The Role of Sticky Prices in An Open Economy DSGE Model: A Bayesian Investigation

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November 2004

Forthcoming in the Journal of the European Economic Association

Abstract

In this paper we use a Dynamic Stochastic General Equilibrium (DSGE) model for an open economy to examine the role of sticky prices in explaining the joint behaviour of inflation and a fairly large set of macroeconomic variables. We find that price stickiness is an important feature for firms active in the domestic, export and import sectors, even though the model embodies variable capital utilization, a working-capital channel and a time-varying inflation target. We also document that price stickiness in all sectors is important even if the markup shocks are allowed to be autocorrelated, although the implied average contract duration falls substantially under this assumption.

JEL Classification Numbers: E40, E50, C11.

1 Introduction

The role of sticky prices in understanding the joint behavior of inflation and aggregate activity is a controversial issue in macroeconomics. In this paper we provide new evidence on the role of sticky prices in domestic, export and import markets by estimating an open economy Dynamic Stochastic General Equilibrium (DSGE) model on the euro area using Bayesian techniques. Our model extends the closed economy DSGE model of Christiano, Eichenbaum and Evans

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Acknowledgements: We would like to thank Frank Smets, Øistein Røisland and discussants at various conferences for useful comments.

Note: The views expressed in this paper are solely the responsibility of the authors and should not be interpreted as reflecting the views of the Executive Board of Sveriges Riksbank.

(2004) by incorporating open economy aspects into it. The introduction of a stochastic unit root trend in technology, following Altig, Christiano, Eichenbaum and Lindé (2003), allows us to estimate the model without detrending the data. By using data for the euro area we offer a direct comparison to the closed economy results in Smets and Wouters (2003a), who have shown that one can successfully estimate closed economy DSGE models using Bayesian methods. Note though that our model differs from Smets and Wouters' in several respects. Apart from bringing in the exchange rate channel, we also include a working capital channel (i.e., firms borrow money from a financial intermediary to finance part of their wage bill). The working capital channel implies that an interest rate change directly affects the firms' marginal costs. Examining the role of the working capital channel is of particular interest since Christiano, Eichenbaum and Evans (2004) obtain a low estimated degree of price stickiness when allowing for working capital when matching the impulse responses after a monetary policy shock. In contrast, Smets and Wouters (2003a, 2003b) obtain a much higher degree of estimated price stickiness in a model without the working capital channel.

Although our model embodies a number of mechanisms that have proven useful to generate persistence in inflation such as variable capital utilization, the working capital channel and a time-varying inflation target, we still find that price stickiness is an important feature for firms active in the domestic, export and import sectors.[1] Under the traditional assumption that the households own the capital stock and assuming that the markup shocks in each sector are white noise, the implied average duration of price contracts are rather long, of about 8 quarters. However, allowing the markup shocks to be serially correlated reduces the estimated degree of price stickiness substantially. In this case, we find that the average duration is less than 2

[1] Christiano, Eichenbaum and Evans (2004) find that when either shutting down the working capital channel or not allowing for variable capital utilization, sticky prices is an important feature for generating inflation persistence after a shock to monetary policy.

quarters for the firms active in the consumption and investment import sectors, and about 3 quarters for the firms active in the domestic and export sectors. Since the marginal likelihoods clearly indicate that the assumption of correlated shocks in the import and export sectors is most plausible, our results suggest price stickiness around $2-3$ quarters on average in these sectors.

For the firms that produce domestic goods, the marginal likelihood is in favor of the model with white noise markup shocks, leaving us with a rather high degree of estimated price stickiness (8 quarters average duration) under the conventional assumption that the households own the capital stock. However, recent research have highlighted the importance of the degree to which capital is specific to the firm for the interpretation of the price stickiness parameter, see e.g. Altig, Christiano, Eichenbaum and Lindé (2004), Sveen and Weinke (2004) and Woodford (2004). If we relax the assumption that the households own the capital stock, and instead assume that the capital is entirely specific to each firm, we can apply the formulas in Altig et al. (2004), and reinterpret our estimates to imply an average duration of about 4.5 quarters, which appear to be in line with microeconomic evidence, see e.g. Mash (2004) and the references therein.

The remainder of the paper is organized as follows. In Section 2 we present the theoretical open economy DSGE model. Section 3 contains the empirical results. Finally, we provide some concluding remarks in Section 4.

2 Model

This section gives an overview of the model and presents the key equations in the log-linearized model. We refer to Adolfson, Laseén, Lindé and Villani (2004) for a more detailed description of the model.

Consumption preferences are subject to habit formation and the households attain utility from consuming a basket consisting of domestically produced goods and imported products. These products are supplied by domestic and importing firms, respectively.

The households can save in domestic bonds and foreign bonds, and also hold cash. Following Benigno (2001), we assume that there is a premium on the foreign bond holdings which depends on the aggregate net foreign asset position of the domestic households. This ensures a well defined steady-state in the model.

The households invest in a basket of domestic and imported investment goods to form the physical capital stock, and decide how much capital services to rent to the domestic firms, given certain capital adjustment costs. These are costs to adjusting the investment rate as well as costs of varying the utilization rate of the physical capital stock. Further, along the lines of Erceg, Henderson and Levin (2000), each household is a monopoly supplier of a differentiated labour service which implies that they can set their own wage. This gives rise to a wage equation with Calvo (1983) stickiness.

The domestic firms determine the capital services and labour inputs used in their production which is exposed to unit root technology growth as in Altig et al. (2003). The firms (domestic, importing and exporting) all produce differentiated goods and set prices according to an indexation variant of the Calvo model. By including nominal rigidities in the importing and exporting sectors we allow for short-run incomplete exchange rate pass-through to both import and export prices, following for example Smets and Wouters (2002).

To simplify the analysis we adopt the assumption that the foreign prices, output (HP-detrended) and interest rate are exogenously given by an identified VAR(4) model. The fiscal policy variables - the capital, labour income, consumption, and pay-roll taxes, together with (HP-detrended) government expenditures - are assumed to follow an identified VAR(2) model.[2]

[2]It should be noted that Adolfson et al. (2004) report that the fiscal shocks have small dynamic effects in the model, presumably because these shocks are transitory and do not generate any wealth effects for the infinitively

The domestic (d), importing consumption (mc), importing investment (mi) and exporting (x) firms operating in this economy each have a particular Phillips curve:

$$\begin{aligned}\left(\widehat{\pi}_t^j - \widehat{\bar{\pi}}_t^c\right) &= \frac{\beta}{1+\kappa_j\beta}\left(\mathrm{E}_t\widehat{\pi}_{t+1}^j - \rho_\pi \widehat{\bar{\pi}}_t^c\right) + \frac{\kappa_j}{1+\kappa_j\beta}\left(\widehat{\pi}_{t-1}^j - \widehat{\bar{\pi}}_t^c\right) \\ & -\frac{\kappa_j\beta\left(1-\rho_\pi\right)}{1+\kappa_j\beta}\widehat{\bar{\pi}}_t^c + \frac{(1-\xi_j)(1-\beta\xi_j)}{\xi_j\left(1+\kappa_j\beta\right)}\left(\widehat{mc}_t^j + \widehat{\lambda}_t^j\right),\end{aligned} \tag{1}$$

where $j = \{d, mc, mi, x\}$, $\widehat{\pi}_t^j = (\hat{P}_t^j - \hat{P}_{t-1}^j)$ denotes inflation in sector j, and $\widehat{\bar{\pi}}_t^c$ a time-varying inflation target of the central bank.[3] The ξ:s are the Calvo price stickiness parameters in each sector, and the κ:s are the indexation parameters.[4] $\widehat{\lambda}_t^d$, $\widehat{\lambda}_t^{mc}$, $\widehat{\lambda}_t^{mi}$, and $\widehat{\lambda}_t^x$ are stochastic AR(1) processes determining the time-varying markups in the four markets. The firms' marginal costs are defined as $\widehat{mc}_t^d = \alpha\left(\hat{\mu}_{z,t} + \hat{H}_t - \hat{k}_t\right) + \widehat{\bar{w}}_t + \hat{R}_t^f - \hat{\epsilon}_t$, $\widehat{mc}_t^{mc} = \widehat{P}_t^* + \widehat{S}_t - \widehat{P}_t^{mc}$, $\widehat{mc}_t^{mi} = \widehat{P}_t^* + \widehat{S}_t - \widehat{P}_t^{mi}$, and $\widehat{mc}_t^x = \widehat{P}_t^d - \widehat{S}_t - \widehat{P}_t^x$, respectively. $\hat{\mu}_{z,t}$ is the stochastic growth rate of the unit root technology shock, $\hat{H}_t$ hours worked, $\hat{k}_t$ the capital services stock, $\widehat{\bar{w}}_t$ the real wage, and $\hat{R}_t^f$ the effective nominal interest rate paid by the firms, reflecting the assumption that a fraction ν of the firms' wage bill has to be financed in advance (throughout the paper, we set $\nu = 1$). $\hat{\epsilon}_t$ is a stationary technology shock, $\widehat{P}_t^*$ the foreign price level and $\widehat{S}_t$ is the nominal exchange rate.

Under the assumption that those households that are not allowed to reoptimize their nominal wage in the current period instead update it according to the indexation scheme $W_{t+1} =$

lived households.

[3] A hat denotes log-linearized variables throughout the paper (i.e, $\widehat{X}_t = dX_t/X$), and variables without time-subscript steady-state values. Variables denoted with small letters have been stationarized with the unit root technology shock.

[4] For the domestic (d) and exporting (x) firms that are not allowed to reoptimize their prices, we adopt the indexation scheme $P_{t+1}^j = \left(\pi_t^j\right)^{\kappa_j}\left(\bar{\pi}_{t+1}^c\right)^{1-\kappa_j} P_t^j$ where $j = \{d, x\}$. Note that the importing firms are assumed not to index to $\bar{\pi}_{t+1}^c$, i.e. $\kappa_{mc} = \kappa_{mi} = 1$.

$\left(\pi_t^c\right)^{\kappa_w}\left(\bar{\pi}_{t+1}^c\right)^{(1-\kappa_w)}\mu_{z,t+1}W_t$, the real wage equation can be written

$$\mathrm{E}_t\left[\begin{array}{c}\eta_0\widehat{\bar{w}}_{t-1}+\eta_1\widehat{\bar{w}}_t+\eta_2\widehat{\bar{w}}_{t+1}+\eta_3\left(\hat{\pi}_t^d-\widehat{\bar{\pi}}_t^c\right)+\eta_4\left(\hat{\pi}_{t+1}^d-\rho_{\widehat{\bar{\pi}}^c}\widehat{\bar{\pi}}_t^c\right)\\+\eta_5\left(\hat{\pi}_{t-1}^c-\widehat{\bar{\pi}}_t^c\right)+\eta_6\left(\hat{\pi}_t^c-\rho_{\widehat{\bar{\pi}}^c}\widehat{\bar{\pi}}_t^c\right)\\+\eta_7\hat{\psi}_{z,t}+\eta_8\hat{H}_t+\eta_9\hat{\tau}_t^y+\eta_{10}\hat{\tau}_t^w+\eta_{11}\hat{\zeta}_t^h\end{array}\right]=0, \tag{2}$$

where $\hat{\pi}_t^c$ denotes CPI inflation, $\hat{\psi}_{z,t}$ the marginal utility of one additional income unit, $\hat{\tau}_t^y$ a labour income tax, $\hat{\tau}_t^w$ a pay-roll tax assumed to be paid by the households, and $\hat{\zeta}_t^h$ a labour supply shock. The η:s are composite parameters determined by the Calvo wage stickiness ξ_w, the pay-roll tax τ^w, the labour income tax τ^y, the labour supply elasticity σ_L, the wage markup λ_w, the wage indexation κ_w, and the discount factor β.

The households' consumption preferences are subject to internal habit formation, which yields the following Euler equation for consumption expenditures:

$$\mathrm{E}_t\left[\begin{array}{c}-b\beta\mu_z\hat{c}_{t+1}+\left(\mu_z^2+b^2\beta\right)\hat{c}_t-b\mu_z\hat{c}_{t-1}+b\mu_z\left(\hat{\mu}_{z,t}-\beta\hat{\mu}_{z,t+1}\right)+\\+\left(\mu_z-b\beta\right)\left(\mu_z-b\right)\hat{\psi}_{z,t}+\frac{\tau^c}{1+\tau^c}\left(\mu_z-b\beta\right)\left(\mu_z-b\right)\hat{\tau}_t^c\\+\left(\mu_z-b\beta\right)\left(\mu_z-b\right)\hat{\gamma}_t^{c,d}-\left(\mu_z-b\right)\left(\mu_z\hat{\zeta}_t^c-b\beta\hat{\zeta}_{t+1}^c\right)\end{array}\right]=0, \tag{3}$$

where $\hat{c}_t$ is consumption, $\hat{\tau}_t^c$ a consumption tax, $\hat{\gamma}_t^{c,d}$ the relative price between consumption and domestically produced goods, $\hat{\zeta}_t^c$ a consumption preference shock, b the habit persistence parameter, and μ_z is the steady-state growth rate.

By combining the first order conditions for the domestic and foreign bond holdings we obtain the following modified uncovered interest rate parity condition:

$$\widehat{R}_t-\widehat{R}_t^*=\mathrm{E}_t\Delta\widehat{S}_{t+1}-\widetilde{\phi}_a\widehat{a}_t+\widehat{\widetilde{\phi}}_t, \tag{4}$$

where $\widehat{R}_t$ is the domestic nominal interest rate, $\widehat{R}_t^*$ the foreign nominal interest rate, $\widehat{a}_t$ the net foreign asset position, and $\widehat{\widetilde{\phi}}_t$ a shock to the risk premium. Because of our assumption of imperfect integration in the international financial markets, the net foreign asset position enters.

The households' first order conditions for the physical capital stock ($\widehat{\bar{k}}_t$), investment ($\hat{\imath}_t$), and the utilization rate ($\widehat{u}_t = \widehat{k}_t - \widehat{\bar{k}}_t$, where $\widehat{k}_t$ denotes capital services) are, respectively:

$$\begin{array}{r} \hat{\psi}_{z,t} + \mathrm{E}_t\hat{\mu}_{z,t+1} - \mathrm{E}_t\hat{\psi}_{z,t+1} - \frac{\beta(1-\delta)}{\mu_z}\mathrm{E}_t\hat{P}_{k',t+1} + \hat{P}_{k',t} \\ -\frac{\mu_z-\beta(1-\delta)}{\mu_z}\mathrm{E}_t\hat{r}^k_{t+1} + \frac{\tau^k}{(1-\tau^k)}\frac{\mu_z-\beta(1-\delta)}{\mu_z}\mathrm{E}_t\hat{\tau}^k_{t+1} = 0, \end{array} \tag{5}$$

$$\hat{P}_{k',t} + \hat{\Upsilon}_t - \hat{\gamma}^{i,d}_t - \mu_z^2\tilde{S}''\left[(\hat{\imath}_t - \hat{\imath}_{t-1}) - \beta(\hat{\imath}_{t+1} - \hat{\imath}_t) + \hat{\mu}_{z,t} - \beta\mathrm{E}_t\hat{\mu}_{z,t+1}\right] = 0, \tag{6}$$

$$\widehat{u}_t = \frac{1}{\sigma_a}\widehat{r}^k_t - \frac{1}{\sigma_a}\frac{\tau^k}{(1-\tau^k)}\widehat{\tau}^k_t, \tag{7}$$

where $\hat{P}_{k',t}$ is the price of capital, $\widehat{r}^k_t$ the firms' real rental rate of capital services given by $\hat{r}^k_t = \hat{\mu}_{z,t} + \widehat{\bar{w}}_t + \hat{R}^f_t + \hat{H}_t - \hat{k}_t$, $\hat{\Upsilon}_t$ an investment specific technology shock, $\hat{\gamma}^{i,d}_t$ the relative price between investment and domestically produced goods, $\hat{\tau}^k_t$ a capital income tax, $\tilde{S}''$ the adjustment cost of changing investments, δ the depreciation rate, and σ_a the cost of varying the capital utilization rate.

The evolution of net foreign assets at the aggregate level satisfies

$$\begin{aligned} \hat{a}_t &= -y^*\widehat{mc}^x_t - \eta_f y^*_t\widehat{\gamma}^{x,*}_t + y^*\hat{y}^*_t + y^*\widehat{\tilde{z}}^*_t + (c^m + i^m)\widehat{\gamma}^f_t \\ &\quad -c^m\left[-\eta_c(1-\omega_c)\left(\gamma^{c,d}\right)^{-(1-\eta_c)}\widehat{\gamma}^{mc,d}_t + \widehat{c}_t\right] \\ &\quad -i^m\left[-\eta_i(1-\omega_i)\left(\gamma^{i,d}\right)^{-(1-\eta_i)}\widehat{\gamma}^{mi,d}_t + \widehat{i}_t\right] + \frac{R}{\pi\mu_z}\hat{a}_{t-1}, \end{aligned} \tag{8}$$

where $\hat{y}^*_t$ denotes foreign output, $\widehat{\tilde{z}}^*_t$ is a stationary shock which measures the degree of asymmetry in the technological progress in the domestic economy versus the rest of the world, and $\widehat{\gamma}^{x,*}_t$,$\widehat{\gamma}^f_t$, $\widehat{\gamma}^{mc,d}_t$ and $\widehat{\gamma}^{mi,d}_t$ are relative prices defined as $\widehat{\gamma}^{x,*}_t = \hat{P}^x_t - \hat{P}^*_t$, $\widehat{\gamma}^f_t = \hat{P}^d_t - \hat{S}_t - \hat{P}^*_t$, $\widehat{\gamma}^{mc,d}_t = \hat{P}^{mc}_t - \hat{P}^d_t$ and $\widehat{\gamma}^{mi,d}_t = \hat{P}^{mi}_t - \hat{P}^d_t$, respectively.

Following Smets and Wouters (2003a), monetary policy is approximated with the instrument rule

$$\begin{aligned} \widehat{R}_t &= \rho_R\widehat{R}_{t-1} + (1-\rho_R)\left[\widehat{\bar{\pi}}^c_t + r_\pi\left(\hat{\pi}^c_{t-1} - \widehat{\bar{\pi}}^c_t\right) + r_y\hat{y}_{t-1} + r_x\hat{x}_{t-1}\right] \\ &\quad + r_{\Delta\pi}\left(\hat{\pi}^c_t - \hat{\pi}^c_{t-1}\right) + r_{\Delta y}\Delta\hat{y}_t + \varepsilon_{R,t}, \end{aligned} \tag{9}$$

where $\varepsilon_{R,t}$ is an uncorrelated monetary policy shock. Thus, the central bank is assumed to adjust the short term interest rate in response to deviations of CPI inflation from the time-varying inflation target $\left(\hat{\pi}_t^c - \hat{\bar{\pi}}_t^c\right)$, the output gap ($\hat{y}_t$, measured as actual minus trend output), the real exchange rate ($\hat{x}_t$) and the interest rate set in the previous period. In addition, note that the nominal interest rate adjusts directly to the inflation target.

These equations together with the law of motion for capital, the aggregate resource constraint, the loan market clearing condition, the definitional equation for money growth, and the first order conditions for money and cash holdings close the model.

3 Empirical results

3.1 Data

To estimate the model we use quarterly euro area data for the period 1970Q1-2002Q4. The data set employed here was first constructed by Fagan et al. (2001).[5] We include a large set of variables when we estimate the model in order to facilitate identification of the parameters, and match the following 15 variables: the domestic inflation rate π_t; the growth rate in consumption Δc_t(Δ denotes the first difference operator), investment Δi_t, GDP Δy_t, exports $\Delta \widetilde{X}_t$, imports $\Delta \widetilde{M}_t$, and the real wage $\Delta \overline{w}_t$; the real exchange rate x_t; the short-run interest rate R_t; employment E_t; the consumption deflator $\pi_t^{def,c}$; the investment deflator $\pi_t^{def,i}$; foreign inflation π_t^*; the foreign interest rate R_t^*; and the growth rate in foreign output Δy_t^*.[6] The reason for modeling

[5] The Fagan data set includes foreign (i.e., rest of the world) output and inflation, but not a foreign interest rate. We therefore use the Fed funds rate as a proxy for R_t^*.

[6] There is no (official) data on aggregate hours worked, $\hat{H}_t$, available for the euro area. Therefore, we use employment $\hat{E}_t$ in our estimations. Since employment is likely to respond more slowly to shocks than hours worked, we model employment using Calvo-rigidity (following Smets and Wouters, 2003a): $\Delta \hat{E}_t = \beta E_t \Delta \hat{E}_{t+1} + \frac{(1-\xi_e)(1-\beta\xi_e)}{\xi_e}\left(\hat{H}_t - \hat{E}_t\right)$. For reasons discussed in greater detail in Adolfson et al. (2004), we take out a linear

the real variables in growth rates is that the unit root technology shock induces a stochastic trend in the levels of the real variables. To calculate the likelihood function of the observed variables we apply the Kalman filter.[7]

3.2 Prior and posterior distributions of the parameters

A number of parameters are kept fixed throughout the estimation procedure. Most of these parameters can be related to the steady-state values of the observed variables in the model, and are therefore calibrated so as to match the sample mean of these.[8] The calibrated parameters, together with some of the estimated parameters (e.g. μ_z, the steady-state growth rate) evaluated at the prior mode, imply a consumption-output ratio of 0.58, an investment-output ratio of 0.22, an import-output (and export-output) ratio of 0.25 in the steady state. Likewise, the quarterly gross interest rate (R) becomes 1.013, and the quarterly gross domestic inflation 1.005 in the steady state.

Table 1 shows the assumptions for the prior distribution of the estimated parameters. The location of the prior distribution of the 49 estimated parameters corresponds to a large extent to those in Smets and Wouters (2003a) and the findings in Altig et al. (2003) on U.S. data. For more details about our choice of prior distributions, see Adolfson et al. (2004).

The joint posterior distribution of all estimated parameters is obtained in two steps. First,

trend in employment and the excess trend in imports and exports relative to the trend in GDP prior to estimation.

[7] We use the period 1970Q1-1979Q4 to form a prior on the unobserved state variables in 1979Q4, and then use the period 1980Q1-2002Q4 for inference.

[8] The calibrated parameters are set to the following: the money growth $\mu = 1.01$; the discount factor $\beta = 0.999$; the depreciation rate $\delta = 0.013$; the capital share in production $\alpha = 0.29$; the share of imports in consumption and investment $\omega_c = 0.31$ and $\omega_i = 0.55$, respectively; the steady-state tax rates on labour income and consumption $\tau^y = 0.177$ and $\tau^c = 0.125$, respectively; government expenditures-output ratio 0.20. For reasons discussed in greater detail in Adolfson et al. (2004), we also set the substitution elasticity between domestic and imported goods $\eta_c = 5$ and the capital utilization parameter $\sigma_a = 10^6$.

the posterior mode and Hessian matrix evaluated at the mode is computed by standard numerical optimization routines. Second, draws from the joint posterior are generated using the Metropolis-Hastings algorithm (see Smets and Wouters (2003a), and the references therein, for details).[9]

3.3 Estimation results

In Table 1, we report the posterior mode for two different specifications of the model. In one specification we assume that the domestic markup shocks are i.i.d., and in the other we assume that they are autocorrelated (ρ_{λ^d} is the persistence coefficient in the assumed AR(1) process). In the case where the domestic markup shocks are i.i.d., the estimated Calvo domestic sticky price coefficient is very high (0.88) and close to the estimate reported in Smets and Wouters (2003a), although our model embodies the working capital channel. This channel along with a time-varying inflation target can thus not reduce the estimated sticky price coefficient when fitting the model to all the variation in the data. We find that the working capital channel is capable of producing a lot of persistence in inflation following a monetary policy shock when ξ_d is low, but not following other shocks in the model. Since the monetary policy shock is not the main source of business cycle fluctuations according to the estimation results, the model needs a higher ξ_d in order to match the joint behaviour of inflation, interest rates and aggregate quantities in response to the other shocks. This is why our estimate of ξ_d is higher than the one reported by Christiano, Eichenbaum and Evans (2004), who estimate their model based on matching the impulse response functions to a monetary policy shock only.

Interestingly, when we allow the markup shocks to be autocorrelated, we find that the estimated sticky price coefficient drops substantially from 0.88 to 0.67 (i.e., from eight to three

[9] A posterior sample of $550,000$ draws was generated from the posterior of which the first $50,000$ draws were discarded as burn-in. Convergence was checked using standard diagnostics such as CUSUM plots and ANOVA on parallel simulation sequences.

quarters average duration). However the posterior mode estimate of the markup shock persistence coefficient is very high, 0.996. Notably, also the estimated persistence coefficients for the consumption preference and stationary technology shocks rise substantially in this case, to account for the persistence in inflation when the degree of estimated price stickiness is low. Note furthermore that the indexation parameters (i.e., the importance of lags in the Phillips curves, see footnote 4) are quite small, so the Phillips curves for the domestic and exporting firms are essentially forward-looking. These findings are in line with the univariate results reported by Levin and Piger (2004), who find that intrinsic persistence is substantially moderated when allowing for a level-shift in the inflation rate.

Our conclusion is that domestic inflation persistence is either due to the low sensitivity to marginal costs, or that the persistence stems from highly autocorrelated shocks. An interesting question to ask is then: which of these explanations is the most plausible one? By judging from the marginal likelihoods in Table 1, the data suggest that the specification with i.i.d. domestic markup shocks is the most plausible, the Bayes factor is about 81.5 in favor of that model.

Turning to the estimated price stickiness parameters for the firms in the export and import sectors, we see in Table 1 that they are substantially lower than for the domestic firms, in particular so for the importing firms, conditional on our decision to allow the markup shocks in these sectors to be autocorrelated.[10] To examine the importance of the autocorrelated markup shocks in the import and export sectors we experiment with the priors on these parameters in Table 2. We calibrate the persistence parameters for the markup shocks to zero, and increase the prior mode of the stickiness parameters to 0.675 in anticipation that these coefficients then need to be high in order for the model to match the data. As expected, the posterior mode for

[10] The a priori reason why we assumed the markup shocks for the firms in the import and export sector to be autocorrelated, is that we work with a very simple production technology in these sectors (i.e., these firms use neither labour nor capital).

the price stickiness parameters of the export and import firms rise substantially to about 0.90 (see Table 2). However, even if the posterior modes for the stickiness parameters ξ_{mc}, ξ_{mi}, and ξ_x are larger, the drop in marginal likelihood is rather severe in comparison to the benchmark specification with correlated markup shocks in the import and export sectors.

The close resemblance between the prior and posterior modes of the price stickiness parameters for the domestic and importing investment firms in the case when we allow for autocorrelated markup shocks, raise the issue of identification of the sticky price parameters. In Table 2, we therefore investigate the identification in more detail by changing the priors for the sticky price parameters and the persistence parameters. We do this by separately lowering the prior modes for the sticky price parameters in the domestic sector ξ_d and in the import and export sectors ξ_{mc}, ξ_{mi} and ξ_x to 0.10, and re-estimating these two models with autocorrelated markup shocks. The results are reported in the last four columns in Table 2. When the prior mode for the domestic price stickiness parameter ξ_d is set to 0.10, we find that the posterior mode is 0.50. This is lower than the posterior mode of 0.67 that resulted from a higher prior on ξ_d (see Table 1). Note though that the marginal likelihood drops considerably from about -1932 to -1947 in the case with the lower prior. The same story applies for the ξ_{mc}, ξ_{mi} and ξ_x parameters (see the last column in Table 2). When we lower the prior mode for these parameters to 0.10, they are driven towards the posteriors reported in Table 1 but does not come all the way back because of the lower prior, which results in a large drop in the marginal likelihood. Consequently, we can safely conclude that the price stickiness parameters are well identified in each sector even when we allow for correlated markup shocks. Moreover, sticky prices are important, in particular for the domestic and importing firms (around $3-4.5$ quarters using the assumption of firm-specific capital, see the introduction), and to a lesser extent for the importing firms ($1-2$ quarters).[11]

[11]It should be emphasized that the lower price duration for the importing firms is due to our assumption of full indexation to past inflation rather than to the inflation target for the firms in this sector. If we relax this

4 Conclusions

In this paper we have studied the role of sticky prices in an open-economy DSGE model estimated on data for the euro area. We interpret our results as suggesting that sticky prices is an empirically important friction. The estimated degree of price stickiness we obtain using macro data is, however, not in direct contrast to the microeconomic evidence when relaxing the assumption of economy wide capital markets in favor of capital being specific to each firm.

References

Adolfson, Malin, Stefan Laseén, Jesper Lindé and Mattias Villani (2004), "Bayesian Estimation of an Open Economy DSGE Model with Incomplete Pass-Through", manuscript, Sveriges Riksbank.

Altig, David, Lawrence Christiano, Martin Eichenbaum and Jesper Lindé (2003), "The Role of Monetary Policy in the Propagation of Technology Shocks", manuscript, Northwestern University.

Altig, David, Lawrence Christiano, Martin Eichenbaum and Jesper Lindé (2004), "Firm-Specific Capital, Nominal Rigidities and the Business Cycle", manuscript, Northwestern University.

Benigno, Pierpaolo (2001), "Price Stability with Imperfect Financial Integration", manuscript, New York University.

Calvo, Guillermo (1983), "Staggered Prices in a Utility Maximizing Framework", *Journal of Monetary Economics* 12, 383-398.

assumption, and assume the same indexation scheme as for the domestic and exporting firms, we find that the average contract duration is around 3 quarters for the importing consumption firms and about 4 quarters for the importing investment firms.

Christiano, Lawrence, Martin Eichenbaum and Charles Evans (2004), "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy", forthcoming, *Journal of Political Economy*, 112(6).

Erceg, Christopher, Dale Henderson and Andrew Levin (2000), "Optimal Monetary Policy with Staggered Wage and Price Contracts", *Journal of Monetary Economics* 46(2), 281-313.

Fagan, Gabriel, Jerome Henry and Ricardo Mestre (2001), "An Area-Wide Model (AWM) for the Euro Area", Working Paper No. 42. European Central Bank.

Levin, Andrew and Jeremy Piger (2004), "Is Inflation Persistence Intrinsic in Industrial Countries", Working paper No. 334, European Central Bank.

Mash, Richard (2004), "Optimising Microfoundations for Inflation Persistence", manuscript, University of Oxford.

Smets, Frank and Raf Wouters (2003a), "An Estimated Stochastic Dynamic General Equilibrium Model of the Euro Area", *Journal of the European Economic Association*, 1(5), 1123-1175.

Smets, Frank and Raf Wouters (2003b), "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach", manuscript, European Central Bank.

Smets, Frank and Raf Wouters (2002), "Openness, Imperfect Exchange Rate Pass-Through and Monetary Policy", *Journal of Monetary Economics* 49(5), 913-940.

Sveen, Tommy and Lutz Weinke (2004), "New Perspectives on Capital and Sticky Prices", Working Paper No. 2004/3, Norges Bank.

Woodford, Michael (2004), "Inflation and Output Dynamics with Firm-Specfic Investment", manuscript, Princeton University.

Table 1: Prior and posterior distributions

Parameter		Prior distribution			Persistent domestic markup shocks $\rho_{\lambda^d} > 0$ Posterior distribution		IID domestic markup shocks $\rho_{\lambda^d} = 0$ Posterior distribution				
		type	mean*	std.dev. /df	mode	std. dev. (Hess-ian)	mode	std. dev. (Hess-ian)	mean	5%	95%
Calvo wages	ξ_w	beta	0.675	0.050	0.653	0.045	0.697	0.046	0.690	0.606	0.765
Calvo domestic prices	ξ_d	beta	0.675	0.050	0.667	0.030	0.882	0.015	0.891	0.863	0.919
Calvo import cons. prices	ξ_{mc}	beta	0.500	0.100	0.299	0.038	0.266	0.032	0.272	0.220	0.329
Calvo import inv. prices	ξ_{mi}	beta	0.500	0.100	0.517	0.043	0.563	0.045	0.547	0.470	0.620
Calvo export prices	ξ_x	beta	0.500	0.100	0.682	0.048	0.657	0.058	0.630	0.523	0.739
Calvo employment	ξ_e	beta	0.675	0.100	0.780	0.029	0.791	0.023	0.787	0.740	0.826
Indexation wages	κ_w	beta	0.500	0.150	0.268	0.115	0.506	0.158	0.498	0.263	0.733
Indexation domestic prices	κ_d	beta	0.500	0.150	0.160	0.083	0.213	0.087	0.231	0.101	0.382
Indexation export prices	κ_x	beta	0.500	0.150	0.137	0.069	0.154	0.079	0.202	0.077	0.375
Markup domestic	λ^d	inv. gamma	1.200	2	1.179	0.059	1.166	0.051	1.230	1.122	1.405
Markup imported cons.	λ^{mc}	inv. gamma	1.200	2	1.741	0.102	1.656	0.069	1.667	1.552	1.795
Markup imported invest.	λ^{mi}	inv. gamma	1.200	2	1.270	0.117	1.238	0.096	1.304	1.153	1.530
Investment adj. cost	$\tilde{S}''$	normal	7.694	1.500	6.605	1.509	8.686	1.380	8.650	6.339	11.005
Habit formation	b	beta	0.650	0.100	0.599	0.045	0.672	0.049	0.691	0.595	0.805
Subst. elasticity invest.	η_i	inv. gamma	1.500	4	1.631	0.224	1.622	0.217	1.674	1.390	2.091
Subst. elasticity foreign	η_f	inv. gamma	1.500	4	1.614	0.151	1.468	0.096	1.494	1.341	1.689
Technology growth	μ_z	trunc. normal	1.006	0.0005	1.005	0.000	1.005	0.001	1.005	1.004	1.006
Capital income tax	τ_k	beta	0.120	0.050	0.277	0.033	0.139	0.040	0.137	0.074	0.202
Labour pay-roll tax	τ_w	beta	0.200	0.050	0.186	0.050	0.185	0.050	0.197	0.119	0.285
Risk premium	$\tilde{\phi}$	inv. gamma	0.010	2	0.189	0.093	0.159	0.053	0.291	0.158	0.475
Unit root tech. shock	ρ_{μ_z}	beta	0.850	0.100	0.751	0.083	0.736	0.117	0.705	0.530	0.861
Stationary tech. shock	ρ_ε	beta	0.850	0.100	0.978	0.011	0.907	0.031	0.885	0.810	0.938
Invest. spec. tech shock	ρ_Υ	beta	0.850	0.100	0.526	0.080	0.750	0.042	0.724	0.646	0.795
Consumption pref. shock	ρ_{ζ^c}	beta	0.850	0.100	0.990	0.006	0.930	0.026	0.899	0.775	0.960
Labour supply shock	ρ_{ζ^h}	beta	0.850	0.100	0.532	0.087	0.672	0.061	0.675	0.562	0.775
Risk premium shock	$\rho_{\tilde{\phi}}$	beta	0.850	0.100	0.945	0.020	0.992	0.009	0.953	0.921	0.989
Asymmetric tech. shock	$\rho_{\tilde{z}^*}$	beta	0.850	0.100	0.990	0.012	0.993	0.002	0.992	0.987	0.996
Domestic markup shock	ρ_{λ^d}	beta	0.850	0.100	0.996	0.002			calibrated to 0		
Imp. cons. markup shock	$\rho_{\lambda^{mc}}$	beta	0.850	0.100	0.980	0.012	0.984	0.012	0.975	0.949	0.993
Imp. invest. markup shock	$\rho_{\lambda^{mi}}$	beta	0.850	0.100	0.992	0.007	0.977	0.013	0.969	0.941	0.990
Export markup shock	ρ_{λ^x}	beta	0.850	0.100	0.905	0.042	0.874	0.051	0.868	0.758	0.951
Unit root tech. shock	σ_{μ_z}	inv. gamma	0.200	2	0.127	0.025	0.131	0.026	0.137	0.099	0.183
Stationary tech. shock	σ_ε	inv. gamma	0.700	2	0.399	0.066	0.455	0.087	0.522	0.364	0.746
Invest. spec. tech. shock	σ_Υ	inv. gamma	0.200	2	0.472	0.058	0.426	0.047	0.469	0.391	0.559
Consumption pref. shock	σ_{ζ^c}	inv. gamma	0.200	2	0.156	0.034	0.154	0.032	0.161	0.111	0.228
Labour supply shock	σ_{ζ^h}	inv. gamma	0.200	2	0.096	0.015	0.095	0.015	0.099	0.075	0.129
Risk premium shock	$\sigma_{\tilde{\phi}}$	inv. gamma	0.050	2	0.169	0.033	0.131	0.023	0.182	0.132	0.241
Asymmetric tech. shock	$\sigma_{\tilde{z}^*}$	inv. gamma	0.400	2	0.193	0.029	0.204	0.031	0.218	0.167	0.278
Domestic markup shock	σ_{λ^d}	inv. gamma	0.300	2	0.119	0.016	0.130	0.013	0.131	0.110	0.155
Imp. cons. markup shock	$\sigma_{\lambda^{mc}}$	inv. gamma	0.300	2	4.084	1.146	4.722	0.978	4.790	3.263	6.656
Imp. invest. markup shock	$\sigma_{\lambda^{mi}}$	inv. gamma	0.300	2	0.732	0.182	0.585	0.153	0.684	0.442	1.020
Export markup shock	σ_{λ^x}	inv. gamma	0.300	2	0.757	0.154	0.927	0.189	1.057	0.735	1.493
Monetary policy shock	σ_R	inv. gamma	0.150	2	0.144	0.014	0.133	0.013	0.136	0.114	0.161
Inflation target shock	$\sigma_{\bar{\pi}^c}$	inv. gamma	0.050	2	0.050	0.012	0.042	0.012	0.052	0.031	0.079
Interest rate smoothing	ρ_R	beta	0.800	0.050	0.824	0.021	0.869	0.022	0.877	0.837	0.912
Inflation response	r_π	normal	1.700	0.100	1.659	0.082	1.703	0.089	1.714	1.565	1.866
Diff. infl response	$r_{\Delta\pi}$	normal	0.300	0.100	0.355	0.061	0.304	0.058	0.300	0.199	0.400
Real exch. rate response	r_x	normal	0.000	0.050	-0.006	0.003	-0.008	0.006	-0.009	-0.022	0.005
Output response	r_y	normal	0.125	0.050	-0.029	0.010	0.069	0.028	0.095	0.046	0.158
Diff. output response	$r_{\Delta\pi}$	normal	0.0625	0.050	0.115	0.031	0.115	0.028	0.125	0.077	0.174
Log marginal likelihood					-1932.24		-1927.84				

*Note: For the inverse gamma distribution, the mode and the degrees of freedom are reported. Also, for the parameters λ^d, λ^{mc}, λ^{mi}, η_i, η_f and μ_z the prior distributions are truncated at 1.

Table 2: Sensitivity analysis with respect to priors on stickiness and markup shocks

Parameter		Benchmark			All markup shocks IID $\rho_{\lambda^d} = \rho_{\lambda^{mc}} = \rho_{\lambda^{mi}} = \rho_{\lambda^x} = 0$		Low prior on domestic price stickiness and corr. markup shocks $\rho_{\lambda^d} > 0$		Low prior on imported and exported price stickiness	
		Distri-bution	Prior mode	Posterior mode	Prior mode	Posterior mode	Prior mode	Posterior mode	Prior mode	Posterior mode
Calvo wages	ξ_w	beta	0.675	0.697		0.691		0.677		0.688
Calvo domestic prices	ξ_d	beta	0.675	0.882		0.880	0.100	0.496		0.892
Calvo import cons. prices	ξ_{mc}	beta	0.500	0.266	0.675	0.871		0.275	0.100	0.203
Calvo import inv. prices	ξ_{mi}	beta	0.500	0.563	0.675	0.932		0.546	0.100	0.463
Calvo export prices	ξ_x	beta	0.500	0.657	0.675	0.898		0.658	0.100	0.486
Calvo employment	ξ_e	beta	0.675	0.791		0.787		0.787		0.789
Indexation wages	κ_w	beta	0.500	0.506		0.485		0.445		0.483
Indexation domestic prices	κ_d	beta	0.500	0.213		0.177		0.611		0.212
Indexation export prices	κ_x	beta	0.500	0.154		0.241		0.160		0.318
Markup domestic	λ^d	inv. gamma	1.200	1.166		1.170		1.154		1.171
Markup imported cons.	λ^{mc}	inv. gamma	1.200	1.656		1.524		1.694		1.758
Markup imported invest.	λ^{mi}	inv. gamma	1.200	1.238		1.161		1.241		1.377
Investment adj. cost	$\tilde{S}''$	normal	7.694	8.686		10.153		8.040		8.484
Habit formation	b	beta	0.650	0.672		0.674		0.617		0.657
Subst. elasticity invest.	η_i	inv. gamma	1.500	1.622		1.408		1.616		1.623
Subst. elasticity foreign	η_f	inv. gamma	1.500	1.468		1.404		1.513		1.428
Technology growth	μ_z	trunc. normal	1.006	1.005		1.005		1.005		1.005
Capital income tax	τ_k	beta	0.120	0.139		0.180		0.217		0.138
Labour pay-roll tax	τ_w	beta	0.200	0.185		0.186		0.186		0.185
Risk premium	$\tilde{\phi}$	inv.	0.010	0.159		0.033		0.143		0.283
Unit root tech. shock	ρ_{μ_z}	beta	0.850	0.736		0.720		0.725		0.748
Stationary tech. shock	ρ_{ε}	beta	0.850	0.907		0.894		0.961		0.913
Invest. spec. tech shock	ρ_{Υ}	beta	0.850	0.750		0.814		0.702		0.699
Cons. pref. shock	ρ_{ζ^c}	beta	0.850	0.930		0.913		0.976		0.931
Labour supply shock	ρ_{ζ^h}	beta	0.850	0.672		0.662		0.602		0.680
Risk premium shock	$\rho_{\tilde{\phi}}$	beta	0.850	0.992		0.943		0.991		0.953
Asymm. tech. shock	$\rho_{\tilde{z}*}$	beta	0.850	0.993		0.991		0.993		0.993
Domestic markup shock	ρ_{λ^d}				calib. 0		0.850*	0.989	calib. 0	
Imp. cons. markup shock	$\rho_{\lambda^{mc}}$	beta	0.850	0.984	calib. 0			0.983		0.984
Imp. invest. markup shock	$\rho_{\lambda^{mi}}$	beta	0.850	0.977	calib. 0			0.990		0.977
Export markup shock	ρ_{λ^x}	beta	0.850	0.874	calib. 0			0.892		0.918
Unit root tech. shock	σ_{μ_z}	inv. gamma	0.200	0.131		0.128		0.130		0.134
Stationary tech. shock	σ_{ε}	inv. gamma	0.700	0.455		0.450		0.333		0.450
Invest. spec. tech. shock	σ_{Υ}	inv. gamma	0.200	0.426		0.352		0.412		0.474
Consumption pref. shock	σ_{ζ^c}	inv. gamma	0.200	0.154		0.147		0.181		0.167
Labour supply shock	σ_{ζ^h}	inv. gamma	0.200	0.095		0.096		0.093		0.094
Risk premium shock	$\sigma_{\tilde{\phi}}$	inv. gamma	0.050	0.131		0.311		0.128		0.146
Asymmetric tech. shock	$\sigma_{\tilde{z}*}$	inv. gamma	0.400	0.204		0.204		0.200		0.206
Domestic markup shock	σ_{λ^d}	inv. gamma	0.300	0.130		0.127		0.164		0.132
Imp. cons. markup shock	$\sigma_{\lambda^{mc}}$	inv. gamma	0.300	4.722		1.033		4.494		7.302
Imp. invest. markup shock	$\sigma_{\lambda^{mi}}$	inv. gamma	0.300	0.585		0.354		0.631		0.989
Export markup shock	σ_{λ^x}	inv. gamma	0.300	0.927		1.146		0.884		1.677
Monetary policy shock	σ_R	inv. gamma	0.150	0.133		0.130		0.141		0.131
Inflation target shock	$\sigma_{\bar{\pi}^c}$	inv. gamma	0.050	0.042		0.050		0.046		0.043
Interest rate smoothing	ρ_R	beta	0.800	0.869		0.863		0.825		0.873
Inflation response	r_{π}	normal	1.700	1.703		1.669		1.741		1.703
Diff. infl response	$r_{\Delta\pi}$	normal	0.300	0.304		0.310		0.327		0.293
Real exch. rate response	r_x	normal	0.000	-0.008		0.006		-0.008		-0.007
Output response	r_y	normal	0.125	0.069		0.048		0.000		0.093
Diff. output response	$r_{\Delta\pi}$	normal	0.0625	0.115		0.085		0.122		0.131
Log marginal likelihood			-1927.84		-1950.93		-1946.60		-1947.11	

*Note: The beta distribution with standard error 0.100 is used for the ρ_{λ^d} -parameter.