Real exchange rate persistence and systematic monetary policy behaviour

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Abstract

This paper estimates forward-looking monetary policy rules for Germany over the 1979-98 period and for the United Kingdom for the periods 1979-90 and 1992-98. The estimation results indicate that there were substantial differences between systematic monetary policy in Germany and in the United Kingdom, as well as shifts in systematic monetary policy in the United Kingdom, over this period. The paper analyses the implications of these estimated policy rules for real exchange rate behaviour in an open economy dynamic stochastic general equilibrium model. The analysis shows that real exchange rate persistence could be attributed to the persistence of real shocks and interest rate smoothing behaviour of central banks. However, the observed cross-country asymmetry in systematic monetary policy behaviour elevates real exchange rate persistence to realistic levels, whereas changes in asymmetric policy behaviour alter the character of real exchange rate persistence.

Key words: Dynamic stochastic general equilibrium models, GMM, monetary policy feedback rules, real exchange rate persistence.

JEL classification: E52, F31, F33, F41.

Summary

This paper focuses on the relationship between real exchange rate persistence and cross-country differences in the way in which national central banks interact with their respective economies. We use a two-country dynamic stochastic general equilibrium (DSGE) model of the ‘new open economy’ strand that has no cross-country and cross-sector differences in price stickiness, and a real sector that is identical across countries. However, the monetary policy rules, ie the feedback mechanisms of the central bank in response to the rest of the economy, are allowed to be asymmetric across countries. We first estimate the monetary policy rules as statistical representations of systematic monetary policy, albeit that this is not intended to suggest that central banks actually followed the estimated rules in setting their policy rates. Next, we calibrate the real side of our model and estimate the persistence and variance of productivity shocks. Finally, we analyse how the real exchange rate behaves in the face of a common productivity shock, a relative productivity shock and policy shocks. One implication of the use of asymmetric monetary policy rules is that the real exchange rate will react to a common productivity shock, which would not have been the case under symmetric monetary policy rules.

The emphasis of the analysis is on the real exchange rate between Germany and the United Kingdom in the period 1979-98. During this period German systematic monetary policy behaviour was broadly stable. In the United Kingdom, on the other hand, the feedback mechanism of monetary policy underwent some significant changes. We identify three phases in the systematic conduct of UK monetary policy. The first is the period 1979-90, in which the United Kingdom tried several frameworks to stabilise inflation. During 1990-92 the United Kingdom participated in the Exchange Rate Mechanism (ERM), thereby fixing its exchange rate to the Deutsche mark. In the period 1992-98, inflation targeting was introduced and inflation came down to low and stable rates.

Under a credible fixed exchange rate regime the degree of real exchange rate persistence should in theory be low, as in this case domestic monetary policy is implicitly used to ensure purchasing power parity (PPP) holds. But there is a great deal of uncertainty in the academic literature on what causes the observed high degree of real exchange rate persistence under flexible exchange rates. We therefore focus on the experience during the first and the third UK monetary policy regime, during which the exchange rate was more or less flexible. Thus, we estimate a German monetary policy rule over 1979-98 and UK monetary policy rules over the periods 1979-90 and 1992-98. We feed the estimated policy rules across different regimes into the DSGE model and analyse how the general

persistence of the real exchange rate is affected by this, *ceteris paribus*: in particular, by holding constant the preference parameters and the production technology processes. The results of our analysis confirm what we find in the historical data. Although the DSGE model generates a high degree of real exchange rate persistence under both the inflation-targeting regime and the pre-ERM regime, the degree of real exchange rate persistence is slightly higher under the former UK policy regime. This was mainly due to the fact that common productivity shocks were transmitted differently across the two regimes. Under the inflation-targeting regime UK monetary authorities reacted almost identically to the German authorities, and as a consequence the nominal exchange rate did not counteract the effect of the common productivity shock.

1 Introduction

The very persistent nature of real exchange rates across industrialised countries under the post-Bretton Woods float has been a topic of extensive research in the international economics literature. Mark (1990), Papell (1997) and O'Connell (1998), among others, apply time series-based and panel data-based unit root tests on bilateral real exchanges rates among the major OECD countries, and these studies generally are unable to reject a unit root in these real exchange rates. As purchasing power parity (PPP) implies that real exchange rates should be mean-reverting around a constant mean, one can interpret the evidence cited from the literature as showing that long-run PPP does not hold.

One reason for this apparent failure of PPP could be that there are real forces that permanently shift the real exchange rate. Balassa (1964) and Samuelson (1964) argue that in fast-growing economies productivity growth in the traded goods sector is higher than in the non-traded goods sector and consequently the relative price of non-traded/traded goods for such an economy would exhibit an acceleration in its growth rate. If the economy at home grows faster than the economy abroad, the corresponding bilateral real exchange rate will exhibit a sustained appreciation and *vice versa*. Nonetheless, the international relative price of traded goods should be mean-reverting around a constant level according to the Law of One Price (LOOP). However, the balance of the empirical evidence on LOOP in the literature is not supportive. Engel (1999) finds for the major US dollar bilaterals that even in the long-run real exchange rate variability is determined by LOOP deviations. Groen and Lombardelli (2004) report evidence that within a monthly 1976-2002 panel of the UK-based real exchange rates of Canada, the euro area (or Germany), Japan and the United States there is a long-run relationship between the real exchange rate and the relative price ratio of non-tradable/tradable goods. However, Groen and Lombardelli (2004) also find that the observed deviations between real exchange rates and the corresponding relative price ratio of non-tradable/tradable goods are very persistent, indicating that LOOP deviations are long-lasting.

We infer from this evidence that there must be short to medium-run factors operating that induce substantial deviations from LOOP and PPP, and identifying a candidate factor is the focus of this paper. One obvious candidate is nominal price stickiness. Chari, Kehoe and McGrattan (2002) build an open-economy dynamic stochastic general equilibrium (DSGE) model with price stickiness, local-currency pricing, and a rich, disaggregated real sector with capital in order to generate artificial real exchange rate series. These series are indeed shown to be persistent, albeit not enough to match the empirically observed degree of real exchange rate persistence. Therefore factors beyond price stickiness and local-currency pricing are needed to explain the observed deviations from LOOP and PPP.

One possibility is to enrich the degree of price stickiness such that the degree of price stickiness varies across countries and across domestically produced and imported goods. Benigno (2002) shows that such an asymmetric degree of price stickiness, in combination with a high degree of persistence in the bilateral interest rate differential, is capable of elevating the persistence of the artificial real exchange series from his model to realistic levels of real exchange rate persistence. Another approach is to include real rigidities in the model in the form of international transaction costs, otherwise known as shipping costs, between spatially separated markets, see eg Dumas (1992). In this approach the prediction is that the real exchange rate will be non-mean reverting within a certain range, in which arbitrage trade profits do not outstrip the shipping costs, and mean-reverting outside this range. Utilising non-linear autoregressive time series models, Obstfeld and Taylor (1997) and Taylor, Peel and Sarno (2001), in the context of LOOP and PPP respectively, claim to have found empirical evidence for this prediction of the shipping costs view on real exchange rate persistence.

Rather than focusing on asymmetric price stickiness or real rigidities, we take in this paper a different approach, in that we focus on how real exchange rate persistence is affected by cross-country differences in how national central banks interact with their respective economies. We use a two-country DSGE model of the ‘new open economy’ strand in which we have no cross-country and cross-sector differences in price stickiness, and a real sector which is identical across countries. However, the monetary policy rules, ie how the central bank responds to developments in the rest of the economy, are allowed to be asymmetric across countries. After calibrating the real side of our model and estimating the persistence and variance of the productivity shocks as well as each of the monetary policy rules, we analyse how the real exchange rate behaves in the face of a common productivity shock, a relative productivity shock and policy shocks. One implication of the usage of asymmetric monetary policy rules is that the real exchange rate will react to a common productivity shock, which would not have been the case under symmetric monetary policy rules. We also analyse what the implications are both for the real exchange rate of each of the aforementioned shocks, and for the general half-life of the real exchange rate when in one country the central bank changes its feedback behaviour. Our analysis is very much in the spirit of Clarida, Galí and Gertler (2000), who calibrate a closed-economy DSGE model for the United States and analyse the consequences for inflation and output dynamics when they feed into this model monetary policy rules that are estimated under different US monetary policy regimes.

The emphasis of the analysis in this paper is on the real exchange rate between Germany and the United Kingdom over the 1979-98 sample. During this period German systematic monetary policy behaviour has been broadly stable. In the United Kingdom, on the other hand, the framework for monetary policy has undergone some significant changes over the 1979-98 sample (see for example Nelson (2003)). We identify three phases in the systematic conduct of UK monetary policy. The first is the period 1979-90 in which the United Kingdom tried several frameworks to stabilise inflation. During 1990-92 the United Kingdom fixed its exchange rate to the Deutsche mark (DM) within the Exchange Rate Mechanism (ERM). In the period 1992-98, finally, inflation targeting was introduced and inflation came down to low and stable rates.

Mussa (1986) compares real exchange rate behaviour under the Bretton Woods fixed exchange rate regime and the post-Bretton Woods float, and he showed that real exchange rates were much more persistent and volatile under flexible exchange rates than under fixed exchange rates. Solely focusing on real exchange rate persistence, Rogoff (1996) draws the same conclusion and he wonders why half-life estimates of shocks to real exchange rates are so much more higher under flexible exchange rate regimes than under fixed exchange rate regimes. In case of a credible fixed exchange rate regime the observed low real exchange rate persistence is plausible from a theoretical point of view, as in this case domestic monetary policy is implicitly used to get PPP to hold. Given the aforementioned uncertainty in the literature to what causes the high real exchange rate persistence under flexible exchange rates, however, we focus in our analysis on the first and third UK monetary policy regimes, during which the exchange was more or less flexible. Thus, we estimate a German monetary policy rule over 1979-98 and UK monetary policy rules over the periods 1979-90 and 1992-98. After feeding these estimated policy rules into our calibrated open-economy DSGE model and *ceteris paribus* the preference parameters and the production technology processes, we show that real exchange rate persistence was high under both UK policy regimes, although the character of this persistence was markedly different over the two regimes.

The remainder of this paper is organised as follows. In Section 2 we define an interest rate-based forward-looking monetary policy rule and estimate it for Germany and the United Kingdom. The structure of the open-economy DSGE model, which we utilise in our analysis of real exchange rate persistence, is set out in Section 3. After estimating the productivity shock processes, calibrating the real parameters and feeding in the different estimated monetary policy rules, in Section 4 we use impulse response functions and Monte Carlo simulations to analyse the impact of systematic monetary policy behaviour on real exchange rate persistence. We end with concluding remarks in Section 5.

2 Empirical monetary policy behaviour

Most central banks view the nominal short-term interest rate as their main operating instrument to achieve their medium to long-term policy objectives. Both theoretically as well as empirically one wants to have a convenient numerical tool to model how the nominal short-term interest rate, which is under control of the central bank, responds to developments in the rest of the economy. Following the literature, we utilise a forward-looking version of the familiar Taylor rule as the modelling tool to describe systematic behaviour of central banks in a parsimonious manner without inferring that they literally adhere to such a rule in practice.

In Section 2.1 we show how to specify the central bank reaction function in terms of the short-term interest rate and how to estimate it. Section 2.2 reports the estimation results for Germany and for the United Kingdom, and for the latter under different identified monetary policy regimes.

2.1 Central bank policy reaction functions: specification and estimation issues

Most central banks aim to influence short-term interest rates towards a certain target level in order to achieve their medium to long-term objectives. For the purpose of this exercise, as in reality there is a much more complex process through which monetary authorities set the interest rate in response to primitive shocks that hit the economy, one could formulate these target levels in terms of expected future inflation and the expected future level of the output gap (see eg Clarida *et al* (2000)), ie

$$i_t^* = \bar{i}^* + \phi^* E_t(\pi_{t+k1}) + \psi^* E_t(\dot{Y}_{t+k2}) \qquad \textbf{(1)}$$

In **(1)** π_{t+k1} is the year-on-year inflation rate $k1$ periods ahead, $\dot{Y}_{t+k2}$ is output gap $k2$ periods ahead and E_t is the conditional expectation based on the available information set in period t. From eg Clarida, Galí and Gertler (1998a) we know that a reaction function with an inflation coefficient $0 < \phi^* < 1$ results in an unstable economy and will generate persistent self-fulfilling outbursts in the inflation rate. As in this case the nominal interest rate increases less than an increase in inflation expectations, the resulting decrease in the real interest rate stimulates aggregate demand, which generates a persistent self-fulfilling increase in the actual inflation rate. When $\phi^* \geq 1$ monetary policy itself will not be a source of macroeconomic instability, as the nominal interest rate will increase at least with the same magnitude when we have a rise in inflation expectations. Note, however, that when ϕ^* is slightly bigger than 1, ie just outside the destabilising range, the economy can still be relatively instable as the central bank is close to fully accommodating inflationary pressures, see Clarida *et al* (2000, pages 174-77).

In general, central banks tend not to influence short-term interest rates so strongly that it equals the target level in each period, as central banks want to avoid destabilising effects of sudden changes in interest rates. A gradual adjustment of interest rates to the target level also helps monetary authorities to focus agents' expectations on its policy objectives (see eg Woodford (1999)). We therefore assume that short-term interest rates evolve as a weighted average of its lag and the target level **(1)**:(1)

$$i_t = \gamma i_{t-1} + (1-\gamma) i_t^* + \varepsilon_t \tag{2}$$

with $0 < \gamma < 1$. After substituting in **(1)** we can write **(2)** as

$$i_t = (1-\gamma)\bar{i^*} + \gamma i_{t-1} + (1-\gamma)\phi^* \pi_{t+k1} + (1-\gamma)\psi^* \dot{Y}_{t+k2} + \upsilon_t \tag{3}$$

with

$$\upsilon_t = \varepsilon_t - (1-\gamma)\phi^* \left(\pi_{t+k1} - E_t(\pi_{t+k1})\right) - (1-\gamma)\psi^* \left(\dot{Y}_{t+k2} - E_t(\dot{Y}_{t+k2})\right)$$

The variable ε_t in **(2)** and **(3)** is a stationary, zero-mean disturbance which we interpret as an exogenous monetary policy shock. Following Clarida, Galí and Gertler (1998b) and Christiano, Eichenbaum and Evans (2000) we can interpret ε_t in several ways. One interpretation is that ε_t captures exogenous shocks to the preferences of policymakers. Second, it could reflect the inability of policymakers to keep the interest rate on target, for example when money demand shocks occur and policymakers do not rely solely on the interest rate to achieve their policy objectives. Next, it could be a consequence of decisions by policymakers to deliberately deviate temporarily from target levels. Finally, ε_t may follow from technical factors, such as measurement error.

The composite error term υ_t is a linear term of forecast errors which should by definition be uncorrelated with any of variables in the current information set I_t. When we have a vector Z_t of instrument variables such that $Z_t \subset I_t$, we can write based on **(3)** a set of orthogonality conditions,

$$E\left[\left(i_t - (1-\gamma)\bar{i^*} - \gamma i_{t-1} - (1-\gamma)\phi^* \pi_{t+k1} - (1-\gamma)\psi^* \dot{Y}_{t+k2}\right) Z_t\right] = \mathbf{0} \tag{4}$$

We now can use the Generalised Method of Moments (GMM) approach, see Hansen (1982), to estimate the parameters in **(3)** through the orthogonality conditions **(4)**. The weighting matrix for our GMM estimators are based on the Newey and West (1987) disturbance covariance matrix estimator which is asymptotically robust to heteroskedasticity and autocorrelation in the disturbances.

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(1) Although we, like Woodford (1999), give a structural interpretation to the autoregressive parameter γ, ie policy inertia, Rudebusch (2002) argues that the apparent inertia in interest rates could alternatively reflect that central banks respond to serially correlated shocks that hit the economy, and as such the lagged interest rate in **(2)** is only a statistical tool to correct for residual serial correlation.

2.2 Estimation results

The focus of this paper is on the Germany/UK real exchange rate relationship. We do not consider the euro-area policy rule, and thus the euro/UK relationship, as the sample is too short. We use monthly data, covering the period July 1979 - December 1998.(2) Only the period prior to the launch of EMU will be considered. Simply splicing the Bundesbank policy rule to that of the ECB would be inappropriate as Faust, Rogers and Wright (2001) have shown that these are most likely to be different. In the case of Germany we will estimate **(3)** over the entire July 1979 - December 1998 sample. For the United Kingdom, however, this would be inappropriate as the monetary framework in the United Kingdom has changed quite substantially over the period. In order to preserve a long enough sample we can identify for the United Kingdom three subsamples, each typified by a different (set of) monetary policy settings:

- **Regime 1: 1979-90.** Up to the third quarter of 1990 the United Kingdom tried several frameworks for monetary policy (among others targeting broad money growth).
- **Regime 2: 1990-92.** From the last quarter of 1990 up to September 1992 the United Kingdom fixed its exchange rate relative to the DM within the ERM, and dedicated its monetary policy to achieve this.
- **Regime 3: 1992-98.** From the last quarter of 1992 onwards the United Kingdom introduced inflation targeting as the guiding principle for its monetary policy, which successfully stabilised UK inflation at a moderate level.

In the remainder of this paper we will focus on Regimes 1 and 3, as under Regime 2 in the United Kingdom the interest rate policy rule **(3)** was in essence replaced by a rule in which interest rates were set in order to keep the pound-sterling/DM exchange rate close to its ERM parity value.

The inflation rate π_t is the log difference between the CPI level in the same month over two consecutive years in percentages. As our measure of the output gap $\dot{Y}_t$ we use the percent deviation of log industrial production from its Hodrick and Prescott (1997) filtered value.(3) Our nominal short-term interest rate i_t for both countries is the one-month

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(2) The sample period starts in July 1979, as this is the first full quarter that the Conservative government led by Mrs. Thatcher was in power. Thus, this is the first point in time that this government was able to put through a markedly different type of monetary policy *vis-à-vis* the previous regimes; see Nelson (2003).

(3) Although it is straightforward to theoretically identify the output gap, this is not at all the case in practice as there are several ways to empirically measure 'the' output gap. Monetary authorities are therefore likely to examine a range of different indicators of demand pressure on inflation.

maturity euro-market interest rate, which facilitates a cross-country comparison.(4)

Estimating **(3)** with GMM through the orthogonality conditions **(4)** means that we have to take a stand on the contents of instrument vector Z_t. We consider Z_t to consist of the lags of the variables in **(3)**, ie $Z_t = (i_{t-1}, \ldots, i_{t-l1}, \pi_{t-1}, \ldots, \pi_{t-l2}, \dot{Y}_t, \ldots, \dot{Y}_{t-l3})'$. Thus, selecting the optimal Z_t instrument vector boils down to selecting optimal lag orders $l1$, $l2$ and $l3$. Often the Hansen (1982) J-test is used to determine the optimal lag orders $l1$, $l2$ and $l3$, and therefore the optimal number of instrument variables. The finite sample properties of this test, however, are known to be very poor and often result in overrejection of the selected number of orthogonality conditions. As an alternative selection procedure for the appropriate number of instruments we apply the GMM-BIC criterion of Andrews (1999). This GMM-BIC criterion is the GMM analogue of the well known Bayesian-Schwarz Information Criterion, and it yields consistent estimates of the optimal number of orthogonality conditions and has better finite sample properties than the J-test.(5) We apply the GMM-BIC criterion in a downward testing procedure, ie we start with $l1 = l2 = l3 = 12$ and then, upon rejection of this particular number of orthogonality conditions, decrease each $l1$, $l2$ and $l3$ until the GMM-BIC criterion indeed accepts the number of orthogonality conditions. Conditional on the optimal number of instrumental variables, we then use the GMM-BIC criterion to choose the optimal forecasting horizons for the inflation expectation ($k1$) and the expected output gap measure ($k2$) in the interest rate policy rule **(3)**.

The first row in Table A contains the GMM estimates of **(3)**. The estimation results show that the German Bundesbank overall pursued a stabilising strategy relative to inflation, and also took into account news about economic prospects in general. Estimation results for the United Kingdom over the 1979-90 regime are reported in the second row of Table A. For this period taken as a whole, the UK inflation coefficient ϕ^* was approximately 1, suggesting that inflation could have been destabilised by shocks whose effect on inflation were not immediately counteracted in the short to medium term. For the 1992-98 inflation-targeting regime, on the other hand, we have to add an extra lag to **(3)** for the United Kingdom,

$$\begin{aligned} i_t = (1-\gamma_1-\gamma_2)\bar{i^*} + \gamma_1 i_{t-1} + \gamma_2 i_{t-2} \\ + (1-\gamma_1-\gamma_2)\phi^*\pi_{t+k1} + (1-\gamma_1-\gamma_2)\psi^*\dot{Y}_{t+k2} + \upsilon_t \quad \textbf{(5)} \end{aligned}$$

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(4) The euro-market interest rates are supplied by Datastream, whereas all the other series are from the *International Financial Statistics* CD-rom of the IMF.

(5) Andrews (1999) also proposes a GMM analogue of the Akaike Information Criterion, but this GMM-AIC criterion is asymptotically inconsistent and has a tendency to select too few orthogonality conditions.

Table A: Estimated monetary policy rules, July 1979 - December 1998[(a)]

	γ_1	γ_2	ϕ^*	ψ^*	S.E.
Germany	0.94^{***} (0.02)	–	1.48^{***} (0.14)	0.45^{***} (0.12)	0.30
UK, 1979:07-1990:10	0.91^{***} (0.02)	–	0.99^{***} (0.19)	0.82^{**} (0.32)	0.84
UK, 1992:11-1998:12	1.29^{***} (0.02)	-0.36^{***} (0.06)	2.08^{***} (0.61)	0.62 (0.44)	0.24

(a) The table contains GMM estimates of **(3)** or in case of the United Kingdom for 1992:11-1998:12 period **(5)**. The values in parentheses are Newey and West (1987)-based standard errors with a truncation lag of 12. The set of instrument variables are selected based on minimizing the Andrews (1999) GMM-BIC criterion. For Germany we have $k1 = 12$, $k2 = 0$, $l1 = 12$, $l2 = 11$ and $l3 = 11$, for 1979:07-1990:10 UK we have $k1 = 12$, $k2 = 3$, $l1 = 7$, $l2 = 7$ and $l3 = 5$, and for 1992:11-1998:12 UK we have $k1 = 6$, $k2 = 3$, $l1 = 8$, $l2 = 6$ and $l3 = 3$ (see **(3)** or **(5)**).

The results corresponding to **(5)** can be found in the third row of Table A and they show that in this period there was a high inflation coefficient ϕ^* and an insignificant output gap coefficient ψ^*.(6)

Compared to Clarida *et al* (1998b) the estimation results in Table A based on **(3)** differ to the extent that they do not include the real exchange rate as a target variable next to expected inflation and the expected output gap. We tried to add the real effective exchange rate in the case of Germany and either the real effective exchange rate or the real pound-sterling/DM exchange rate in the case of the United Kingdom as a target variable to **(3)**. However, the corresponding GMM-BIC criteria indicated that these behaved empirically inferior to estimates of **(3)** without a real exchange rate target and in most cases the addition of the real exchange rate target led to implausible estimates of the inflation and output gap target variables.

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(6) As noted before, these estimated policy rules should not be interpreted as factual representations of how monetary policy in Germany and the United Kingdom was conducted over the sample period, but they rather should be seen as convenient statistical summaries of how monetary policies in the respective countries responded to shocks that occurred in their economies.

3 The structure of the theoretical model

We use a two-country DSGE model, with countries denoted as Home and Foreign, based on Benigno (2002). Infinitely lived households are drawn from the unit interval $[0, 1]$ where a fraction of n households reside in the home country and a fraction $1 - n$ households operate abroad. Each household owns a firm that monopolistically supplies a consumer good z as in Blanchard and Kiyotaki (1987). A firm produces a consumer good z using labour and sets its price in advance. We assume Calvo (1983)-type price stickiness with local-currency pricing.(7) A continuum of consumption goods are traded internationally and we abstract from non-traded goods. Therefore, in our model real exchange rate fluctuations are mainly due to violations of the law of one price. This seems to be in compliance with empirical evidence as, for example, Engel (1999) shows that most of the observed real exchange rate movements among industrialised economies is not attributable to the relative-relative price of non-traded goods.(8)

Within our DSGE set-up, we describe monetary policy through a forward-looking version of the familiar Taylor interest rate rule, as formulated and estimated in Section 2. The feedback coefficients (ie feedback to expected inflation and output gap fluctuations) in these interest rules are allowed to differ at home and abroad. The focus of our analysis is on the relationship between real exchange rate persistence and cross-country differences in how monetary policy interacts with the rest of the economy. As a consequence, we take in our model a simplified view on the real side (eg preferences, production technology and so on) and enrich the nominal side of our artificial two-country world. This contrasts with the usual approach in the open-economy macro literature, such as Chari *et al* (2002), where one builds models with an extended real side and real inertia in order to replicate the empirically observed levels of real exchange rate persistence and volatility. This more traditional approach has been shown, however, to have been only partly successful in doing that.

In the remainder of this section we use the following notation. We use E_t as the symbol for the expected value conditional on time t information, while for a variable X we indicate the log deviation from the steady state as $\hat{X}_t$ and $\bar{X}$ indicates its value in steady state. Let

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(7) See Taylor (1999) for a detailed discussion on Calvo-type pricing. The usage of local-currency pricing has been criticised because of the counterfactual implied movement of the terms of trade. However, by introducing distributors, like Devereux, Engel and Tille (2002) and Devereux and Engel (2002), one can fix this problem to some degree since the terms of trade at the port level moves as observed in the data; see Matsumoto (2002) for a detailed discussion. However, under the complete nominal asset market assumption this would not make a significant difference (see the NBER working paper version of Devereux *et al* (2002)).

(8) That is the price ratio of non-traded goods to traded goods abroad relative to a similar domestic price ratio.

C_t be the index of the consumption goods basket at time t, M_t be nominal money balance, P_t be the unit price index corresponding to C_t, and L_t be the amount of labour. Next to time subscripts we use subscripts H or F to indicate whether goods are produced at home or abroad, whereas using H or F as a superscript denotes the amount or value facing the consumer at home or abroad. Finally, a superscript like $j \in W, R$ denotes that we either use a world aggregate of a variable or its value at home relative to abroad, ie for given variables X^H and X^F, $X^W \equiv nX^H + (1-n)X^F$, and $X^R \equiv X^H - X^F$. So, for example, $C^H_{F,t}$ indicates the consumed amount of foreign goods by the consumer at home at time t, while $C_t(z)$ is a consumption good produced by household z at time t.

3.1 Households

A household z owns a firm which produces a good $C_t(z)$ and receives a profit $PR_t(z)$ from it. Shocks are idiosyncratically distributed among households and we assume that each national asset market is complete, and therefore there is no heterogeneity among the agents in an economy. Households also receive a transfer from the government. The government supplies money to meet liquidity demands from households, and the value of seignorage is in turn distributed by the government to each individual on a per capita basis:

$$TR^i_t = \Delta M^i_t \equiv M^i_t - M^i_{t-1} \qquad \textbf{(6)}$$

A household receives utility from consumption, real balances, and leisure. Let U, N, and V denote sub-utility functions for each argument, which are twice differentiable and concave. A representative household in country i solves the following maximisation problem based on separable utility:[9]

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \left[U(C^i_t) + N\left(\frac{M^i_t}{P^i_t}\right) - V(L^i_t) \right] \qquad \textbf{(7)}$$

subject to a budget constraint,

$$A^i_t + M^i_t + P^i_t C^i_t = A^i_{t-1}R^i_{t-1} + M^i_{t-1} + W^i_t L^i_t + PR^i_t + TR^i_t \qquad \textbf{(8)}$$

In **(8)** A_t is the sum of the nominal value of financial assets excluding the money balance, M_t is the amount of nominal money as supplied by the government, R_{t-1} is the weighted average gross nominal return on the financial assets carried over from the last period, W_t is the nominal wage received for the amount of used labour L_t, PR_t denotes the nominal profit from the representative firm and TR_t is defined in **(6)**.

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(9) We chose a separable form of the utility function as Chari *et al* (2002) find that it is hard to generate historically reasonable artificial business cycles if one uses a combination of a policy rule and a non-separable form of the utility function.

Aggregate consumption in a country i is constructed according to a CES function,

$$C^i \equiv \left[n^{1/\varsigma} {C^i_H}^{(\varsigma-1)/\varsigma} + (1-n)^{1/\varsigma} {C^i_F}^{(\varsigma-1)/\varsigma} \right]^{\varsigma/(\varsigma-1)}, \quad \varsigma \geq 1 \tag{9}$$

where C^i_H and C^i_F are subindices defined by

$$C^i_H \equiv \left[\frac{1}{n} \int_0^n C^i(z)^{(\sigma-1)/\sigma} dz \right]^{\sigma/(\sigma-1)} \quad \text{and} \quad C^i_F \equiv \left[\frac{1}{1-n} \int_n^1 C^i(z)^{(\sigma-1)/\sigma} dz \right]^{\sigma/(\sigma-1)} \tag{10}$$

In **(10)** $\sigma > 1$ is the elasticity of substitution among within-country goods and $C^i(z)$ is per capita consumption of goods z in country i. Given the prices of goods and total consumption C, the optimal consumption for the representative household in country i of a good z is

$$C^i(z) = \left(\frac{P^i(z)}{P^i_{i'}} \right)^{-\sigma} C^i_{i'} \quad \text{and} \quad C^i_{i'} = \left(\frac{P^i_{i'}}{P^i} \right)^{-\varsigma} C^i \tag{11}$$

where $C^i_{i'}$ denotes per capita demand in country i for goods produced in country i', and $i' = H$ if $z \leq n$ and $i' = F$ otherwise. The price index that corresponds with aggregate consumption equals

$$P^i = \left[n {P^i_H}^{1-\varsigma} + (1-n) {P^i_F}^{1-\varsigma} \right]^{1/(1-\varsigma)} \tag{12}$$

and again P^i_H and P^i_F are price subindices of the goods from domestic and foreign origin available in country i,

$$P^i_H = \left[\frac{1}{n} \int_0^n P^i(z)^{1-\sigma} dz \right]^{1/(1-\sigma)} \quad \text{and} \quad P^i_F = \left[\frac{1}{1-n} \int_n^1 P^i(z)^{1-\sigma} dz \right]^{1/(1-\sigma)} \tag{13}$$

The first-order conditions with respect to real money balances, leisure and consumption imply,

$$\begin{aligned} N_M \left(\frac{M^i_t}{P^i_t} \right) &= U_C(C^i_t) - \beta E_t \left[U_C(C^i_{t+1}) \frac{P^i_t}{P^i_{t+1}} \right] && \textbf{(14)} \\ V_L(L^i_t) &= U_C(C^i_t) \frac{W^i_t}{P^i_t} && \textbf{(15)} \\ U_C(C^i_t) &= (1+i_t) \beta E_t \left[U_C(C^i_{t+1}) \frac{P^i_t}{P^i_{t+1}} \right] && \textbf{(16)} \end{aligned}$$

where i_t is the nominal interest rate. Equation **(16)** is the familiar Euler equation, in which the real interest rate reflects the intertemporal allocation of consumption. If we combine **(16)** with **(14)** we get a kind of ‘LM equation’:

$$N_M \left(\frac{M^i_t}{P^i_t} \right) = \frac{i_t}{1+i_t} U_C(C^i_t) \tag{17}$$

This LM equation can be interpreted as a link between a money supply target policy rule and an interest rate policy rule.(10)

We assume in our model that markets within each country are complete resulting in identical consumption levels across the individuals in country i. In the same vein we assume international asset market completeness such that we allow nominal contingent claims to be internationally traded as in Chari *et al* (2002). As a consequence the real exchange rate is proportional to the ratio of the marginal utilities of consumption in the two countries in our model, ie

$$Q_t \equiv \frac{S_t P_t^F}{P_t^H} = \kappa \frac{U_C(C_t^F)}{U_C(C_t^H)} \qquad \textbf{(18)}$$

with

$$\kappa = \frac{S_0 P_0^F U_C(C_0^H)}{P_0^H U_C(C_0^F)}$$

where S_t is a nominal exchange rate and κ is a constant initial value that is assumed to be 1.(11)

3.2 Firms and production technology

In each country i the representative firm is producing its output according to a production function which depends linearly on the amount of labour available

$$Y^i = A^i L^i \qquad \textbf{(19)}$$

where A^i is the level of labour productivity in country i. The labour force is assumed to be homogeneous within a country and perfectly competitive. Thus, the wages are set in order to satisfy the labour supply condition in equation **(15)**.

Both in domestic and overseas markets firms set the prices of their products in the currency of consumers. These prices will be fixed until a firm receives a signal to change its price, and this will occur with probability $1 - \alpha$ in each period. Let

$$\Xi_{t,s}^i = \beta^s \frac{U_C(C_{t+s}^i)}{U_C(C_t^i)} \frac{P_t^i}{P_{t+s}^i}$$

be the stochastic discount factor of a firm in country i. If a domestic firm receives a signal to change its price, it will set the price of its good in the domestic and foreign markets at t

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(10) See Woodford (2003, Chapter 2) for a more detailed discussion.

(11) Note that the assumption of complete nominal markets generates the ‘consumption-real exchange rate anomaly’ as pointed out in Chari *et al* (2002), ie the implied high correlation between relative consumption levels and real exchange rates is not observed in the data. Devereux and Engel (2002) study exchange rate movements under incomplete markets. By adding noise traders, they show that the correlation between consumption and the real exchange rate can be low. This is, however, beyond the scope of this paper since our main focus is on real exchange rate persistence.

such that the expected value of the firm's discounted profits is maximised, ie

$$E_t \sum_{s=t}^{\infty} \alpha^s \Xi_{t,s}^H \bigg[P_t^H(z) n C_{t+s}^H(z) + S_{t+s} P_t^F(z)(1-n) C_{t+s}^F(z) - \frac{W_{t+s}^H}{A_{t+s}^H} \{ n C_{t+s}^H(z) + (1-n) C_{t+s}^F(z) \} \bigg] \quad \textbf{(20)}$$

The aggregate price level is taken as given by an individual firm, and therefore the first-order conditions yield the optimal prices for a domestic firm, with $z \in [0, n]$, in both the domestic and overseas markets:

$$P_t^H(z) = \frac{\sigma}{\sigma - 1} \frac{E_t \sum_{s=t}^{\infty} \alpha^s \Xi_{t,s}^H \frac{W_{t+s}^H}{A_{t+s}^H} C_{t+s}^H(z)}{E_t \sum_{s=t}^{\infty} \alpha^s \Xi_{t,s}^H C_{t+s}^H(z)} \quad \textbf{(21)}$$

$$P_t^F(z) = \frac{\sigma}{\sigma - 1} \frac{E_t \sum_{s=t}^{\infty} \alpha^s \Xi_{t,s}^H \frac{W_{t+s}^H}{A_{t+s}^H} C_{t+s}^F(z)}{E_t \sum_{s=t}^{\infty} \alpha^s \Xi_{t,s}^H S_{t+s} C_{t+s}^F(z)} \quad \textbf{(22)}$$

Analogously, we can derive the optimal price levels for a foreign firm, with $z \in (n, 1]$, again for the home and foreign markets:

$$P_t^H(z) = \frac{\sigma}{\sigma - 1} \frac{E_t \sum_{s=t}^{\infty} \alpha^s \Xi_{t,s}^F \frac{W_{t+s}^F}{A_{t+s}^F} C_{t+s}^H(z)}{E_t \sum_{s=t}^{\infty} \alpha^s \Xi_{t,s}^F \frac{1}{S_{t+s}} C_{t+s}^H(z)} \quad \textbf{(23)}$$

$$P_t^F(z) = \frac{\sigma}{\sigma - 1} \frac{E_t \sum_{s=t}^{\infty} \alpha^s \Xi_{t,s}^F \frac{W_{t+s}^F}{A_{t+s}^F} C_{t+s}^F(z)}{E_t \sum_{s=t}^{\infty} \alpha^s \Xi_{t,s}^F C_{t+s}^F(z)} \quad \textbf{(24)}$$

As we assume an infinite number of firms in each country i, the law of large number holds for the aggregate price level in each country. This implies that as each individual firm receives a price signal with probability $1 - \alpha$, a fraction α of all firms in a country cannot change their prices. Consequently, a fraction $1 - \alpha$ of firms in each country sets a new price, $P_t^i(z)$. Hence, equation **(13)** can be rewritten as

$$P_{i',t}^i = \left(\alpha P_{i',t-1}^i(z)^{(1-\sigma)} + (1-\alpha) P_{i',t}^i(z)^{(1-\sigma)} \right)^{1/(1-\sigma)} \quad \textbf{(25)}$$

3.3 Linear dynamic system

In order to get a linear system of equations we log-linearise the system. We define the relative risk aversion parameter,

$$\rho \equiv -\frac{U_{CC}(\bar{C})\bar{C}}{U_C(\bar{C})}$$

and $\eta \equiv \frac{V_{LL}(\bar{L})\bar{L}}{V_L(\bar{L})}$. Time subscripts are omitted if the equation is intratemporal in nature.

The linearisation of our model can provide insight into the dynamic behaviour of households as well as firms in our model. In particular, it can give insight into the determination of fluctuations in the nominal and real exchange rates, domestic and foreign output and domestic and foreign rates of inflation.

Households

When we log-linearise Euler equation **(16)** we get

$$\begin{aligned} E_t\hat{C}^i_{t+1} - \hat{C}^i_t &= \frac{1}{\rho}(\hat{i}^i_t - E_t\pi^i_{t+1}) && \textbf{(26)} \\ E_t\hat{C}^W_{t+1} - \hat{C}^W_t &= \frac{1}{\rho}(\hat{i}^W_t - E_t\pi^W_{t+1}) && \textbf{(27)} \end{aligned}$$

Note that the world aggregate Euler equation is a weighted average of the Euler equations in two countries in our model.

A log approximation for the real exchange rate can be extracted from equation **(18)**,

$$\hat{Q} = \rho(\hat{C}^H - \hat{C}^F) \qquad \textbf{(28)}$$

When we combine equations **(26)** and **(28)**, we get the uncovered interest parity (UIP) relationship

$$E_t(\Delta S_{t+1}) = \hat{i}^H_t - \hat{i}^F_t = \hat{i}^R_t \qquad \textbf{(29)}$$

UIP holds in our model because of our complete market assumption and the use of rational expectations.

The output gap

We can define potential output as the level of output under fully flexible prices. The output gap is therefore defined as the log difference between actual output under sticky prices and potential output. Below we define the output gap in our model and discuss its economic implications. A detailed derivation of some of the variables can be found in Appendix A.

If we log-linearise the demand function **(11)** for each country, we can write the level of output under sticky prices as:

$$\begin{aligned}\hat{Y}^H &= n\left\{-\varsigma(\hat{P}^H_H - \hat{P}^H) + \hat{C}^H\right\} + (1-n)\left\{-\varsigma(\hat{P}^F_H - \hat{P}^F) + \hat{C}^F\right\} \\ &= \hat{C}^W + (1-n)\varsigma\hat{T}^W\end{aligned} \tag{30}$$

$$\begin{aligned}\hat{Y}^F &= n\left\{-\varsigma(\hat{P}^H_F - \hat{P}^H) + \hat{C}^H\right\} + (1-n)\left\{-\varsigma(\hat{P}^F_F - \hat{P}^F) + \hat{C}^F\right\} \\ &= \hat{C}^W - n\varsigma\hat{T}^W\end{aligned} \tag{31}$$

with

$$\hat{T}^W \equiv n\ln\left(\frac{P^H_F}{P^H_H}\right) + (1-n)\ln\left(\frac{P^F_F}{P^F_H}\right) \tag{32}$$

The terms of trade **(32)** is a weighted average of the relative price of foreign to home-produced goods in both the domestic and overseas market.

When we log-linearise our model under the assumption of flexible prices per capita consumption will be the same across countries and therefore through **(28)** the real exchange rate will be constant, which guarantees that the law of one price holds in the long run. Fluctuations in the relative price of overseas to domestic-produced goods(12) can thus only occur due to relative productivity movements. The log-linearised flexible price model now results in

$$\tilde{C}^H = \tilde{C}^F = \tilde{C} \;=\; \frac{\eta+1}{\eta+\rho}\left[n\hat{A}^H + (1-n)\hat{A}^F\right] \tag{33}$$

$$\tilde{T} \;=\; \frac{\eta+1}{\eta\varsigma+1}\left[\hat{A}^H - \hat{A}^F\right] \tag{34}$$

where $\tilde{X}$ is the log-deviation from the flexible price steady-state value of X for $X = C,\ T$. Log-deviations in consumption and the terms of trade under flexible prices therefore reflect movements in the world level of production technology and relative production technology respectively. For convenience we assume that world technology $\tilde{C}$ and relative technology $\tilde{T}$ behave like AR(1) processes

$$\tilde{C}_t = \varrho_C\tilde{C}_{t-1} + \nu^C_t, \qquad |\varrho_C| < 1 \tag{35}$$

$$\tilde{T}_t = \varrho_T\tilde{T}_{t-1} + \nu^T_t, \qquad |\varrho_T| < 1 \tag{36}$$

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(12) Across domestic and foreign markets this relative price is equal, as the law of one price holds in each period under flexible prices.

where, ν's are mean zero iid processes.

By analogy with the sticky-price output levels **(30)** and **(31)**, we can describe the potential output levels at home and abroad as

$$\tilde{Y}^H = \tilde{C} + (1-n)\varsigma\tilde{T} \quad \text{and} \quad \tilde{Y}^F = \tilde{C} - n\varsigma\tilde{T} \tag{37}$$

The output gap levels at home and abroad, denoted as $\dot{Y}$, can therefore be written as:

$$\dot{Y}_t^H = (\hat{C}_t^W - \tilde{C}_t) + (1-n)\varsigma(\hat{T}_t^W - \tilde{T}_t) \quad \text{and} \quad \dot{Y}_t^F = (\hat{C}_t^W - \tilde{C}_t) - n\varsigma(\hat{T}_t^W - \tilde{T}_t) \tag{38}$$

Our output gap measures are driven by a world output gap $(\hat{C}_t^W - \tilde{C}_t)$ common to both countries as well as relative productivity. Engel and West (2002) also use relative productivity shocks as a determinant for relative output gap movements.

The Phillips curve relationships

By log-linearising the price equations **(21)-(24)** we can get forward-looking Phillips curves to describe aggregate supply at home and abroad (see Appendix B),

$$\pi_t^H = \frac{\eta+\rho}{1+\sigma\eta}\zeta(\hat{C}_t^W - \tilde{C}_t) + \zeta(1-n)\widehat{Q}_t + \beta E_t\pi_{t+1}^H \tag{39}$$

$$\pi_t^F = \frac{\eta+\rho}{1+\sigma\eta}\zeta(\hat{C}_t^W - \tilde{C}_t) - \zeta n\widehat{Q}_t + \beta E_t\pi_{t+1}^F \tag{40}$$

where $\pi_t^i = \ln(P_t^i/P_{t-1}^i)$ for $i = H,\ F$ and

$$\zeta = \frac{(1-\alpha\beta)(1-\alpha)}{\alpha}$$

Hence, inflation in both countries is a function of inflation expectations, the world output gap and the real exchange rate. These Phillips curves can be rewritten as follows

$$\pi_t^W = \frac{\eta+\rho}{1+\sigma\eta}\zeta(\hat{C}_t^W - \tilde{C}_t) + \beta E_t\pi_{t+1}^W \tag{41}$$

$$\pi_t^R = \zeta\hat{Q}_t + \beta E_t\pi_{t+1}^R \tag{42}$$

and combining the country-specific Phillips curves like this makes it more obvious that real exchange rate movements are a major determinant of cross-country inflation differences.

In order to complete our linear dynamic system we define

$$\hat{Q}_t = \hat{Q}_{t-1} + \Delta S_t - \pi_t^R \tag{43}$$

$$\begin{aligned} \hat{T}_t^W &= \hat{T}_{t-1}^W + n(\pi_{F,t}^H - \pi_{H,t}^H) + (1-n)(\pi_{F,t}^F - \pi_{H,t}^F) \\ &= \hat{T}_{t-1}^W - \frac{1+\varsigma\eta}{1+\sigma\eta}\zeta(\hat{T}_t^W - \tilde{T}_t) + \beta E_t(\hat{T}_{t+1}^W - \hat{T}_t^W) \end{aligned} \tag{44}$$

based on our log-linearisation results for the households, the output gap measures and aggregate supply behaviour. Under certain conditions we can rewrite **(44)** as

$$\hat{T}_t^W = \lambda_1 \hat{T}_{t-1}^W + \lambda_1 \frac{\zeta(1+\varsigma\eta)}{1+\sigma\eta} \frac{1}{1-\beta\lambda_1\varrho_T} \tilde{T}_t \qquad \textbf{(45)}$$

where λ_1 is the smaller root of $x^2 - \left[1 + \frac{1}{\beta} + \frac{1}{\beta}\frac{\zeta(1+\varsigma\eta)}{1+\sigma\eta}\right] x + \frac{1}{\beta} = 0$ and $\lambda_1 \in (0,1)$. As shown in Benigno (2002), $\hat{T}_t^W$ only depends on relative productivity shocks as in **(45)**. This is because of our assumption of a common price stickiness parameter α for all goods across all countries. Benigno (2002) considers the case where the degree of price stickiness is different across and within countries. Note that even if relative productivity shocks are non-persistent, the terms of trade follows an AR(1) process since λ_1 cannot be zero.

Monetary policy rules

We use a forward-looking version of the policy rule to describe in our model monetary policy at home and abroad:

$$\begin{aligned}
\hat{i}_t^H &= \gamma_H \hat{i}_{t-1}^H + \phi_H E_t(\pi_{t+1}^H) + \psi_H \dot{Y}_t^H + \vartheta_H \widehat{Q}_t + \varepsilon_t^H && \textbf{(46)} \\
\hat{i}_t^F &= \gamma_F \hat{i}_{t-1}^F + \phi_F E_t(\pi_{t+1}^F) + \psi_F \dot{Y}_t^F - \vartheta_F \widehat{Q}_t + \varepsilon_t^F && \textbf{(47)}
\end{aligned}$$

where π is the inflation rate and $\dot{Y}$ is the output gap. The parameters ϕ and ψ are related to ϕ^* and ψ^* in **(3)** or **(5)** through $\phi = (1-\gamma)\phi^*$ and $\psi = (1-\gamma)\psi^*$. Interest rate rules **(46)** and **(47)** are typical open-economy monetary policy rules, in that the central bank not only targets inflation and the degree of economic activity but also the real exchange rate, see eg Engel and West (2002).

Although the empirical analysis in Section 2 was based on monetary policy functions without a real exchange rate target, as the inclusion of this target appears to be rejected by the data, we will examine the theoretical effect in our DSGE setting for sake of completeness. We assume for the monetary policy rule shocks

$$\varepsilon_t^i = \varrho_i \varepsilon_{t-1}^i + \nu_t^i, \quad \text{for } i = \text{H, F} \qquad \textbf{(48)}$$

where the ν^i's are mean zero and bounded variance iid processes. Again, we theoretically analyse the effect of persistent monetary policy rule shocks for completeness, even though the empirical analysis in Section 2 has shown that econometrically well-behaved estimated policy rules imply for our data that $\varrho_i = 0$ for $i = H,\ F$.

While most of the theoretical work assume identical parameters across domestic and foreign interest rate policy rules, see for example Engel and West (2002), we allow for asymmetric values of these parameters. As such we can determine how cross-country differences in how central banks set their monetary policy can affect the rate of real exchange rate persistence.

The complete linear dynamic system

We can assemble the linear equations **(27)**, **(29)**, **(35)**, **(36)**, **(41)-(43)**, and **(45)-(48)** in a system like[13]

$$\mathbf{A}E_t \begin{pmatrix} \mathbf{y}_{t+1} \\ \mathbf{x}_t \end{pmatrix} = \mathbf{B} \begin{pmatrix} \mathbf{y}_t \\ \mathbf{x}_{t-1} \end{pmatrix} + \mathbf{C}\nu_t \qquad \mathbf{(49)}$$

where $\mathbf{A}$ is a 12×12 matrix, $\mathbf{B}$ is a 12×12 matrix, $\mathbf{C}$ is a 12×4 matrix, the vector of endogenous variables reads $\mathbf{y} = (\hat{C}^W\ \pi^W\ \pi^R\ \Delta\hat{S})'$, the vector of predetermined variables equals $\mathbf{x} = (\hat{\imath}^H\ \hat{\imath}^F\ \hat{Q}\ \hat{T}^W\ \tilde{C}\ \tilde{T}\ \varepsilon^H\ \varepsilon^F)'$, and the vector of shocks is $\nu = (\nu^T\ \nu^C\ \nu^H\ \nu^F)'$.(14) Linear system **(49)** can be rewritten as

$$E_t \begin{pmatrix} \mathbf{y}_{t+1} \\ \mathbf{x}_t \end{pmatrix} = \mathbf{D} \begin{pmatrix} \mathbf{y}_t \\ \mathbf{x}_{t-1} \end{pmatrix} + \mathbf{F}\nu_t \qquad \mathbf{(50)}$$

with $\mathbf{D} = \mathbf{A}^{-1}\mathbf{B}$ and $\mathbf{F} = \mathbf{A}^{-1}\mathbf{C}$. As shown in Blanchard and Kahn (1980), when we assume that $\mathbf{D}$ in **(50)** has 8 eigenvalues inside the unit circle and 4 outside this will result in a unique bounded rational expectation solution given the initial values $\mathbf{x}_0$. As we are not interested in, for example, the bubble solution of our system we assume hereafter that $\mathbf{D}$ indeed complies with the rational expectations condition.

3.4 Some analytical results

The linear dynamic system that we set up in Section 3.3 can be used to derive some theoretical insights. In particular, we attempt to show in this subsection what role systematic monetary policy plays in the degree of real exchange rate persistence within our DSGE model.

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(13) We use the programs from Woodford's web site, www.princeton.edu/˜woodford/Tools/, to solve this system of linear equations.

(14) A more detailed description of this linear dynamic system can be found in Appendix C.

Table B: List of variables and parameters

Variables[a]	Description
S	Nominal exchange rate
Q	Real exchange rate
C	Consumption
π	Inflation rate
i	Nominal interest rate
T	Terms of trade
$\tilde{C}$	World production technology
$\tilde{T}$	Relative production technology
ε^H	Domestic policy rule shock ($\varepsilon_t^H = \varrho_H \varepsilon_{t-1}^H + \nu_t^H$)
ε^F	Foreign policy rule shock ($\varepsilon_t^F = \varrho_F \varepsilon_{t-1}^F + \nu_t^F$)
ν^C	World production technology shock
ν^T	Relative production technology shock
ν^H	Domestic interest rate shock
ν^F	Foreign interest rate shock

Parameters	Description
β	Discount factor
ρ	The relative risk averse parameter (the inverse of intertemporal rate of substitution)
η	The inverse of the labour supply elasticity
ς	The elasticity of substitution between 'home' goods and 'foreign' goods
σ	The elasticity of substitution among the variety of goods within 'home' goods and 'foreign' goods
ϱ_x	Persistence of exogenous shocks (eg $\tilde{C}_t = \varrho_C \tilde{C}_{t-1}$, $\varepsilon_t^H = \varrho_H \varepsilon_{t-1}^H + \nu_t^H$)
γ	Coefficient of interest rate smoothing in the monetary policy rules **(46)** and **(47)**
ϕ	Coefficient on expected inflation in the monetary policy rules **(46)** and **(47)**
ψ	Coefficient on the output gap in the monetary policy rules **(46)** and **(47)**
ϑ	Coefficient on the real exchange rate in the monetary policy rules **(46)** and **(47)**

(a) For given variables X^H and X^F, a world variable is defined as $X^W \equiv nX^H + (1-n)X^F$, and a relative variable is defined as $X^R \equiv X^H - X^F$.

Identical monetary policy behaviour across countries

If monetary policy at home and abroad are set in an identical manner we have $\gamma_H = \gamma_F \equiv \gamma$, $\phi_H = \phi_F \equiv \phi$, $\psi_H = \psi_F \equiv \psi$, $\vartheta_H = \vartheta_F \equiv \vartheta$ in **(46)** and **(47)**.(15) By subtracting equation **(47)** from **(46)** we get

$$\hat{i}_t^R = \gamma \hat{i}_{t-1}^R + \phi E_t(\pi_{t+1}^R) + \psi\varsigma(\hat{T}_t^W - \tilde{T}_t) + 2\vartheta\widehat{Q}_t + \varepsilon^R \qquad \textbf{(51)}$$

Using equations **(29)**, **(42)**, **(43)**, **(45)**, and **(51)**, we can close our linear dynamic system with π^R, i^R, ΔS, $\hat{T}^W$ and the exogenous variables $\tilde{T}$, ε^H, ε^F. Therefore, $\hat{Q}$, π^R, i^R, ΔS, and $\hat{T}^W$ only depend on each other and the current and lagged values of the predetermined variables $\tilde{T}$, ε^H, ε^F. Hence, when monetary authorities at home and abroad exhibit the same behaviour the real exchange rate is not affected by movements in world consumption $\hat{C}^W$ and shocks to world productivity $\tilde{C}$.

This result makes it clear that if the monetary authorities of both countries react in the same manner, then common productivity shocks will not have any effect on the relative terms in our artificial two-country economy. Therefore if world productivity ($\tilde{C}_t$) is persistent then the persistence of the real exchange rate can only be influenced by the persistence of $\tilde{C}_t$ if there are cross-country differences in monetary policies behaviour. We will show in the calibration exercises in Section 4, that common technology shock can generate interesting real exchange rate movements if one allows for these differences in central bank behaviour.(16)

Sources of real exchange rate persistence

If monetary policy does not exhibit any interest rate smoothing, the monetary authority will immediately adjust its interest rate in response to movements in the potential target variables, ie expected inflation, the output gap and the real exchange rate. However, this will markedly change the role of monetary policy in generating persistent real exchange rate movements:

Proposition 3.1 If monetary policies in both countries does not exhibit interest rate smoothing, ie $\gamma_H = \gamma_F = 0$ in **(46)** and **(47)**, real exchange rate persistence can only be due

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(15) A summary of the parameters and variables in our model and their meaning can be found in Table B.

(16) Note that in this case we assume that the home and foreign central banks have different loss functions. On the other hand, throughout the paper we always assume that representative consumers at home and abroad have identical utility functions, and thus the home and foreign welfare functions are identical. While this apparent contradiction is inevitably a comprise to allow for asymmetries in the nominal side of the model, one can justify it by assuming that utility can be identical across countries because it is a description of human nature, while cross-country differences in central bank loss functions can occur due to differences in political institutions, legal systems and so on.

to the persistence of the exogenous variables T^W, $\tilde{T}$, $\tilde{C}$, ε^i, given that we have a unique bounded rational expectation solution.(17)

Proof. See Appendix D. This result is a more general version of Proposition 2 in Benigno (2002). Note that this result does not depend on whether we allow for cross-country differences in the parameters in the domestic and foreign interest rate policy rules, **(46)** and **(47)**, or whether we allow for the case that monetary authorities target the real exchange rate.

Proposition 3.1 makes it clear that, in contrast to Engel and West (2002), interest rate smoothing needs to be part of the monetary policy rules at home and abroad in our model instead of real exchange rate targeting to generate real exchange rate persistence with monetary shocks. In fact, the observed real exchange rate persistence may result from monetary policy inertia rather than price stickiness *per se*, and if we have non-persistent exogenous shocks interest rate smoothing is the most important source for real exchange rate persistence. Given the previous results we can identify the following sources of real exchange rate persistence:

1. Persistent monetary policy rule shocks ($\varrho_H > 0$ in **(46)** and/or $\varrho_F > 0$ in **(47)**).
2. Persistent world production technology, ie $\varrho_C > 0$ in **(35)** in combination with monetary policies which are asymmetric across the two countries.
3. Non-constant relative production technology $\tilde{T}_t$ only if at least one of the monetary authorities targets the output gap, ie $\psi \neq 0$ in **(46)** or **(47)**. The reason for this is that $\tilde{T}_t$ affects the output gap measures at home and abroad; see **(38)**.
4. Interest rate smoothing.

4 The interaction between real exchange rates and systematic monetary policy

In this section we analyse the implications of the estimated German and UK monetary policy rules from Section 2 for the real exchange rate within the structure of the DSGE model from Section 3. We focus in particular on how the different types of cross-country asymmetry in monetary policy rules affect the transmission of nominal and productivity shocks through the real exchange rate and how these differences affect the degree of real exchange rate persistence.

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(17) See Table B for an overview of the parameters and variables in our model.

Section 4.1 describes how we calibrate our DSGE model, how we identify the productivity shock processes using our data, and how we want to analyse the aforementioned phenomena. The results of our analysis are reported in Section 4.2.

4.1 Parameterisation and stylised facts

In order to be able to assess the effect of systematic monetary policy on real exchange rate persistence we have to parameterise the DSGE model from Section 3. The Home country size n is computed using the 2000 PPP-based US dollar values of real GDP for Germany and the United Kingdom. Based on these values the German economy is roughly twice as large as the UK economy and thus we set $n = \frac{1}{3}$. Following the calibration in Benigno (2002) and Chari *et al* (2002) we assume the following values for our preference parameters:

- The discount rate β is set equal to $\beta = 0.996$, which implies an annual discount rate of 0.953 in our monthly setting.
- The relative risk averse parameter (otherwise known as the inverse of the intertemporal rate of substitution) ρ is set equal to $\rho = 6$.
- The inverse of labour supply elasticity η is set equal to $\eta = 2$.
- We assume a value of 1.5 for the elasticity of substitution between Home goods and Foreign goods, ie $\varsigma = 1.5$.
- Finally, the elasticity between the variety of goods from each country σ is assumed to be 10, ie $\sigma = 10$.
- We estimate **(35)** by estimating an AR(1) model on a quadratically detrended weighted average (see **(37)**) of the German and UK HP-filter trend values of log industrial production from Section 2.2, which yields $\varrho_c = 0.96$ and STD($\nu_c) = 0.012.$ (18)
- We estimate **(36)** by estimating an AR(2) model on the difference (based on **(37)**) between the UK and German HP-filter trend values of log industrial production from Section 2.2, which yields $\varrho_c = 0.95$ (equals the sum of the two autoregressive parameters) and STD($\nu_T) = 0.0179)$. We than rescale the process by $1/\varsigma$, see **(37)**.

The aforementioned set of calibrated preference and technology parameters is assumed to have remained constant over our 1979-98 sample. For monetary policy behaviour this is, however, not appropriate, as we showed in Section 2.2. In that subsection we showed that

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(18) We detrend the HP-filter trends as we do not allow for population growth and capital formation in our DSGE model.

Table C: Real exchange rate facts under different UK monetary policy regimes[(a)]

	Corr($\hat{Q}_t$, $\hat{Q}_{t-1}$)	STD($\hat{Q}$)	STD(ΔQ)	STD(ΔS)	Corr (ΔS_t,ΔQ_t)
	Empirical real exchange rate facts				
1979:07-1990:10	0.962	6.09%	2.33%	2.22%	0.960
1990:11-1992:10	0.503	2.92%	1.67%	2.23%	0.972
1992:11-1998:12	0.973	8.17%	1.90%	1.93%	0.956
	Real exchange rate facts from DSGE model: $\alpha = 0.94$				
1979:07-1990:10	0.935	4.87%	1.75%	1.82%	0.992
1992:11-1998:12	0.919	1.25%	0.50%	0.52%	0.991
	Real exchange rate facts from DSGE model: different α*'s*				
1979:07-1990:10 ($\alpha = 0.92$)	0.914	3.75%	1.55%	1.64%	0.986
1992:11-1998:12 ($\alpha = 0.96$)	0.946	1.95%	0.64%	0.65%	0.995

(a) The values are based on monthly data. The variable $\hat{Q}_t$ is the log-deviation from its steady-state value, which equals the log of the real exchange rate Q_t as in the long-run PPP is assumed to hold in the model. Variable ΔQ_t (ΔS_t) is the relative change of the real exchange rate Q_t (nominal exchange rate S_t). The expression 'Corr(a, b)' indicates the correlation between two variables a and b, whereas 'STD(a)' equals the standard deviation of a variable a. The parameter α is the Calvo price stickiness parameter used in our DSGE model.

for Germany we could comfortably identify a single interest rate policy rule for the whole 1979-98 sample, but for the United Kingdom we identified three regimes: pre-ERM, ERM and inflation targeting. In the forthcoming calibration and simulation exercises we will focus on regimes 1 and 3, meaning using the above-mentioned values of preference and technology parameters, the single 1979-98 estimated German policy rule, and either the 1979-90 pre-ERM UK estimated policy rule (Regime 1) or the 1992-98 inflation targeting UK-estimated policy rule (Regime 3). Table A reports the different parameter values in the German and UK-estimated Taylor rules.(19)

One crucial feature is the value of the Calvo price stickiness parameter α. As a baseline case we set this parameter equal to a value $\alpha = 0.94$, which implies an average price rigidity of a little less than 1.5 years. How does our DSGE model compare to the data when using the aforementioned values of the preference parameters, $\alpha = 0.94$, and the parameter values of the estimated monetary policy feedback rules for Germany and the

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(19) In the case of the inflation-targeting estimate of the UK policy rule, we sum the parameters on the two lags of the interest rate into one when we feed this estimated rule in our calibrated DSGE model.

United Kingdom from Section 2? In the upper panel of Table C we report some stylised facts on the Germany/UK real exchange rate relationship over the three identified phases in UK monetary policy: pre-ERM, ERM and inflation targeting. The real exchange rate is highly autocorrelated in the first and third period, whereas under the ERM the real exchange rate is not very persistent and less volatile, which is not surprising given the results in Mussa (1986). As we are interested solely in the effects of systematic monetary policy under floating rates, we focus on the effects of the first and third regimes in our DSGE model. In the middle panel of Table C we show the main result of our calibration exercise under $\alpha = 0.94$. We observe a very high correlation between ΔS_t and ΔQ_t, and this is because we have a volatile nominal exchange rate relative to the inflation differential π^R. This result is consistent with, for example, Engel and West (2002). However, the observed ranking of first-order real exchange rate autocorrelation does not match the data. In order to check whether this ranking is due to an improper calibration of the preference parameters in our DSGE model, we show in Chart 1 the implied first-order autocorrelation and standard deviation of the real exchange rate across the two regimes in our DSGE model (using $\alpha = 0.94$) over a wide range of different preference parameter values. From this chart it becomes apparent that the ranking of real exchange rate persistence and volatility over the two regimes is not affected by variations in the preference parameters.

Given the observed switch in systematic monetary policy behaviour, see Table A, it is doubtful that the degree of price stickiness remains constant over time. Under high and variable inflation, firms have the incentive to change their prices more frequently, whereas under low and stable rates of inflation it becomes less necessary for firms to change prices. There is empirical evidence that suggests that monetary policy regime-dependent shifts in the degree of price stickiness have occurred. For the United States, Ireland (2002), for example, estimates a New Keynesian model with Rotemberg-style costs of price adjustment with data from the pre-Volcker-Greenspan era up to 1979, and the Volcker-Greenspan period after 1979, and he finds that the estimated cost of price adjustment for firms is higher in the latter period when, on average, inflation is lower. In the case of the United Kingdom, Benati (2004) finds that the Phillips trade-off between inflation and unemployment, measured at business cycle frequencies, became flatter after the introduction of inflation targeting by the end of 1992, suggesting that UK prices became more rigid after the monetary regime change in 1992 Q4. Ideally, one would like to use a framework in which the degree of price stickiness depends on the state of the economy, as in Dotsey, King and Wolman (1999), or is dependent on the average inflation rate (Bakhshi, Burriel-Llombart, Khan and Rudolf (2003)) to model this phenomenon. However, due to their complexity these models have up to now only been used in a closed-economy setting. Hence, for sake of tractability, we do not allow for endogenous price rigidity in our model, but let the Calvo price stickiness parameter shift exogenously over the different monetary regimes.

In order to investigate this shift in the degree of price stickiness over the regimes, we recalculate the implied stylised facts from our DSGE model with $\alpha = 0.92$ under Regime 1 and with $\alpha = 0.96$ under Regime 3. A Calvo parameter $\alpha = 0.92$ implies an expected price rigidity of about one year for 1979:03-1990:10, whereas $\alpha = 0.96$ implies an expected price rigidity of about two years for 1992:11-1998:12. When we use these values of α over the two regimes we can see from the lower panel of Table C that in terms of the first-order autocorrelation of the real exchange rate the implied ranking from the DSGE model matches the observed ranking in the data.(20)

4.2 Characterising real exchange rate persistence under different regimes

Based on the model-implied real exchange rate stylised facts from Section 4.1, we will analyse within our DSGE model the implications of different types of systematic monetary policy on real exchange rate persistence with $\alpha = 0.92$ for the pre-ERM regime and $\alpha = 0.96$ for the inflation-targeting regime plus the corresponding estimated monetary policy rules from Section 2.2. We will compute the implied response of real exchange rate under each regime to each of the four shocks in our DSGE model: a common productivity shock, a relative productivity shock, a Home monetary shock and a Foreign monetary shock. Next, we utilise Monte Carlo experiments to back out the implied half-life of the real exchange rate under each regime when the system is hit at random by the four shocks.

In order to investigate the effect from each shock, we use the impulse response functions in our model, and these are reported in Chart 2 for the 1979-90 pre-ERM regime or Regime 1 and in Chart 3 for the 1992-98 inflation-targeting regime or Regime 3. The implied DM/UK real exchange rate reaction to either Home or Foreign monetary shocks (bottom panels of Charts 2 and 3 respectively) does not seem to differ much between Regime 1 and Regime 3. While the Home and Foreign monetary shocks themselves are not persistent

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(20) From a more mechanical point of view, with a stable Calvo parameter over the two UK monetary policy regimes, the fact that real exchange rate persistence is lower under inflation targeting is due to the insignificance of the output gap target in the estimated UK policy rule under that regime. By setting the output gap coefficient to zero in the inflation-targeting regime UK policy rule, the persistent relative shock has less of an impact on the real exchange rate in the model than otherwise would be the case. One alternative, contrary to introducing regime-dependent shifts in price stickiness, would be to consider the sterling bilateral *vis-à-vis* the euro area, with synthetic data before 1999, so that one can extend the sample to 2002/03. In this case one would have more observations for the United Kingdom under the inflation-targeting regime, which would facilitate a more powerful estimation of the UK policy rule, possibly resulting in a significant output gap coefficient in this policy rule. We intend to pursue this in a future version of the paper.

Chart 1: Model sensitivity to the real parameters

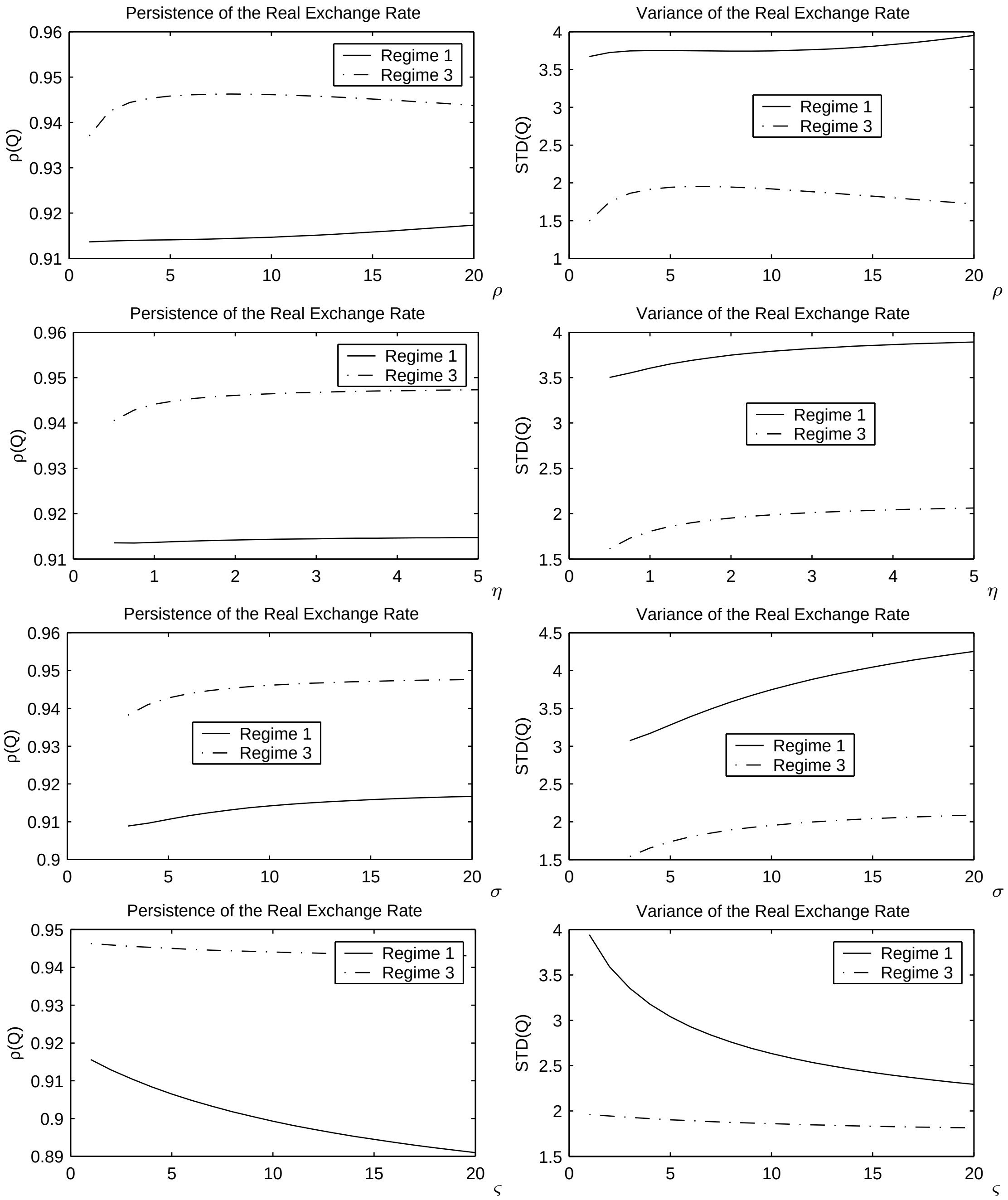
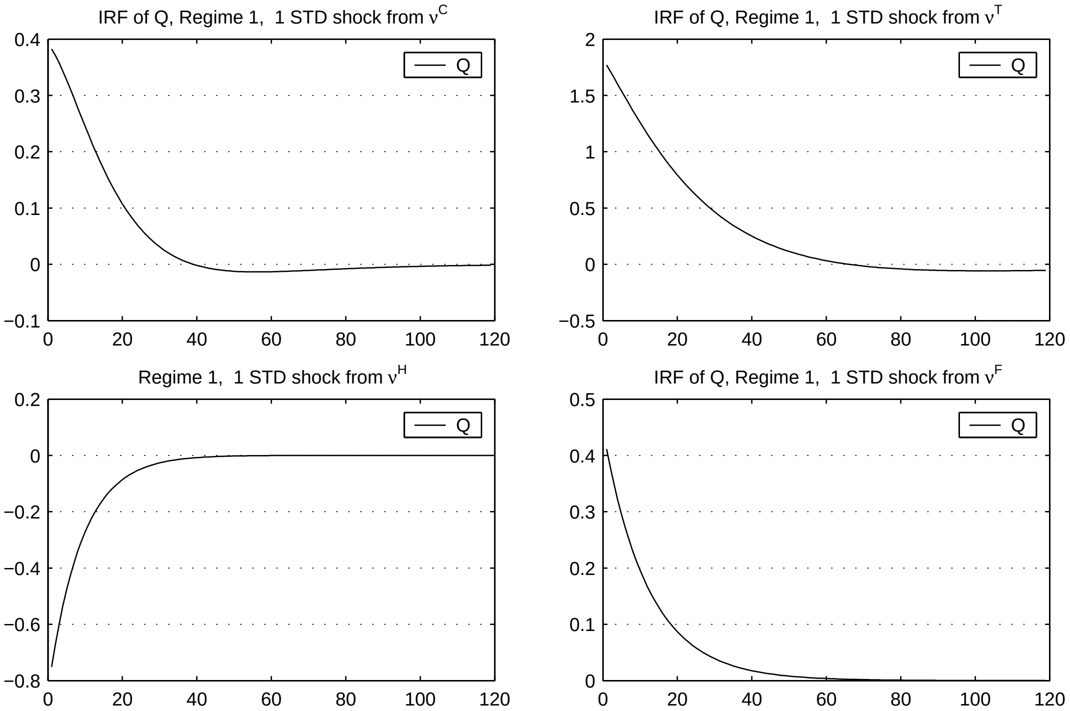
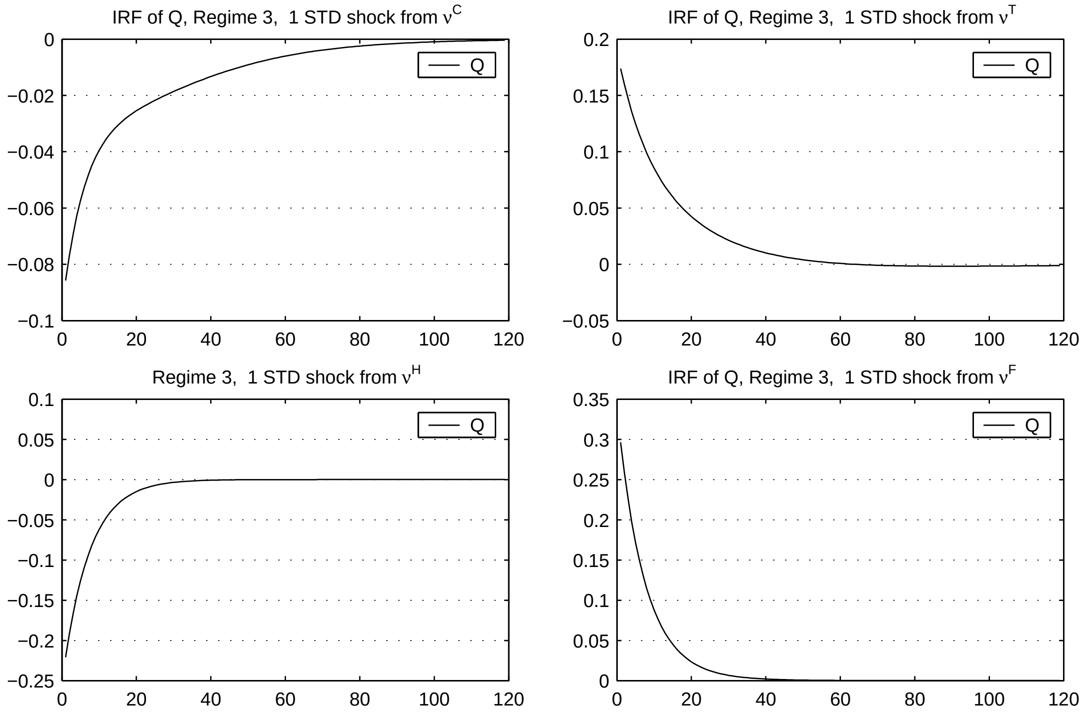


Chart 2: Impulse response function of the real exchange rate, Regime 1



The chart reports the response of the real exchange rate to a common production technology shock, a relative production technology shock, a UK monetary policy shock and a German monetary policy shock respectively. In each graph the y-axis is in units of log deviation from the steady-state level, whereas the x-axis depicts the number of months.

Chart 3: Impulse response function of the real exchange rate, Regime 3



The chart reports the response of the real exchange rate to a common production technology shock, a relative production technology shock, a UK monetary policy shock and a German monetary policy shock respectively. In each graph the y-axis is in units of log deviation from the steady-state level, whereas the x-axis depicts the number of months.

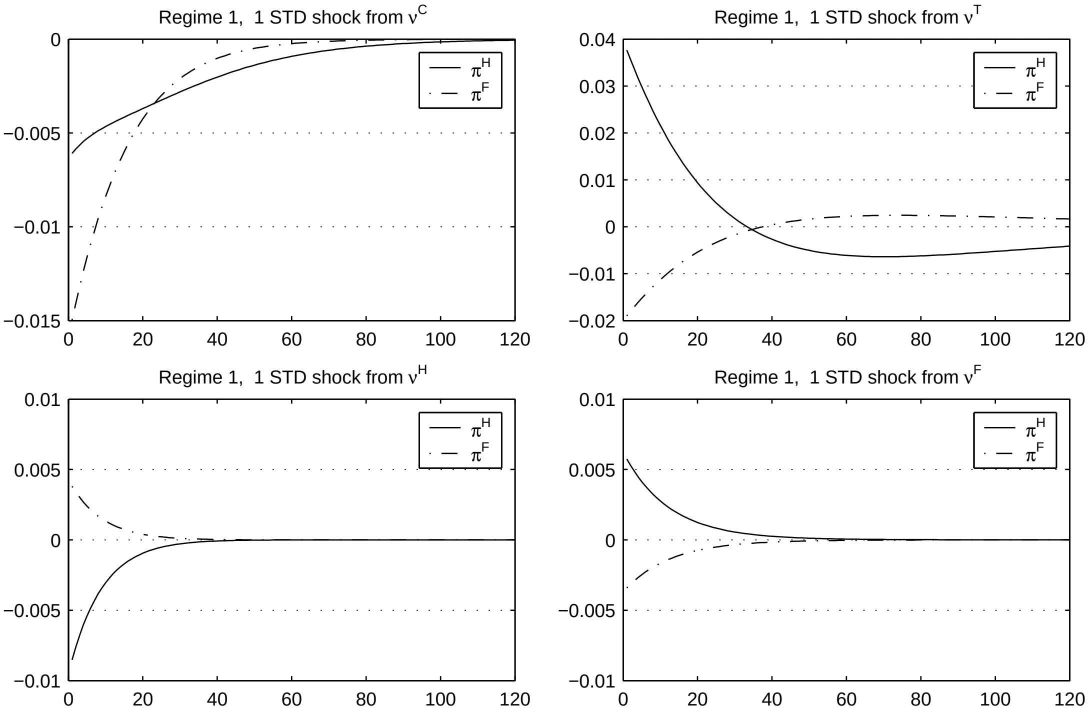
they still generate persistent effects on the real exchange rate, mainly due to interest rate smoothing and local-currency pricing. Nonetheless, the real exchange rate persistence caused by these shocks in Charts 2 and 3 is not large.

The effect of a common productivity shock, however, differs significantly among the two regimes, see the left-hand graph in the upper rows of Charts 2 and 3. In Regime 1, the DM/UK real exchange rate depreciates, then comes back to its original level within 2 years, after which it slightly appreciates and returns to its steady-state value. Compared to Regime 3, however, the effect of the common productivity shock is generally small. In Regime 3, the common shock results in a real appreciation of sterling and the real exchange rate returns to its steady-state value very slowly, ie after approximately 6.5 years. From the right-hand side graphs in the upper rows of Charts 2 and 3 it becomes apparent that the magnitude of the impact of the relative productivity shock on the real exchange rate was relatively higher in the pre-ERM Regime 1 than under the inflation-targeting Regime 3. The effect of the relative productivity shock is slightly more persistent under the UK inflation-targeting regime than under Regime 1, where under the latter it ceases to have an effect after approximately 3 years as supposed to approximately 5 years under the former. Note, however, that in contrast to the common real shock the direction of change of the real exchange rate as a consequence of a relative productivity shock is not different across the monetary policy regimes. One must also be aware of the fact that the observation that productivity shocks in our DSGE model have a more persistent effect on the real exchange rate is due to the persistent effect of these shocks on the steady-state values of consumption and the terms of trade, ie $\tilde{C}$ and $\tilde{T}$. The difference in systematic monetary policy behaviour matters, as it affects the dynamics after the occurrence of the productivity shocks.

Charts 4 to 7 report how inflation and interest rates at home and abroad react to the four shocks. In particular, in the case of the common real shock UK monetary authorities seem to have reacted in a more accommodating way than Germany under the pre-ERM Regime 1. But under Regime 3 German and UK monetary authorities reacted in a fairly similar direction and as a result the persistency of the common productivity shock was fully transmitted to the real exchange rate.

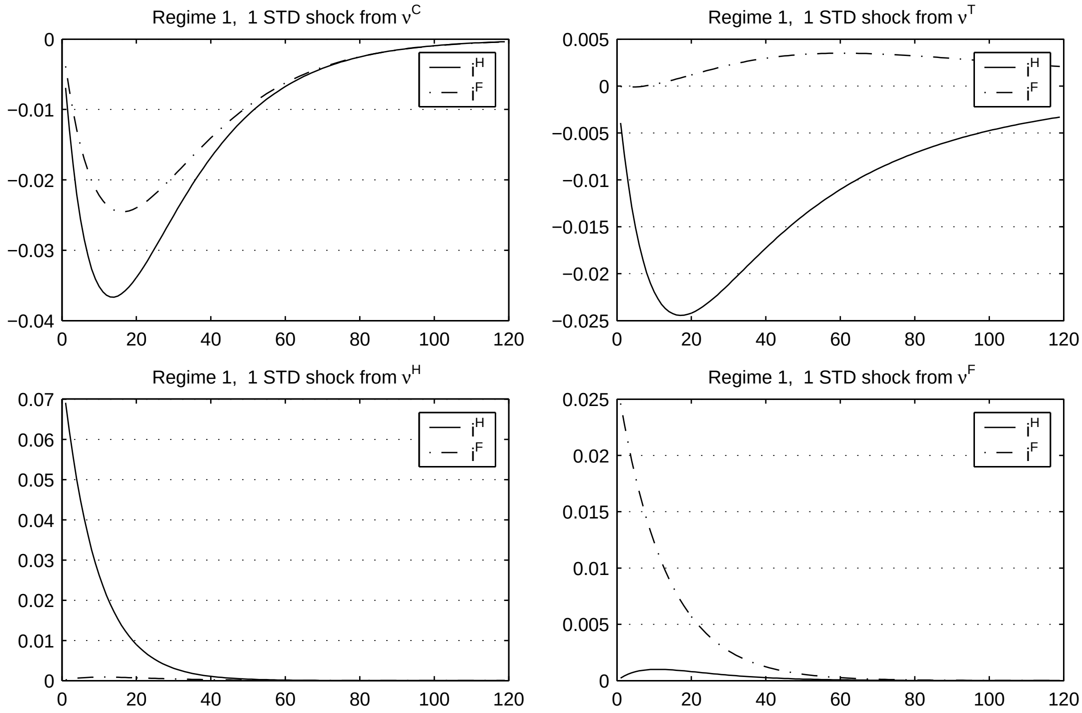
A commonly used measure of the degree of real exchange rate persistence generated by DSGE models is the first-order autocorrelation of the real exchange rate, see Table C. This is, however, a very crude measure of persistence as it ignores higher-order dynamics and potential non-stationarity. An alternative measure used in the empirical exchange rate literature is the augmented Dickey and Fuller (1979) (ADF) unit root test, which is a t-test

Chart 4: Impulse response functions of the inflation rates, Regime 1



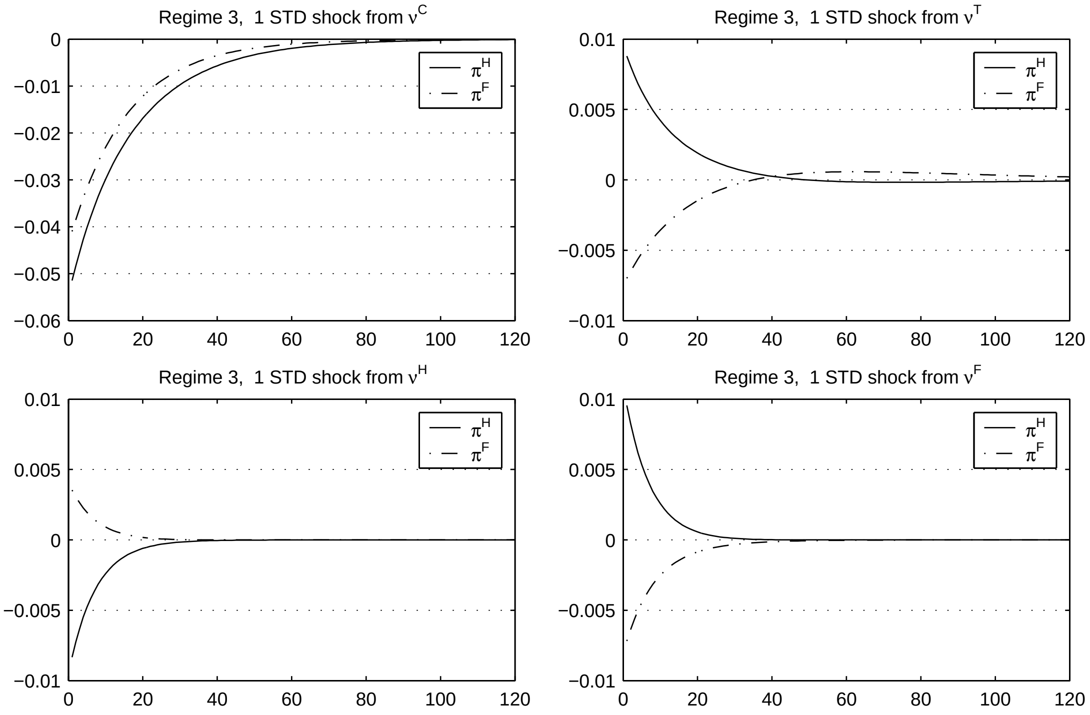
The chart reports the responses of UK and German inflation to a common production technology shock, a relative production technology shock, a UK monetary policy shock and a German monetary policy shock respectively. In each graph the y-axis is in units of log deviation from the steady-state level, whereas the x-axis depicts the number of months.

Chart 5: Impulse response functions of the interest rates, Regime 1



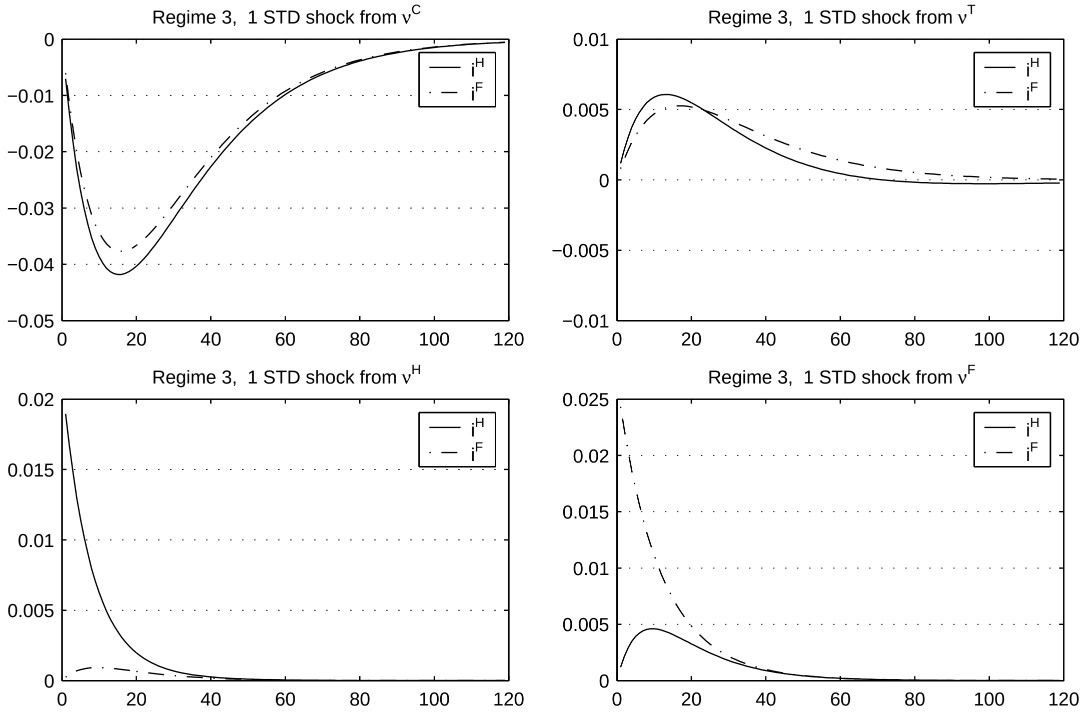
The chart reports the responses of the UK and German interest rates to a common production technology shock, a relative production technology shock, a UK monetary policy shock and a German monetary policy shock respectively. In each graph the y-axis is in units of log deviation from the steady-state level, whereas the x-axis depicts the number of months.

Chart 6: Impulse response functions of the inflation rates, Regime 3



The chart reports the responses of UK and German inflation to a common production technology shock, a relative production technology shock, a UK monetary policy shock and a German monetary policy shock respectively. In each graph the y-axis is in units of log deviation from the steady-state level, whereas the x-axis depicts the number of months.

Chart 7: Impulse response functions of the interest rates, Regime 3



The chart reports the responses of the UK and German interest rates to a common production technology shock, a relative production technology shock, a UK monetary policy shock and a German monetary policy shock respectively. In each graph the y-axis is in units of log deviation from the steady-state level, whereas the x-axis depicts the number of months.

Table D: Persistence of the DM/UK real exchange rate under different UK monetary policy regimes[(a)]

		ADF-AIC	Lags	HL-AIC	ADF-BIC	Lags	HL-BIC
		Historical persistence					
1979:07-1990:10		-2.94^{**}	1	12	-2.94^{**}	1	12
1992:11-1998:12		-1.92	8	16	-0.63	1	53
Persistence implied by DSGE model: Simulated power ADF and mean half-life							
Pre-ERM regime	$T = 136$	36.2%		7.6	42.8%		7.5
	$T = 100$	26.5%			30.4%		
Inflation-targeting regime	$T = 74$	18.2%		12.2	17.5%		12.1
	$T = 100$	19.0%			18.9%		

(a) The column denoted with 'ADF-AIC' report in the upper panel the empirical value of the ADF unit root t-test based AIC lag order selection, where * (**) [***] denotes a rejection of the unit root null hypothesis based on MacKinnon (1991) critical values, whereas in the lower panel the values in this column report the empirical power ratios based on Monte Carlo simulations of our DSGE model. The column denoted with 'HL-AIC' reports in the upper panel the empirical half-life estimate through **(53)** via **(52)** using AIC lag order selection, whereas in the lower panel we report the Monte Carlo mean of the half-life from our DSGE model. Similar statistics can be found in columns 'ADF-BIC' and 'HL-BIC' based on BIC lag order selection.

of H_0: $\rho - 1 = 0$ in

$$\Delta q_t = \delta_0 + (\rho - 1)q_{t-1} + \sum_{j=1}^{p-1} \delta_j \Delta q_{t-j} + \epsilon_t \tag{52}$$

where q_t is the log real exchange rate and ρ measures the sum of the autoregressive parameters of the AR(p) model of the *level* of q_t. In the upper panel of Table D we report the ADF unit root test result for each of the two subperiods, ie the 1979:07-1990:10 pre-ERM period and the 1992:11-1998:12 inflation-targeting period, both within **(52)** where the lag order $p-1$ is selected through the Akaike Information Criterion (AIC) as well as the Bayesian-Schwarz Information Criterion (BIC). These empirical unit root test results indicate that for the first pre-ERM regime we have a pretty robust rejection of the unit root in the real exchange rate, whereas for the inflation targeting Regime 3 we have the opposite result. The estimated ρ from **(52)** can also be used to construct a measure of the half-life of shocks to the real exchange rate through

$$\text{HL} = \frac{\ln(0.5)}{\ln(\rho)} \tag{53}$$

and these half-life measures are also reported in the upper panel of Table D. For Regime 1 we have a robust finding of a half-life of 1 year, whereas under Regime 3 half-life estimates are much more variable and range from 1.33 years up to about 4.5 years. Hence, it most likely has been the case that real persistence rose to a certain extent under inflation targeting relative to the pre-ERM framework up to 1990.

Can we reproduce this different pattern in real exchange rate persistence across policy regimes within our DSGE setting? In order to be able to answer this, we do some Monte Carlo analysis with our DSGE model both under the first regime based on $\alpha = 0.92$ and the corresponding policy rule estimates from Section 2.2 as well as under Regime 3 with $\alpha = 0.96$ and corresponding policy rule estimates. We draw the productivity shocks from normal distributions which are parameterised through the calibration of Section 4.1, and are assumed to be identical over the two regimes. The Home and Foreign monetary shocks are drawn from zero-mean normal distributions with a standard deviation set equal to the estimated standard error of the policy rule regressions from Table 2.2.

The first type of Monte Carlo experiment we do is estimating the empirical power of the ADF unit root test on the finite sample generated from our DSGE model for each of the two regimes. As the DSGE model imposes long-run PPP, and therefore generates a stationary real exchange rate series, the empirical power ratio at a certain significance level is simply the number of rejections of the null hypothesis of a unit root across the number of Monte Carlo iterations. The results of this Monte Carlo-based power analysis at the 5% significance level based on either using AIC or BIC in **(52)**, utilising 10,000 simulations, can be found in the lower panel of Table D.(21) The first row in the lower panel of this table reports the empirical power for the empirical sample size under each regime. At the empirical sample size the ADF unit root test has certainly more power to reject the false null of a unit root in the real exchange rate under the pre-ERM regime than under the inflation-targeting regime. However, one can partly explain the larger power under the first pre-ERM regime based on the longer empirical sample size. We therefore repeated the exercise under an identical finite sample of 100 observations for each regime. From the second row for each regime in the lower panel of Table D it becomes clear that the results remain qualitatively unchanged.

Related to the first Monte Carlo experiment we also conduct an analysis of the distribution of the half-life shocks to the real exchange rate based on Monte Carlo simulations. The set-up is comparable to the previous Monte Carlo simulation but we now use **(52)** to compute the half-life through **(53)** based on 1,000 observations per iteration. In the lower panel of Table D we report the mean of the half-life estimates across the 10,000 Monte Carlo samples. The results indicate that even in large samples the half-life is bigger under the inflation-targeting regime than under the pre-ERM regime.

5 Conclusions

The persistence of real exchange rates since the breakdown of the Bretton Woods system of fixed exchange rates has been a long-standing issue in exchange rate research. Although nominal price stickiness plays a major role in real exchange rate persistence, studies like Chari *et al* (2002) have shown that this is not enough to explain the full extent of the observed degree of persistence. In this paper we investigate the role of cross-country differences in systematic monetary policy behaviour in generating real exchange rate persistence. Our approach is similar to the analysis in Clarida *et al* (2000) for the United States, in that we use a dynamic stochastic general equilibrium model and combine it with estimated monetary policy rules to investigate how real exchange rate persistence is affected by differences in the feedback mechanism of monetary policy at home and abroad.

We focus on the real exchange rate relationship between Germany and the United Kingdom over the period 1979-98 and in particular on subsamples when the corresponding nominal exchange rate was more or less flexible, ie the 1979-90 pre-ERM period and the 1992-98 inflation-targeting era. As a first step we estimate interest rate-based forward-looking monetary policy rules of the Clarida *et al* (1998b, 2000) type for

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(21) In each iteration we generate $T + 100$ observations on the artificial real exchange rate and then discard the first 100 in order to deal with initial value bias.

Germany over the whole sample and for the United Kingdom over the two subsamples. The estimation results indicate that for Germany and the United Kingdom under inflation-targeting monetary policy had a stabilising effect on inflation, whereas under the pre-ERM frameworks it on average more or less fully accommodated inflationary pressures in the short to medium term. Next, we build a two-country DSGE model with local-currency pricing, Calvo-type price stickiness, persistent real shock processes and asymmetric monetary policy rules. In analysing the model we show that real exchange rate persistence depends on the degree of interest rate smoothing by central banks at home and abroad as well as the persistent productivity measures. Finally, we calibrate the preference parameters and the productivity shocks as realistically as possible. Given these calibrations we feed the estimated policy rules across different regimes into the DSGE model and analyse how the general persistence of the real exchange rate is affected by this. The results of our analysis show that, as in the data, our DSGE model has the result that the degree of real exchange rate persistence is higher under the inflation-targeting regime than under the pre-ERM regime. This is mainly due to the fact that common productivity shocks are transmitted differently across the two regimes. Under the inflation-targeting regime UK monetary authorities react almost identically to the German authorities and as a consequence the nominal exchange rate will not counter-move the effect of the common productivity shock.

In future work we aim to analyse other real exchange rate relationships, in particular the relationship between Germany and the United States, in order to investigate the robustness of our results. We also want to make our DSGE model more realistic, in that we plan to allow in the simulations for cross-country differences in nominal price stickiness, where we now assume that this is identical across countries. Another feature of the current model is that the real exchange rate is assumed to be positively correlated with the cross-country consumption differential. Empirically, however, we do not observe this correlation, and one extension of the model, in order to replicate the absence of the above-mentioned correlation, is to assume incomplete asset markets and to add a noise component to the UIP relationship.

Appendix A: The model under flexible prices

Under fully flexible prices the nominal complete market assumption becomes the usual complete market assumption, which guarantees that $C^H = C^F$ and $P^H = SP^F$ (implying $\tilde{Q} = 0$) from period to period. However, relative prices still fluctuate due to productivity shocks.

The labour supply equation **(15)** can be linearised as,

$$\eta\tilde{L}^i + \rho\tilde{C} = \tilde{W}^i - \tilde{P}^i \qquad \textbf{(A-1)}$$

Based on **(A-1)** we can now construct world and relative labour supply relationships

$$\begin{aligned} \eta L^W + \rho\tilde{C} &= \tilde{W}^W - \tilde{P}^H + (1-n)\tilde{S} && \textbf{(A-2)} \\ \eta\tilde{L}^R &= \tilde{W}^R - \tilde{S} && \textbf{(A-3)} \end{aligned}$$

The law of one price holds and therefore prices reflect marginal costs and exchange rate movements in the case of imported goods

$$\begin{aligned} \tilde{P}^H_H &= \tilde{W}^H - \hat{A}^H && \textbf{(A-4)} \\ \tilde{P}^H_F &= \tilde{W}^F - \hat{A}^F + \tilde{S} && \textbf{(A-5)} \end{aligned}$$

Since $\tilde{P}^H = n\tilde{P}^H_H + (1-n)\tilde{P}^H_F$, we can write the domestic aggregate price level as

$$\tilde{P}^H = \tilde{W}^W + (1-n)\tilde{S} - n\hat{A}^H - (1-n)\hat{A}^F \qquad \textbf{(A-6)}$$

If we combine **(A-2)** and **(A-6)**, we get

$$\eta\tilde{L}^W + \rho\tilde{C} = n\hat{A}^H + (1-n)\hat{A}^F \tag{A-7}$$

The market-clearing conditions for domestic and overseas goods will give us

$$\begin{aligned} \hat{A}^H + \tilde{L}^H &= -\varsigma(\tilde{P}_H^i - \tilde{P}^i) + \tilde{C} && \textbf{(A-8)} \\ \hat{A}^F + \tilde{L}^F &= -\varsigma(\tilde{P}_F^i - \tilde{P}^i) + \tilde{C} && \textbf{(A-9)} \end{aligned}$$

where $i = H,\ F$. Hence

$$n\hat{A}^H + (1-n)\hat{A}^F + \tilde{L}^W = \tilde{C} \tag{A-10}$$

Combining **(A-10)** and **(A-7)** results in **(33)**

$$\tilde{C} \;=\; \frac{\eta+1}{\eta+\rho}\left[n\hat{A}^H + (1-n)\hat{A}^F\right]$$

Based on **(A-4)** and **(A-5)** we get

$$\tilde{T} = \tilde{P}_F^H - \tilde{P}_H^H = -\tilde{W}^R + \hat{A}^H - \hat{A}^F + \tilde{S} \tag{A-11}$$

Combining this with **(A-3)** will result in

$$\tilde{T} = \hat{A}^H - \hat{A}^F - \eta\tilde{L}^R \tag{A-12}$$

Equations **(A-8)** and **(A-9)** gives us

$$\hat{A}^H - \hat{A}^F + \tilde{L}^R = \varsigma \tilde{T} \qquad \textbf{(A-13)}$$

Hence, we get **(34)**:

$$\tilde{T} \;\; = \;\; \frac{\eta + 1}{\eta\varsigma + 1}\left[\hat{A}^H - \hat{A}^F\right]$$

Appendix B: The Phillips curve relationships

Following Benigno (2002), we can take the first-order Taylor expansion around the steady state of price equations **(21)-(24)**. This will turn these price equations into Phillips curves:

$$\pi^H_{H,t} = k_C(\hat{C}^W_t - \tilde{C}_t) + k^H_{H,T^H}(\hat{T}^H_t - \tilde{T}_t) + k^H_{H,T^F}(\hat{T}^F_t - \tilde{T}_t) + k^H_Q\hat{Q}_t + \beta E_t\pi^H_{H,t+1} \quad \textbf{(B-1)}$$

$$\pi^H_{F,t} = k_C(\hat{C}^W_t - \tilde{C}_t) + k^H_{F,T^H}(\hat{T}^H_t - \tilde{T}_t) + k^H_{F,T^F}(\hat{T}^F_t - \tilde{T}_t) + k^H_Q\hat{Q}_t + \beta E_t\pi^H_{F,t+1} \quad \textbf{(B-2)}$$

$$\pi^F_{H,t} = k_C(\hat{C}^W_t - \tilde{C}_t) + k^F_{H,T^H}(\hat{T}^H_t - \tilde{T}_t) + k^F_{H,T^F}(\hat{T}^F_t - \tilde{T}_t) + k^F_Q\hat{Q}_t + \beta E_t\pi^F_{H,t+1} \quad \textbf{(B-3)}$$

$$\pi^F_{F,t} = k_C(\hat{C}^W_t - \tilde{C}_t) + k^F_{F,T^H}(\hat{T}^H_t - \tilde{T}_t) + k^F_{F,T^F}(\hat{T}^F_t - \tilde{T}_t) + k^F_Q\hat{Q}_t + \beta E_t\pi^F_{F,t+1} \quad \textbf{(B-4)}$$

where $\hat{T}^H = \ln\left(\frac{P^H_F}{P^H_H}\right)$ is the domestic terms of trade, $\hat{T}^F = \ln\left(\frac{P^F_F}{P^F_H}\right)$ is the inverse of the terms of trade abroad, and

$$\begin{aligned}
k_C &= \frac{\eta+\rho}{1+\sigma\eta}\zeta & & \\
k^H_{H,T^H} &= \frac{\zeta(1-n)}{1+\sigma\eta}[1+\varsigma\eta n+\sigma\eta(1-n)] & \qquad k^H_{H,T^F} &= \frac{\zeta(1-n)^2}{1+\sigma\eta}\eta[\varsigma-\sigma] \\
k^H_{F,T^H} &= -\frac{\zeta n}{1+\sigma\eta}[1+\varsigma\eta n+\sigma\eta(1-n)] & \qquad k^H_{F,T^F} &= -\frac{\zeta n(1-n)}{1+\sigma\eta}\eta[\varsigma-\sigma] \\
k^F_{H,T^H} &= \frac{\zeta(1-n)n}{1+\sigma\eta}\eta[\varsigma-\sigma] & \qquad k^F_{H,T^F} &= \frac{\zeta(1-n)}{1+\sigma\eta}[1+\varsigma\eta(1-n)+\sigma\eta n] \\
k^F_{F,T^H} &= -\frac{\zeta n^2}{1+\sigma\eta}\eta[\varsigma-\sigma] & \qquad k^F_{F,T^F} &= -\frac{\zeta n}{1+\sigma\eta}[1+\varsigma\eta(1-n)+\sigma\eta n] \\
k^H_Q &= (1-n)\zeta & \qquad k^F_Q &= -n\zeta
\end{aligned}$$

By combining these subcategory Phillips curves we get the aggregate Phillips curves for each country as well as a world Phillips curve and a relative Phillips curve across countries.

Appendix C: A detailed description of the linear dynamic system

As mentioned in the main text we can assemble linear dynamic equations as follows in one system:

$$\mathbf{A}E_t \begin{pmatrix} \mathbf{y}_{t+1} \\ \mathbf{x}_t \end{pmatrix} = \mathbf{B} \begin{pmatrix} \mathbf{y}_t \\ \mathbf{x}_{t-1} \end{pmatrix} + \mathbf{C}\nu_t \qquad \textbf{(49)}$$

where $\mathbf{A}$ is a 12×12 matrix, $\mathbf{B}$ is a 12×12 matrix, $\mathbf{C}$ is a 12×4 matrix, the vector of endogenous variables reads as $\mathbf{y} = (\hat{C}^W \ \pi^W \ \pi^R \ \Delta\hat{S})'$, the vector of predetermined variables equals $\mathbf{x} = (\hat{i}^H \ \hat{i}^F \ \hat{Q} \ \hat{T}^W \ \tilde{C} \ \tilde{T} \ \varepsilon^H \ \varepsilon^F)'$, and the vector of shocks is $\nu = (\nu^T \ \nu^C \ \nu^H \ \nu^F)'$.

The 12×12 matrix $\mathbf{A}$ equals

$$\mathbf{A} = \begin{pmatrix}
1 & 1/\rho & 0 & 0 & -\frac{n}{\rho} & -\frac{1-n}{\rho} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \beta & 0 & 0 & 0 & 0 & 0 & 0 & k_c & 0 & 0 & 0 \\
0 & 0 & \beta & 0 & 0 & 0 & \zeta & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\phi^H & -(1-n)\phi^H & 0 & 1 & 0 & -\vartheta^H & -(1-n)\varsigma\psi^H & \psi^H & (1-n)\varsigma\psi^H & -1 & 0 \\
0 & -\phi^F & n\phi^F & 0 & 0 & 1 & \vartheta^F & n\varsigma\psi^F & \psi^F & -n\varsigma\psi^F & 0 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -k_t & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}$$

where $k_c = \dfrac{\eta + \rho}{1 + \sigma\eta}\zeta$ and $k_t = \lambda_1 \dfrac{\zeta(1 + \varsigma\eta)}{1 + \sigma\eta} \dfrac{1}{1 - \beta\lambda_1\varrho_T}$.

The 12×12 matrix $\mathbf{B}$ is identical to

$$\mathbf{B} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -k_c & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \psi^H & 0 & 0 & 0 & \gamma^H & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \psi^F & 0 & 0 & 0 & 0 & \gamma^F & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \varrho_C & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \varrho_T & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \varrho_H & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \varrho_F \end{pmatrix}$$

whereas the 12×4 matrix $\mathbf{C}$ equals

$$\mathbf{C} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Appendix D: Proof of Proposition 3.1

By examining our linear dynamic equations under the absence of interest rate smoothing, that is $\gamma_H = \gamma_F = 0$ in **(46)** and **(47)**, we can reduce our linear dynamic system further and describe it as

$$E_t \begin{pmatrix} \mathbf{y}_{t+1} \\ \hat{Q}_t \end{pmatrix} = \mathbf{G} \begin{pmatrix} \mathbf{y}_t \\ \hat{Q}_{t-1} \end{pmatrix} + \mathbf{H}\varepsilon_t \qquad \textbf{(D-1)}$$

where, $\mathbf{y}_t = (\Delta S_t \; \hat{C}_t^W \; \pi_t^W \; \pi_t^R)'$ is a 5×1 vector endogeneous variables, $\varepsilon_t = (\hat{T}_t^W \; \tilde{C}_t \; \tilde{T}_t \; \varepsilon_t^H \; \varepsilon_t^F)'$ is a 5×1 vector of exogeneous shocks, **H** is a 5×5 matrix equal to

$$\mathbf{H} = \begin{pmatrix} ((1-n)\psi_H + n\psi_F)\varsigma & \Psi_1 - \frac{k_c}{\beta}\Phi_2 & -((1-n)\psi_H + n\psi_F)\varsigma & 1 & -1 \\ \Psi_1 n(1-n)\varsigma & \Psi_2 - \frac{k_c}{\beta}\Phi_4 - 1 & -\Psi_1 n(1-n)\varsigma & n & (1-n) \\ 0 & \frac{k_c}{\beta} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \qquad \textbf{(D-2)}$$

and **G** is another 5×5 matrix which reads like

$$\mathbf{G} = \begin{pmatrix} -\frac{\zeta}{\beta}\Phi_1 + \theta_1 & \Psi_1 - \frac{k_c}{\beta}\Phi_2 & \frac{1}{\beta}\Phi_2 & \frac{\zeta+1}{\beta}\Phi_1 - \theta_1 & -\frac{\zeta}{\beta}\Phi_1 + \theta_1 \\ -\frac{\zeta}{\beta}\Phi_3 + \theta_2 & \Psi_2 - \frac{k_c}{\beta}\Phi_4 & \frac{1}{\beta}\Phi_4 & \frac{\zeta+1}{\beta}\Phi_3 - \theta_2 & -\frac{\zeta}{\beta}\Phi_3 + \theta_2 \\ 0 & -\frac{k_c}{\beta} & \frac{1}{\beta} & 0 & 0 \\ -\frac{\zeta}{\beta} & 0 & 0 & \frac{\zeta+1}{\beta} & -\frac{\zeta}{\beta} \\ 1 & 0 & 0 & -1 & 1 \end{pmatrix} \qquad \textbf{(D-3)}$$

In **(D-2)** and **(D-3)** $k_C = \dfrac{\eta+\rho}{1+\sigma\eta}\zeta$, $\Phi_1 = (1-n)\phi_H + n\phi_F$, $\Phi_2 = \phi_H - \phi_F$, $\Phi_3 = \dfrac{(1-n)n}{\rho}\Phi_2$, $\Phi_4 = \dfrac{n\phi_H + (1-n)\phi_F - 1}{\rho}$, $\Psi_1 = \psi_H - \psi_F$, $\Psi_2 = \dfrac{n\psi_H + (1-n)\psi_F}{\rho} + 1$, $\theta_1 = \vartheta_H + \vartheta_F$, and $\theta_2 = \dfrac{n\vartheta_H - (1-n)\vartheta_F}{\rho}$.

From **(D-3)** it becomes clear that matrix G has a rank value that cannot be larger than 4. The 4 corresponding eigenvalues are by assumption outside the unit circle. Since $\hat{Q}$ is the only one predetermined variable in linear dynamic system **(D-1)** we can write the real exchange rate, following Blanchard and Kahn (1980), as

$$\hat{Q}_t \quad = \quad a_Q \hat{Q}_{t-1} + \mathbf{b}'_Q \varepsilon_t \qquad \textbf{(D-4)}$$

where a_Q is a scalar and $\mathbf{b}_Q$ is a 5×1 vector. Note that a_Q is an eigenvalue of $\mathbf{G}$ inside the unit circle, which should be zero as $\mathbf{G}$ has a maximum rank value of 4. Since $a_Q = 0$, the real exchange rate can only be persistent if at least one of the exogenous shocks is persistent.

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