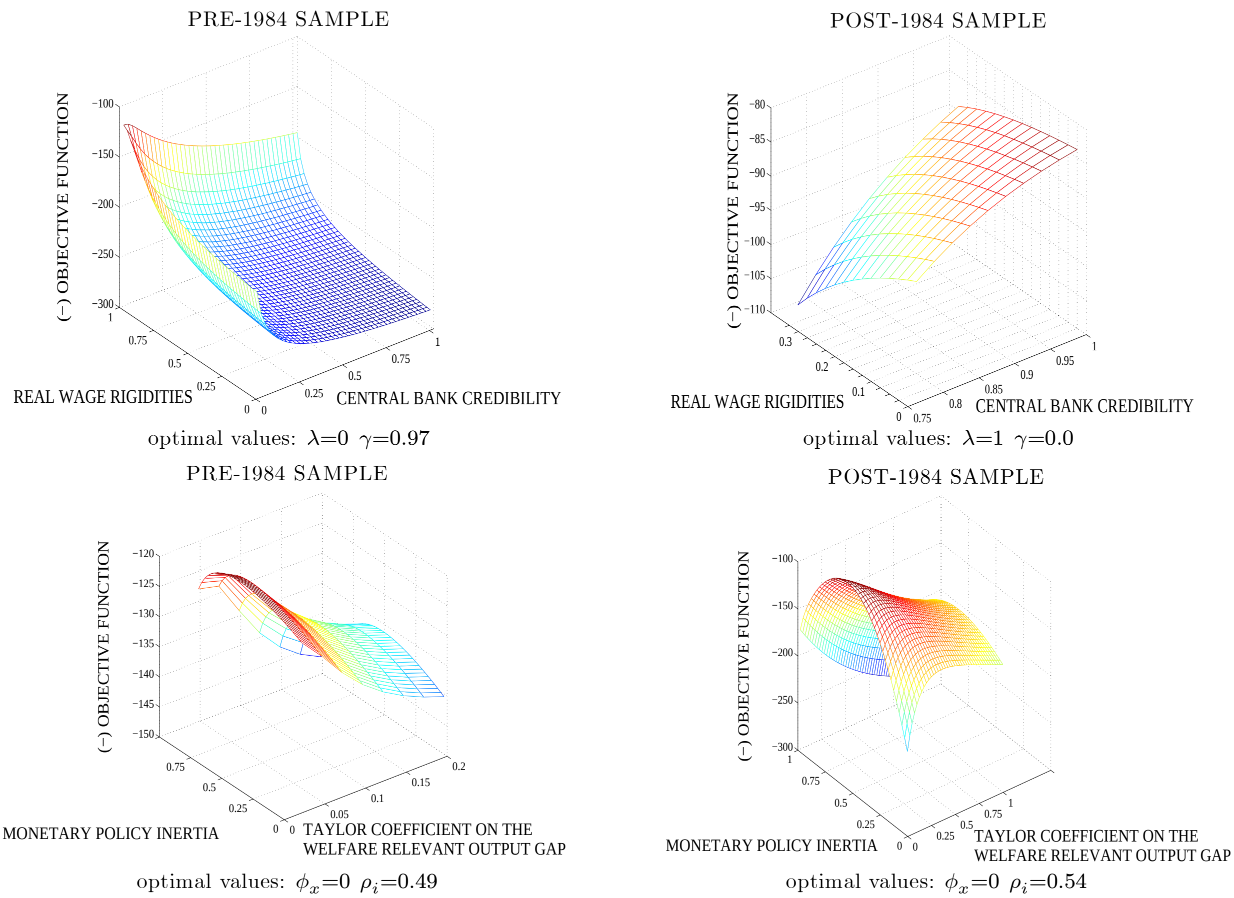
Figure 3. Estimated and implied IRFs. Benchmark estimation



$-\bullet-$ SVAR-IRFs

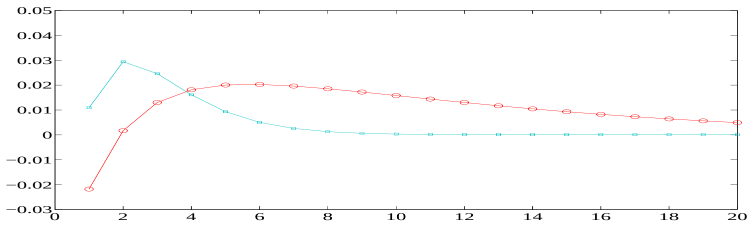
$-*-$ MODEL-IRFs

Figure 4. The shape of the objective function



Notes: The figure plots the curvature of the (negative of the) distance function. In each panel we vary two parameters at a time within the range shown in the horizontal axes, keeping the other parameters at their true values.

Figure 5. Model-based IRFs of the real interest rate

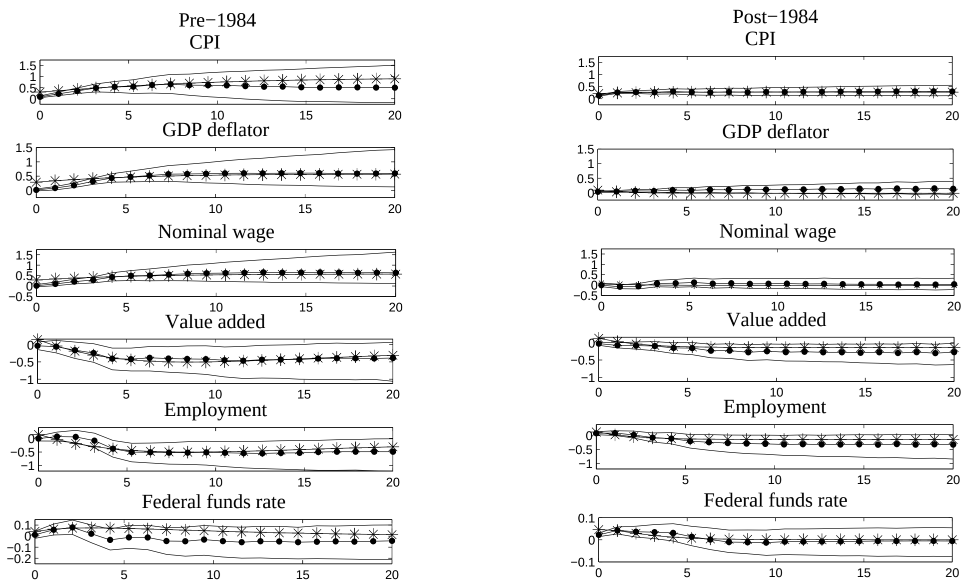


–◯– Pre-1984 sample

–⊡– Post-1984 sample

Notes: Model parameters are set at their benchmark estimated values shown in Table 1.

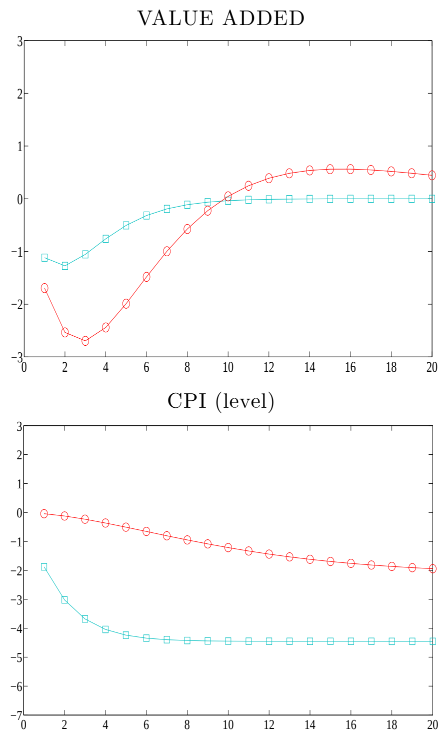
Figure 6. Estimated and implied IRFs. Leontief technology



– • – SVAR-IRFs

– ∗ – MODEL-IRFs

Figure 7. IRFs to a 1 per cent monetary policy shock under the benchmark estimated parameters



—○— Pre-1984 sample

—⊡— Post-1984 sample

Notes: The monetary policy shock is assumed to follow a first-order autoregressive process. The autoregressive parameter of the policy shock is set at 0.5. The other parameters are set at their benchmark estimated values shown in Table 1.

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