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PRICE SETTING IN GENERAL EQUILIBRIUM: ALTERNATIVE SPECIFICATIONS

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Abstract

This paper compares a number of alternative specifications for price setting in the context of the Smets-Wouters (2003) Dynamic Stochastic General Equilibrium (DSGE) model. We first show that an empirically plausible alternative interpretation of the estimated price mark-up shocks is that they represent relative price (e.g. productivity) shocks in a flexible price sector. We then compare the Calvo model with a standard Taylor contracting model and show that by allowing for sector-specific capital the Taylor contracting model with a relatively short contract length of three quarters is performing as well as the Calvo model.

Key words: sticky prices, DSGE models; business cycle fluctuations

JEL-classification: E1-E3

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1. Introduction

Following the theoretical work of Yun (1996) and Woodford (2003) and the empirical work of Gali and Gertler (1999) and Sbordone (1999), the New-Keynesian Phillips curve has become very popular in monetary policy analysis. In previous work (Smets and Wouters, 2003, 2004a,b), we estimated a Dynamic Stochastic General Equilibrium model (using euro area and US data) that embedded a hybrid version of the New-Keynesian Phillips curve. Overall, the estimated parameters, and in particular the degree of indexation and the elasticity of inflation with respect to its main driver, the real marginal cost, were very similar to those estimated by Gali and Gertler (1999) and Gali, Gertler and Lopez-Salido (2001) using a very different methodology. However, these estimates lead to two surprising and somewhat implausible findings regarding the price setting mechanism and the sources of inflation movements. First, in both economies, the estimated degree of nominal price stickiness was very large and corresponded to an average duration of prices not being re-optimised for more than 2 years. Clearly, this is not in line with existing micro evidence that suggests that prices are sticky for around 6 months on average.[1,2] Second, in both countries so-called price mark-up shocks turned out to be the most important source of variability in inflation in the short and medium term. This is of relevance for two reasons. First, the interpretation of those mark-up shocks is not very clear. In Smets and Wouters (2003), they are modelled as stochastic variation in the elasticity of substitution between differentiated goods. Those shocks could also stand in for stochastic variations in tax rates on profits, but it is implausible that changes in tax rates can explain the high frequency movements of the estimated shocks. Second, these shocks create a potential trade-off for monetary policy makers between stabilising inflation versus stabilising output. For both reasons, it is important to investigate the deeper sources of such estimated shocks.

In this paper, we investigate those two issues in more detail. First, we propose an alternative interpretation of the estimated mark-up shocks as shocks affecting the relative price of a flexible-price goods sector. In particular, we show that such a two-sector model can deliver a similar empirical performance in terms of explaining the main macro-economic data. Also, the impulse responses to the various shocks are very similar. However, the implications for monetary policy are quite different. As discussed in Aoki (2001), from a welfare point of view, the central bank should focus on stabilising sticky prices and allow the flexible prices to adjust freely. In contrast, when those shocks are interpreted as mark-up shocks, it may not be advisable for the policy maker to fully stabilise prices in the sticky-price goods sector, as this will create inefficient variations in the level of output.

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[1] See the evidence in Bils and Klenow (2002) for the US and various papers produced in the context of the Eurosystem's Inflation Persistence Network for euro area countries (e.g. Aucremanne and Dhyne (2004), Neves et al. (2004)).

[2] However, one should be careful with using the micro-evidence to interpret the macro estimates. Because of indexation and a positive steady state inflation rate, all prices change all the time. However, only a small fraction of prices are set optimally. The alternative story for introducing a lagged inflation term in the Phillips curve based on the presence of rule-of-thumb price setters is more appealing from this perspective, as it does not imply that all prices change all the time. In that case, the comparison of the Calvo parameter with the micro evidence makes more sense. As the reduced form representations are almost identical, one could still argue that the estimated Calvo parameter is implausibly high.

Second, we compare the Calvo specification with a standard Taylor contracting specification (Taylor, 1980). While analytically very tractable, the Calvo model has a number of implications that are less attractive. In particular, it implies that at any time there are some firms that have not adjusted their price optimally for a very long time. We analyse the differences in the impulse responses between the two price setting schemes. When making this comparison, we maintain the assumption that firms are price-takers in the factor markets, i.e. the labour and capital market, and hence all firms face the same flat marginal cost curve. Not surprisingly, we find that the Taylor contract needs to be quite long in order to match some of the data. However, even in that case, there is a cost in terms of empirical performance compared to the Calvo scheme.

Finally, we then examine whether introducing cohort-specific capital can rescue the Taylor model. As argued in Coenen and Levin (2004) for the Taylor model and Woodford (2003), Sveen and Weinke (2004a,b), Eichenbaum and Fischer (2004) and Altig et al (2004) for the Calvo model, firm-specific capital will lower the elasticity of prices with respect to the real marginal cost for a given degree of price stickiness. We re-estimate the Taylor contracting models with firm-specific capital and analyse the impact on the empirical performance of Taylor contracts and on the optimal contract length. Introducing firm-specific capital does lead to a fall in the estimated Taylor contract length to a more reasonable 3-4 quarters. It also improves the empirical fit of the Taylor model making it comparable with the estimated Calvo model. However, the estimated elasticity of substitution between the goods in the various sectors is implausibly high, a result also highlighted by Coenen and Levin (2004).

The rest of the paper is structured as follows. First, we briefly review the estimated DSGE model of Smets and Wouters (2004b) with a special focus on the estimated degree of price stickiness and the sources of inflation variation. We then present the alternative model with a flexible price sector in Section 3. Section 4 compares the Calvo model with the standard Taylor-contracting model. Section 5 shows the impact of introducing firm-specific capital. The concluding remarks are in Section 6.

2. Calvo price-setting in a linearised DSGE model

In this Section, we briefly describe the DSGE model that we estimate using euro area data. For a discussion of the micro-foundations of the model we refer to Smets and Wouters (2004b). Next, we review the main estimation results with regard to price setting and the sources of inflation variability.

2.1 The DSGE model

The DSGE model contains many frictions that affect both nominal and real decisions of households and firms. The model is based on Smets and Wouters (2004a). Households maximise a non-separable utility function with two arguments (goods and labour effort) over an infinite life horizon. Consumption appears in the utility function relative to a time-varying external habit variable. Labour is differentiated, so that there is some monopoly power over wages, which results in an explicit wage equation and allows for the introduction of sticky nominal wages à la Calvo (1983). Households rent capital services to firms and decide how much capital to accumulate taking into account capital adjustment costs.[3]

The main focus of this paper is on the firms' price setting. A continuum of firms produce differentiated goods, decide on labour and capital inputs, and set prices. Following Calvo (1983), every period only a fraction ξ_p of firms in the monopolistic competitive sector are allowed to re-optimise their price. This fraction is constant over time. Moreover, those firms that are not allowed to re-optimise, partially index their prices to the past inflation rate and the time-varying inflation target of the central bank. An additional important assumption is that all firms are price takers in the factor markets for labour and capital and thus face the same marginal cost. The marginal costs depend on wages, the rental rate of capital and productivity.

As shown in Smets and Wouters (2004a), this leads to the following linearised *inflation equation*:

(1)
$$\pi_t - \bar{\pi}_t = \frac{\beta}{1+\beta\gamma_p}(E_t\pi_{t+1} - \bar{\pi}_t) + \frac{\gamma_p}{1+\beta\gamma_p}(\pi_{t-1} - \bar{\pi}_t) + \frac{1}{1+\beta\gamma_p}\frac{(1-\beta\xi_p)(1-\xi_p)}{\xi_p}\left[\alpha\hat{r}_t^k + (1-\alpha)\hat{w}_t - \hat{\varepsilon}_t^a - (1-\alpha)\gamma t\right] + \eta_t^p$$

The deviation of inflation π_t from the target inflation rate $\bar{\pi}_t$ depends on past and expected future inflation deviations and on the current marginal cost, which itself is a function of the rental rate on capital $\hat{r}_t^k$, the real wage $\hat{w}_t$ and the productivity process, that is composed of a deterministic trend in labour efficiency $\gamma\tau$ and a stochastic component ε_t^a, which is assumed to follow a first-order autoregressive process: $\varepsilon_t^a = \rho_a\varepsilon_{t-1}^a + \eta_t^a$ where η_t^a is an IID-Normal productivity shock. Finally, η_t^p is an IID-Normal price mark-up shock.

When the degree of indexation to past inflation is zero ($\gamma_p = 0$), this equation reverts to the standard purely forward-looking New Keynesian Phillips curve. By assuming that all prices are indexed to the inflation objective in that case, this Phillips curve will be vertical in the long run. Announcements of changes in the inflation objective will be largely neutral even in the short run. This is based on the strong assumption that indexation habits will adjust immediately to the new inflation objective. With $\gamma_p > 0$, the degree of indexation to lagged inflation determines how backward looking the inflation process is or, in other words, how much structural persistence there is in the inflation process. The elasticity of inflation with respect to changes in the marginal cost depends mainly on the degree of price stickiness. When all prices are flexible ($\xi_p = 0$) and the price-mark-up shock is zero, this equation reduces to the normal condition that in a flexible price economy the real marginal cost should equal one.

[3] In the version of the model estimated in this paper, we have not introduced variable capacity utilisation for two reasons. First, as shown in Smets and Wouters (2004a), empirically this friction is not very important once one allows for the other frictions that smooth marginal costs such as nominal wage rigidities. Second, as discussed in section 5, allowing for a relatively insensitive marginal cost of changing the utilisation of capital substantially reduces the impact of introducing cohort-specific capital.

The rest of the linearised DSGE model is summarised in the appendix. In sum, the model determines nine endogenous variables: inflation, the real wage, capital, the value of capital, investment, consumption, the short-term nominal interest rate, the rental rate on capital and hours worked. The stochastic behaviour of the system of linear rational expectations equations is driven by ten exogenous shock variables. Five shocks arise from technology and preference parameters: the total factor productivity shock, the investment-specific technology shock, the preference shock, the labour supply shock and the government spending shock. Those shocks are assumed to follow an autoregressive process of order one. Three shocks can be interpreted as "cost-push" shocks: the price mark-up shock, the wage mark-up shock and the equity premium shock. Those are assumed to follow a white-noise process. And, finally, there are two monetary policy shocks: a permanent inflation target shock and a temporary interest rate shock.

2.2 Findings in the baseline model

The linearised DSGE model is estimated for the euro area using seven key macro-economic time series: output, consumption, investment, hours worked, real wages, prices and a short-term interest rate. The full information Bayesian estimation methodology is extensively discussed in Smets and Wouters (2003). Table 1 reports the estimates of the main parameters governing the hybrid New Keynesian Phillips curve and compares these estimates with those obtained by Gali, Gertler and Lopez-Salido (2001) which use single-equation GMM methods to estimate a similar equation on the same euro area data set.

Insert Table 1

Comparison of estimated Phillips-curve parameters with Gali, Gertler and Lopez-Salido (GGL,2001)

A number of observations are worth mentioning. First, the degree of indexation is rather limited. The parameter γ_p equals 0.30, which implies a coefficient on the lagged inflation rate of 0.23. As shown in Table 2, putting the degree of indexation equal to zero actually improves the log data density of the model by about five. Second, the degree of Calvo price stickiness is very large: each period 89 percent of the firms do not re-optimise their price setting.[4] The average duration of non re-optimisation is therefore more than 2 years. This is implausibly high. Moreover, reducing the degree of Calvo price stickiness to more reasonable numbers such as 75 percent or a duration of about 4 quarters reduces the log data density of the estimated model drastically (by about 100 as shown in Table 2). Similar to the findings in Smets and Wouters (2004a), the degree of price stickiness is one of the most costly frictions to remove in terms of the empirical fit of the DSGE model. Overall, those results are very similar to the ones reported by GGL (2001). Our estimates generally fall in the range of estimates reported by GGL (2001), if they assume constant returns to scale as we do in our model (Table 1).

Insert Table 2

[4] This is true in spite of the fact that the prior distribution is concentrated quite narrowly around the mean of 0.75.

Log data density and selected parameter estimates

Third, the standard deviation of the price mark-up shocks is relatively high. A variance decomposition of inflation as shown in Graph 1 indicates that more than 50 percent of inflation variability in the first quarter can be accounted for by the price mark-up shocks. The more fundamental shocks, such as various productivity and preference shocks, only play a limited role in explaining forecast errors in inflation. One exception is the investment shock, which accounts for about 20% of the inflation forecast error variance at horizons between 1 and 3 years. The limited role played by productivity and preference shocks may be due to the fact the monetary authorities are quite successful in stabilising inflation in response to those shocks. Indeed, those fundamental shocks should not create a trade-off between the stabilisation of inflation and the output gap. In the medium to longer run, the time-varying inflation target becomes the most important driver of inflation.

Insert Graph 1

Forecast error variance decomposition of inflation (baseline)

Finally, when we allow for a persistent price mark-up shock, the estimated degree of price stickiness drops to 0.73 (see last column of Table 2). Moreover, this model does almost as well as the baseline model in terms of the log data density, suggesting that using aggregate macro-economic variables it is difficult to determine empirically whether the inflation persistence is structural (i.e. part and parcel of the price setting mechanism) or the result of persistent shocks. Graph 2 shows that allowing for such a persistent price shock increases the contribution of the productivity and preference shocks to the forecast variance of inflation at the short to medium term horizon (at the cost of the inflation target shock). With more flexible price setting, the immediate impact of such shocks on inflation becomes larger. This is also clear from the impulse responses depicted in Graph 3. Inflation responds more quickly to a monetary policy shock, but it is less persistent, when allowing for persistence in the price mark-up shock. In contrast, the effect on output and the real wage is much less in the former case.

Insert Graph 2

Forecast error variance decomposition of inflation (with a persistent price shock)

Insert Graph 3

Selected impulse response functions to a monetary policy shock

3. An alternative interpretation of the price mark-up shocks

As discussed in the introduction, the importance of price mark-up shocks for inflation movements in the short to medium run suggests it is worthwhile to further examine the source of those shocks. While a change in market power definitely is a possible source of fluctuations, one would not expect such changes to be of the very volatile and temporary nature that is apparent from the estimated price mark-up shocks. An alternative interpretation is that those shocks represent changes in the tax rate on profits. Also this interpretation is, however, not appealing in light of the volatile nature of the estimated shocks. In this section, we propose an alternative interpretation based on the presence of a flexible price goods sector. The shocks may represent shocks to the relative price of such goods. Indeed, when examining the empirically estimated price mark-up shocks, we found that the mark-up shocks are correlated with innovations in oil prices and other imported goods prices. As shown in a number of micro studies, the frequency of changes in the prices of such goods is much higher than that of other consumption goods. In this section, we will model the source of the relative price changes as due to relative productivity shocks.

Define final good production as the composite of two composite goods. Both composite goods are produced in a monopolistically competitive goods sector with a continuum of firms. However, in the first sector prices are sticky as in the baseline model, whereas in the second sector prices are perfectly flexible. The production of the final good (Y_t) is given by

(1) $$Y_t = \left[\mu\left(Y_t^{s}\right)^{1/1+\rho} + (1-\mu)(Y_t^{f})^{1/1+\rho}\right]^{1+\rho},$$

where μ is the share of sticky-price goods in the total basket and the elasticity of substitution between the sticky price and flexible price goods is given by $\frac{1+\rho}{\rho}$. As the parameter ρ is not well identified using only the seven aggregate observable data series, we will assume throughout most the analysis that the elasticity is one.

Perfect competition in the final goods sector implies that the demand for sticky and flexible price goods is given by:

(2) $$Y_t^{s} = \left(\mu\frac{P_t}{P_t^{s}}\right)^{\frac{1+\rho}{\rho}} Y_t \quad and \quad Y_t^{f} = \left((1-\mu)\frac{P_t}{P_t^{f}}\right)^{\frac{1+\rho}{\rho}} Y_t$$

The final good price index is

(3) $$P_t = \left[\mu^{\frac{1+\rho}{\rho}}\left(P_t^{s}\right)^{-1/\rho} + (1-\mu)^{\frac{1+\rho}{\rho}}\left(P_t^{f}\right)^{-1/\rho}\right]^{-\rho}$$

Production takes an identical form in both sectors (i.e. a Cobb-Douglas production function with fixed costs). Also the elasticity of substitution between the varieties within each group is the same. The only feature that differs is price setting. The sticky price goods sector is modelled as before (see Smets and Wouters, 2004a). In the flexible price sector, prices are set as a constant mark-up over the marginal cost.

In anticipation of the discussion in section 5, we allow for two assumptions regarding the mobility of capital across the two sectors. In one case, capital is freely mobile across the two sectors, so that the marginal cost is identical in both sectors. In the other case, capital is sector-specific, which implies a sector-specific rental rate of capital and marginal cost. In both cases, labour is assumed to be perfectly mobile across the two sectors.

Table 3 reports the most important estimation results of the various models. As mentioned before, the elasticity of substitution is calibrated to be equal to one. The prior mean of the parameter capturing the share of flexible price goods sector was 15%, which corresponds to the findings in some of the micro studies referred to in the introduction.

Insert Table 3

Selected parameter estimates: adding a flexible price sector

A number of observations can be made. First, as indicated by the log data density the alternative model generally speaking does as well as the baseline model. The specification with capital mobility across the two sectors does better than the one without capital mobility. Second, the size of the flexible price sector is estimated to be smaller than a priori assumed. In general, there will be a trade-off between this parameter and the variability of the productivity shocks in the flexible price sector. A bigger flexible-price sector will reduce the estimated variability of the flexible price productivity shock. However, a bigger flexible-price sector will also speed up the general price effects of the aggregate shocks, which may be counterfactual. In part this effect is compensated by a larger estimated degree of inflation indexation, which rises from 0.29 to the range of 0.40 to 0.46. Third, overall the effect of introducing the flexible price sector on the other parameters is small. For example, the estimated degree of price stickiness is about the same. As shown in Graph 4 also the variance decomposition of inflation is very similar. Graph 5 compares the impulse responses of various selected shocks under the various model specifications. Focusing on the effects of a monetary policy shock, it is interesting to note that, as expected, the output effect is smaller in absolute value when a part of aggregate output is produced at flexible prices. The inflation effects are more similar. Overall, the results in this section suggest that interpreting the price mark-up shocks in Smets and Wouters (2003) as relative price shocks to a flexible price sector is a reasonable interpretation.

Insert Graph 4

Variance decomposition of inflation: adding a flexible price sector

Insert Graph 5

Selected impulse responses: adding a flexible price sector

4. Comparing Calvo and Taylor contracts

One unattractive feature of the Calvo price setting model is that some firms do not re-optimise their prices for a very long time.[5] As indicated by Wolman (2001), this not only introduces an implausibly large persistence in the price level following shocks, but it also has important welfare implications as the resulting misalignments due to relative price distortions may be very large. The standard Taylor contracting model avoids this problem.[6] In this model firms set prices for a fixed number of periods and price setting is staggered over the duration of the contract, i.e. the number of firms adjusting their price is the same every period.[7] In order to be able to compare this price-setting model with the Calvo model discussed above, we also maintain the assumption of partial indexation to lagged inflation and the inflation objective. In the baseline Taylor contracting model discussed in this section we also assume that all sectors face identical marginal costs.

As discussed in Whelan (2004) and Coenen and Levin (2004), the staggered Taylor contracting model gives rise to the following linearised equations for the newly set optimal price $\hat{P}_t^*$ and the general price index $\hat{P}_t$:

(4) $$\hat{P}_t^* = \frac{1}{\sum_{i=0}^{n}\beta^i}\left[\left(\sum_{i=0}^{n-1}\hat{m}c_{t+i} + \hat{P}_{t+i}\right) - \gamma_p \sum_{i=0}^{n-2}\hat{\pi}_{t+i}\left(\sum_{j=1}^{n-i}\beta^j\right)\right] + d\eta_p$$

(5) $$\hat{P}_t = \frac{1}{n}\cdot\left[\left(\sum_{i=0}^{n-1}\hat{P}_{t-1}^*\right) + \gamma_p \sum_{i=1}^{n}\left(\sum_{j=1}^{n-i}\hat{\pi}_{t-j}\right)\right] + (1-d)\eta_p$$

where $m\hat{c}_t$ is the marginal cost, β is the discount factor, γ_p is the degree of indexation to the lagged inflation rate, n is the duration of the contract, d is a binary parameter $d \in \{0,1\}$ and $\eta_p = \rho_p \eta_{t-1} + \varepsilon_p$, with ε_p an i.i.d. shock. We experiment with two ways of introducing the price mark-up shocks in the Taylor contracting model. The first method (d = 1), is fully analogous with the Calvo model. We assume a time-varying mark-up in the optimal price setting equation, which introduces a shock in the linearised price setting equation (4) as shown above. The second method (d = 0) is somewhat more ad hoc. It consists of introducing a shock in the aggregate price equation (5). As discussed above, this could be justified as a relative price shock to a flexible-price sector that is not explicitly modelled. Of course, such a shortcut ignores the general equilibrium implications (e.g. in terms of labour and capital reallocations). The big difference between the two shocks is their persistence. While the effects of the first type of shock disappear after the length of the contract, the second shock has a more persistent effect.

Insert Graph 6

Selected impulse responses: comparing Calvo with Taylor contracts

5 See, however, Levy et al. (2003) for an exception. The 5-nickel price of a bottle of coca cola has been fixed for a period of almost 80 years.

6 Another alternative is the truncated Calvo model as analysed in Bakhshi et al (2003).

7 See Coenen and Levin (2004) for a generalisation of the standard Taylor contracting model where different firms may set prices for different lengths of time.

Graph 6 compares the impulse responses to respectively a productivity and monetary policy shock in the Calvo and 4, 8 and 10 quarter Taylor-contracting model using the estimated parameters of the baseline model. In other words, in this case the parameters have not been re-estimated. Generally speaking, two main observations can be made. First , typically the inflation response in the Taylor contracting models is larger in size, but less persistent. The peak effect on inflation increases with the length of the contract. This is the case in spite of the fact that prices are partially indexed to past inflation. Conversely, the output and real wage responses are closer to the flexible price outcome under Taylor contracting. For example, in response to a monetary policy shock the response of output is considerably smaller in absolute value under Taylor contracting. Second, as the duration of the Taylor contract lengthens, the impulse responses appear to approach the outcome under the Calvo model. However, one needs a very long duration (more than 10 quarters) in order to come close to the Calvo model. Even in that case, the inflation response changes sign quite abruptly after the length of the contract. This feature is absent in the Calvo specification. As discussed in Whelan (2004), in reduced-form inflation equations the reversal of the inflation response after the contract length is captured by a negative coefficient on lagged inflation once current and expected future marginal costs are taken into account.

Insert Graph 7

Impulse responses to a price shock: comparing alternative specifications

Graph 7 shows the impact of the two different ways of introducing the price mark-up shock. The right-hand column shows that introducing a persistent shock in the GDP deflator equation allows the model to mimic most closely the response to a mark-up shock in the Calvo specification. The latter finding explains why this specification does best in terms of the log data density (Table 4). Comparing across the various contract lengths (4, 8 and 10 quarters), it appears that the 8-quarter contract specification performs best (Table 4). Even in that case, however, the log data density is considerably lower than that of the Calvo model (the log difference is about 13). While many of the other parameters are estimated to be very similar, it is noteworthy that the estimated degree of indexation rises quite significantly to 0.74 (from 0.30 in the baseline). Possibly, this reflects the need to overcome the negative dependence on past inflation in the standard Taylor contract. The impact of re-estimating the parameters on the impulse responses is quite limited. The variance decomposition in Graph 8 shows that as the contract length increases the influence of the price mark-up shock increases, while the effect of the fundamental shocks is reduced.

Insert Table 4

Selected parameter estimates: Calvo versus Taylor contracts

Insert Graph 8

Variance decomposition of inflation: Taylor contracts

5. Introducing firm-specific capital

As shown in Coenen and Levin (2004) for the Taylor model and Woodford (2003), Weinke and Sveen (2004a,b), Eichenbaum and Fischer (2004) and Altig et al (2004) for the Calvo model, the introduction of firm-specific capital, everything else equal, reduces the sensitivity of inflation with respect to its driving variables. The extent of this effect will depend on the elasticity of the individual firms' marginal cost with respect to changes in the demand for its products and the elasticity of substitution between the goods produced by the firm and those produced by its competitors.

In order to illustrate this mechanism, Graph 9 compares the impulse responses for selected shocks across an 8-quarter Taylor contractng model with and without mobile capital and with two different elasticities of substitution between the differentiated goods. In one case the elasticity of substitution is high at about 20 implying that small changes in the firm's price will have large effects on the relative demand for its products. In the other case, the elasticity of substitution is relatively low at about 3. The other parameters are identical and correspond to those estimated for the baseline Calvo model.

The effects on the inflation response to the various shocks are clear. The firm-specificity of capital reduces the impact effect of shocks (e.g. a monetary policy shock) on inflation and increases the persistence of the inflation response, the more so, the higher the elasticity of substitution. However, the shape of the impulse responses of inflation remains very similar. In particular, the inflation response builds up during the length of the contract, but reverses quite abruptly after that.[8]

As indicated by Gali and Gertler (1999) and Eichenbaum and Fisher (2003), allowing for firm-specific capital in the Calvo model will reduce the estimated degree of nominal price stickiness for a given estimated sensitivity of inflation to its driving factors. Both Gali and Gertler (1999) and Eichenbaum and Fisher (2003) show that introducing this feature does indeed reduce the estimated degree of nominal price stickiness in US data. In particular, it reduces the implied duration of nominal contracts from an implausibly high number of more than 2 years to a duration of typically less than a year. Next, we test whether similar results are obtained in the context of Taylor contracts.

Table 5 shows the results of re-estimating the Taylor contracting models without capital mobility. Compared to the case with mobile capital, we also estimate the elasticity of substitution between the goods of the various cohorts. A number of findings are worth noting. First, introducing cohort-specific

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[8] Please note that in this paper, we have closed down the variable capacity utilisation effect. If firms were allowed to vary the utilisation of capital at a constant marginal cost, the effect of allowing for immobile capital would again be very much reduced.

capital does indeed reduce the contract length that fits the data best. Graph 10 illustrates this point by showing the log data densities for contract lengths going from one to ten quarters for both cases. While the log data density is maximised at a contract length of 8 quarters in the case of mobile capital, it is maximised at only three quarters when capital can not move across sectors. Moreover, it turns out that the three and four quarter Taylor contracting model with sector-specific capital performs as well as the baseline Calvo model. This confirms the findings of Gali and Gertler (1999) and Eichenbaum and Fischer (2003). Second, allowing for sector-specific capital leads to a drop in the estimated degree of inflation indexation in the goods sector. As shown in Table 5, in this case the γ_p parameter drops back to the low level found for the Calvo model. Also the estimated degree of nominal wage stickiness falls somewhat. This confirms that allowing for sector-specific capital introduces some endogenous persistence in the model as was illustrated above in Graph 9. Finally, as discussed in Coenen and Levin (2004), one needs a very high elasticity of substitution to match the Calvo model in terms of empirical performance. As shown in Table 5, the estimated λ_p parameter is 0.003, which implies a very high elasticity of substitution of about 334.

6. Conclusions

In this paper, we have examined two counter-intuitive findings regarding price setting behaviour and the sources of inflation variability that we encountered in previous work which estimated a sticky-price DSGE model on euro area and US data. First, in the previous work we found that price mark-up shocks were the dominant source of inflation variability in the short term. These shocks are difficult to interpret. In this paper, we have shown that those shocks can also be interpreted as relative productivity (or demand) shocks to a flexible-price sector. This finding is of importance because the policy implications of the two types of shocks are quite different. In future work, we plan to further investigate the relative importance of those shocks by adding additional information about relative price movements between the flexible price and sticky price goods sectors in the estimation process.

A second, counterintuitive finding in our previous work was that the average duration of price contracts in the goods market was longer than 2 years. We hypothesised that this finding was the result of assuming identical marginal costs across differentiated firms. In this paper we compare the Calvo model with a staggered Taylor contracting model and show that the estimated length of the Taylor contract can be reduced to more plausible numbers of 3 to 4 quarters, if one introduces firm-specific capital and a high elasticity of substitution between the sectors. In further work we plan to broaden the set of possible price setting mechanisms in our analysis in order to further improve the empirical fit of the model.

Data appendix

All data are taken from the AWM database from the ECB (see Fagan et al., 2000). Investment includes both private and public investment expenditures. Real variables are deflated with their own deflator. Inflation is calculated as the first difference of the log GDP deflator. In the absence of data on hours worked, we use total employment data for the euro area. As explained in Smets and Wouters (2003), we therefore use for the euro area model an auxiliary observation equation linking labour services in the model and observed employment based on a Calvo mechanism for the hiring decision of firms. The series are updated for the most recent period using growth rates for the corresponding series published in the Monthly Bulletin of the ECB. Consumption, investment, GDP, wages and hours/employment are expressed in 100 times the log. The interest rate and inflation rate are expressed on a quarterly basis corresponding with their appearance in the model (in the graphs the series are translated on an annual basis).

Model appendix

This appendix describes the other linearised equations of the Smets-Wouters model.

Indexation of nominal wages results in the following real wage equation:

(A1)

$$\begin{aligned}\hat{w}_t = {} & \frac{\beta}{1+\beta}E_t\hat{w}_{t+1} + \frac{1}{1+\beta}\hat{w}_{t-1} + \frac{\beta}{1+\beta}(E_t\hat{\pi}_{t+1} - \bar{\pi}_t) - \frac{1+\beta\gamma_w}{1+\beta}(\hat{\pi}_t - \bar{\pi}_t) + \frac{\gamma_w}{1+\beta}(\hat{\pi}_{t-1} - \bar{\pi}_t) \\ & - \frac{1}{1+\beta}\frac{(1-\beta\xi_w)(1-\xi_w)}{(1+\frac{(1+\lambda_w)\sigma_L}{\lambda_w})\xi_w}\left[\hat{w}_t - \sigma_L\hat{L}_t - \frac{1}{1-h}(\hat{C}_t - h\hat{C}_{t-1}) + \hat{\varepsilon}_t^L\right] + \eta_t^w\end{aligned}$$

The real wage $\hat{w}_t$ is a function of expected and past real wages and the expected, current and past inflation rate where the relative weight depends on the degree of indexation γ_w to lagged inflation of the non-optimised wages. When $\gamma_w = 0$, real wages do not depend on the lagged inflation rate. There is a negative effect of the deviation of the actual real wage from the wage that would prevail in a flexible labour market. The size of this effect will be greater, the smaller the degree of wage stickiness (ξ_w), the lower the demand elasticity for labour (higher mark-up λ_w) and the lower the inverse elasticity of labour supply (σ_l) or the flatter the labour supply curve. ε_t^L is a preference shock representing a shock to the labour supply and is assumed to follow a first-order autoregressive process with an IID-Normal error term: $\varepsilon_t^L = \rho_L\varepsilon_{t-1}^L + \eta_t^L$. In contrast, η_t^w is assumed to be an IID-Normal wage mark-up shock.

The dynamics of aggregate *consumption* is given by:

(A2)

$$\begin{aligned}\hat{C}_t = {} & \frac{h}{1+h}\hat{C}_{t-1} + \frac{1}{1+h}E_t\hat{C}_{t+1} + \frac{(\sigma_c - 1)}{\sigma_c(1+\lambda_w)(1+h)}(\hat{l}_t - \hat{l}_{t+1}) \\ & - \frac{1-h}{(1+h)\sigma_c}(\hat{R}_t - E_t\hat{\pi}_{t+1}) + \frac{1-h}{(1+h)\sigma_c}\hat{\varepsilon}_t^b\end{aligned}$$

Consumption $\hat{C}_t$ depends on the ex-ante real interest rate $(\hat{R}_t - E_t\hat{\pi}_{t+1})$ and, with external habit formation, on a weighted average of past and expected future consumption. When $h = 0$, only the traditional forward-looking term is maintained. In addition, due to the non-separability of the utility function , consumption will also depend on expected employment growth $(\hat{l}_{t+1} - \hat{l}_t)$. When the elasticity of intertemporal substitution (for constant labour) is smaller than one $(\sigma_c > 1)$, consumption and labour supply are complements. Finally, $\hat{\varepsilon}_t^b$ represents a preference shock affecting the discount rate that determines the intertemporal substitution decisions of households. This shock is assumed to follow a first-order autoregressive process with an IID-Normal error term: $\varepsilon_t^b = \rho_b \varepsilon_{t-1}^b + \eta_t^b$.

The *investment equation* is given by:

(A3) $$\hat{I}_t = \frac{1}{1+\beta}\hat{I}_{t-1} + \frac{\beta}{1+\beta}E_t\hat{I}_{t+1} + \frac{1/\varphi}{1+\beta}\hat{Q}_t + \hat{\varepsilon}_t^I$$

where $\varphi = \overline{S}''$ depends on the adjustment cost function (S) and β is the discount factor applied by the households. As discussed in CEE (2001), modelling the capital adjustment costs as a function of the change in investment rather than its level introduces additional dynamics in the investment equation, which is useful in capturing the hump-shaped response of investment to various shocks including monetary policy shocks. A positive shock to the investment-specific technology, $\hat{\varepsilon}_t^I$, increases investment in the same way as an increase in the value of the existing capital stock $\hat{Q}_t$. This investment shock is also assumed to follow a first-order autoregressive process with an IID-Normal error term: $\varepsilon_t^I = \rho_I \varepsilon_{t-1}^I + \eta_t^I$

The corresponding *Q equation* is given by:

(A4) $$\hat{Q}_t = -(\hat{R}_t - \hat{\pi}_{t+1}) + \frac{1-\tau}{1-\tau+\overline{r}^k}E_t\,\hat{Q}_{t+1} + \frac{\overline{r}^k}{1-\tau+\overline{r}^k}E_t\,\hat{r}_{t+1}^k + \eta_t^Q$$

where τ stands for the depreciation rate and $\overline{r}^k$ for the rental rate of capital so that $\beta = 1/(1-\tau+\overline{r}^k)$. The current value of the capital stock depends negatively on the ex-ante real interest rate, and positively on its expected future value and the expected rental rate. The introduction of a shock to the required rate of return on equity investment, η_t^Q, is meant as a shortcut to capture changes in the cost of capital that may be due to stochastic variations in the external finance premium. We assume that this equity premium shock follows an IID-Normal process. In a fully-fledged model, the production of capital goods and the associated investment process could be modelled in a separate sector. In such a case, imperfect information between the capital producing borrowers and the financial intermediaries could give rise to a stochastic external finance premium. Here, we implicitly assume that the deviation between the two returns can be captured by a stochastic shock, whereas the steady-state distortion due to such informational frictions is zero.

The *capital accumulation equation* becomes a function not only of the flow of investment but also of the relative efficiency of these investment expenditures as captured by the investment-specific technology shock:

(A5) $$\hat{K}_t = (1-\tau)\hat{K}_{t-1} + \tau\hat{I}_{t-1} + \tau\,\hat{\varepsilon}_{t-1}^I$$

The equalisation of marginal cost implies that, for a given installed capital stock, *labour demand* depends negatively on the real wage (with a unit elasticity) and positively on the rental rate of capital:

(A6) $$\hat{L}_t = -\hat{w}_t + (1+\psi)\hat{r}_t^k + \hat{K}_{t-1}$$

where $\psi = \frac{\psi'(1)}{\psi''(1)}$ is the inverse of the elasticity of the capital utilisation cost function.

The *goods market equilibrium condition* can be written as:

(A7) $$\begin{aligned}\hat{Y}_t &= (1-\tau k_y - g_y)\hat{C}_t + \tau k_y \hat{I}_t + g_y \varepsilon_t^G \\ &= \phi\hat{\varepsilon}_t^a + \phi\alpha\hat{K}_{t-1} + \phi\alpha\psi\hat{r}_t^k + \phi(1-\alpha)(\hat{L}_t + \gamma t) - (\phi-1)\gamma t\end{aligned}$$

where k_y is the steady state capital-output ratio, g_y the steady-state government spending-output ratio and ϕ is one plus the share of the fixed cost in production. We assume that the government spending shock follows a first-order autoregressive process with an IID-Normal error term: $\varepsilon_t^G = \rho_G \varepsilon_{t-1}^G + \eta_t^G$.

Finally, the model is closed by adding the following empirical monetary policy reaction function:

(A8) $$\begin{aligned}\hat{R}_t &= \overline{\pi}_t + \rho(\hat{R}_{t-1} - \overline{\pi}_{t-1}) + (1-\rho)\{r_\pi(\hat{\pi}_{t-1} - \overline{\pi}_{t-1}) + r_Y(\hat{Y}_{t-1} - \hat{Y}_{t-1}^p)\} + \\ & r_{\Delta\pi}\left[(\hat{\pi}_t - \overline{\pi}_t) - (\hat{\pi}_{t-1} - \overline{\pi}_{t-1})\right] + r_{\Delta y}\left[(\hat{Y}_t - \hat{Y}_t^p) - (\hat{Y}_{t-1} - \hat{Y}_{t-1}^p)\right] + \eta_t^R\end{aligned}$$

The monetary authorities follow a generalised Taylor rule by gradually responding to deviations of lagged inflation from an inflation objective and the lagged output gap defined as the difference between actual and potential output. Consistently with the DSGE model, potential output is defined as the level of output that would prevail under flexible price and wages in the absence of the three "cost-push" shocks. The parameter ρ captures the degree of interest rate smoothing. In addition, there is also a short-run feedback from the current changes in inflation and the output gap. Finally, we assume that there are two monetary policy shocks: one is a temporary IID-Normal interest rate shock (η_t^R) also denoted a monetary policy shock; the other is a permanent shock to the inflation objective ($\overline{\pi}_t$) which is assumed to follow a non-stationary process ($\overline{\pi}_t = \overline{\pi}_{t-1} + \eta_t^\pi$). The dynamic specification of the reaction function is such that changes in the inflation objective are immediately and without cost reflected in actual inflation and the interest rate if there is no exogenous persistence in the inflation process.

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Table 1: Comparison of estimated Phillips-curve parameters with Gali, Gertler and Lopez-Salido (GGL, 2001)

	Smets-Wouters	GGL (2001) (1)	GGL (2001) (2)
Structural parameters			
ξ_p	0.89 (0.01)	0.90 (0.01)	0.92 (0.03)
γ_p	0.30 (0.08)	0.02 (0.12)	0.33 (0.12)
D	9.0	10.0	12.8
Reduced-form parameters			
γ_f	0.76	0.87 (0.04)	0.68 (0.04)
γ_b	0.23	0.02 (0.12)	0.27 (0.07)
λ	0.011	0.018 (0.012)	0.006 (0.007)

Notes: The GGL (2001) estimates are those obtained under the assumption of constant returns to labour under two alternative specifications. Strictly speaking, the structural parameters are not directly comparable as GGL use the inclusion of rule-of-thumb price setters (rather than indexation) as a way of introducing lagged inflation. γ_f is the implied reduced-form coefficient on expected future inflation; γ_b is the coefficient on lagged inflation and λ is the coefficient on the real marginal cost. D stands for duration in number of quarters.

Table 2: Testing the nominal rigidities using the marginal likelihood

	Baseline	$\xi_p = 0.75$	$\gamma_p = 0$	$\xi_p = 0.75$ and $\gamma_p = 0$	Adding persistent price shock
Log data density	-464.27	-539.28	-459.63	-532.37	-470.35
ρ_a	0.997	0.998	0.996	0.998	0.9961
	(0.002)	(0.000)	(0.003)	(0.000)	(0.004)
σ_a	0.675	0.609	0.641	0.567	0.625
	(0.084)	(0.064)	(0.075)	(0.056)	(0.067)
σ_p	0.194	0.407	0.234	0.2861	0.176
	(0.016)	(0..027)	(0.019)	(0.030)	(0.021)
ξ_w	0.711	0.732	0.719	0.545	0.736
	(0.044)	(0.054)	(0.045)	(0.050)	(0.040)
ξ_p	0.890	0.75	0.877	0.75	0.732
	(0.010)	-	(0.010)	-	(0.038)
γ_w	0.562	0.214	0.548	0.723	0.537
	(0.155)	(0.087)	(0.159)	(0.186)	(0.145)
γ_p	0.301	0.984	0.000	0.000	0.320
	(0.079)	(0.017)	-	-	(0.128)
σ_{pp}	-	-	-	-	0.065
					(0.011)
ρ_p	-	-	-	-	0.884
					(0.043)

Notes: ρ_a : persistency parameter of the productivity shock; σ_a : standard error of the productivity shock; σ_p : standard error of the price mark-up shock; ξ_w : Calvo wage stickiness parameter; ξ_p : Calvo price stickiness parameter; γ_w : wage indexation parameter; γ_p : price indexation parameter; σ_{pp} : standard error of the persistent price mark-up shock; ρ_p : persistency parameter of the persistent price mark-up shock..

Table 3: Selected parameter estimates: adding a flexible price sector

	Baseline	Two-sector model with mobile capital	Two-sector model without mobile capital
Log Data Density	-464.27	-463.39	-467.80
ξ_p	0.89	0.89	0.88
	(0.01)	(0.01)	(0.01)
γ_p	0.30	0.46	0.40
	(0.08)	(0.12)	(0.10)
σ_a	0.67	0.64	0.64
	(0.08)	(0.07)	(0.08)
ρ_a	0.99	0.98	0.98
	(0.00)	(0.00)	(0.00)
σ_p	0.19	-	-
	(0.01)		
σ_{af}	-	3.69	2.99
		(1.63)	(1.26)
ρ_{af}	-	1.00	1.00
		-	-
μ	-	0.94	0.94
		(0.02)	(0.02)

Notes: The elasticity of substitution between the two sectors is assumed to be one (Cobb-Douglas). ρ_a : persistency parameter of the productivity shock; σ_a : standard error of the productivity shock; σ_p : standard error of the price mark-up shock; ξ_p : Calvo price stickiness parameter; γ_p : price indexation parameter; σ_{af} : standard error of the flexible-price sector productivity shock which is modelled as a permanent shock (ρ_{af} =1), μ : share of the sticky price sector in the economy.

Table 4: Comparing the Calvo model with Taylor contracting models

	Calvo	4-quarter Taylor	8-quarter Taylor	10-quarter Taylor
	i.i.d. price shock in the optimal price setting equation			
Log data density	-464.27	-654.59	-609.29	-652.10
	Persistent price shock in the optimal price setting equation			
Log data density	-464.27	-631.29	-595.36	-612.74
	i.i.d. price shock in the GDP price equation			
Log data density	-464.27	-642.21	-573.64	-571.51
	Persistent price shock in the GDP price equation			
Log data density	-464.27	-484.079	-477.539	-479.42
ρ_a	0.997	0.983	0.999	0.999
	(0.002)	(0.006)	(0.000)	(0.000)
σ_a	0.675	0.680	0.705	0.692
	(0.084)	(0.079)	(0.085)	(0.085)
σ_p	0.194	-	-	-
	(0.016)			
ξ_w	0.711	0.743	0.752	0.738
	(0.044)	(0.040)	(0.045)	(0.046)
ξ_p	0.890	-	-	-
	(0.010)			
γ_w	0.562	0.449	0.456	0.454
	(0.155)	(0.118)	(0.129)	(0.136)
γ_p	0..301	0.819	0.743	0.778
	(0.079)	(0.145)	(0.167)	(0.131)
σ_{pp}	-	0.393	0.329	0.339
		(0.030)	(0.030)	(0.029)
ρ_p	-	0.997	0.934	0.932
		(0.003)	(0.014)	(0.016)
trend	0.220	0.433	0.233	0.237
	(0.028)	(0.044)	(0.027)	(0.028)

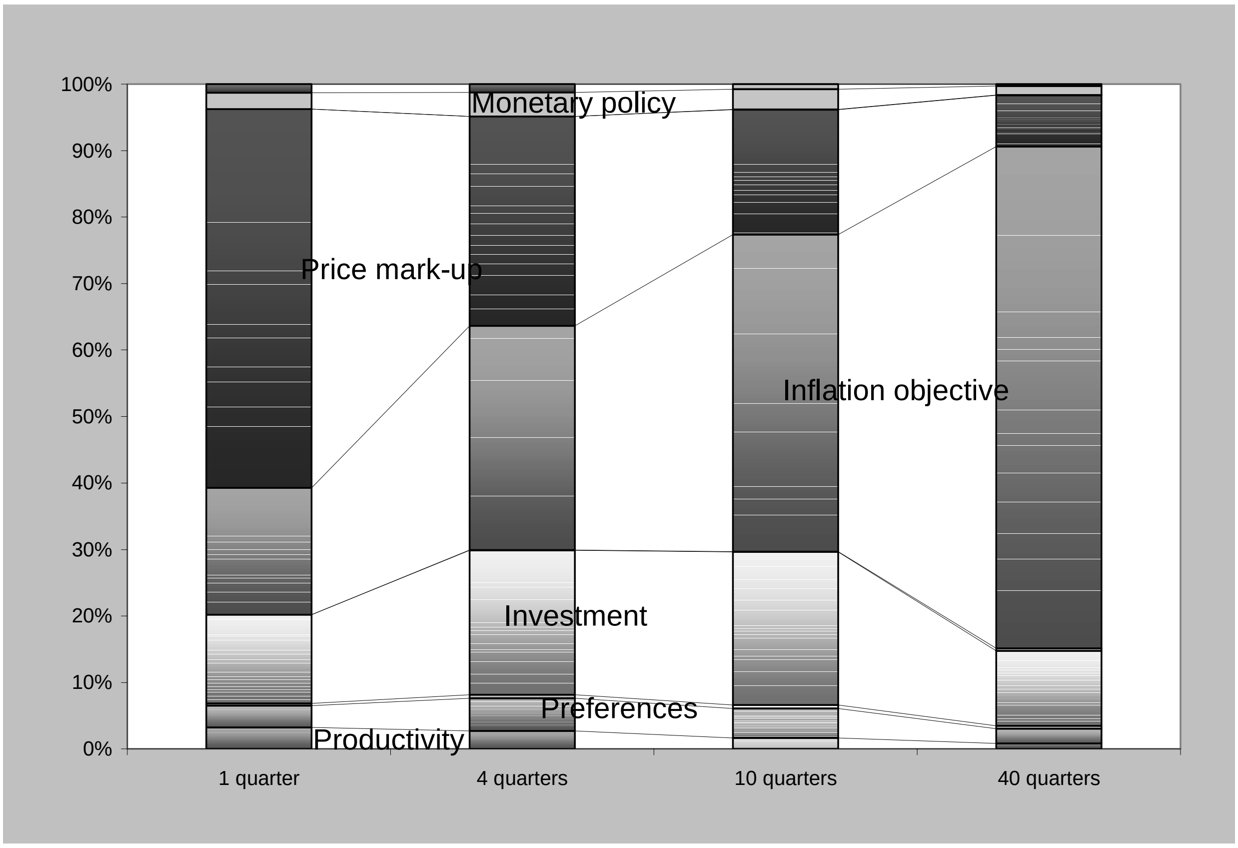
Notes: ρ_a : persistency parameter of the productivity shock, σ_a : standard error of the productivity shock, σ_p : standard error of the price mark-up shock; ξ_w : Calvo wage stickiness parameter; ξ_p : Calvo price stickiness parameter; γ_w : wage indexation parameter; γ_p : price indexation parameter; σ_{pp} : standard error of the persistent price mark-up shock; ρ_p : persistency parameter of the persistent price mark-up shock.

Table 5: Comparing the Calvo model with Taylor contracting models without capital mobility.

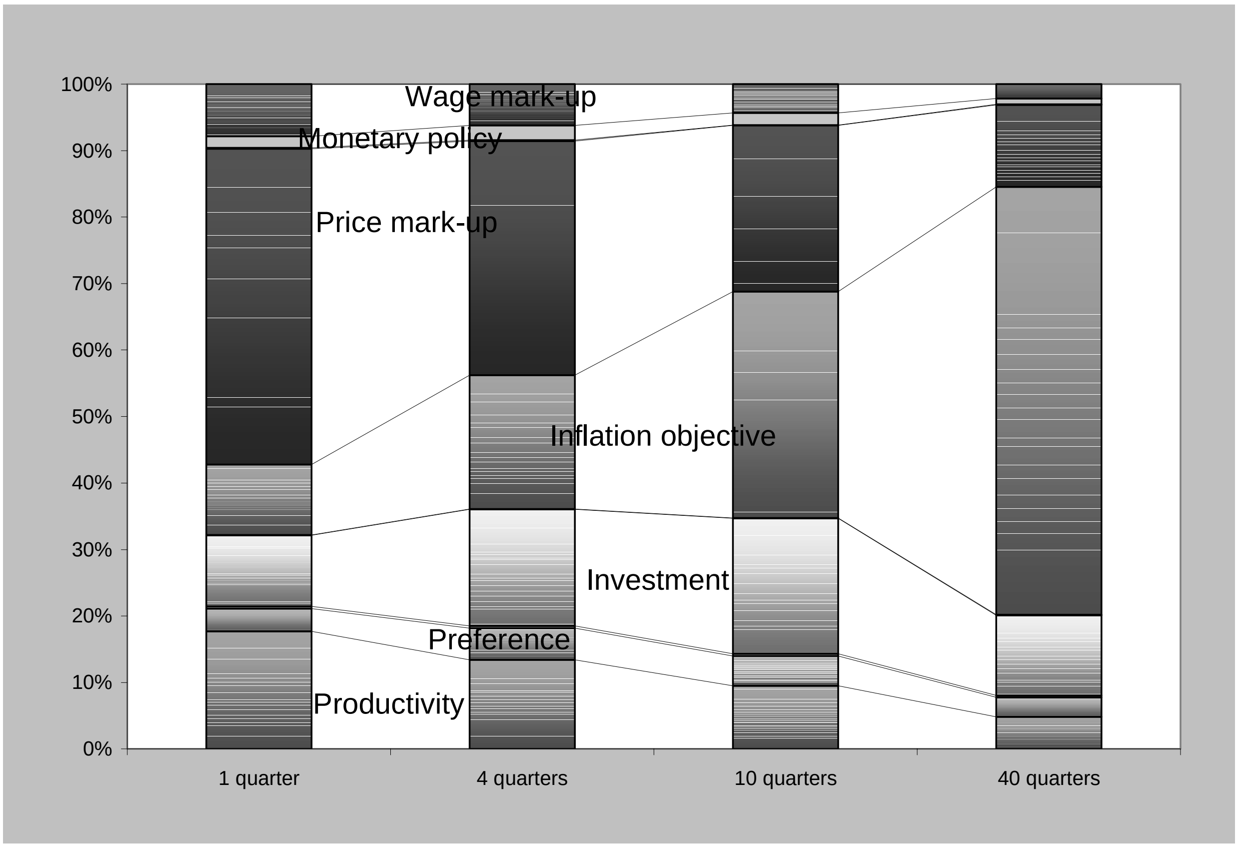
	Calvo	4-quarter Taylor	8-quarter Taylor	10-quarter Taylor
Log Data Density	-464.27	-463.71	-468.37	-469.61
σ_p	0.19	-	-	-
	(0.01)			
ξ_w	0.71	0.704	0.697	0.692
	(0.04)	(0.049)	(0.047)	(0.047)
ξ_p	0.89	-	-	-
	(0.01)			
λ_p	-	0.003	0.012	0.023
		(0.001)	(0.004)	(0.009)
γ_w	0.56	0.526	0.502	0.504
	(0.15)	(0.164)	(0.165)	(0.163)
γ_p	0.30	0.248	0.324	0.362
	(0.07)	(0.080)	(0.084)	(0.094)
σ_{pp}	-	0.236	0.253	0.250
		(0.018)	(0.018)	(0.019)
ρ_p	-	0.968	0.976	0.884
		(0.024)	(0.017)	(0.123)
trend	0.22	0.243	0.253	0.248
	(0.028)	(0.031)	(0.029)	(0.027)

Note: The price mark-up shock is modelled as a persistent shock in the GDP price equation.
σ_p: standard error of the price mark-up shock, ξ_w: Calvo wage stickiness parameter, ξ_p: Calvo price stickiness parameter, λ_p: substitution parameter ($\frac{1+\lambda_p}{\lambda_p}$ is the elasticity of substitution), γ_w: wage indexation parameter, γ_p: price indexation parameter, σ_{pp}: standard error of the persistent price mark-up shock, ρ_p: persistency parameter of the persistent price mark-up shock..

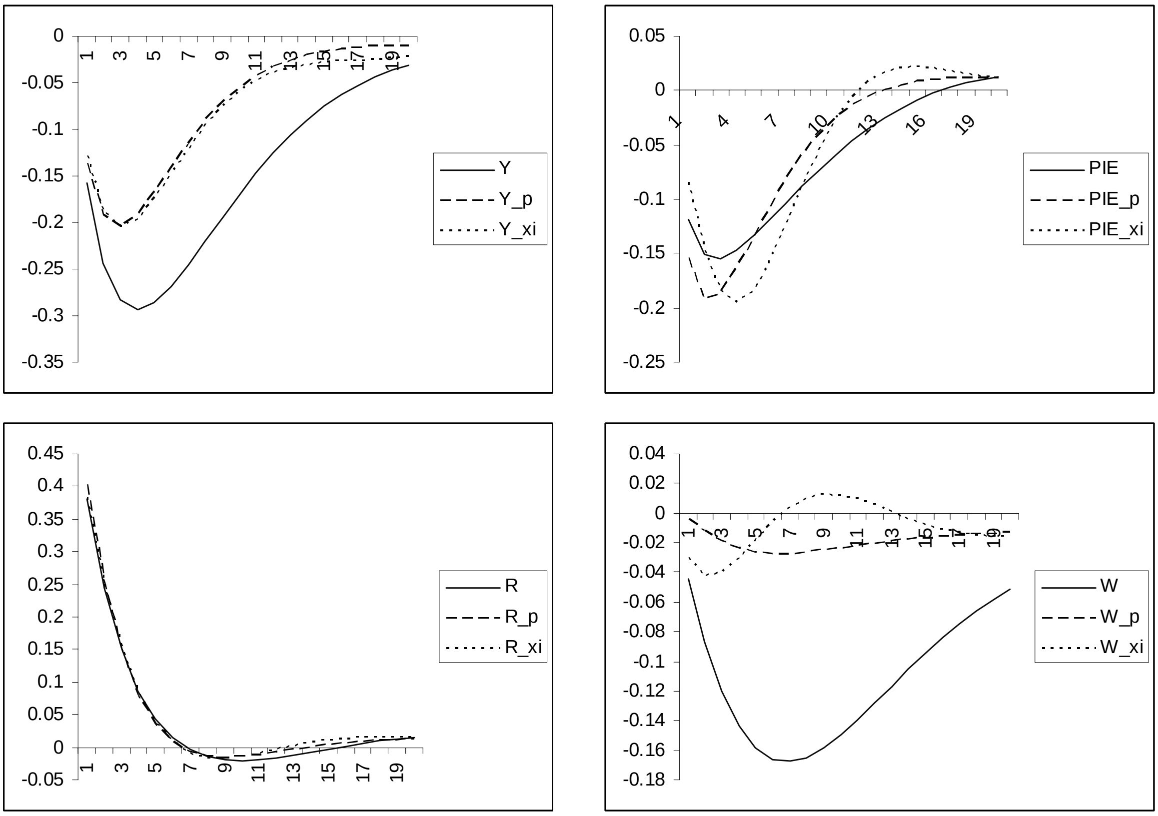
Graph 1: Forecast error variance decomposition of inflation (baseline model)



Graph 2: Forecast error variance decomposition of inflation (with a persistent price shock)

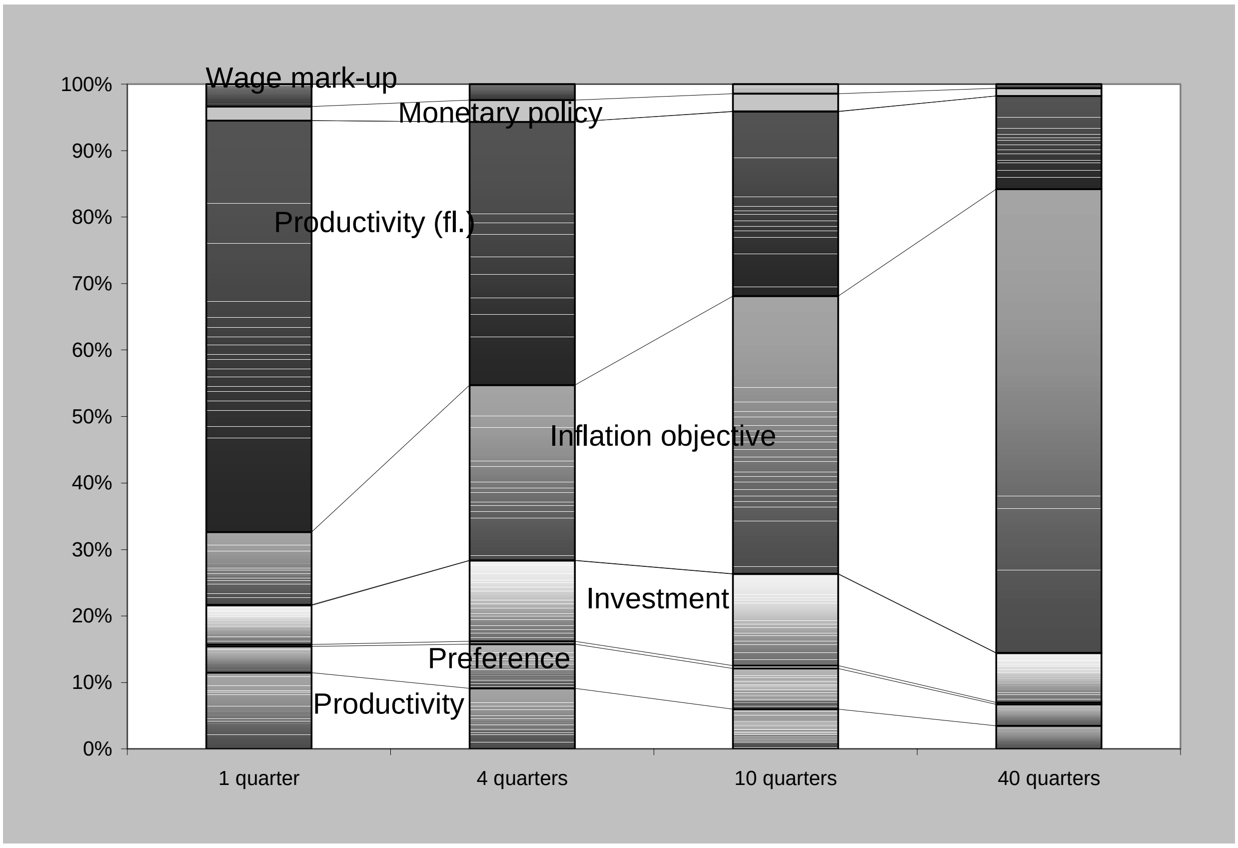


Graph 3: Selected impulse responses following a monetary policy shock with and without persistence in the price shock



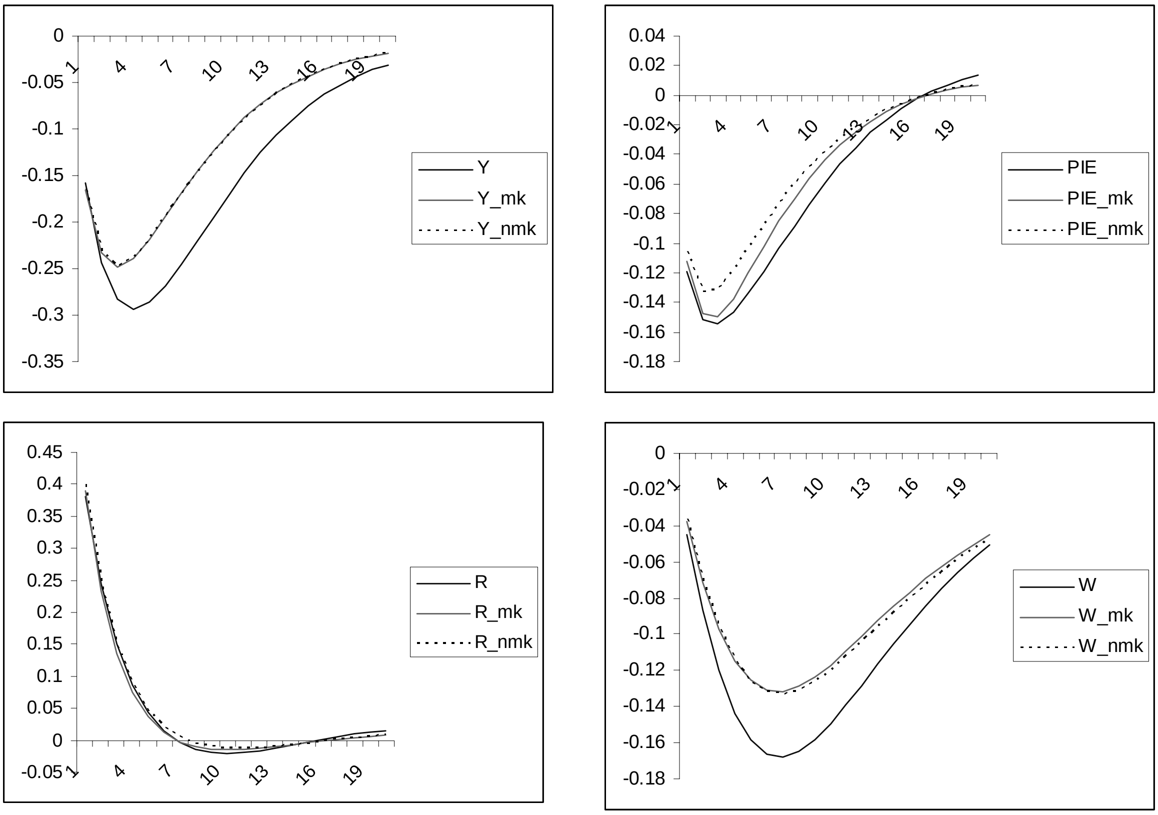
Notes: Y: real output; PIE: inflation; R: nominal short-term interest rate; W: real wage. Solid line refers to the baseline model. Var_p refers to the model with a persistent price shock. Var_xi refers to a model where the Calvo price parameter is set equal to 0.75.

Graph 4: Forecast error variance decomposition of inflation for the 2 sector model (the mobile capital case)



Graph 5a: Selected estimated impulse responses with and without a flexible price sector

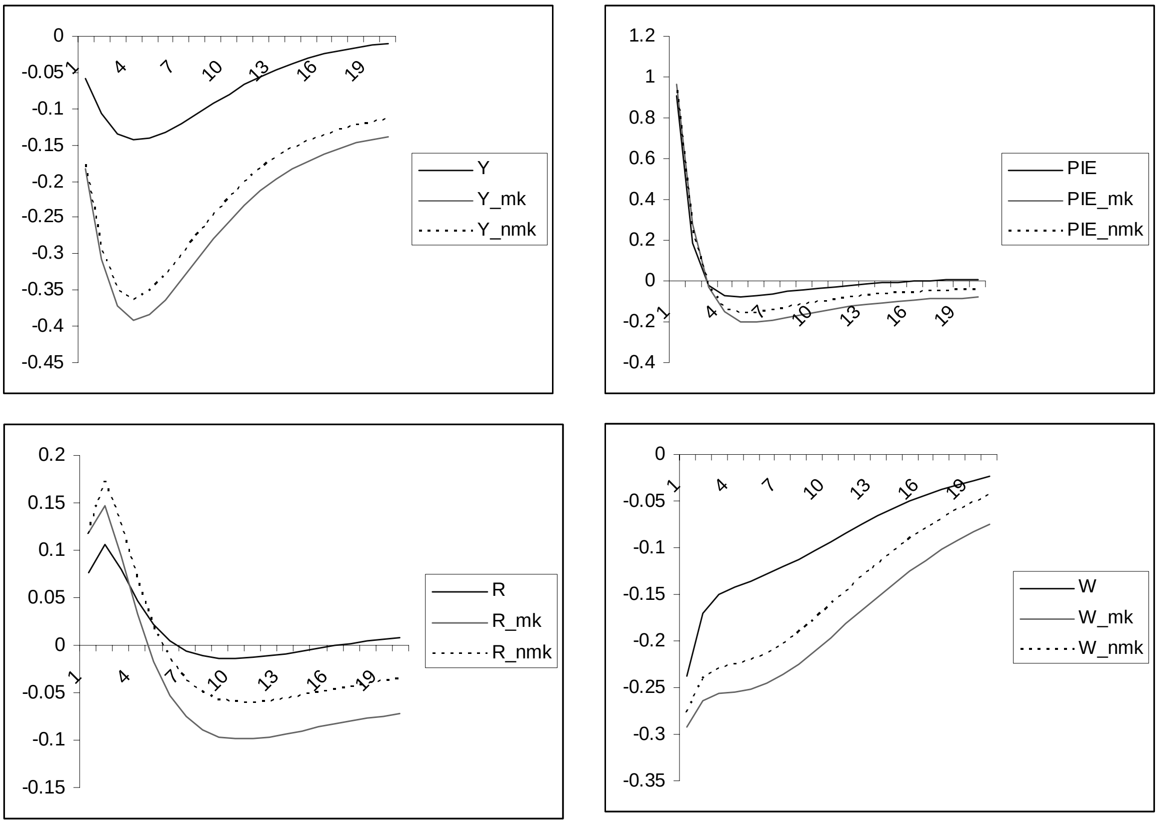
The effects of a monetary policy shock



Notes: See Graph 4. Var_mk: 2-sector model; Var_nmk: 2-sector model, non-mobile capital

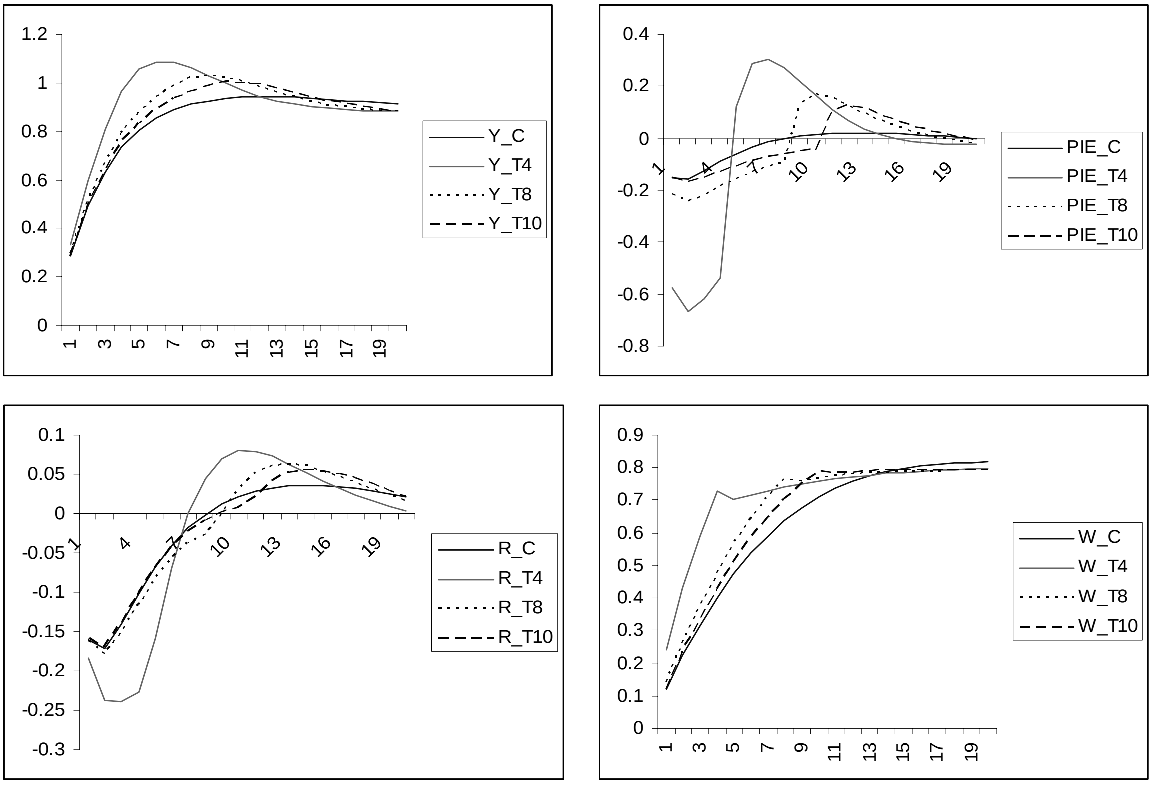
Graph 5b: Selected estimated impulse responses with and without a flexible price sector

The effects of a price mark-up shock versus a flexible-price productivity shock



Graph 6a: Selected impulse responses: Calvo versus Taylor contracts (baseline parameters)

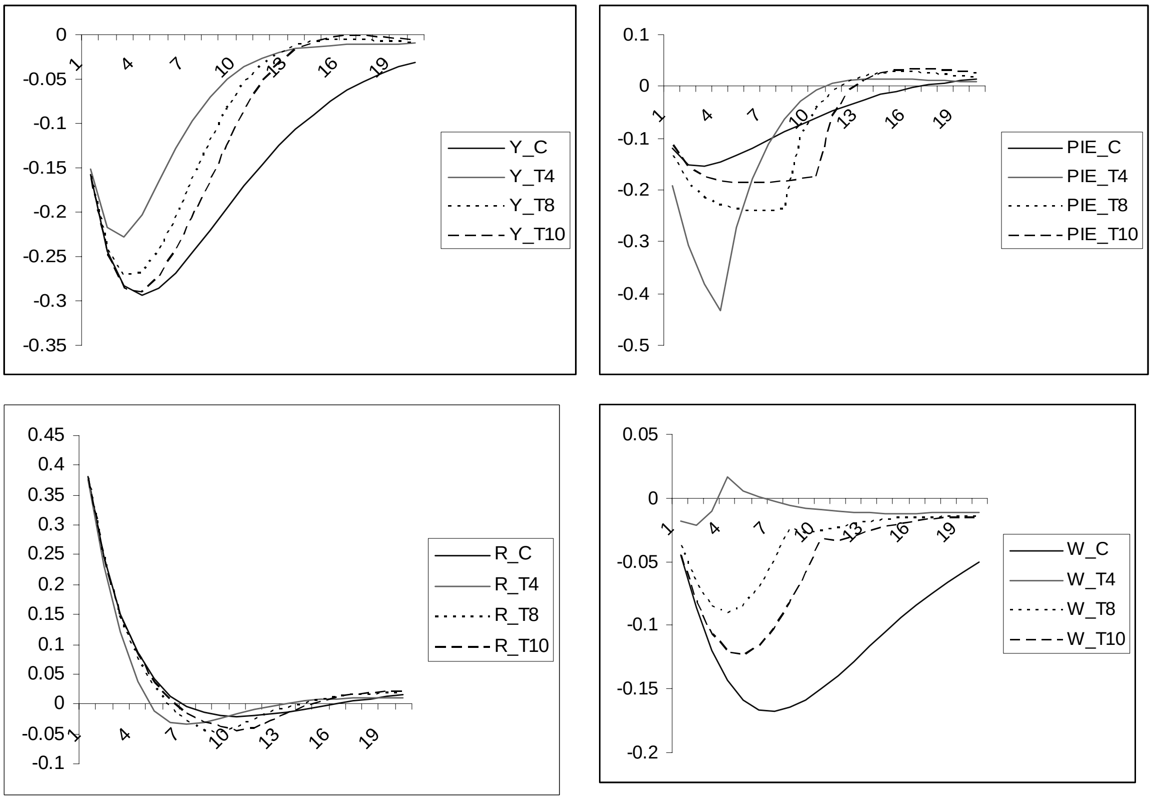
The effects of a productivity shock



Notes: See Graph 4. Var_C is Calvo; Var_Tn is Taylor with contract length of n quarters.

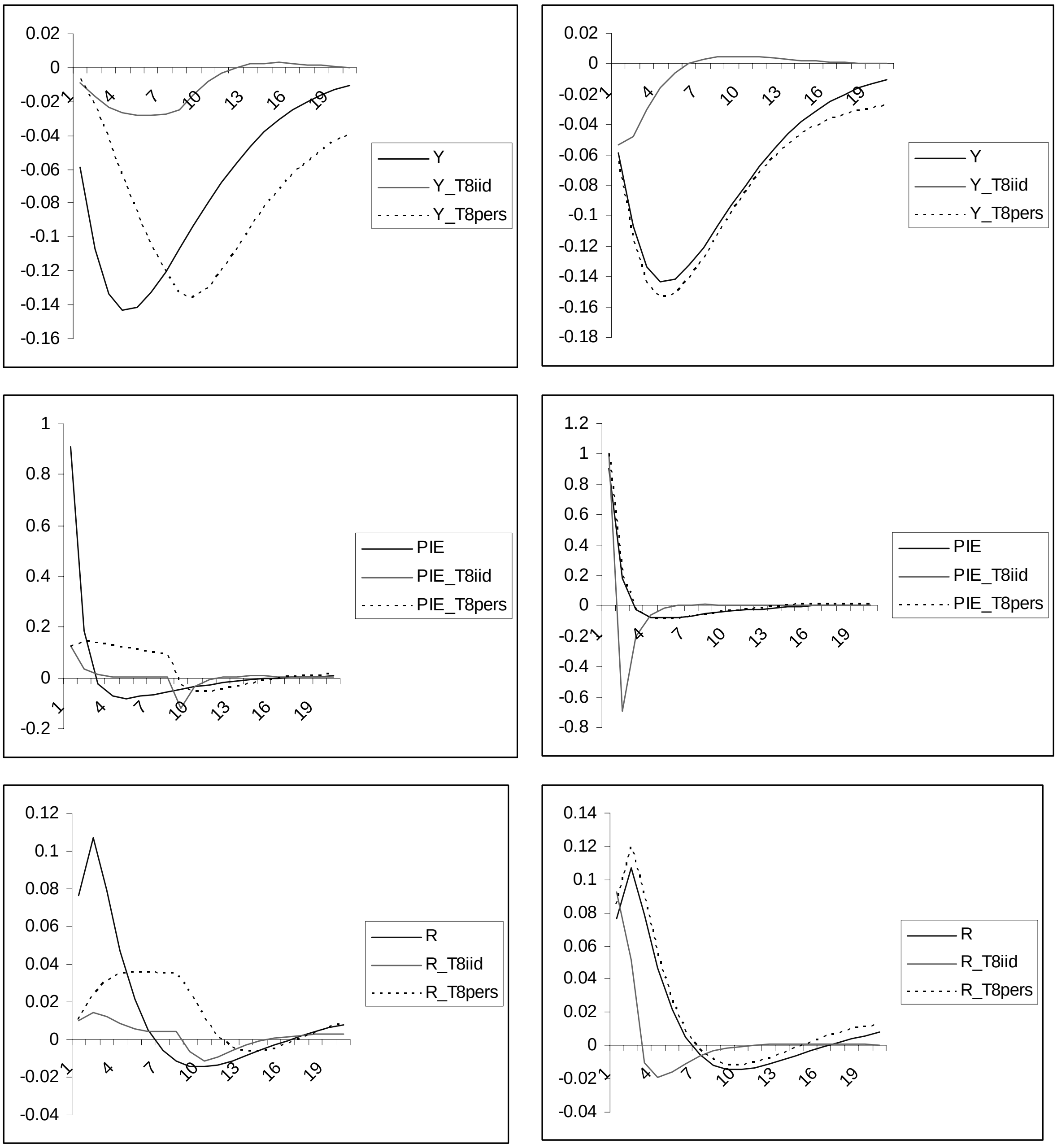
Graph 6b: Selected impulse responses: Calvo versus Taylor contracts (baseline parameters)

The effects of a monetary policy shock



Graph 7: Impulse responses to a price mark-up shock in the 8-quarter Taylor contracting model for different specifications of the price shock (baseline parameters)

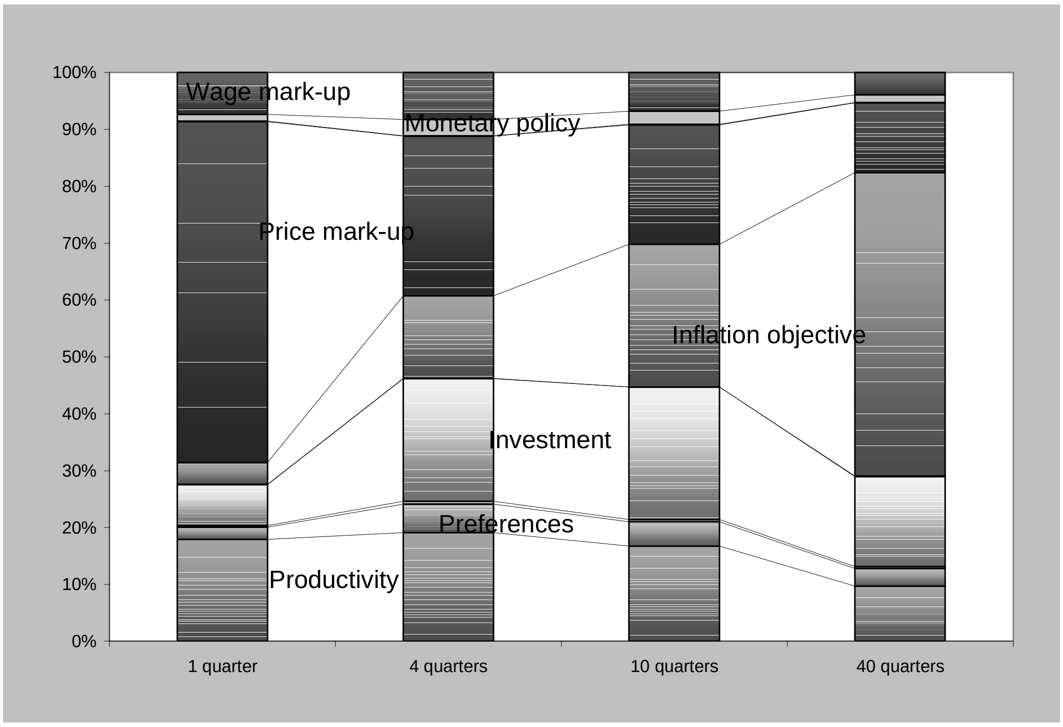
Price shock in the optimal price equation **Price shock in the price index equation**



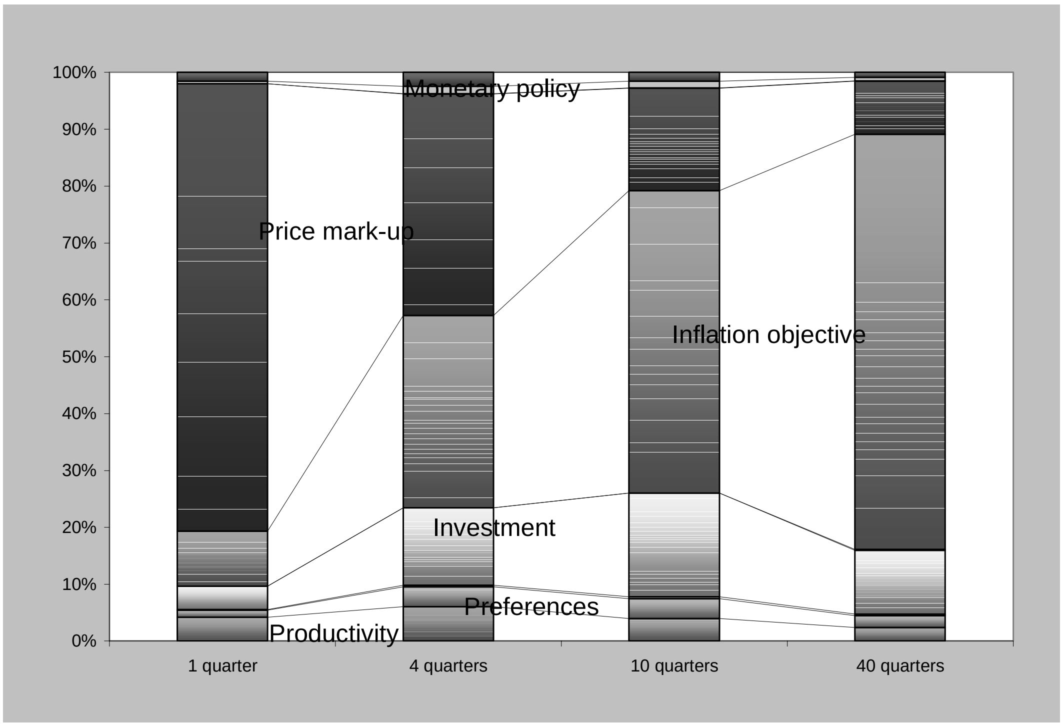
Notes: See Graph 4. Var is baseline; Var_T8iid: 8-period Taylor contract with iid price shock; var_T8pers: 8-period Taylor contract with persistent price shock.

Graph 8: Forecast error variance decomposition of inflation: Taylor contract models

4-quarter Taylor contract

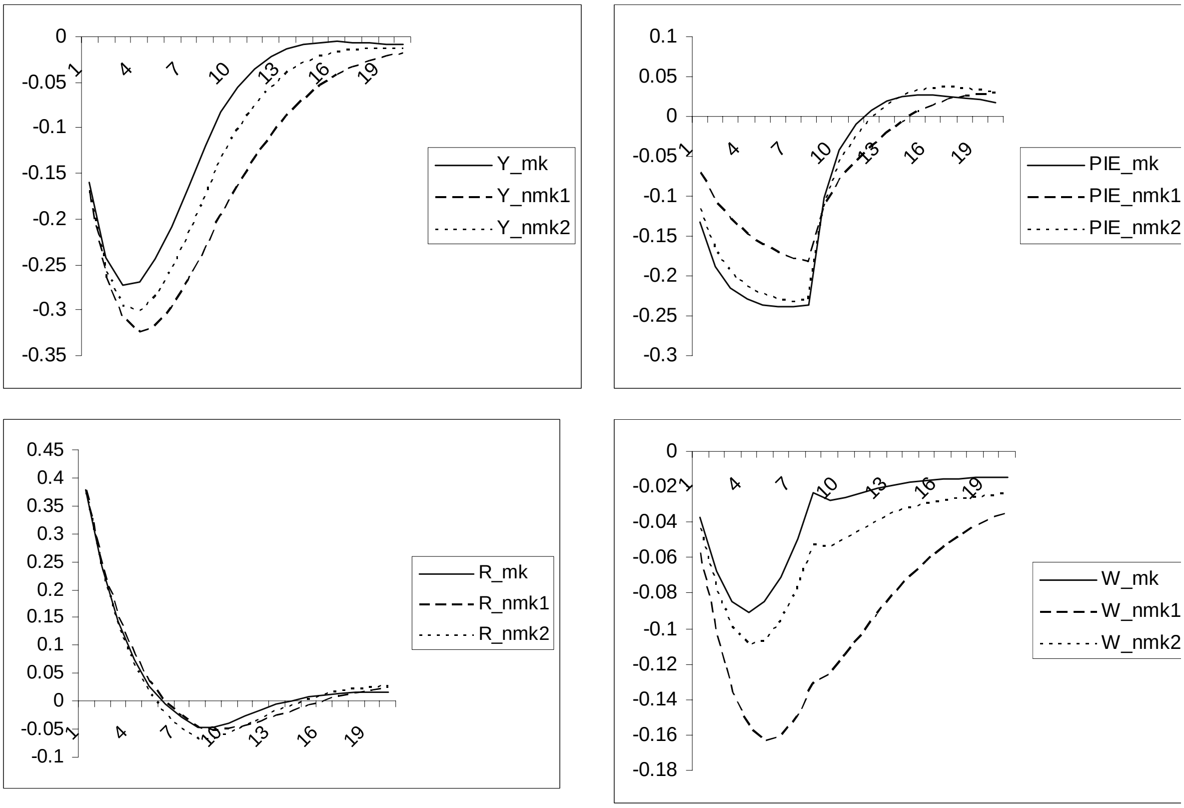


8-quarter Taylor contract



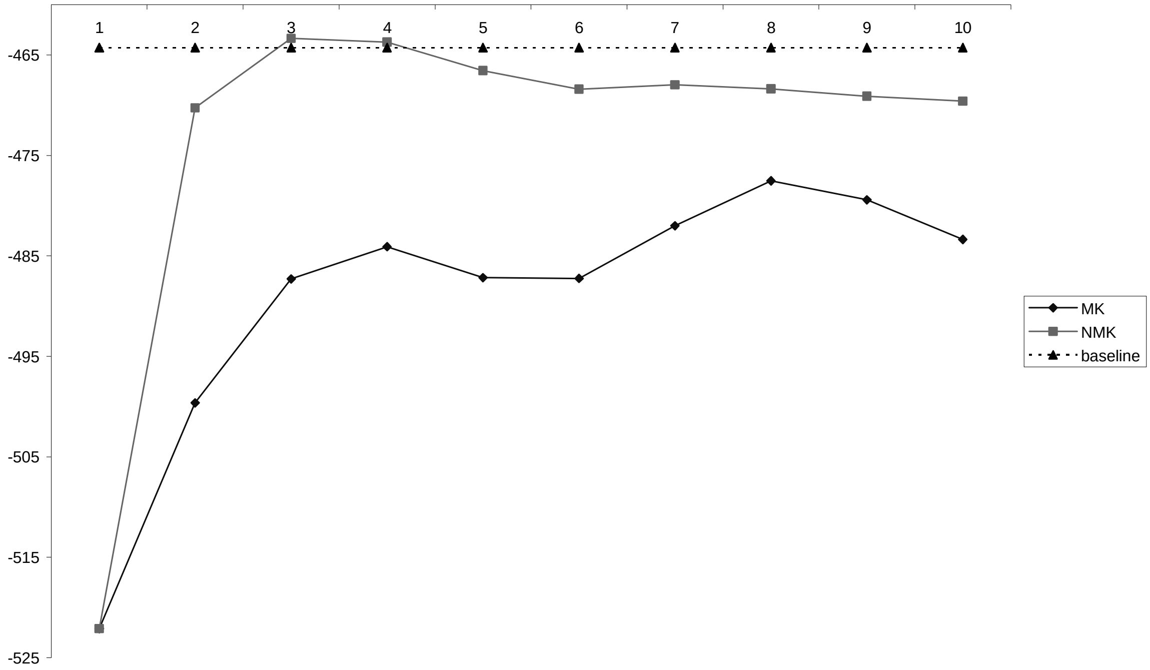
Graph 9: Impulse responses for a 8-quarter Taylor contract (baseline parameters)

The effects of a monetary policy shock



Notes: See Graph 4. Var_mk: mobile capital; Var_nmk1: non mobile capital with lambda_p = 0.05 (elasticity of subst. = +/-20); Var_nmk2: non mobile capital with lambda_p = 0.5 (elasticity of subst. = 3).

Graph 10: The log data density for Taylor contracting model with different contract lengths (with and without mobile capital)



Notes: Vertical axis: log data density. Horizontal axis: Taylor contract length. Baseline refers to the Calvo baseline model. MK refers to Taylor contracting models with mobile capital. NMK refers to Taylor contracting models without mobile capital.