DOCUMENT

DE TRAVAIL

N° 320

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February 2011

BANQUE DE FRANCE

EUROSYSTÈME

DIRECTION GÉNÉRALE DES ÉTUDES ET DES RELATIONS INTERNATIONALES

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Key words and phrases. Welfare; Monetary policy objectives; DSGE model; Bayesian econometrics.

Abstract

This paper quantifies the effects on welfare of misspecified monetary policy objectives in a stylized DSGE model. We show that using inappropriate objectives generates relatively large welfare costs. When expressed in terms of 'consumption equivalent' units, these costs correspond to permanent decreases in steady-state consumption of up to two percent. The latter are generated by both the inappropriate choice of weights and the omission of variables. In particular, it is costly to assume an interest-rate smoothing incentive for central bankers when it is not socially optimal to do so. Finally, a parameter uncertainty decomposition indicates that uncertainty about the properties of markup shocks gives rise to the largest welfare costs.

Keywords: Welfare; Monetary policy objectives; DSGE model; Bayesian econometrics.

JEL Classifications: C11, C32, E58.

Résumé

Ce papier mesure les effets sur le bien-être d'une erreur de spécification de la fonction objectif d'une banque centrale dans le cadre d'un modèle DSGE. Il est montré qu'utiliser des objectifs inappropriés engendre des coûts en bien-être relativement importants. Exprimés en termes d'unités de consommation des ménages, ces derniers correspondent à des baisses permanentes de consommation d'état stationnaire pouvant atteindre 2 %. Ces coûts sont induits à la fois par des choix inappropriés de poids dans la fonction objectif et par une omission de variables. En particulier, il est coûteux d'imposer un lissage de taux d'intérêt lorsqu'il n'est pas socialement optimal de le faire. Enfin, une décomposition de l'incertitude entourant les paramètres du modèle indique que celle affectant la mesure des chocs de markups entraîne les plus forts coûts en bien-être.

Mots clés : Bien-être, objectifs de la politique monétaire, modèle DSGE, estimation Bayésienne

Codes JEL : C11, C32, E58

1. Introduction

While an increasing number of central banks are using calibrated or estimated dynamic stochastic general equilibrium models, a large body of the literature still continues to perform ad–hoc analyses for monetary policy. A general practice is to assume that policy objectives are independent of the model representing the economy. However, a convenient advantage of a micro–founded model is that it provides us with a natural social welfare function –the expected utility of the representative household– which strongly depends on the specification and parameter values of the model. Such a function should then constitute the appropriate objective for the central bank.[1]

It is well known in microeconomics that ad–hoc objective functions may bias conclusions or policy recommendations. Yet, few studies are devoted to this issue in macroeconomics, though it induces suboptimal outcomes. Walsh (2005) examined the impact of the choice of policy objectives on the assessment of targeting rules and showed that it may affect the assessment of alternative policies. Moreover, Levin *et al.* (2005), Kimura and Kurozumi (2007) and Edge *et al.* (2010) explored various aspects of monetary policy under parameter uncertainty where the central banker aims to maximize the appropriate policy objective functions. None of these contributions explores further the consequences on welfare of using an inappropriate objective function.

The purpose of this paper is to *quantify* the welfare costs of misspecified monetary policy objectives.[2] We do so by estimating a dynamic stochastic general equilibrium model with imperfectly competitive products and labor markets, and sticky prices and wages. Such a stylized model allows us to derive a formal expression of the social welfare function.[3] We then consider two alternative modelling approaches. In the first one, the economist assumes ad–hoc central bank's objectives while in the second approach she uses the correct welfare–theoretic criterion. We compute the optimal monetary policy that maximizes each criterion and we calculate the welfare costs of using the inappropriate objective function. A decomposition is also performed to identify the main source of the costs, *i.e.* the omission of lagged variables or the inappropriate choice of weights.

In addition, we apply Bayesian methods in order to take into account parameter uncertainty. In this context, the posterior distribution of the model parameters may be used to display the distribution of the welfare costs of misspecified policy objectives. This econometric method allows us to explore the sensitivity of the welfare costs to each parameter and shocks innovation.

[1]We abstract here from the various sorts of delegation problems that could cause policymakers' incentives to deviate from those of the public.

[2]The costs emanate from an error of modelling made by the economist who tries to approximate the monetary policy objectives.

[3]Larger models, such as the Smets and Wouters (2003) model for instance, lead to untractable second–order approximation of the welfare expressions.

Three important and novel results emerge from our investigation. First, as expected, using inappropriate policy objectives may generate relatively large welfare costs. When expressed in terms of 'consumption equivalent' units, these costs correspond to permanent decreases in steady–state consumption of up to two percent.[4] They are also model–dependent, meaning that in larger models the expression of the welfare function gets more and more complicated. The welfare costs associated with the difference between the suitable objectives and a simple loss function (depending only on inflation and the output gap) should then increase. Second, our analysis indicates that welfare costs are generated by both the inappropriate choice of weights and the omission of relevant lagged variables. For instance, leaving out wage inflation in the objective function (by putting the associated weight to zero) leads to sizeable costs. Finally, uncertainty about markup shocks can double the welfare costs.

The remainder of the paper is organized as follows. Section 2 describes the structural model. Section 3 focuses on the model estimation and summarizes the empirical results. Section 4 presents the welfare costs of using inappropriate policy objectives. Section 5 examines the sensitivity of welfare costs to variations in the structural parameters by making use of the posterior distribution obtained from model estimation. The last section concludes.

2. A small quantitative model of the euro area

In this section, we briefly describe our micro–founded model of the euro area economy (see Appendix A for more details). The model is similar to that of Giannoni and Woodford (2005) and sufficiently stylized for it to yield a simple and intuitive expression of the quadratic objective of the central bank. The economy is populated by a continuum of identical households each supplying a different type of labor that is an imperfect substitute for the other labor types. They maximize a separable utility function in consumption and labor effort over an infinite life horizon. Consumption appears in the utility function relative to a time–varying internal habit that depends on past consumption. There is also a continuum of intermediate goods producers each producing a type of good that is an imperfect substitute for the other goods. The structure of the goods and labor markets is monopolistic competition. Both price and wage setters are assumed to face a Calvo–type restriction (1983) when setting their prices and wages optimally. In order to increase the persistence of inflation, we assume that price setters index their prices to lagged inflation

[4] The 'consumption equivalent' unit is the percentage point reduction in steady–state consumption (under the social welfare function) that would yield the same welfare level as implied by the use of ad–hoc objectives.

rates. Finally, to smooth the behavior of real marginal costs of production, we assume that wage setters also follow indexation rules whenever they are not authorized to re–optimize.[5]

The Calvo's (1983) contracting scheme has emerged as a standard in the DSGE literature. It is used in important contributions such as Woodford, (2003), Giannoni and Woodford (2005), Smets and Wouters (2003, 2005) or Levin *et al.* (2005). This is the reason why we deliberatory make our quantitative analysis under this price/wage contracting scheme. It allows us to highlight the importance of the welfare costs in this traditional framework, often retained in central banks. We discuss later the implications of this choice. In what follows, we briefly describe the log–linearized version of the model.[6]

The *output* equations:

$$(1-\beta\gamma)(1-\gamma)\hat{\upsilon}_t = \sigma\beta\gamma\left(\mathrm{E}_t\hat{y}_{t+1} - \gamma\hat{y}_t\right) - \sigma\left(\hat{y}_t - \gamma\hat{y}_{t-1}\right) + (1-\gamma)(1-\beta\gamma\rho_b)\,\hat{\varepsilon}_{b,t}, \quad (2.1)$$

$$\hat{\upsilon}_t = \mathrm{E}_t\hat{\upsilon}_{t+1} + \left(\hat{\imath}_t - \mathrm{E}_t\hat{\pi}_{t+1}\right). \quad (2.2)$$

The marginal utility of wealth $\hat{\upsilon}_t$ is a weighted average of present, past and expected future output, $\hat{y}_t$. It also depends on an exogenous disturbances to preferences, $\hat{\varepsilon}_{b,t}$. In turn, $\hat{\upsilon}_t$ is linked to the ex–ante real interest rate $\hat{\imath}_t - \mathrm{E}_t\hat{\pi}_{t+1}$. The parameter γ captures the degree of internal habit formation in consumption and ranges between zero and one. $\sigma > 0$ is the inverse of the elasticity of intertemporal substitution and β is the subjective discount factor. Note that, in our context, $\hat{y}_t = \hat{c}_t$.

The *price inflation* equation:

$$\left(\hat{\pi}_t - \xi_p\hat{\pi}_{t-1}\right) = \beta\mathrm{E}_t\left(\hat{\pi}_{t+1} - \xi_p\hat{\pi}_t\right) + \zeta_p\left(\hat{w}_t + \frac{(1-\phi)\,\hat{y}_t - \hat{\varepsilon}_{a,t}}{\phi}\right) + \hat{\varepsilon}_{p,t}. \quad (2.3)$$

Price inflation, $\hat{\pi}_t$, depends on its past and expected future values and on current real marginal costs, which itself is a function of the real wage $\hat{w}_t$, output, and a productivity shock $\hat{\varepsilon}_{a,t}$. The parameter $\zeta_p > 0$ is a function of the degree of price stickiness α_p, the steady–state value of the elasticity of substitution between differentiated goods θ_p and the share of labor in the production function ϕ.[7] In addition, ξ_p is the degree of indexation of prices to past inflation. The exogenous disturbance $\hat{\varepsilon}_{p,t}$ is an inefficient supply shock since it represents a perturbation to the natural rate of output (the equilibrium level of output under complete price and wage flexibility) that is not efficient (Giannoni, 2007).

The *wage inflation* equation:

[5]We can cast some doubts on the nature of some parameters which may not be view as invariant to changes in policy. However, in order to not mix together different issues, we follow the standard practice and consider all the parameters as structural. We then conduct policy evaluation keeping them fixed.

[6]Here and in the rest of the paper, a lower variable with a hat refers either to a percentage deviation from steady state or the natural logarithm of a gross rate. In addition, E_t denotes the expectation operator conditional on the information set at time t.

[7]The coefficient is defined as $\zeta_p \equiv (1-\alpha_p)(1-\beta\alpha_p) / \left(\alpha_p\left(1+\theta_p(1-\phi)/\phi\right)\right)$.

$$\left(\hat{\pi}_t^w - \xi_w \hat{\pi}_{t-1}\right) = \beta \mathrm{E}_t \left(\hat{\pi}_{t+1}^w - \xi_w \hat{\pi}_t\right) + \zeta_w \left(\frac{\eta}{\phi}\left(\hat{y}_t - \hat{\varepsilon}_{a,t}\right) - \hat{\upsilon}_t - \hat{w}_t\right). \tag{2.4}$$

Nominal wage inflation, $\hat{\pi}_t^w$, is a function of its expected future value, past and present inflation, as well as the wage gap $\left[\eta\left(\hat{y}_t - \hat{\varepsilon}_{a,t}\right)\right] / (1-\phi) - \hat{\upsilon}_t - \hat{w}_t$. The parameter $\zeta_w > 0$ depends on the degree of wage stickiness, α_w, the elasticity of labor supply with respect to the real wage, η, and labor demand elasticity θ_w.[8] In addition, the parameter ξ_w accounts for the degree of indexation of nominal wages to lagged price inflation. Note that price inflation and wage inflation are linked through the identity

$$\hat{\pi}_t^w = \hat{\pi}_t + \hat{w}_t - \hat{w}_{t-1}. \tag{2.5}$$

The *efficient output* equation (*i.e.* the level of output that would prevail under perfect competition):[9]

$$\kappa_0 \hat{y}_t^e = \sigma\gamma \hat{y}_{t-1}^e + \sigma\beta\gamma \mathrm{E}_t \hat{y}_{t+1}^e + \kappa_1 \hat{\varepsilon}_{a,t} + (1-\gamma)\left(1-\beta\gamma\rho_p\right)\hat{\varepsilon}_{b,t}. \tag{2.6}$$

The efficient output, $\hat{y}_t^e$, depends on its past and expected future values and on productivity and preference shocks.[10]

The *historical monetary policy rule*:

$$\hat{\imath}_t = r_i \hat{\imath}_{t-1} + (1-r_i)\left[r_\pi \hat{\pi}_{t-1} + r_x \hat{x}_{t-1}\right] + r_{\Delta\pi}\Delta\hat{\pi}_t + r_{\Delta x}\Delta\hat{x}_t + \hat{\varepsilon}_{i,t}, \tag{2.7}$$

where $\hat{x}_t = \hat{y}_t - \hat{y}_t^e$ is the output gap, defined as the difference between actual and efficient output. We assume that the short–term interest rate responds to lagged inflation, the lagged output gap, and current changes in inflation and the output gap (Smets and Wouters, 2003). We also allow for policy inertia by including the lagged short–term interest rate in the feedback equation. This interest–rate rule is designed to capture historical policy and is of use only in the estimation stage.

Finally, we assume that all exogenous disturbances follow AR(1) processes: $\hat{\varepsilon}_{\varsigma,t} = \rho_\varsigma \hat{\varepsilon}_{\varsigma,t-1} + \hat{\epsilon}_{\varsigma,t}$, where $\varsigma = a, b, i, p$.

3. Taking the model to the data

As explained by Sims (2008), the frequentist approach is not well suited to inference in an uncertain environment. First, the standard errors describe the variability of the estimators but not the distribution of the unknown parameters. Second, the probabilities associated with confidence intervals do not represent the probabilities that the unknown

[8] The coefficient is defined as $\zeta_w \equiv (1-\alpha_w)(1-\beta\alpha_w) / (\alpha_w(1+\eta\theta_w))$.

[9] The level of efficient output is a function of our model's structural shocks and is derived in Appendix B.

[10] The coefficients are defined as $\kappa_0 \equiv \left[\sigma\left(1+\beta\gamma^2\right)\phi + (1-\beta\gamma)(1-\gamma)(1-\phi+\eta)\right]/\phi$ and $\kappa_1 \equiv \left[(1-\beta\gamma)(1-\gamma)(1+\eta)\right]/\phi$.

parameters are in the interval, based on the observed data, but rather the probabilities that a similarly constructed interval would contain the true parameters if we repeatedly constructed such intervals. This means that frequentist measures of uncertainty fail to reflect a major component of actual uncertainty. Consequently, we follow the Bayesian approach to estimate the log–linearized model and properly assess the uncertainty surrounding the structural parameters.

3.1. **Econometric methodology.** The dynamic system is cast in a state–space representation for the set of observable variables. The Kalman filter is then used *(i)* to measure the likelihood of the observed variables and *(ii)* to form the posterior distribution of the structural parameters by combining the likelihood function with a joint density characterizing some prior beliefs. Given the specification of the model, the posterior distribution cannot be recovered analytically but may be computed numerically, using a Monte–Carlo Markov Chain (MCMC) sampling approach. More specifically, we rely on the Metropolis-Hastings algorithm to obtain a random draw of size 250,000 from the posterior distribution of the parameters[11].

The data used to estimate the model are extracted from an updated AWM database compiled by Fagan, Henry, and Mestre (2005). The model explains the behavior of log differences in real GDP and real wages, the log difference in the GDP deflator and short–term interest rates at quarterly frequency over the period 1985:I through 2007:IV. The corresponding measurement equation is

$$\begin{bmatrix} dlGDP_t \\ dlWAG_t \\ dlP_t \\ INTRATE_t \end{bmatrix} = \begin{bmatrix} \bar{\nu} \\ \bar{\nu} \\ \bar{\pi} \\ \bar{\imath} \end{bmatrix} + \begin{bmatrix} \hat{y}_t - \hat{y}_{t-1} \\ \hat{w}_t - \hat{w}_{t-1} \\ \hat{\pi}_t \\ \hat{\imath}_t \end{bmatrix}$$

where dl stands for 100 times log difference, $\bar{\nu}$ is the common quarterly trend growth rate of real GDP and wages, and $\bar{\pi}$ and $\bar{\imath}$ are the steady–state price inflation and nominal interest rate, respectively.

3.2. **Estimation results.** The prior distribution is summarized in Table 1. Our choices are in line with the literature, especially with Smets and Wouters (2003, 2005), Rabanal and Rubio-Ramirez (2008) and Sahuc and Smets (2008). The quarterly discount rate β pins down the equilibrium real interest rate in the model, which we set at 0.99 to generate an equilibrium annual rate of 4.0 percent. Based on our data, the steady–state share of labor income is set at $\phi = 0.70$. Finally, we calibrate θ_p and θ_w because these parameters cannot be separately identified as long as we want to estimate the probabilities of price and wage fixity, *i.e.* α_p and α_w. We set $\theta_p = \theta_w = 10$, so that the long–run markup charged by firms and the markup on wages amount to 11%.

[11]See Appendix C for a general presentation.

Table 1
Structural parameter estimates (1985:I–2007:IV)

	Prior distribution			Posterior distribution		
	Type	Mean	S.E.	5%	Mean	95%
σ_a	inv. gamma	0.250	2.000	0.2839	0.529	0.770
σ_b	inv. gamma	0.250	2.000	0.1026	0.138	0.173
σ_i	inv. gamma	0.250	2.000	0.0886	0.102	0.115
σ_p	inv. gamma	0.250	2.000	0.0762	0.113	0.150
γ	beta	0.700	0.100	0.808	0.840	0.875
σ	normal	1.000	0.375	0.835	1.367	1.909
η	normal	2.000	0.500	1.606	2.324	3.049
α_p	beta	0.750	0.050	0.807	0.837	0.867
α_w	beta	0.750	0.050	0.611	0.677	0.747
ξ_p	beta	0.500	0.150	0.050	0.167	0.277
ξ_w	beta	0.500	0.150	0.127	0.312	0.487
r_i	beta	0.750	0.100	0.802	0.870	0.939
r_π	normal	1.700	0.250	0.978	1.379	1.758
$r_{\Delta\pi}$	normal	0.250	0.100	0.031	0.096	0.161
r_x	normal	0.125	0.050	0.001	0.054	0.107
$r_{\Delta x}$	normal	0.125	0.050	0.031	0.104	0.172
ρ_a	beta	0.750	0.150	0.880	0.919	0.961
ρ_b	beta	0.750	0.150	0.348	0.504	0.672
ρ_i	beta	0.750	0.150	0.413	0.560	0.713
ρ_p	beta	0.750	0.150	0.327	0.497	0.661
$\bar{\nu}$	normal	0.400	0.100	0.377	0.454	0.529
$\bar{\pi}$	normal	0.600	0.100	0.512	0.652	0.789
$\bar{\imath}$	normal	0.600	0.100	0.479	0.623	0.777

The estimation results are summarized in the right–hand side panels of Table 1, where the posterior mean and the 95% confidence interval are reported. As regards the behavior of households, our estimate of the inverse of the consumption elasticity of substitution, σ, is equal to 1.37, while the inverse of the elasticity of labor disutility, η, is equal to 2.32. In the case of η, the prior and posterior distributions are relatively close, meaning that the aggregate data typically used have nothing to say about this parameter. This lack of identification syndrome is familiar in the literature (Smets and Wouters, 2003, 2005). The habit persistence parameter γ rises to 0.84, indicating that the reference for current consumption is about 80% of past consumption. This value is slightly higher than what is generally found, but this might not come as a surprise given that we estimate a model in which no formal distinction is established between output and consumption. The wage indexation parameter is $\xi_w = 0.31$, higher than the price indexation parameter $\xi_p = 0.17$. This reflects a now standard result that the euro area data do not require too high a degree of price indexation.

The probability that firms are not allowed to re-optimize their price is $\alpha_p = 0.84$, implying an average duration of price contracts of about 6 quarters. Although this degree of price stickiness seems high, the 95% confidence interval is consistent with the findings of the ECB *Inflation Persistence Network* reported in Dhyne *et al.* (2006). The probability of no wage change is $\alpha_w = 0.68$. This value is consistent with results drawn from micro–analysis and reported by the ECB *Wage Dynamics Network* (Druant *et al.,* 2009). The estimate of the monetary policy rule is only indicative of how short–term interest rates reacted to macroeconomic developments over the sample period. We obtain similar values to those of Smets and Wouters (2003) or Sahuc and Smets (2008): a response to inflation of $r_\pi = 1.38$, to the output gap of $r_x = 0.05$, to changes in inflation of $r_{\Delta\pi} = 0.10$, to changes in the output gap of $r_{\Delta x} = 0.10$.

In addition, the degree of nominal interest rate smoothing is found to be high with $r_i = 0.87$. The value of the interest rate feedback to the output gap suggests that, in the euro area, monetary policy paid a moderate amount of attention to stabilizing real activity. Regarding the estimates of the serial correlation of shocks, our mean estimates are around 0.50, except the productivity shock, which is highly autocorrelated (0.92). This result suggests that our structural model is able to reproduce most persistence in the data without resorting too heavily to the serial correlation of shocks. The standard errors of shocks are also very similar to those found in the literature. Finally, unsurprisingly, we find close prior and posterior distributions for the trend growth rate $\bar{\nu}$, and the steady–state values $\bar{\pi}$ and $\bar{\imath}$ since we impose prior mean values equal to their empirical counterparts.

4. Welfare costs of misspecified monetary policy objectives

In this section, we perform a welfare analysis based on the posterior mean values of the estimated parameters reported above. We first present the model–independent objective functions that are usually examined in the literature and describe the welfare–based objective function (an approximation of the expected utility of the representative household). Then, we proceed with an assessment of the welfare implications of choosing ad–hoc objectives rather than the appropriate one.

Under discretion, the central bank re–optimizes every period, taking expectations of the private sector as given. This leads to a time–consistent Markov–perfect Nash equilibrium. Discretionary equilibrium re–optimization leads to the same interest rate rule, which is optimal for any given range of expectations that cannot be affected by the current actions of the central bank.

4.1. **Ad–hoc *vs.* welfare–based policy objectives.** Due to the dichotomy between the model of the economy and the preferences of the policymaker, the economist is faced with a menu of alternative choices. In the standard literature, researchers have considered the case where the central banker has ad–hoc objectives. In this case the central banker chooses in a discretionary manner the target variables and the weights associated with them. As a result, the objective function is fixed, whereas other aspects of the structural model vary. The most common ad–hoc objective function assumes that the policymaker seeks to stabilize both inflation and the output gap

$$\mathcal{L}_0^{ah} = \frac{\tilde{\Lambda}}{2} \mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\hat{\pi}_t^2 + \tilde{\lambda}_x \hat{x}_t^2 \right], \tag{4.1}$$

where $\tilde{\lambda}_x$ is the discretionary weight placed on the output gap volatility relative to inflation volatility; the scaling parameter $\tilde{\Lambda}$ is also exogenous.

However, in models based on well–defined optimization problems for the private sector, the monetary authorities should act as a benevolent social planner whose target is to maximize the appropriate welfare objective. For instance, Woodford (2003) shows that the maximization of the representative household's lifetime utility is the appropriate objective policy. Standard yet tedious calculations yield the following second–order approximation to the present discounted value of utility of the representative household

$$-\mathrm{E} \left[\mathcal{L}_0^w \right] + t.i.p. + \mathcal{O} \left(\|\epsilon\|^3 \right), \tag{4.2}$$

where E is the unconditional expectations operator and the welfare loss function is of the form

$$\mathcal{L}_0^w = \frac{\Lambda}{2} \mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\lambda_p \left(\hat{\pi}_t - \xi_p \hat{\pi}_{t-1} \right)^2 + \lambda_w \left(\hat{\pi}_t^w - \xi_w \hat{\pi}_{t-1} \right)^2 + \lambda_x \left(\hat{x}_t - \delta \hat{x}_{t-1} \right)^2 \right], \tag{4.3}$$

where $t.i.p.$ corresponds to "terms independent of policy" and where $\mathcal{O} \left(\|\epsilon\|^3 \right)$ denotes terms of third order or smaller. Now, the weights λ_p,λ_w, and λ_x are a function of the underlying model's parameters[12]

$$\lambda_p \equiv \frac{\theta_p \zeta_p^{-1}}{\theta_p \zeta_p^{-1} + \phi \theta_w \zeta_w^{-1}}, \lambda_w \equiv \frac{\phi \theta_w \zeta_w^{-1}}{\theta_p \zeta_p^{-1} + \phi \theta_w \zeta_w^{-1}}, \lambda_x \equiv \frac{\sigma \vartheta \left[(1-\gamma)(1-\beta\gamma) \right]^{-1}}{\theta_p \zeta_p^{-1} + \phi \theta_w \zeta_w^{-1}}. \tag{4.4}$$

This welfare expression depends on the square deviations of price and wage inflation and of the output gap. Price (resp. wage) deviations represent the difference between price (resp. wage) inflation and the rate that would minimize relative price (resp. wage) distortions, given that prices (resp. wages) are sticky. Due to the indexation of both prices and wages to a lagged price index, the loss–minimizing rates of wage and price inflation coefficients are determined by the lagged inflation rate and the indexation coefficients in

[12] We obtain that $\Lambda \equiv \bar{\mathcal{U}}_{\bar{c}} \bar{c} (1-\beta\gamma) \left(\theta_p \zeta_p^{-1} + \phi \theta_w \zeta_w^{-1} \right)$. The coefficients δ and ϑ in turn satisfy $\delta = \gamma / \vartheta$ and $\vartheta = \frac{\beta}{2} \left(\chi + \sqrt{\chi^2 - 4\gamma^2 \beta^{-1}} \right)$, where $\chi = \left[(1-\phi+\eta)(1-\gamma)(1-\beta\gamma) \right] / (\phi\sigma\beta) + \left(1 + \beta\gamma^2 \right) / \beta$.

each case. Finally, the presence of habit formation persistence implies that the objective function depends not on the square of the output gap but rather on the square of $\hat{x}_t - \delta\hat{x}_{t-1}$.

4.2. **Welfare costs calculation.** Having determined the functional form of the policy objectives, we may now compute the welfare costs of choosing the ad–hoc objectives rather than the welfare–based objectives. We have in mind that monetary authorities should act as a benevolent social planner whose objective is to maximize the household's welfare objective. It is crucial to emphasize that the values of the two objective functions are not directly comparable since they are assessed under different criteria. To ensure the comparability of the two functions, the welfare–based objective function is used to measure the social loss that would arise from the optimal policy derived under the incorrect specification of the policy objectives.

We assume that all endogenous variables in the initial period are at their unconditional expectation of zero. This assumption ensures that the desirability of the chosen plan does not depend on the initial conditions at time 0. We thus define the unconditional expectation of the objective function as $\breve{\mathcal{L}}_0^i(.) = (1-\beta)\,\mathrm{E}\left[\mathcal{L}_0^i\right]$, $i = ah, w$. Let $\breve{\mathcal{L}}_0^w(\mathrm{ah})$ denote the value of the welfare–based objective function when the central bank implements the monetary policy optimal for $\breve{\mathcal{L}}_0^{ah}(.)$.

We then deduce the cost of using inappropriate objectives by comparing $\breve{\mathcal{L}}_0^w(\mathrm{ah})$ and $\breve{\mathcal{L}}_0^w(\mathrm{w})$. This cost is measured as a permanent percentage shift in steady–state consumption. It is defined by

$$\frac{\breve{\mathcal{L}}_0^w(\mathrm{ah}) - \breve{\mathcal{L}}_0^w(\mathrm{w})}{\bar{\mathcal{U}}_{\bar{c}}\bar{c}} \tag{4.5}$$

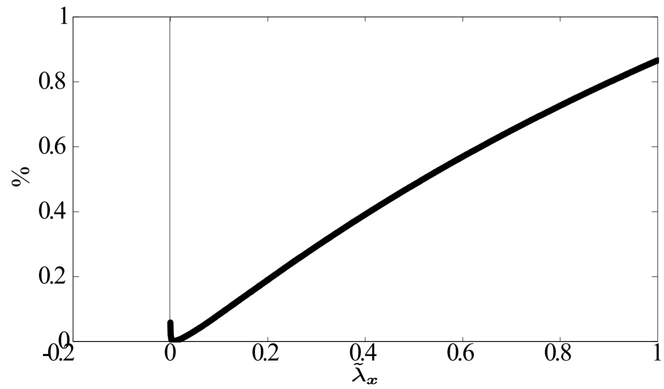
where $\bar{\mathcal{U}}_{\bar{c}}$ is the marginal utility of consumption and $\bar{c}$ is the steady–state level of consumption.

As shown previously, the weights associated with the welfare–based objectives are a combination of the structural parameters. Two striking results emerge from our estimation. First, the European monetary authorities are more sensitive to price inflation, since $\lambda_p = 0.572$. Second, the weight on the output gap is close to zero, $\lambda_x = 0.023$. This result is frequently obtained in presence of Calvo price adjustment (Woodford, 2003, Paustian, 2005). With alternative contracting schemes like the one suggested by Taylor (1980), this weight could be larger.

Figure 1 shows the welfare costs of missing the appropriate objectives according to the discretionary weight on the output gap $\tilde{\lambda}_x$. This function is truncated in zero, with a minimum obtained for $\tilde{\lambda}_x = 0.006$. It means that, if the economist chooses this value in conjunction with the inappropriate objective function, the misspecification error should be reduced. Beyond this value, the welfare costs quickly reach high values. This is not surprising given that the optimal value of the weight on the output gap is close to zero. As $\tilde{\lambda}_x$ varies, the output gap is stabilized to a much greater extent in the case of the ad–hoc objective function than in the case of the welfare–based function. Indeed, the optimal policy instructs the interest rate to adjust the output gap more aggressively in response to inflation. This large emphasis on output gap stabilization means that inflation is high and much more persistent when using some misspecified objectives.

FIGURE 1

Welfare costs of misspecified policy objectives according to $\tilde{\lambda}_x$ (percent of consumption)



For illustrative purposes, we consider three cases: *(i)* a small weight, $\tilde{\lambda}_x = 0.1$, *(ii)* a medium weight, $\tilde{\lambda}_x = 0.5$, and *(iii)* a larger weight, $\tilde{\lambda}_x = 1$. The welfare costs are equivalent to a permanent reduction in households consumption of 0.089%, 0.485% and 0.856% respectively. To gauge these welfare results more concretely, we note that European personal consumption expenditures amounted to about €15,900 per person in 2008; thus, missing the right objectives would permanently decrease welfare by about €14 (case 1) to €136 (case 3) per person. Notice that our analysis is based on steady–states comparisons excluding transition dynamics, it implies that the costs should be larger.

Of course, an alternative contracting scheme should lead to different welfare costs, since the weights associated with the different components of the objective function vary. Paustian (2005), for instance, showed that welfare costs of business cycle fluctuations under Taylor (1980) contracts can be three times lower than those under the Calvo's (1983) approach. However, in our context, the crucial factor is not the relative value of the weights associated with the policy objectives but the discrepancy between appropriate and ad–hoc weights.

4.3. **Welfare costs decomposition.** The welfare costs reported above stem from two sources of misspecification: *(i)* the omission of lagged variables and *(ii)* the inappropriate choice of weights. Indeed, the ad–hoc objective function (4.1) is a particular case of the welfare–based one (4.3) in which the constraints on the endogenous variables are given by $\xi_p = \xi_w = \delta = 0$, and the constraints associated with the weights are given by $\lambda_w = 0$,

$\lambda_p = 1$ and $\lambda_x = \tilde{\lambda}_x$. In order to identify the main source of the welfare costs, we separate the effects of each source of misspecification.

TABLE 2

Welfare costs of misspecified policy objectives (percent of consumption)

A. Missing lags of endogenous variables		B. Inappropriate weights	
Constraint on (4.3)	Welfare costs	Constraint on (4.3)	Welfare costs
$\delta = 0$	0.0030	$\lambda_p = 1$	0.0021
$\xi_p = 0$	0.0003	$\lambda_w = 0$	0.0523
$\xi_w = 0$	0.0165	$\lambda_x = 0.1$	0.0152
$\delta = \xi_p = \xi_w = 0$	0.0207	$\lambda_p = 1$, $\lambda_w = 0$, and $\lambda_x = 0.1$	0.0745

4.3.1. ***Missing lags of endogenous variables.*** As suggested above, allowing for habit formation in household consumption and for indexation of both prices and wages encourages the economy to evolve in a history–dependent way. More importantly, *(i)* the objective function depends on the square of $\hat{x}_t - \delta\hat{x}_{t-1}$ and *(ii)* the loss minimizing rates of wage and price inflation coefficients are determined by the lagged inflation rate and the indexation coefficients in each case. Panel A of Table 2 shows the welfare costs of omitting one lagged endogenous variable at a time. We observe large welfare costs stemming from the omission of price inflation in the wage inflation stabilization term ($\xi_w = 0$). In this case, wage indexation helps to stabilize real wages and is therefore likely to increase the effects of monetary policy on the labor market. This consideration is absent in the context of the ad–hoc objective function and the central bank's ability to stabilize the economy is then reduced.

Conversely, missing the lag of the output gap ($\delta = 0$) does not seem to be very costly in our model. This result stems from the fact that the optimal weight on the quasi–differenced output gap term, λ_x, is close to zero. This translates in a minor role on the lag of the output gap. However, with a higher value of the habit parameter, the relative weight on the output gap terms and the contribution of the lagged output gap in the welfare–based objective function also rise. The central bank should optimally place a greater weight on stabilizing the quasi–differenced output gap and missing the lag of the output gap might imply significant welfare effects.

Finally, *simultaneously* imposing several constraints (no lagged endogenous variables at all, for instance) increases significantly the welfare costs.

4.3.2. ***Choosing inappropriate weights.*** Let us now consider the situation of an economist who imposes inappropriate weights in the objective function. As shown in Panel

B of Table 2, such a misspecification has huge negative effects on welfare. For instance, leaving out wage inflation in the objective function, by imposing $\lambda_w = 0$, leads to sizeable welfare costs. The reason is that sticky wages create additional frictions that may give rise to conflicting stabilization aims. The optimal policy derived from the case where $\lambda_w = 0$ does not assign a large value to real wage dynamics, whereas the appropriate optimal policy clearly does. It is important to notice that such a constraint can be view as well as emanating from the omission of a relevant variable (wage inflation). Omitting wage inflation comes at a cost, which may be substantial if the stabilization of both price and wage inflation is the predominant aim according to preferences.

Imposing a larger weight on the output gap ($\lambda_x = 0.1$) when the optimal one is small is also costly. Conversely, if one assumes that price inflation stabilization is the primary objective of the central bank ($\lambda_p = 1$) whereas it represents a part of the objective is not very costly. Once again, jointly imposing several constraints ($\lambda_p = 1$, $\lambda_w = 0$, and $\lambda_x = 0.1$) dramatically increases welfare costs.

Our analysis so far indicates that imposing unsuitable weights is an important source of welfare costs but not necessarily the only one. Indeed, the total costs are generated by *both* the inappropriate choice of weights and the omission of lagged variables. Finally, we would like to emphasize that it is the combination of several incorrect constraints that leads to a huge increase in costs.

4.4. **Sensitivity to an augmented ad–hoc objective function.** The vast majority of DSGE models have adopted a cashless economy and so have explicitly abstracted from any transactions frictions that account for the demand for the monetary base. However, monetary policy is sometimes assumed to minimize a generalized loss function, which is quadratic in the inflation rate and the output gap, augmented by an interest–rate smoothing objective (that should not appear in a cashless economy):

$$\mathcal{L}_0^{ah} = \frac{\tilde{\Theta}}{2}\mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\hat{\pi}_t^2 + \tilde{\lambda}_x \hat{x}_t^2 + \tilde{\lambda}_i \left(\hat{\imath}_t - \hat{\imath}_{t-1}\right)^2\right] \tag{4.6}$$

where $\tilde{\lambda}_x$ and $\tilde{\lambda}_i$ are the ad–hoc relative weights imposed by the policymaker on the output gap and on the first difference of the interest rate.

We consider a range of different relative weights on the output gap and on the interest rate term. For each pair $(\tilde{\lambda}_x, \tilde{\lambda}_i) \in [0,1] \times [0,1]$, we compute the welfare cost of using the ad–hoc objective function. As shown in Table 3, increasing the weight on the output gap and penalizing the variability of the interest rate instrument raise the welfare cost dramatically. The welfare cost rises from about 0.058 percent when the variability of both the output gap and the interest rate is of no concern to about 1.243 percent (a permanent welfare loss of about €197 per person) when there are equal weights on these two variables $(\tilde{\lambda}_x, \tilde{\lambda}_i) = (1, 1)$. The penalty on interest rate variations introduces a trade–off between the stabilization of inflation and the output gap on one hand and the stabilization of the interest rate on the other hand. The higher the penalty on the interest rate the less the central bank will want to stabilize inflation and the output gap. It is then difficult to stabilize price inflation and the output gap with a stable interest rate if the ad–hoc objective function is used, whereas it is possible to very effectively control both inflation and the measure of real activity if there is no concern about instrument stability, as in the case of the welfare–based objective function. In other words, it is costly to assume an interest–rate smoothing incentive for central bankers when it is not socially optimal to do so.

TABLE 3

Welfare costs of misspecified policy objectives according to the ad–hoc weights in $\mathcal{L}_0^{ah}$

Output Gap	Interest Rate Smoothing			
	$\tilde{\lambda}_i$= 0	$\tilde{\lambda}_i$= 0.1	$\tilde{\lambda}_i$= 0.5	$\tilde{\lambda}_i$= 1
$\tilde{\lambda}_x$= 0	0.058	0.065	0.083	0.091
$\tilde{\lambda}_x$= 0.1	0.088	0.096	0.115	0.128
$\tilde{\lambda}_x$= 0.5	0.485	0.523	0.647	0.726
$\tilde{\lambda}_x$= 1	0.856	0.944	1.115	1.243

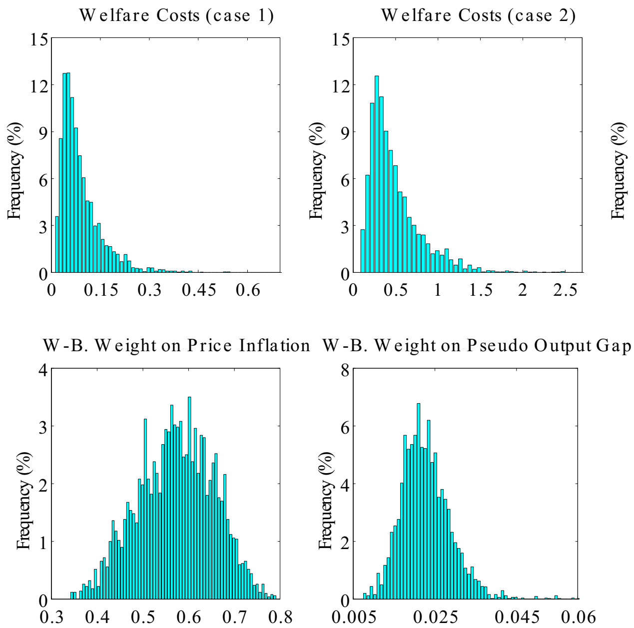
Naturally, if we consider the way in which households places value on holding money or there was some concern for stabilizing the interest rate due to a lower bound on the nominal interest rate, then the welfare loss function (4.3) could well include a penalty on the interest rate and, in this case, the costs should be reduced. However, our conclusion would not be reversed since varying the weight $\tilde{\lambda}_i$ would imply effects close to those varying $\tilde{\lambda}_x$. The welfare costs of misspecified policy objectives according to $\tilde{\lambda}_i$ are a convex function with a minimum obtained when the ad–hoc weight on the interest rate variation equals the welfare–based one. With the same arguments as above, beyond the welfare–based value, the welfare costs quickly reach high values.

5. Welfare costs of misspecified monetary policy objectives under parameter uncertainty

We now examine the sensitivity of welfare costs of misspecified policy objectives to variations in the structural parameters. We integrate out the uncertainty surrounding structural parameters by making use of the posterior distribution for these parameters obtained from model estimation. For this purpose, we first compute the ad–hoc and welfare–based optimal policies at the posterior mean values of the parameters. Second, we randomly select 10,000 draws of the parameter vector from the posterior distribution. For each draw, we compute the welfare costs of using ad–hoc objectives, evaluated under the optimal rules obtained in step one. Such an exercise implies that the economist knows the posterior distribution of the parameter values but not their specific realization. We start by computing welfare losses with joint parameter uncertainty (including those associated with the shock processes).

FIGURE 2

The distribution of welfare costs and welfare–based (w-b.) weights



Note: We consider three values for the weight on the output gap in the ad–hoc objective function (case 1: $\tilde{\lambda}_x = 0.1$; case 2: $\tilde{\lambda}_x = 0.5$; case 3: $\tilde{\lambda}_x = 1$).

Figure 2 presents the results of this exercise: the upper panels show the welfare costs for the three basic cases concerning the ad–hoc function and the lower panels show the resulting distribution of the associated welfare–based weights.

As regards uncertainty about the structural parameters, we obtain the following results: the distributions of the welfare costs are highly synchronized with the fatness of the left tail; for instance, in case 3, the 90 percent confidence interval ranges from 0.34 to 2.54, meaning that the costs may reach €404 per person. It is worth noting that the mean and the spread of the posterior distributions are highly sensitive to the assumed prior distributions. The distributions of the welfare–based weights are concentrated. The 90 percent confidence interval of the weights on price inflation and the pseudo output gap are respectively 0.42–0.76 (centered on 0.572) and 0.014–0.035 (centered on 0.023). Point estimates and their standard errors are sensitive to the estimation methodology, the sample, and the calibrated parameters.

Rather than using the posterior distribution to capture uncertainty inherent in any given model parameter, we now look at the welfare implications of getting a particular parameter wrong. We want to uncover which parameters entail costly consequences when an estimate is far from the true value. The thought experiment is one that assumes that the policymaker knows with certainty the values of the remaining parameters. The approach has the advantage of clearly identifying for which remaining parameters precise inference is crucial in order to avoid possibly large losses when designing monetary policy.

We then vary specific parameters one at a time, holding all other parameters at their respective mean estimates. Figure 3 displays the distribution of the welfare costs of missing the appropriate objectives for each deep parameter. For purposes of graphic clarity, each welfare costs distribution has been computed for $\tilde{\lambda}_x = 1$.[13] Two groups of parameters appear: *(i)* a sub–set of parameters that have few effects on welfare costs (such as Calvo's probability on nominal wage, price and wage indexations); and *(ii)* those for which uncertainty has huge effects (such as Calvo's probability on price, the habit parameter, the elasticity of intertemporal substitution, the elasticity of labor supply or the standard error and autocorrelation of shocks). In the former group, the distributions are concentrated around the mean value whereas in the latter group, the distributions display fat tails.

For example, uncertainty surrounding the value of the Calvo's probability on price may lead to double the welfare costs. Why? Under an ad–hoc function, a flat price Phillips curve prompts policymakers to reduce the systematic output gap response to inflation deviations precisely because such movements are less effective in stabilizing price inflation. But this function ignores the welfare implications of price inflation whereas the welfare–based criterion accounts for.

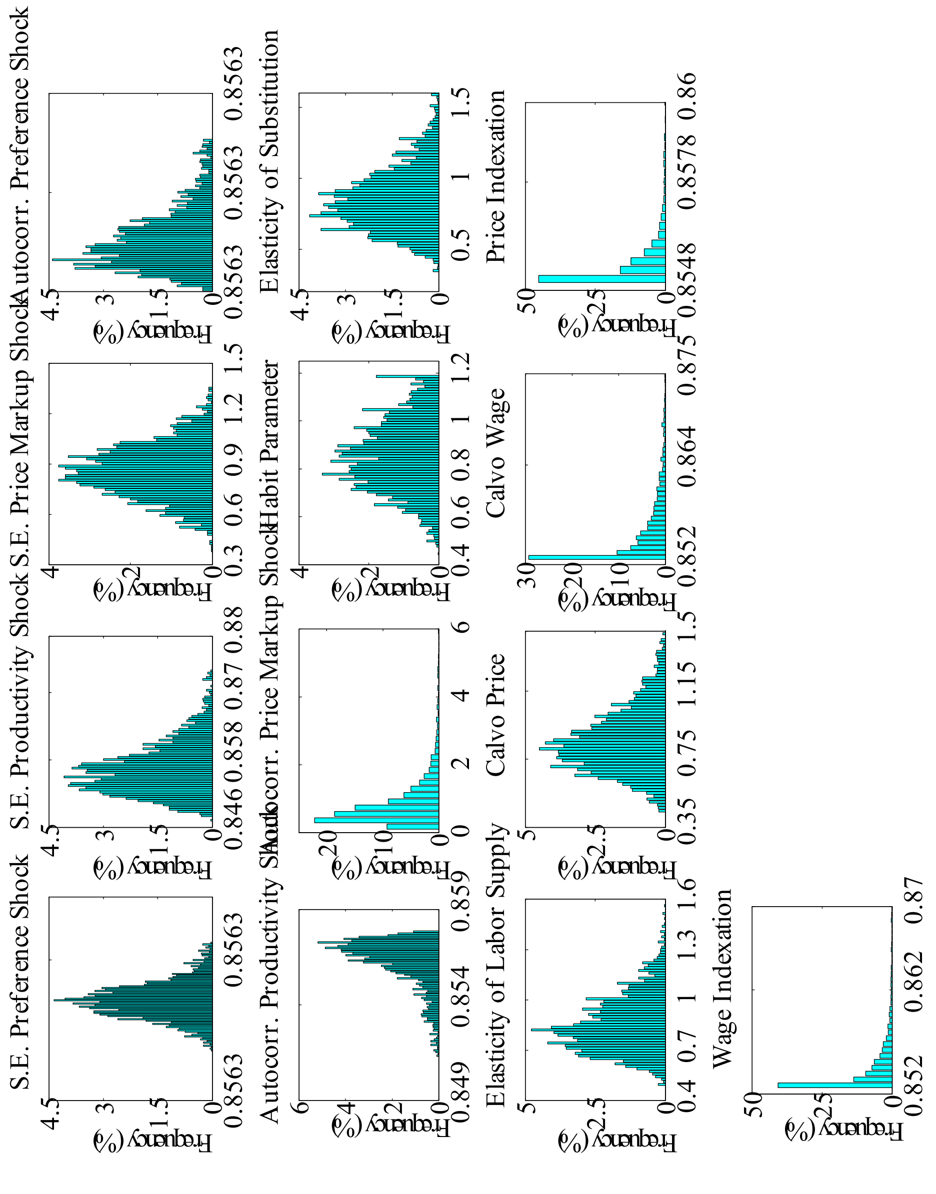
Indeed, the central bank should place a lower weight on the output gap in order to prompt policymakers to increase output gap movements to stabilize both price and wage inflation. Another example is related to the inverse of the elasticity of labor supply. In the presence of sticky wages, households tend to vary their labor supply without any such compensation taking place. Wage inflation stabilization is then closely related to the value of the inverse of the labor supply elasticity, but this notion is absent from ad–hoc objectives. Uncertainty about this structural parameter generates uncertainty about the value of the welfare–based weights. The dominant feature of Figure 3 is clearly that price markup shocks are the most important source of welfare costs that would stem from missing the appropriate objectives.[14] For instance, in the presence of uncertainty about the autocorrelation of the price markup shock, the welfare cost may easily reach 2% (a permanent welfare loss of about €318).

[13] We obtain similar shapes whatever the values of $\tilde{\lambda}_x$ but with different mean values.

[14] That remains true if we replace the price markup shock by a wage markup shock.

Figure 3

The distribution of welfare costs of misspecified policy objectives: Parameter uncertainty



Note: Each welfare cost distribution has been computed for $\tilde{\lambda}_x = 1$.

In fact, markup shocks have a special characteristic here. Indeed, unlike the other shocks, markup shocks change private incentives but have no impact on the efficient level of output. The reason is that while it is optimal for a central bank to accommodate shocks that arise from changes in technology or preferences, it is not optimal to allow inefficient variations in output. Markup shocks then create a trade–off between the output gap and both price and wage inflations stabilization. It means that a positive weight on the output gap in the ad–hoc function will reduce the variability of the output gap, but increase inflation volatility. It implies an optimal ad–hoc policy that does not care enough about the volatility of inflation, generating so much welfare costs if used in coordination with the welfare–based criterion.

6. Concluding remarks

This paper quantifies the welfare costs of misspecified monetary policy objectives in a stylized DSGE model. Our results confirm that using inappropriate objectives is costly but more importantly that welfare costs are relatively large, corresponding to permanent decreases in steady–state consumption reaching up to two percent. The latter are generated by both the inappropriate choice of weights and the omission of variables. In particular, it is costly to assume an interest–rate smoothing incentive for central bankers when it is not socially optimal to do so. Finally, a parameter uncertainty decomposition indicates that uncertainty about the properties of markup shocks gives rise to the largest welfare costs. Note that we deliberatory perform our analysis under the Calvo's contracting scheme in order to highlight the importance of the welfare costs in this traditional framework, often retained in central banks. Although in our context, the crucial factor is the discrepancy between appropriate and ad–hoc weights, it should be interesting to assess the effects of alternative contracting schemes.

Appendix A: Model details

A.1 Final-good firms

A time t, a final consumption good, y_t, is produced by a perfectly competitive, representative firm. The firm produces the final good by combining a continuum of intermediate goods, indexed by $z \in [0,1]$, using the technology

$$y_t = \left[\int_0^1 y_t\left(z\right)^{\frac{\theta_{p,t}-1}{\theta_{p,t}}} \mathrm{d}z \right]^{\frac{\theta_{p,t}}{\theta_{p,t}-1}}, \tag{6.1}$$

where $y_t\left(z\right)$ denotes the time t input of intermediate good z, and $\theta_{p,t} > 1$ is the elasticity of substitution between differentiated goods. We let the elasticity of substitution vary exogenously over time. Such perturbations to the elasticity of substitution imply a time variation in the price elasticity of demand of each good, and variations in the desired price markup. The firm takes its output price, p_t, and its input prices, $p_t\left(z\right)$, as given and beyond its control. Profit maximization implies the Euler equation

$$y_t\left(z\right) = \left(\frac{p_t\left(z\right)}{p_t} \right)^{-\theta_{p,t}} y_t. \tag{6.2}$$

Integrating (6.2) and imposing (6.1), we obtain the following relationship between the final good and the price of the intermediate good

$$p_t \equiv \left[\int_0^1 p_t\left(z\right)^{1-\theta_{p,t}} \mathrm{d}z \right]^{\frac{1}{1-\theta_{p,t}}}. \tag{6.3}$$

A.2 Aggregate labor index

We assume for the sake of simplicity that a representative labor aggregator ("employment agency") combines households' labor hours $n_t\left(h\right)$, $h \in [0,1]$, in the same proportions as firms would choose to do. Thus, the aggregator's demand for each household's labor is equal to the sum of firms' demands. The labor index l_t has the Dixit-Stiglitz form:

$$l_t = \left[\int_0^1 n_t\left(h\right)^{\frac{\theta_w-1}{\theta_w}} \mathrm{d}h \right]^{\frac{\theta_w}{\theta_w-1}}, \tag{6.4}$$

where the labor demand elasticity $\theta_w > 1$. The aggregator minimizes the cost of producing a given amount of the aggregate labor index, taking each household's wage rate $w_t\left(h\right)$ as given, and then sells units of the labor index to the production sector at their unit cost w_t

$$w_t \equiv \left(\int_0^1 w_t\left(h\right)^{1-\theta_w} \mathrm{d}h \right)^{\frac{1}{1-\theta_w}}. \tag{6.5}$$

It is natural to interpret w_t as the aggregate wage index. The aggregator's demand for labor hours of household h –or equivalently, the total demand for this household's labor by all goods–producing firms– is given by

$$n_t(h) = \left(\frac{w_t(h)}{w_t}\right)^{-\theta_w} l_t. \tag{6.6}$$

A.3 Intermediate-goods firms

Intermediate good $z \in [0,1]$ is produced by a monopolist which uses the following production function

$$y_t(z) = \varepsilon_{a,t} \breve{k}^{1-\phi} l_t(z)^{\phi}, \tag{6.7}$$

where ϕ denotes the share of labor in the production function, the variable $\varepsilon_{a,t} > 0$ is an exogenous productivity shock, and capital, $\breve{k}$, is assumed to be fixed so that labor, $l_t(z)$, is the only variable input. We rule out entry into and exit out of the production of intermediate good z. Intermediate firms rent labor in a perfectly competitive factor market.

Since input markets are perfectly competitive, the standard static first-order condition for cost minimization implies that all firms have an identical real marginal cost, mc_t, given by,

$$mc_t = \frac{w_t l_t{}^{1-\phi}}{\phi p_t \varepsilon_{a,t} \bar{k}^{1-\phi}} \tag{6.8}$$

Firms set prices according to a modified version of Calvo's (1983) staggering mechanism. In addition to the baseline mechanism, we allow for the possibility that firms that do not optimally set their prices may nonetheless adjust them to keep up with the increase in the general price level in the previous period. In each period, a firm faces a constant probability, $1-\alpha_p$, of being able to re-optimize its price and chooses the new price $p_t^{\star}(z)$ that maximizes the expected discounted sum of profits

$$\mathrm{E}_t \sum_{j=0}^{\infty} \alpha_p^j \Upsilon_{t,t+j} \left[(1+\tau_p)\frac{p_t^{\star}(z)\,\Psi_{t,t+j}^p}{p_{t+j}} - mc_{t,t+j}\right] y_{t,t+j}(z) \tag{6.9}$$

subject to the sequence of demand equations

$$y_{t,t+j}(z) = \left(\frac{p_t^{\star}(z)\,\Psi_{t,t+j}^p}{p_{t+j}}\right)^{-\theta_{p,t}} y_{t+j} \tag{6.10}$$

where E_t denotes the mathematical expectation operator conditional upon information being available in period t. By choosing $\tau_p = \left(\bar{\theta}_p - 1\right)^{-1}$, the effect of imperfect competition in goods markets on the steady–state output level may be offset. $\Upsilon_{t,t+j} = \beta^k \upsilon_{t+j}/\upsilon_t$ is the stochastic discount factor by which financial markets discount random nominal income in period $t+k$ to determine the current value of claim such income in t, and

$$\Psi_{t,t+j}^p = \begin{cases} \prod_{\nu=0}^{j-1} \bar{\pi}^{1-\xi_p} \pi_{t+v}^{\xi_p} & j > 0 \\ 1 & j = 0, \end{cases} \tag{6.11}$$

where $\pi_t \equiv p_t/p_{t-1}$ represents the gross inflation rate, $\bar{\pi}$ is trend inflation and the coefficient $\xi_p \in [0,1]$ indicates the degree of indexation to past prices, during the periods in which a firm is not allowed to re–optimize. $\Psi^{p}_{t,t+j}$ is a correcting term that accounts for the fact that, if the firm z does not re-optimize its price, it updates it according to the rule:

$$p_t(z) = \bar{\pi}^{1-\xi_p} \pi_{t-1}^{\xi_p} p_{t-1}(z). \tag{6.12}$$

Consequently, the first–order condition associated with the profit maximization implies that firms set their price equal to the discounted stream of expected future real marginal costs

$$\mathrm{E}_t \sum_{j=0}^{\infty} \alpha_p^k \Upsilon_{t,t+j} \left[(1+\tau_p)\, \bar{\pi}^{(1-\xi_p)j} \left(\frac{p_{t+j-1}}{p_{t-1}} \right)^{\xi_p} \frac{p_t^\star(z)}{p_{t+j}} - \frac{\theta_{p,t+j}}{\theta_{p,t+j}-1} mc_{t,t+j} \right] y_{t,t+j}(z) = 0. \tag{6.13}$$

If prices are assumed to be flexible ($\alpha_p = 0$), this expression gives the optimal relative price $p_t^\star(z)/p_t = (\varepsilon_{p,t}/(1+\tau_p))\, mc_t$, where $\varepsilon_{p,t} \equiv \theta_{p,t}/(\theta_{p,t}-1)$ is the optimal time–varying markup in a flexible–price economy. As there are no firm-specific shocks in this economy, all firms that are allowed to re-optimize their price at date t select the same optimal price $p_t^\star(z) = p_t^\star$, $\forall z$.

Staggered price setting under partial indexation implies the following expression for the price index dynamics

$$p_t = \left[\alpha_p \left(\bar{\pi}^{1-\xi_p} \pi_{t-1}^{\xi_p} p_{t-1} \right)^{1-\theta_{p,t}} + (1-\alpha_p)\,(p_t^\star)^{1-\theta_{p,t}} \right]^{\frac{1}{1-\theta_{p,t}}}. \tag{6.14}$$

A.4 Households

There is a continuum of households, indexed by $h \in [0,1]$. The hth household makes a sequence of decisions during each period. First, it makes consumption decision. Second, it purchases securities, whose payoffs are contingent on whether it may re–optimize its wage decision. Third, it sets its wage after having found out whether it is able to re–optimize its wage or not. Fourth, it receives a lump–sum transfer from the monetary authority.

Since the uncertainty faced by households about whether they are able to re–optimize their wage is idiosyncratic in nature, they provide different levels of labor and earn different wages. So, in principle, they are also heterogenous with respect to consumption and asset holdings.

We then assume that financial markets are complete and that state–contingent securities exist that insure households against variations in household–specific labor income (risks are efficiently shared). Our notation then reflects that households are homogenous with respect to consumption and asset holdings but heterogenous with respect to the wage they earn and the number of hours that they work.

The preferences of the hth household are given by

$$\mathcal{U}_t = \mathrm{E}_t \sum_{j=0}^{\infty} \beta^j \left[\varepsilon_{b,t+j} \frac{(c_{t+k} - \gamma c_{t+k-1})^{1-\sigma}}{1-\sigma} - \frac{(n_{t+j}(h))^{1+\eta}}{1+\eta} \right], \tag{6.15}$$

where c_t denotes consumption at time t. $\beta \in (0,1)$ is the subjective discount factor and the stationary process $\varepsilon_{b,t}$ represents an exogenous disturbances to preferences. The parameter $0 \leq \gamma \leq 1$ denotes the degree of habit formation. $\sigma > 0$ is the inverse of the elasticity of intertemporal substitution and $\eta > 0$ is the elasticity of labor supply with respect to the real wage.

The household's intertemporal budget constraint is given by

$$c_t + \frac{b_{t+1}}{(1+i_t)\, p_t} = (1+\tau_w)\frac{w_t(h)\, n_t(h)}{p_t} + \frac{b_t}{p_t} + div_t - tr_t, \tag{6.16}$$

where b_t denotes holdings of a riskless bond that costs the inverse of the gross nominal rate and pays one unit of currency in the next period. tr_t denotes real lump–sum taxes paid to the government, div_t is the dividend received from firms, and i_t is the nominal short–term interest rate. Real labor income $(w_t(h)\, n_t(h))/p_t$ is subsidized at a fixed rate τ_w to eliminate the monopolistic distortion associated with a positive markup. The government's budget is balanced in every period, so that total lump–sum transfers are equal to seigniorage revenue minus output and labor subsidies.

Households set nominal wages in staggered contracts that are analogous to the price contracts described above. In particular, we allow for the possibility that households that do not optimally set their wages may nonetheless adjust them to keep up with the increase in the general wage level in the previous period. In each period, a household faces a constant probability, $1-\alpha_w$, of being able to re–optimize its nominal wage and chooses the new wage $w_t^\star(h)$ that maximizes,[15]

$$\mathrm{E}_t \sum_{j=0}^{\infty} (\beta\alpha_w)^j \left[(1+\tau_w)\, \upsilon_{t+j} \frac{w_t^\star(h)\, \Psi^w_{t,t+j}}{p_{t+j}} n^\star_{t,t+j}(h) - \frac{n^\star_{t,t+j}(h)^{1+\eta}}{1+\eta} \right], \tag{6.17}$$

subject to the sequence of labor demand equations

$$n^\star_{t,t+j}(h) = \left(\frac{w_t^\star(h)\, \Psi^w_{t,t+j}}{w_{t+j}} \right)^{-\theta_w} n_{t+j}, \tag{6.18}$$

and

$$\Psi^w_{t,t+j} = \begin{cases} \prod_{\nu=0}^{j-1} \bar{\pi}^{1-\xi_w} \pi_{t+v}^{\xi_w} & j > 0 \\ 1 & j = 0, \end{cases} \tag{6.19}$$

where the coefficient $\xi_w \in [0,1]$ indicates the degree of indexation to past prices, during the periods in which a household is not allowed to re–optimize. By choosing $\tau_w = (\theta_w - 1)^{-1}$, the effect of imperfect competition in labor markets on the steady–state output level may be offset. $\Psi^w_{t,t+j}$ is a correcting term that accounts for the fact that, if household h does not re-optimize its wage, it updates it according to the rule

$$w_t(h) = \bar{\pi}^{1-\xi_w} \pi_{t-1}^{\xi_w} w_{t-1}(h). \tag{6.20}$$

[15]We use $n^\star_{t,t+j}(h)$ to denote the number of hours supplied by a household that charges wage $w_t^\star(h)$ in period $t+j$ when aggregate wages and hours are w_{t+j} and n_{t+j}, respectively.

Consequently, the first-order condition for $w_t^\star(h)$ may be expressed as

$$\mathrm{E}_t \sum_{j=0}^{\infty} (\beta\alpha_w)^j \left[(1+\tau_w)\, \upsilon_{t+j} \bar{\pi}^{(1-\xi_w)j} \left(\frac{w_{t+j-1}}{w_{t-1}}\right)^{\xi_w} \frac{w_t^\star(h)}{p_{t+j}} \right.$$
$$\left. - \frac{\theta_w}{\theta_w - 1} n_{t,t+j}^\star(h)^\eta \right] n_{t,t+j}^\star(h) = 0. \tag{6.21}$$

In the case where wages are flexible (i.e. $\alpha_w = 0$), this expression implies that the effective real wage $(1+\tau_w)\, w_t^\star(h)/p_t$ is set as a markup $\varepsilon_w \equiv \theta_w/(\theta_w - 1)$ over the marginal rate of substitution between consumption and leisure.

Staggered wage setting under partial indexation implies the following expression for the wage index dynamics

$$w_t = \left[\alpha_w \left(\bar{\pi}^{1-\xi_w} \pi_{t-1}^{\xi_w} w_{t-1} \right)^{1-\theta_w} + (1-\alpha_w)\, (w_t^\star)^{1-\theta_w} \right]^{\frac{1}{1-\theta_w}}. \tag{6.22}$$

A.5 Equilibrium

The market clearing conditions require that in all inputs, intermediate goods and final goods markets supply equals demand. For the final good such that the resource constraint may be written as

$$\frac{y_t}{\Delta_{p,t}} = c_t. \tag{6.23}$$

where $\Delta_{p,t} = \int_0^1 \left(\frac{p_t(z)}{p_t}\right)^{-\theta_{p,t}} dz$ is a measure of the price dispersion.

Appendix B. Efficient rate of output

Let us take the following notations:

$$\mathbb{U}_t = \frac{\left(c_{t+k} - \gamma c_{t+j-1}\right)^{1-\sigma}}{1-\sigma};\ \mathbb{V}_t = \frac{\left(n_{t+k}\left(h\right)\right)^{1+\eta}}{1+\eta} \text{ and } f\left(l_t\left(z\right)\right) = l_t\left(z\right)^{\phi}$$

To determine the natural rate of output, we first note that the first–order condition for the optimal supply of labor by household h is given by

$$\frac{\mathbb{V}'_{n,t}}{\mathbb{U}'_{c,t}} = \frac{w_t\left(h\right)}{p_t},\ \forall t. \tag{6.24}$$

Next, the firm's profits are given by

$$\begin{aligned}\Pi_t\left(z\right) &\equiv \left(1+\tau_p\right) p_t\left(z\right) y_t\left(z\right) - w_t\left(z\right) n_t\left(z\right) \\ &= \left(1+\tau_p\right) p_t\left(z\right)^{1-\theta_{p,t}} p_t^{\theta_{p,t}} y_t - w_t\left(z\right) f^{-1}\left(p_t\left(z\right)^{-\theta_{p,t}} p_t^{\theta_{p,t}} y_t/\varepsilon_{a,t}\right),\end{aligned}$$

To derive the last equation, we use the Dixit-Stiglitz demand for good z, $y_t\left(z\right) = \left(p_t\left(z\right)/p_t\right)^{-\theta_{p,t}} y_t$ and we invert the production function $y_t\left(z\right) = \varepsilon_{a,t} f\left(l_t\left(z\right)\right)$. When prices are flexible, the optimal pricing decision for firm z, i.e. the price that would maximize profits at each period, is given by

$$p_t\left(z\right) = \left[\frac{\varepsilon_{p,t}}{1+\tau_p} \frac{w_t}{\varepsilon_{a,t} f'\left(f^{-1}\left(y_t\left(z\right)/\varepsilon_{a,t}\right)\right)}\right],$$

where the desired markup $\varepsilon_{p,t} \equiv \frac{\theta_{p,t}}{\theta_{p,t}-1}$ and f' denotes the derivative of f. Using again the demand for good z, the relative supply of good z must in turn satisfy

$$\left(\frac{y_t\left(z\right)}{y_t}\right)^{-\frac{1}{\theta_{p,t}}} = \left[\frac{\varepsilon_{p,t}}{1+\tau_p} \frac{w_t}{p_t} \frac{1}{\varepsilon_{a,t} f'\left(f^{-1}\left(y_t\left(z\right)/\varepsilon_{a,t}\right)\right)}\right].$$

Because all wages are the same in the case of flexible wages, we have $w_t\left(h\right) = w_t$ and $n_t\left(h\right) = l_t$ for all h. Thus, (6.24) implies that when wages and prices are flexible, all sellers supply a quantity y_t^n that satisfies,

$$1 = \left[\frac{\varepsilon_{p,t}}{1+\tau_p} \frac{\mathbb{V}'_{n,t}\left(f^{-1}\left(y_t^n/\varepsilon_{a,t}\right)\right)}{\upsilon_t^n} \frac{1}{\varepsilon_{a,t} f'\left(f^{-1}\left(y_t^n/\varepsilon_{a,t}\right)\right)}\right], \tag{6.25}$$

where υ_t^n denotes the marginal utility of income in the case of flexible prices and flexible wages. In a steady state, it reaches the constant level of output, $\bar{y}$, which satisfies

$$\frac{\bar{\mathbb{V}}'_n}{\bar{\upsilon} f'} = \left[\left(\frac{\bar{y}}{\bar{\varepsilon}_a}\right)^{\frac{\eta}{\phi}} / \left(\bar{\upsilon}\left(1-\eta\right)\left(\bar{y}\right)^{-\frac{1-\phi}{\phi}} \bar{\varepsilon}_a^{\frac{1}{\phi}}\right)\right] = \frac{1+\tau_p}{\bar{\varepsilon}_p} \equiv 1,$$

Furthermore, we observe that $\bar{\upsilon} = \bar{\mathbb{U}}'_c\left(1-\beta\gamma\right)$, so that

$$\bar{\mathbb{V}}'_n = \left(1-\beta\gamma\right)\bar{\mathbb{U}}'_c f'. \tag{6.26}$$

Log–linearizing (6.25) around this steady state and solving for $\hat{y}_t^n \equiv \log\left(y_t^n/\bar{y}\right)$ yields

$$\frac{1-\phi+\eta}{\phi}\hat{y}_t^n = \frac{1+\eta}{\phi}\hat{\varepsilon}_{a,t} - \hat{\varepsilon}_{p,t} + \hat{\upsilon}_t^n. \tag{6.27}$$

The natural rate of output is given by:

$$\begin{aligned} \hat{y}_t^n &= \frac{\gamma}{1+\beta\gamma^2}\hat{y}_{t-1}^n + \frac{\beta\gamma}{1+\beta\gamma^2}\mathrm{E}_t\hat{y}_{t+1}^n - \frac{(1-\beta\gamma)(1-\gamma)}{\sigma(1+\beta\gamma^2)}\hat{\upsilon}_t^n \\ &+ \frac{(1-\gamma)}{\sigma(1+\beta\gamma^2)}\left(\hat{\varepsilon}_{b,t} - \beta\gamma\mathrm{E}_t\hat{\varepsilon}_{b,t+1}\right) \end{aligned} \tag{6.28}$$

Putting (6.27) in (6.28) yields

$$\begin{aligned} \left[\sigma\left(1+\beta\gamma^2\right)\phi + (1-\beta\gamma)(1-\gamma)(1-\phi+\eta)\right]\hat{y}_t^n &= \sigma\gamma\phi\hat{y}_{t-1}^n \\ +\sigma\beta\gamma\phi\mathrm{E}_t\hat{y}_{t+1}^n + (1-\beta\gamma)(1-\gamma)(1+\eta)\hat{\varepsilon}_{a,t} \\ +\phi(1-\gamma)\left(\hat{\varepsilon}_{b,t} - \beta\gamma\mathrm{E}_t\hat{\varepsilon}_{b,t+1}\right) - (1-\beta\gamma)(1-\gamma)\phi\hat{\varepsilon}_{p,t} \end{aligned} \tag{6.29}$$

When $\hat{\varepsilon}_{p,t}$ is exogenously time–varying, variations in the natural rate of output $\hat{y}_t^n$ differ from fluctuations in the efficient rate of output, $\hat{y}_t^e$, *i.e.* the equilibrium rate of output that would be obtained in the absence of price rigidities and distortions due to market power. The efficient rate of output solves

$$1 = \left[\frac{\mathbb{V}_{n,t}\left(f^{-1}\left(y_t^e/\varepsilon_{a,t}\right)\right)}{\upsilon_t^e}\frac{1}{\varepsilon_{a,t}f'\left(f^{-1}\left(y_t^e/\varepsilon_{a,t}\right)\right)}\right], \tag{6.30}$$

In steady state, it also reaches the constant level of output, $\bar{y}$. Log-linearizing (6.30) around $y_t^e = \bar{y}$, and solving for $\hat{y}_t^e \equiv \log\left(y_t^e/\bar{y}\right)$, we obtain:

$$\begin{aligned} \left[\sigma\left(1+\beta\gamma^2\right)\phi + (1-\beta\gamma)(1-\gamma)(1-\phi+\eta)\right]\hat{y}_t^e &= \sigma\gamma\phi\hat{y}_{t-1}^e \\ +\sigma\beta\gamma\phi\mathrm{E}_t\hat{y}_{t+1}^e + (1-\beta\gamma)(1-\gamma)(1+\eta)\hat{\varepsilon}_{a,t} \\ +\phi(1-\gamma)(1-\beta\gamma\rho_b)\hat{\varepsilon}_{b,t} \end{aligned} \tag{6.31}$$

Appendix C: Empirical aspects

C.1 Bayesian econometrics

Let $\hat{x}_t$ denote the vector of observable variables. The log-linearized MCM is cast in a state-space representation for $\hat{q}_t$ in order to form the likelihood function of the data:

$$\hat{s}_t = A(\Theta)\hat{s}_{t-1} + B(\Theta)\varsigma_t \quad (6.32)$$

$$\hat{q}_t = C\hat{s}_t \quad (6.33)$$

where $\hat{s}_t$ is the vector of state variables. In addition to observable variables, the model includes unobservable variables such as natural output or shock processes. Last, ς_t is a vector of i.i.d. variables with mean zero and covariance matrix $\Sigma(\Theta)$. The $A(\Theta)$, $B(\Theta)$ and $\Sigma(\Theta)$ are all functions of the parameter vector Θ, while C does not depend on Θ since it selects elements of $\hat{s}_t$.

A Kalman filter is used to estimate the system (6.32)–(6.33). The algorithm preliminary evaluates the number of explosive eigenvalues. Consequently, indeterminate models (that do not satisfy the Blanchard-Kahn conditions) are directly ruled out during the course of the estimation.

For a given structural model $\mathcal{M}_i$ and a set of parameters Θ, we denote $\Gamma(\Theta|\mathcal{M}_i)$ the prior distribution of Θ and $L(Q_T|\Theta,\mathcal{M}_i)$ the likelihood function associated with the observable variables $Q_T = \{\hat{q}_t\}_{t=1}^T$. Then, from Bayes rule, the posterior distribution of the parameter vector is proportional to the product of the likelihood function and the prior distribution of Θ,

$$\Gamma(\Theta|Q_T,\mathcal{M}_i) \propto \mathcal{L}(Q_T|\Theta,\mathcal{M}_i)\,\Gamma(\Theta|\mathcal{M}_i). \quad (6.34)$$

Given the specification of the model, the posterior distribution cannot be recovered analytically. However, it can be evaluated numerically, using a Monte-Carlo Markov Chain (MCMC) sampling approach. More specifically, we rely to the Metropolis-Hastings (MH) algorithm to obtain a random draw of size 250,000 from the posterior distribution of the parameters.[16] The mode and the Hessian of the posterior distribution evaluated at the mode are used to initialize the MH algorithm. The algorithm is the following:

(1) Start with an initial value Θ_0. From that value, evaluate the expression

$$L\left(Q^T|\Theta,\mathcal{M}\right)\Gamma(\Theta|\mathcal{M}).$$

(2) For each i,

$$\hat{\Theta}_i = \begin{cases} \hat{\Theta}_{i-1} \text{ with probability } 1 - prob \\ \Theta_i^* \text{ with probability } prob \end{cases}$$

where

$$\Theta_i^* = \Theta_{i-1} + \wp\mho,$$

[16] The first 50,000 observations are discarded to eliminate any dependence on the initial values.

and

$$prob = \min\left(1, \frac{\mathcal{L}\left(Q^T|\Theta_i^*, \mathcal{M}\right)\Gamma\left(\Theta_i^*|\mathcal{M}\right)}{\mathcal{L}\left(Q^T|\hat{\Theta}_{i-1}, \mathcal{M}\right)\Gamma\left(\hat{\Theta}_{i-1}|\mathcal{M}\right)}\right)$$

$\mho$ defines the hessian matrix of the posterior distribution evaluated at the mode. The value of $\wp$ determines the acceptation rate of the algorithm. If this rate is too low, the Markov chain does not visit an enough large set of values in a reasonable number of iterations. If this rate is too high, the Markov chain does not stay enough time in areas of high probabilities. We set $\wp$ to 0.38, which gives an acceptation rate of approximately 30%.

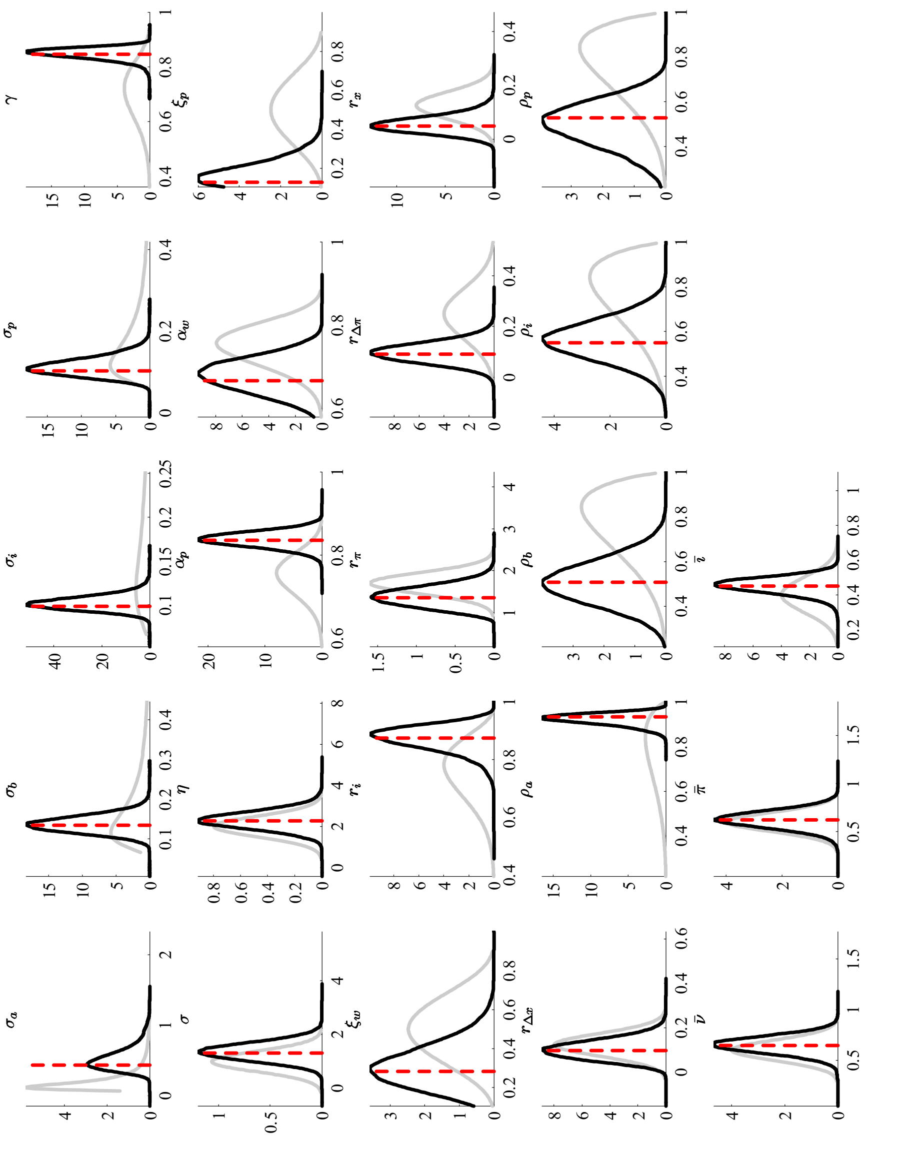
C.2 Prior distribution

Our choices are in line with the literature, especially with Smets and Wouters (2003, 2005), Rabanal and Rubio-Ramirez (2008), and Sahuc and Smets (2008). The habit persistence parameter, γ, follows a beta distribution, with a mean of 0.7 and a standard error of 0.1. The inverse of the intertemporal elasticity of substitution of consumption, σ, and the inverse of the elasticity of labor disutility, η, are assumed to follow a normal distribution, because they may theoretically take rather large values, with a mean of 1 and a standard error of 0.375 for the first parameter and a mean of 2 and a standard error of 0.50 for the second one. The fraction of firms (resp. households) that are not allowed to re-optimize their price (resp. wage), α_p (resp. α_w), are assumed to follow a beta distribution, centered on 0.75 (i.e. an average duration of prices and wages of 4 quarters) and a standard error of 0.05. Without additional information on the degrees of price and wage indexations, ξ_p and ξ_w, they are assumed to follow a beta distribution, with a mean of 0.5 and a standard error of 0.15.[17] Regarding the monetary policy parameters, we adopt similar priors to those used by Smets and Wouters (2003): the long–term parameter for inflation r_π is 1.7 (with a standard error of 0.25), the long–term parameter for the output gap r_x is 0.125 (with a standard error of 0.05), the change in inflation parameter $r_{\Delta\pi}$ is 0.25 (with a standard error of 0.1), and the change in the output gap $r_{\Delta x}$ is 0.125 (with a standard error of 0.05). They follow a normal distribution. The smoothing parameter r_i follows a beta distribution, with a mean of 0.75 and a standard error of 0.1. Finally, the common trade growth rate and the steady–state inflation and interest rate follow a normal distribution with mean set at their empirical counterpart and a standard error of 0.1.

All the standard deviations of shocks ($\sigma_a, \sigma_b, \sigma_i,$ and σ_p) are assumed to be distributed as an inverted gamma distribution with a degree of freedom equal to 2. The autoregressive

[17] In some empirical papers, the densities for the indexation parameters are assumed to be uniform over the unit interval. We do not have strong beliefs regarding this hypothesis, so we adopt a beta distribution similar to the assumption made by Smets and Wouters.

parameters (ρ_a, ρ_b, ρ_i and ρ_p) are assumed to follow a beta distribution, with a mean of 0.75 and a standard error of 0.15. The figure below plots the prior and posterior distributions.



Note: The vertical line denotes the posterior mode, the light grey line is the prior distribution, and the black line is the posterior distribution.

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