Monetary policy rules for an open economy

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Abstract

The most popular simple rule for the interest rate, due to Taylor (1993a), is meant to inform monetary policy in economies that are closed. On the other hand, its main open-economy alternative, ie Ball's (1999) rule based on a monetary conditions index (MCI), may perform poorly in the face of specific types of exchange rate shocks and thus cannot offer guidance for the day-to-day conduct of monetary policy. In this paper we specify and evaluate a comprehensive set of simple monetary policy rules that are suitable for small open economies in general, and for the United Kingdom in particular. We do so by examining the performance of a battery of simple rules, including the familiar Taylor rule and MCI-based rules à la Ball. This entails comparing the asymptotic properties of a two-sector open-economy dynamic stochastic general equilibrium model calibrated on UK data under different rules. We find that an inflation-forecast-based rule (IFB), ie a rule that reacts to deviations of expected inflation from target, is a good simple rule in this respect. Adding a separate response to the level of the real exchange rate (contemporaneous and lagged) appears to reduce the difference in adjustment between output gaps in the two sectors of the economy, but the improvement is only marginal. Importantly, an IFB rule, with or without exchange rate adjustment, appears robust to different shocks, in contrast to naïve or Ball's MCI-based rules.

Summary

The literature on simple rules for monetary policy is vast. However, the literature does not contain a thorough normative analysis of simple rules for open economies, ie, for economies where the exchange rate channel of monetary policy plays an important role in the transmission mechanism. The most popular simple rule for the interest rate — the 'Taylor rule' — for example, was designed for the United States and, thus, on the assumption that the exchange rate channel is less important. And the main open-economy alternatives — such as a rule based on a monetary conditions index (MCI) — may perform poorly in the face of specific types of exchange rate shocks.

This paper analyses the performance of a variety of simple rules using a model of the UK economy. To do so, we specify and evaluate a family of simple monetary policy rules that may stabilise inflation and output at a lower social cost than existing rules. These rules parsimoniously modify alternative closed or open-economy rules to analyse different ways of explicitly accounting for the exchange rate channel of monetary transmission. We compare the performance of this family of rules to that of the Taylor rule, naïve MCI-based rules as well as Ball's MCI-based rule, and inflation-forecast-based rules when the model economy is buffeted by various shocks.

To test the rules, we stylise the economy — that we calibrate to UK data — as a two-sector open-economy dynamic stochastic general equilibrium model. The export/non-traded sector split is important because it allows us to discern different impacts of the same shock on output and inflation in the two sectors. Identification of sectoral inflation and output dynamics is a key element on which to base the design of efficient policy rules.

To mimic observed stickiness in the adjustment of prices and wages in the United Kingdom, our model also features a wide range of nominal rigidities, modelled using the Calvo (1983) approach. These nominal rigidities have two crucial implications for our model. First, in our model economy macroeconomic equilibrium is inefficient, as with sticky prices changes in aggregate demand give rise to 'Okun gaps', in turn arising from specific microeconomic distortions. Second, monetary policy has real effects, and can be designed optimally to offset these various distortions. Specifically, since in an open economy monetary impulses are transmitted via multiple channels, in our model an efficient simple policy rule is one that offsets distortions by exploiting effectively all those channels.

Finally, because it is theoretically derived on the assumption that consumers maximise utility and firms maximise profits, the model has a rich structural specification. This enables us to contemplate shocks that could not be analysed in reduced-form small macro-models. For example, we can analyse the impact of a relative productivity shock on the two sectors. The ability to examine this range of shocks is important when comparing alternative policy rules for an open economy, because the efficient policy response to changes in the exchange rate will typically depend on the shocks hitting the economy — with different shocks sometimes requiring opposite responses. One drawback to this approach is that it is difficult to account for some features of the UK economy (most notably, the persistence of inflation) using a micro-founded model.

We find that a good rule for our small open-economy model is an inflation-forecast-based rule (IFB), ie a rule that reacts to deviations of expected inflation from target, if the forecast horizon is chosen appropriately. This rule is associated with a lower-than-average variability of inflation when compared with the other rules. Adding a separate response to the level of the real exchange rate improves stabilisation only marginally, suggesting that the inflation forecast contains all of the

information relevant to policy-makers, including information about the exchange rate channel of the transmission mechanism. Importantly, an IFB rule, with or without exchange rate adjustment, appears quite robust to different shocks, in contrast to the MCI-based rules we examine.

These results on the relative performance of the rules are broadly confirmed by results using the utility losses faced by the households in our model economy under each rule, implying that the distortions in our economy are quantitatively and qualitatively similar to those envisaged in existing closed-economy models.

1 Introduction

The literature on simple rules for monetary policy is vast.[1] It contains theoretical research comparing rules that respond to alternative intermediate and final targets, backward and forward-looking rules, and rules that include or exclude interest rate smoothing terms. It also contains work on historical estimates of monetary policy rules for various countries. However, the literature does not contain a thorough normative analysis of simple rules for open economies, ie for economies where the exchange rate plays an important role in the transmission of monetary policy impulses.[2] The most popular simple rule for the interest rate — due to Taylor (1993a) — for example, was designed for the United States and, thus, on the assumption that the economy is closed.[3] And the main open-economy alternatives (for example, the rule proposed by Ball (1999) based on a monetary conditions index (MCI)), may perform poorly in the face of specific types of exchange rate shocks and thus cannot offer guidance for the day-to-day conduct of monetary policy.[4]

In this paper we specify and evaluate a family of simple monetary policy rules that may stabilise inflation and output in small open economies at a lower social cost than existing rules. These rules parsimoniously modify alternative closed or open-economy rules to analyse different ways of explicitly accounting for the fact that the economy is open. We compare the performance of these rules to that of a battery of existing rules when the model economy is buffeted by various shocks. The existing rules include the Taylor closed-economy rule, naïve MCI-based rules as well as Ball's MCI-based rule, and inflation-forecast-based rules. Some of the rules in the family that we consider appear to be robust across a set of different shocks, including shocks from the rest of the world. This is in contrast to rival closed-economy simple rules, which ignore the fact that the economy is open, and MCI-based rules, the performance of which can be highly shock-specific.

To test the rules, we stylise the economy — that we calibrate to UK data — as a two-sector open-economy dynamic stochastic general equilibrium model. The export/non-traded sector split is important because it allows us to discern different impacts of the same shock on output and inflation in the two sectors. Identification of sectoral inflation and output dynamics is a key element on which to base the design of efficient policy rules. More generally, it also makes it possible for the monetary authority to consider the costs of price stabilisation on each sector of the economy.
To mimic observed stickiness in the adjustment of prices and wages in the United Kingdom, our model also features a wide range of nominal rigidities, modelled using the Calvo (1983) approach.[5]

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[1] See Bryant *et al* (1993) and Taylor (ed) (1999).

[2] Clarida, Galí and Gertler (1998, 2000) offer a wealth of empirical international evidence on monetary policy rules. Clarida (2000) employs the empirical framework of Clarida *et al* (1998, 2000) to explore the performance of historical monetary policy rules in open economies. More recently, Clarida *et al* (2001) also compared optimal monetary policy in open versus closed economies. Using a structural, small open-economy model they show that 'under certain standard conditions, the (optimal) monetary policy design problem for the small open economy is isomorphic to the problem of the closed economy [...] considered earlier', (Clarida *et al* (2001), page 1, text in brackets added).

[3] For simplicity, in what follows we refer to rules devised for economies that are closed as 'closed-economy' rules and to rules devised for economies that are open as 'open-economy' rules. By this we do not necessarily imply, however, that closed-economy rules are intrinsically unsuited as demand-stabilising tools in economies that are open. See Taylor (2001) for a discussion of this terminology.

[4] See King (1997) and Batini and Turnbull (2000) on the potential flaws of MCI-based rules.

[5] We use the Calvo approach because it is easy to implement. However, the results that we derive may be sensitive to this assumption as other (similar) specifications of price stickiness can lead to quite different inflation dynamics (see Kiley (1999) and Wolman (1999) for details).

Specifically, we assume that non-traded goods prices and nominal wages are sticky. Moreover, we suppose that the price-setting decisions of importers (of both final goods and intermediate inputs) are subject to both Calvo-style price stickiness and a one-period decision lag. This helps to capture the empirical fact that exchange rate pass-through is sluggish. These nominal rigidities have two crucial implications for our model. First, in our model economy macroeconomic equilibrium is inefficient, as with sticky prices changes in aggregate demand give rise to 'Okun gaps', in turn arising from specific microeconomic distortions. Second, monetary policy has real effects, and can be designed optimally to offset these various distortions. Specifically, since in an open economy monetary impulses are transmitted via multiple channels, in our model an efficient simple policy rule is one that offsets distortions by exploiting effectively all those channels.(6)

Since our model is theoretically derived on the assumption that consumers maximise utility and firms maximise profits, the model has a rich structural specification. This enables us to contemplate shocks that could not be analysed in less structural or reduced-form small macro-models. In particular, with our model, we can examine the implications of shocks to aggregate demand such as a shock to households' preferences, or a shock to overseas output. On the supply side, we can consider shocks to overseas inflation. We can analyse the impact of a relative productivity shock on the two sectors and investigate how this affects the real exchange rate by altering the relative price of non-tradables and exports. We can also look at the effects of a change in the price of imported intermediate goods. We can examine the effects of shocks to the foreign exchange risk premium. Finally, we can look at the implications of a monetary policy shock, both at home and abroad.

The ability to examine all these different shocks is important when comparing alternative policy rules for an open economy, because, for instance, the efficient policy response to changes in the exchange rate will typically depend on the shocks hitting the economy, with different shocks sometimes requiring opposite responses. For this purpose our small economy general equilibrium model is sufficient. A two-country model would enable us to look at these same shocks, but we believe the small-economy assumption is more realistic for the United Kingdom.

The rest of the paper is organised as follows. In Section 2 we lay out the model that we use throughout. The calibration of the model is discussed in Section 3. In Section 4 we study some properties of the model and compare them to the properties of UK data. In Section 5 we specify a family of simple open-economy rules; we then compare the stabilisation properties of these rules with those of a battery of alternative simple rules in the face of various disturbances. Section 6 concludes. The technical annexes contain further details about the model's non-linear and log-linear specifications.(7)

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(6) Of course, our model does not fully capture all the dynamics evident in the data. In addition, in evaluating the various rules, for tractability we use a loss function defined over quarterly inflation, rather than the annual inflation rate, which is more often of concern to policy-makers. For both reasons the analysis is probably more instructive about the relative performance of different rules, rather than the optimal setting for the coefficients or horizon in a particular rule.

(7) Once the model was cast into log-linear form, we found a solution consisting of decision rules for all the endogenous variables in terms of the state variables. This solution was computed using Klein's (2000) algorithm.

2 A two-sector open-economy optimising model

The model we use is a calibrated stochastic dynamic general equilibrium model of the UK economy with a sectoral split between exported and non-traded goods. Its specification draws on the literature on open-economy optimising models by Svensson and van Wijnbergen (1989), Correia, Neves and Rebelo (1995), Obstfeld and Rogoff (1996), and more recent work by McCallum and Nelson (1999). In this sense, the model is close in spirit to a number of open-economy models developed at or after the time of writing by Monacelli (1999), Galí and Monacelli (1999), Ghironi (2000), Smets and Wouters (2000), Benigno and Benigno (2000) and Devereux and Engle (2000). However, it builds on all of these, individually (and other closed-economy optimising models), by introducing several novel features that are described in detail below.

The model describes an economy that is 'small' with respect to the rest of the world. In practice, this means that the supply of exports does not affect the foreign price of these goods. It also means that the foreign price of imported goods, foreign interest rates and foreign income are exogenous in this model, rather than being endogenously determined in the international capital and goods markets, as would happen in a multiple-country, global-economy model. Finally, it means that all consumption of traded goods consists of imports and all intermediate goods used in production are also imported.[8]

2.1 Household preferences and government policy

The economy is populated by a continuum of households indexed by $j \in (0,1)$. Each household is infinitely lived and has identical preferences defined over consumption of a basket of (final) imported and non-traded goods, leisure and real money balances at every date. Households differ in one respect: they supply differentiated labour services to firms. Preferences are additively log-separable and imply that household $j \in (0,1)$ maximises:

$$\mathrm{E}_0 \sum_{t=0}^{\infty} b^t \left(e^{n_t} \ln\left(c_t(j) - x_c c_{t-1}(j)\right) + d \ln\left(1 - h_t(j)\right) + \frac{c}{1-e}\left(\frac{\Omega_t(j)}{P_t}\right)^{1-e} \right) \qquad \textbf{(1)}$$

where $0 < b < 1$; d, c and e are restricted to be positive and E_0 denotes the expectation based on the information set available at time zero. In equation **(1)**, $c_t(j)$ is total time t real consumption of household j, n_t is a white noise shock to preferences — essentially a demand shock, described in more detail in Sections 3 and 4 — and $h_t(j)$ is labour supplied to market activities, expressed as a fraction of the total time available. So the term $(1 - h_t(j))$ captures the utility of time spent outside work. The last term $\Omega_t(j)/P_t$ represents the flow of transaction-facilitating services yielded by real money balances during time t (on which more later). Hence here, as in the standard Sidrauski-Brock model, money enters the model by featuring directly in the utility function.

In addition, since $x_c \in [0,1)$, preferences over consumption exhibit habit formation, with the functional form used in equation **(1)** similar to that of Carrol, Overland and Weil (1995)

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[8] This assumption clearly does not hold as a large proportion of intermediate goods and finally consumed traded goods are produced domestically. However, it considerably simplifies our analysis, and because we are not interested here in studying either the transmission of economic shocks across countries or issues of policy interdependence, it comes at a relatively small price.

and Fuhrer (2000). This implies that preferences are not time-separable in consumption, so that households' utility depends not only on the level of consumption in each period, but also on their level in the previous period.

Total consumption is obtained by aggregating the consumption of imported and non-traded goods $c_{M,t}$ and $c_{N,t}$ via the geometric combination $c_t = c_{M,t}^{g} c_{N,t}^{1-g}$, where $\gamma \in (0,1)$. Here $c_{M,t}$ and $c_{N,t}$ represent imported and non-traded goods purchased by the consumer from retailers at prices $P_{M,t}$ and $P_{N,t}$, respectively. It is easily shown that the consumption-based price deflator is given by:

$$P_t = \frac{P_{M,t}^{g} P_{N,t}^{1-g}}{g^{g}(1-g)^{1-g}}.$$ (9)

Households have access to a state-contingent bond market. Bond $b(s)$ in this market is priced in units of consumption, has price $r(s)$ in period t, and pays one unit of consumption in state s in period t+1. In practice, this means that households within the domestic economy can perfectly insure themselves against idiosyncratic shocks to income. In equilibrium, consumption and real money balances are equal across households. So households differ only because labour supply varies across the population.

In addition to this bond market, each household can also access a domestic and a foreign nominal government bond market at interest rates i and i_f respectively. For the time being, we assume that both kinds of bond are riskless, but we investigate what happens when there is a foreign exchange rate risk premium in Subsection 2.4. Money is introduced into the economy by the government. Because Ricardian equivalence holds in this model, we can assume without loss of generality a zero net supply of domestic bonds. Then the public sector budget constraint requires that all the revenue associated with money creation must be returned to the private sector in the form of net lump-sum transfers in each period:

$$M_t - M_{t-1} = T_t \quad \textbf{(2)}$$

where M_t is end-of-period t nominal money balances and T_t is a nominal lump-sum transfer received from the home government at the start of period t.

We assume that the monetary authority sets policy according to a simple 'monetary policy rule' that relates the nominal interest rate (its instrument) to a set of endogenous variables. These could include current or lagged endogenous variables as well as current-period expectations of future values of endogenous variables. The exact rules we consider are described in Section 5 below.

Household j's dynamic budget constraint in each period is given by equations **(3)** and **(4)** below. Equation **(3)** describes the evolution of nominal wealth. Equation **(4)** defines the nominal balances available to consumers to spend at time t. This reflects the assumption that consumers participate in the financial markets before spending money on goods and services. As suggested by Carlstrom and Fuerst (2001), entering money balances as defined in **(4)** in the utility function gives a better measure of period utility; one in which we account exclusively for the services of balances that are actually available to households when spending decisions are taken.

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(9) Formally, P_t defines the minimum cost of financing a unit of consumption, c_t. See Obstfeld and Rogoff (1996, pages 226-8) for a simple example.

$$M_t(j) + B_t(j) + \frac{B_{f,t}(j)}{e_t(j)} + P_t \int r_t(s) b_t(s,j) ds = M_{t-1}(j) + (1+i_{t-1}) B_{t-1}(j)$$
$$+ (1+i_{f,t-1}) \frac{B_{f,t-1}(j)}{e_t} + P_t \int b_{t-1}(s,j) ds + W_t(j) h_t(j) + D_t + T_t - P_t c_t(j) \quad \textbf{(3)}$$

$$\Omega_t(j) = M_{t-1}(j) + T_t + (1+i_{t-1}) B_{t-1}(j) + (1+i_{f,t-1}) \frac{B_{f,t-1}(j)}{e_t} - B_t(j) - \frac{B_{f,t}(j)}{e_t} \quad \textbf{(4)}$$

where M_{t-1} is nominal money balances at time *t*-1, $B_{t-1}(j)$ and $B_{f,t-1}(j)$ are time *t*-1 holdings of domestic and foreign bonds respectively and D_t are lump-sum dividends from shares held in (domestic) firms. Household *j*'s holdings of (state-contingent) bond $b_t(s)$ are $b_t(s,j)$. With e_t we denote the nominal exchange rate, expressing domestic currency in terms of units of foreign currency.(10) Finally, $W_t(j)$ is the nominal wage rate received by household *j*. Because each household supplies differentiated labour services, it has some market power over the wage rate. So we assume that household *j* chooses $c_t(j)$, $B_{t-1}(j)$, $B_{f,t-1}(j)$, $\Omega_t(j)$, $M_t(j)$ and *b*(*s,j*) to maximise **(1)** subject to **(3)** and **(4)**. The choice of wage *W*(*j*) is discussed in Subsection 2.3.2.

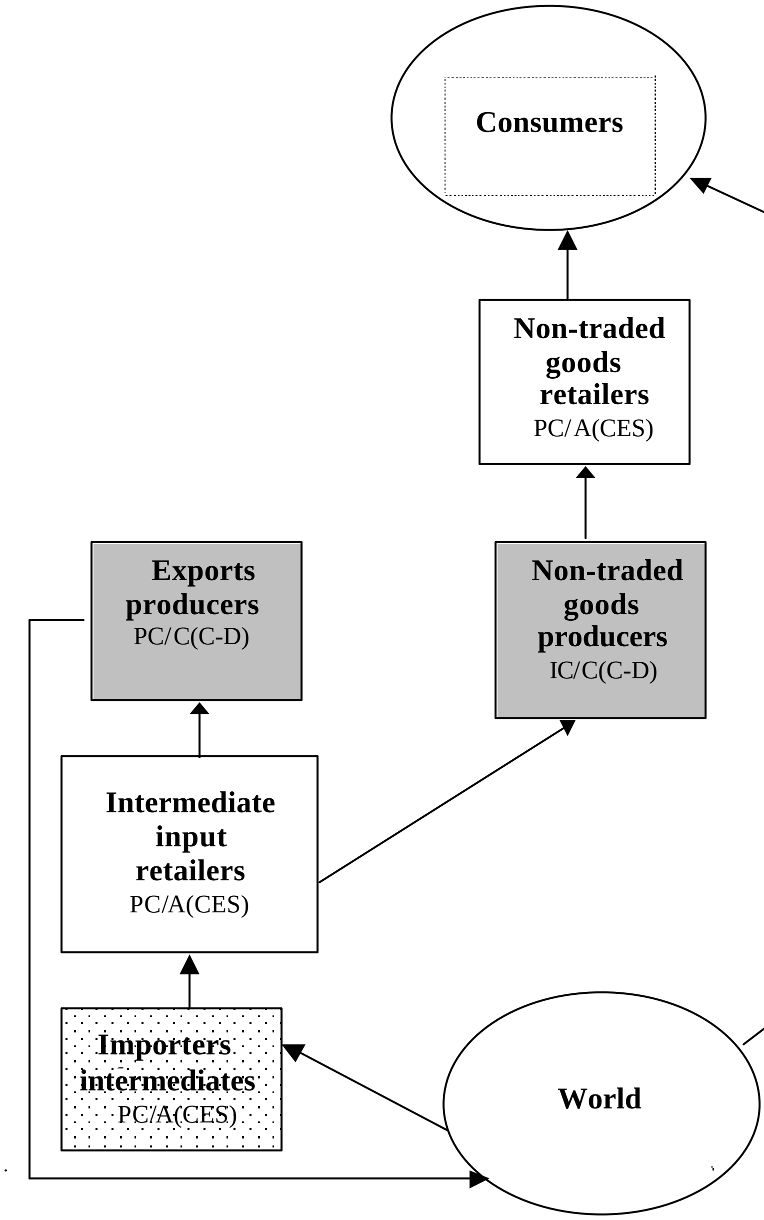
2.2 Technology and market structure

This subsection describes the supply side of the economy by sector.

We assume that in our economy there are two kinds of producing firms: non-traded goods producers and export producers. By definition, non-traded goods are only consumed domestically, while we assume that exports produced at home are only consumed abroad. To produce, the exports and non-traded goods producers buy intermediate non-labour inputs for production (labour is purchased domestically from the households) from a group of 'imported intermediate input retailers'. Since consumers also purchase their final imports and non-traded goods via 'retailers', the economy has a total of three groups of retailing firms: imported intermediates retailers, non-traded goods retailers and final imports retailers. Finally, both final imports retailers and imported intermediates retailers originally purchase their 'input' from a group of 'importers' who, in turn, acquire goods from the world markets. There are two types of importers, one for each import. We refer to the first group as 'final goods importers' and to the second group as 'intermediate inputs importers'. Chart 1 depicts the goods market structure of the model, indicating for each group of firms the degree of market power and the technological constraints that they face.

(10) So that an increase in e_t represents an appreciation of the domestic currency.

Chart 1: Goods markets structure



Note: PC = perfectly competitive; IC = imperfectly competitive; A = aggregates differentiated goods only; C = combines labour and intermediate goods to produce; CES = constant elasticity of substitution production function; C-D = Cobb-Douglas production function.

This seemingly complicated representation of the supply side is desirable because, as we discuss later (Subsection 2.4), it enables us easily to introduce nominal rigidities, which mimic observed UK empirical evidence on price and wage dynamics as well as give scope to monetary policy actions. In what follows, we describe each sector in turn, starting from the non-traded goods sector. By 'sector' we mean a larger group of firms, which includes producers and retailers operating in the market of the same good. The behaviour of the two groups of 'importers' is described in the 'final imports sector' and in the 'intermediate goods sector' subsections, rather than in separate subsections. Next, we discuss the way in which the labour market is organised (Subsection 2.2.5), and then focus on price and wage-setting behaviour (Subsection 2.3).

2.2.1 Non-traded goods sector

We assume that non-traded goods retailers are perfectly competitive. These retailers purchase differentiated goods from a unit continuum of monopolistically competitive non-traded goods producers and combine them using a CES technology:[11]

$$y_{N,t} = \left[\int_0^1 y_{N,t}(k)^{1/(1+q_N)} \, dk \right]^{1+q_N} \quad \textbf{(5)}$$

Profit maximisation implies that the demand for non-traded goods from producer $k \in (0,1)$ is given by

$$y_{N,t}(k) = \left(\frac{P_{N,t}(k)}{P_{N,t}} \right)^{-\frac{1+q_N}{q_N}} y_{N,t} \quad \textbf{(6)}$$

where $P_{N,t}(k)$ is the price of the non-traded good set by firm k. The assumption of perfect competition implies that retailers' profits are zero. This requires that:

$$P_{N,t} = \left[\int_0^1 P_{N,t}(k)^{-1/q_N} \, dk \right]^{-q_N} \quad \textbf{(7)}$$

Producers of non-traded goods use a Cobb-Douglas technology with inputs of an intermediate good (I) and labour (h):

$$y_{N,t}(k) = A_{N,t} h_{N,t}(k)^{a_N} I_{N,t}(k)^{1-a_N} \quad \textbf{(8)}$$

Non-traded goods producers are price-takers in factor markets and purchase inputs from imported intermediates retailers (on which more later). So non-traded goods producers choose factor demands and a pricing rule (discussed in Subsection 2.3) subject to technology **(5)** and a demand function **(6)**.

2.2.2 Export sector

The export sector produces using a Cobb-Douglas technology:

$$y_{X,t} = A_{X,t} h_{X,t}^{a_X} I_{X,t}^{1-a_X} \quad \textbf{(9)}$$

where $A_{X,t}$ is a productivity shock. We assume that production is efficient in the export sector, ie that marginal cost is equal to price in equilibrium.

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[11] This technology facilitates the introduction of nominal rigidities and has been widely used in recent micro-founded models.

We assume that the scale of exports is determined by a downward-sloping demand curve:

$$X_t = \left(\frac{e_t P_{X,t}}{P_t^*} \right)^{-h} y_{f,t} \quad \textbf{(10)}$$

where P_t^* is the exogenous foreign currency price of exports and $y_{f,t}$ is exogenous world income.(12) This is the same formulation of export demand as McCallum and Nelson (1999). The exogenous foreign price of exports is the same as the exogenous foreign currency price of imports used in equation **(14)** below.

2.2.3 Intermediate goods sector

Intermediate goods are sold to export and non-traded goods producers by retail firms that operate in the same way as the retailers discussed in Subsection 2.2.1. These 'imported intermediates retailers' purchase inputs from 'intermediate goods importers' who buy a homogenous intermediate good in the international markets and then costlessly transform it into a differentiated good that they sell to retailers. This yields a nominal profit for importer k of:

$$D_{I,t}(k) = \left[P_{I,t}(k) - \frac{P_{I,t}^*}{e_t} \right] y_{I,t}(k) \quad \textbf{(11)}$$

where $y_{I,t}(k) = \left(\frac{P_{I,t}(k)}{P_{I,t}} \right)^{-\frac{1+q_I}{q_I}} y_{I,t}$, as in previous sections and $P_{I,t}^*$ is the exogenous foreign currency price of the intermediate good. The firm chooses a pricing rule (discussed in Subsection 2.3) to maximise the discounted future flow of real profits.

2.2.4 Final imports sector

We assume that retailers of final imports are perfectly competitive, purchase differentiated imports from 'final goods importers' and combine them using a technology analogous to that used by non-traded retailers. Following the analysis of Subsection 2.2.1 we get:

$$y_{M,t}(k) = \left(\frac{P_{M,t}(k)}{P_{M,t}} \right)^{-\frac{1+q_M}{q_M}} y_{M,t} \quad \textbf{(12)}$$

and

$$P_{M,t} = \left[\int_0^1 P_{M,t}(k)^{-1/q_M} \, dk \right]^{-q_M} \quad \textbf{(13)}$$

As for intermediate imported goods, final imported goods are purchased from world markets by importers who buy a homogenous final good from overseas and costlessly convert it into a differentiated good.(13) Nominal profits for these importers in period t are then given by

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(12) Note that firms in the export sector cannot exploit the downward-sloping demand curve if the price elasticity of demand is less than unity, as we assume below.
(13) Intuitively, this can be thought of as 'branding' a product.

$$D_{M,t}(k) = \left[P_{M,t} - \frac{P_t^*}{e_t} \right] y_{M,t}(k) \qquad \textbf{(14)}$$

where P_t^* is the exogenous foreign currency price of the imported good. Firms choose a pricing rule (discussed in Subsection 2.3) to maximise the discounted flow of real profits subject to demand **(12)**.

2.2.5 Labour market

As discussed in Subsection 2.1, households set the nominal wage that must be paid for their differentiated labour services. We assume that a perfectly competitive firm combines these labour services into a homogenous labour input that is sold to producers in the non-traded and export sector. This set-up follows Erceg, Henderson and Levin (2000) and relies on an aggregation technology analogous to those discussed in previous sections:

$$h_t = \left[\int_0^1 h_t(j)^{1/(1+q_W)} dj \right]^{1+q_W} \qquad \textbf{(15)}$$

This implies a labour demand function for household *j*'s labour of the form:

$$h_t(j) = \left(\frac{W_t(j)}{W_t} \right)^{-\frac{1+q_W}{q_W}} h_t \qquad \textbf{(16)}$$

Households take the labour demand curve **(16)** into account when setting their wages, as discussed in the next section.

2.3 Price and wage setting

As we have anticipated, the supply-side structure described in Subsection 2.2 facilitates the introduction of nominal rigidities. We assume that in both prices and nominal wages prices are sticky and model them in the same way as Calvo (1983).(14) Below we discuss what this implies for the pricing decisions facing different economic agents, starting with the pricing decisions of non-traded goods producers.

2.3.1 Price setting

We assume that the non-traded goods producers solve the following optimisation problem:

$$\max \mathrm{E}_t \sum_{s=0}^{\infty} (b\, f_N)^s \Lambda_{1,t+s} \left(\frac{(1+p)^s P_{N,t}(k)}{P_{t+s}} - V_{t+s} \right) y_{N,t+s}(k)$$

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(14) As noted earlier, Kiley (1999) and Wolman (1999) show that different specifications of price stickiness (where the probability of price adjustment is not constant) can lead to significant differences in the behaviour of inflation. So our results are conditional on a special case of staggered price setting. However, the Calvo pricing structure is commonly used in recent papers in the literature on monetary policy rules. In this sense, we are retaining a degree of comparability with previous studies.

subject to $y_{N,t+s}(k) = \left(\frac{(1+p)^s P_{N,t+s}(k)}{P_{N,t+s}} \right)^{-\frac{(1+q_N)}{q_N}} y_{N,t+s}$

where f_N is the probability that the firm cannot change its price in a given period, and Λ_1 is the consumer's real marginal utility of consumption. The steady-state gross inflation rate is $(1+p)$ and prices are indexed at the steady-state rate of inflation. So when a firm sets a price at date t, the price automatically rises by p% next period if the firm does not receive a signal allowing it to change price. The parameter q_N represents the net mark-up over unit costs that the firm would apply in a flexible-price equilibrium. Finally V (expressed below) is the minimised unit cost of production (in units of final consumption) that solves:

$$V_{t+s} = \min \left\{ \frac{W_{t+s}}{P_{t+s}} h_{N,t+s}(k) + \frac{P_{I,t+s}}{P_{t+s}} I_{N,t+s}(k) \right\} \text{ subject to } A_{N,t+s} h_{N,t+s}(k)^{a_N} I_{N,t+s}(k)^{(1-a_N)} = 1$$

The first-order condition for the firm's pricing decision can be written as:

$$\mathrm{E}_t \sum_{s=0}^{\infty} (b f_N)^s \Lambda_{1,t+s} \left(\frac{-q_N (1+p)^s P_{N,t}(k)}{P_{t+s}} + (1+q_N) V_{t+s} \right) y_{N,t+s}(k) = 0 \tag{17}$$

Importers of the final import good for consumption and importers of the intermediate good used in production face the same pricing problem confronting non-traded goods producers. But to introduce sluggishness in the pass-through of exchange rate changes to import prices, we assume that pricing decisions are based on the information set available in the previous period. This is the assumption made by Monacelli (1999). Given this additional assumption, the first-order conditions become:

$$\mathrm{E}_{t-1} \sum_{s=0}^{\infty} (b f_M)^s \Lambda_{1,t+s} \left(\frac{-q_M (1+p)^s P_{M,t}(k)}{P_{t+s}} + (1+q_M) V_{M,t+s} \right) y_{M,t+s}(k) = 0 \tag{18}$$

$$\mathrm{E}_{t-1} \sum_{s=0}^{\infty} (b f_I)^s \Lambda_{1,t+s} \left(\frac{-q_I (1+p)^s P_{I,t}(k)}{P_{t+s}} + (1+q_I) V_{I,t+s} \right) y_{I,t+s}(k) = 0 \tag{19}$$

where the notation is analogous to that used above. The trivial production structures in these sectors imply that unit costs are simply given by $V_{M,t} = \frac{P_t^*}{e_t P_t}$ and $V_{I,t} = \frac{P_{I,t}^*}{e_t P_t}$

2.3.2 Wage setting

The wage-setting behaviour of households is based on Erceg, Henderson and Levin (2000) and is closely related to the price-setting behaviour of non-traded goods producing firms.[15] Following Erceg *et al* (2000), we suppose that household *j* is able to reset its nominal wage contract with probability $(1 - f_W)$. If the household is allowed to reset its contract at date *t*, then it chooses a nominal wage $W_t(h)$ that will be indexed by the steady-state inflation rate until the contract is reset once more. The household chooses this wage rate to maximise discounted expected utility for the duration of the contract, subject to the budget constraint **(3)** and the labour demand function **(16)**. Hence, the first-order condition is:

$$\mathrm{E}_t \sum_{s=0}^{\infty} (b f_W)^s \left[\frac{(1+p)^s W_t(j)}{P_{t+s}} \Lambda_{1,t+s} - (1+q_W) \frac{d}{1-h_{t+s}(j)} \right] h_{t+s}(j) = 0 . \qquad \textbf{(20)}$$

2.4 The exchange rate and the balance of payments

Combining the first-order conditions for domestic and foreign bonds from the household's optimisation problem gives the familiar uncovered interest parity condition. A first-order approximation gives:

$$E_t \log e_{t+1} - \log e_t = i_{f,t} - i_t + z_t \qquad \textbf{(21)}$$

where we have added a stochastic risk premium term (z_t) to reflect temporary but persistent deviations from UIP, as in Taylor (1993b).

Despite the fact that domestic nominal bond issuance is assumed to be zero at all dates, domestic households can intertemporally borrow or save using foreign government bonds. Positive holdings of foreign bonds mean that the domestic economy can run a trade deficit in the steady state financed by the interest payments received on foreign bond holdings.[16] In addition, since the economy is small, the foreign interest rate is exogenous in the model. So the supply of foreign government bonds is perfectly elastic at the exogenous world nominal interest rate. This means that steady-state foreign bond holdings are indeterminate in our model. As a result, temporary nominal shocks can shift the real steady state of the model through the effects on nominal wealth (see Obstfeld and Rogoff (1996, pages 684-6) for a simple exposition). This means that the equilibrium around which log-linear approximations are taken is moving over time.

This is a common feature of small open-economy monetary models and can be addressed in a number of ways. One approach is to make assumptions about the form of the utility function (see, for example, Correia *et al* (1995)) or the way in which consumption is aggregated. This is difficult to implement in our model if we wish to retain a rich structural specification. Another approach is to impose a global equilibrium condition on asset holdings (and restrict the trade balance to be zero in all periods). But this seems too restrictive. So instead we assume that these steady-state effects arising from changes in the level of foreign bond holdings are small enough to be ignored; this enables us to

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(15) In a closed-economy model, this set-up leads to a trade-off between output and inflation stabilisation in the presence of price and nominal wage stickiness. See Erceg, Henderson and Levin (2000) for details.

(16) Of course, dynamic responses to shocks can lead these bond holdings to increase (by running a smaller trade deficit) or to be run down (by running a larger trade deficit).

substitute foreign bond holdings out of the model and concentrate on the movements of the other variables, as in McCallum and Nelson (1999).

2.5 The role of monetary policy in our model

In the previous subsection we discussed the range of nominal rigidities included in our model. Specifically, in Subsections 2.3.1 and 2.3.2, we reviewed our assumptions that non-traded goods prices and nominal wages are sticky and the assumption that the price-setting decisions of importers (of both final goods and intermediate inputs) are subject to both Calvo-style price stickiness and a one-period decision lag.

If we abstract from the decision lag in importers' pricing decisions, the microeconomic distortions generated by these assumptions are common to both an open-economy and a closed-economy model, as long as the economy has two sectors with different market power. For example, the distortions associated with wage and price stickiness from Calvo pricing in our model are the same that lead to labour and product market misallocations in the US-calibrated model of Erceg *et al* (2000). Analogously, the distortions associated with different degrees of price stickiness in the two sectors in our model are similar to those characterised in Aoki's (2000) two-sector closed-economy model. From this point of view, the aim of monetary policy in our model is similar to that in a closed-economy model, namely, setting the monetary policy instrument so as to offset the existing (similar) set of distortions.

On the other hand, as explained in the introduction, the transmission of monetary impulses, ie the actual way in which the monetary authority removes the distortions, will differ in an economy that is open relative to an economy that is closed. This is because, although in both types of economies the monetary authorities act by affecting the relative cost of borrowing, this action has different consequences in an open versus a closed economy. In a closed economy changes in the relative cost of borrowing affect demand by altering households consumption plans. In an open economy those changes not only affect demand through the consumer Euler equation (ie via the 'output gap channel'), but also affect the domestic currency price of overseas goods via the changes they elicit in the exchange rate (ie via the 'exchange rate channel'). This is particularly important in a two-sector context. In our open-economy model, for instance, one of the two sectors is 'internationally exposed', with demand depending on the exchange rate. If price stickiness in one of our two sectors gives rise to a relative price distortion (ie a distortion in the ratio of non-traded to traded goods' prices), monetary policy can offset that distortion by affecting directly the price of the 'internationally exposed' sector via changes in the exchange rate. This is not possible in a two-sector closed-economy model, where there is only one channel of transmission: demand.

So in summary, as in most closed-economy models, in our open-economy model optimal monetary policy aim is to offset the distortions (and thus 'Okun gaps') generated by the various nominal rigidities. Typically, these do not differ substantially in closed and open-economy set-ups.

However, we also point out that monetary policy has different effects in an open versus a closed economy, because in the former changes in the interest rate affect not just demand but also the exchange rate. An optimal rule would naturally account for this distinction and respond appropriately to all the variables in the model. Since however our focus is on simple policy rules, the different emphasis on variables in alternative rules becomes relevant. In other words in a simple rules context the selection of feedback variables to include becomes important and we investigate whether ‘obvious’ inclusions (like the exchange rate or trade balance terms) improve the stabilisation properties of existing rules, eg the Taylor rule. For instance, in a simple rule context, it is interesting to see whether adding an exchange rate term to the set of feedback variables matters in this respect. This is a testable proposition. We carry out this and other tests like this by examining the performance of alternative rules under various criteria and discuss our findings in Section 5, below.

3 Model solution and calibration

3.1 Solving the model

To solve the model we first derive the relevant first-order conditions discussed in Section 2. We then solve for the non-stochastic flexible-price steady state and take the log-linear approximation of each non-linear first-order condition around this steady state. This procedure is presented in the technical annexes.

As shown in the technical annexes, the model can be cast in first-order form:

$$\mathbf{A}\mathrm{E}_t z_{t+1} = \mathbf{B}z_t + \mathbf{C}x_t \qquad \textbf{(22)}$$

$$x_{t+1} = \mathbf{P}x_t + u_t \qquad \textbf{(23)}$$

where **A** and **B** are 31×31 matrices, while **C** is a 31×8 matrix. R is an 8×8 matrix containing the first-order cross-correlation coefficients of the exogenous variables, whose white noise iid innovations are expressed by the vector u_t.

Let f_t and k_t denote the endogenous and pre-determined parts of the vector z_t respectively. Then the rational expectations solution to equations **(22)** and **(23)**, expressing the vector of endogenous variables f_t as functions of predetermined (k_t) and exogenous (x_t) variables, can be written as:

$$f_t = \Xi_1 k_t + \Xi_2 x_t \qquad \textbf{(24)}$$

$$\begin{bmatrix} k_{t+1} \\ x_{t+1} \end{bmatrix} = \Psi \begin{bmatrix} k_t \\ x_t \end{bmatrix} + \begin{bmatrix} 0 \\ u_t \end{bmatrix} \qquad \textbf{(25)}$$

In this paper we computed this solution using Klein’s (2000) algorithm.

3.2 Calibration

We calibrate the model to match key features of UK macroeconomic data. For this purpose, we set the discount factor, b, to imply a steady-state annual real interest rate of 3.5%. This is equal to the average ten-year real forward rate derived from the UK index-linked gilt market since March 1983. The steady-state inflation rate was set at 2.5% per year: the current UK inflation target.

We assume that steady-state foreign inflation was equal to steady-state domestic inflation; that is, 2.5% per year. An implication is that the nominal exchange rate is stationary. We normalise the steady-state prices of traded goods and intermediate goods (in foreign currency) to unity.

To set the parameter governing the relative weight of traded and non-traded goods consumption, g, (as well as other parameters associated with the distinction between traded and non-traded goods) we need first to define data analogues of the two sectors in our model. De Gregorio, Giovannini and Wolf (1994) use a sample of 14 OECD countries for the period 1970-85 to estimate the proportion of world output of various sectors that was exported. They suggest that a value of this ratio larger than 10% was enough to imply that the sector could be thought of as producing a traded good. We follow them in defining our traded-goods sector as including ‘Manufacturing’, ‘Transport and Communications’, ‘Agriculture, Forestry and Fishing’ and ‘Metal Extraction and Minerals’. All other goods and services were treated as non-traded goods.

To set the parameter in the utility function reflecting preferences for imports *vis-à-vis* non-traded goods, g, we use data on consumption spending on traded versus non-traded goods. To do so, we equate consumption of non-traded goods with output of non-traded goods and set consumption of imports equal to output of traded goods less exports of traded goods. We set g equal to 0.122, so that the implied constant share of consumption spending on traded versus non-traded goods matched the average value seen in the available data.[17] We set the habit formation parameter such that the persistence of the output response to shocks in the model is similar to that in the UK data. The value chosen is $x_c = 0.7$.

The weight on leisure *vis-à-vis* consumption in the utility function, d, is set to ensure that steady-state hours were equal to 0.3 in the absence of ‘distortions’.[18] The required value is 1.815. Though essentially a normalisation, this choice corresponds to an 18-hour day available to be split between work and leisure time, and workers, on average, working fifty 40-hour weeks in a year. We set $q_W = 0.165$ as this is consistent with steady-state hours of 0.273 when habit formation and monopolistic supply of labour are accounted for. This level of hours represents a deviation from ‘distortion-free’ steady hours equal to 9%, the average level of UK unemployment (LFS measure) between 1983 Q2 and 1999 Q2. We set $f_W = 0.75$ as this implies that wage contracts are expected to last for one year.

We set the weight on money in the utility function to $\chi = 0.005$. This implies that the ratio of real money balances to GDP is around 30% in steady state. Though this is somewhat higher than the ratio of M0 to nominal GDP, it is not clear that ‘money’ in our model is best proxied by M0 in the data. The ratio of M4 to quarterly nominal GDP is larger; the average for 1963 Q1-2000 Q1 is around 1.4. So our calibration fixes the ratio of steady-state real money balances to GDP at an intermediate level. We set e=1, which implies a unit elasticity of money demand. This is consistent with empirical estimates for the United Kingdom.

To calibrate parameters on the production side of the model we used sectoral data where our sectors were defined as described above. We first calibrate the mark-ups that firms in each sector apply to unit marginal costs, using the results of Small (1997). Weighting these mark-ups with the respective shares in value added output,[19] we obtain a value for the non-traded sector gross mark-up of 1.17. Gross mark-ups for the imported and intermediate goods sectors are found to be 1.183 and 1.270. These calibrations imply values for q_N, q_M and q_I of 0.17, 0.183 and 0.270, respectively.

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[17] The ONS data on nominal exports by industry are annual and cover only the period 1989 to 1999.

[18] This involved setting the habit-formation parameter (x) to zero and assuming that the elasticity of substitution between labour types tended to infinity (q_W=0).

[19] Using weights from the 1985 ONS *Blue Book*.

Computing elasticities of non-traded and traded goods output with respect to employment gives estimates of a_N and a_X of 0.793 and 0.632 respectively. To calibrate the probabilities that firms in a particular sector receive signals allowing them to change price, we use data on the average number of price changes each year for different industries. Hall, Walsh and Yates (1997) find that the median manufacturing firm changes price twice a year, the median construction firm three or four times a year, the median retail firm three or four times a year and the median 'Other Services' firm once a year. On this basis, we assume an average duration of prices of six months for firms in the import goods and intermediate goods sectors and an average duration of four months for firms in the non-traded goods sector. This implies values for f_M, f_I and f_N of 0.33, 0.33 and 0.43 respectively.

We set the price elasticity of export demand (h) to 0.2. This approximates the one-quarter response of the UK export equation in the Bank of England's medium-term macroeconomic model (see Bank of England (1999), pages 50-51).

As we did not have any data on imported intermediate inputs by industry (except for those in the input-output tables which are only published every five years or so), we equated 'shocks to total factor productivity' in each sector with 'shocks to labour productivity'. In other words, we used quarterly data on gross value added by industry at constant 1995 prices from 1983 onwards (ETAS Table 1.9) and 'workforce jobs' by industry for the same period[20] to calculate our productivity series as:

$$\ln A_{Z,t} = \ln y_{Z,t} - a_Z \ln h_{Z,t} \quad \textbf{(26)}$$

where Z indexes the sector, y is value added and h is workforce jobs. In order to justify this approach, we need to assume that movements in intermediate inputs are 'small' relative to movements in output and employment.

We now turn to the calibration of the forcing processes. After HP-filtering the two productivity series obtained from **(26)** we estimate the stochastic processes for the productivity terms using a vector autoregressive (VAR) system:

$$\begin{pmatrix} \hat{A}_t^T \\ \hat{A}_t^N \end{pmatrix} = R_A \begin{pmatrix} \hat{A}_{t-1}^T \\ \hat{A}_{t-1}^N \end{pmatrix} + \begin{pmatrix} e_{T,t} \\ e_{N,t} \end{pmatrix} \quad \textbf{(27)}$$

The disturbances $e_{T,t}$ and $e_{N,t}$ are normally distributed with variance-covariance matrix $\mathbf{V}_D$. Given that the model has zero productivity growth in steady state, $\hat{A}^Z$ refers to 'log-deviations of productivity in sector Z from a Hodrick-Prescott trend'. Our estimation results imply:

$$R_A = \begin{pmatrix} 0.705 & 0.227 \\ -0.066 & 0.784 \end{pmatrix} \text{ and } \mathbf{V}_D = 10^{-5} \times \begin{pmatrix} 3.19 & 1.43 \\ 1.43 & 7.044 \end{pmatrix} \quad \textbf{(28)}$$

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[20] We adjusted the workforce jobs series prior to 1995 Q3 to take account of a level shift of about 350,000 in total workforce jobs when the series was rebased. To do this, we added to the figure for each industry a share of the 350,000 workers equal to the industry's share in the published total. We combined the output data using the 1995 weights to get real value added for each of our two sectors.

To calibrate the forcing processes associated with overseas shocks, we estimate another VAR.[21] We derive processes for the shocks to the one-quarter change in the world price of traded goods and the world price of imported materials, as well as to foreign interest rates, the exchange rate risk premium and world demand. We construct a series for the foreign interest rate as a weighted average of three-month euromarket rates for each of the other G6 countries, using the same weights used to construct the UK effective exchange rate index. For intermediate goods imports we follow Britton, Larsen and Small (1999) and construct an index based on the imported components of the producer price index. For the world price of traded goods we use the G7 (excluding the UK) weighted average of exports of goods and services deflators where the weights match those in the UK effective exchange rate index. For world output, we use the G7 (excluding the UK) average GDP weighted by the countries' share in total UK exports of goods and services in 1996.

We estimate the following VAR:

$$\begin{pmatrix} i_{f,t} - i_f \\ \log(P^*_{I,t}/P^*_t) - \log(P^*_I/P^*) \\ \Delta\log P^*_t - \Delta\log P^* \\ \hat{y}_{F,t} \end{pmatrix} = R_F \begin{pmatrix} i_{f,t-1} - i_f \\ \log(P^*_{I,t-1}/P^*_{t-1}) - \log(P^*_I/P^*) \\ \Delta\log P^*_{t-1} - \Delta\log P^* \\ \hat{y}_{F,t-1} \end{pmatrix} + \begin{pmatrix} e_{i_f,t} \\ e_{P_{I,t}} \\ e_{P^*_t} \\ e_{y_F,t} \end{pmatrix} \qquad \textbf{(29)}$$

where variables without time subscripts refer to their averages in the data and $\hat{y}_{F,t}$ is the log-deviation of world demand from its Hodrick-Prescott trend. The disturbances $e_{i,t}$, $e_{P_I,t}$, $e_{P^*,t}$ and $e_{yF,t}$ are normally distributed with variance-covariance matrix $\mathbf{V}_F$. The VAR is specified in this way because the rest of the world is modelled in a reduced-form way that does not place restrictions on the long-run behaviour of variables. In particular, if we included inflation of foreign intermediates prices as a separate variable then there would be no reason to expect the long-run responses of foreign intermediates prices and the general foreign price level to be equal. If this restriction did not hold, then temporary shocks could shift the steady-state relationships between (exogenous) world variables and destabilise the relationships between the endogenous variables in our model. Rather than place long-run restrictions on a VAR including foreign inflation rates, we estimate the system in **(29)**.

Using data over the period 1977 Q3 – 1999 Q2 we obtained the following results:

$$R_F = \begin{pmatrix} 0.448 & -0.006 & 0.083 & 0.140 \\ 2.392 & 0.902 & 0.290 & -1.07 \\ -0.359 & -0.019 & 0.711 & -0.019 \\ -0.357 & 0.003 & 0.079 & 0.962 \end{pmatrix}$$

$$\mathbf{V}_F = 10^{-6} \times \begin{pmatrix} 3.82 & 4.47 & 3.08 & 0.54 \\ & 760 & 31.9 & -22.3 \\ & & 27.6 & 0.49 \\ & & & 7.79 \end{pmatrix}$$

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[21] This VAR can be regarded as a reduced-form representation of the rest of the world. Shocks to the world economy affect world variables that – because they are forcing processes in our model – affect domestic variables.

We derived a measure of the sterling exchange rate risk premium derived from the Consensus Survey[22] and estimated the following process:

$$z_t = 0.261 z_{t-1} + e_{z,t}, s_z = 0.009 \quad \textbf{(30)}$$

Finally, in line with McCallum and Nelson (*op cit*), we assume that the preference shock n_t is white noise, and, for simplicity, we set its standard deviation equal to 0.011 as they do for the United States.

4 Properties of the model

To analyse the dynamic properties of the model, we have derived impulse response functions for the key endogenous variables when the model is hit by a monetary policy shock.

Throughout, we close the model with a policy rule for the nominal interest rate i_t. The rule used here was estimated using UK data over the period 1981 Q2-1998 Q2. We estimated a reduced-form model in which there were also equations determining the (log) aggregate output gap $\hat{y}_t$,[23] the deviation of the annual log-change in the RPIX from target[24] (measured in quarterly units, so that $\hat{p}_{4,t} \equiv (\hat{P}_t - \hat{P}_{t-4})/4$) and changes in the (log of the) nominal trade-weighted effective exchange rate ($\Delta \ln e_t$). The model, which is similar to that in Batini and Nelson (2001), also contains two dummies ($DERM_t$ and $D92_t$) to capture the years of the UK membership of the ERM and the shift in policy regime which occurred in 1992 Q4.

To compute the impulse responses, we need to identify the monetary policy shock. To do so we estimate a VAR of the following form:

$$\begin{bmatrix} 1 & -a_{ip} & -a_{iy} & -a_{ie} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_t \\ \hat{p}_{4,t} \\ \hat{y}_t \\ \Delta \ln e_t \end{bmatrix} = \begin{bmatrix} b_{ii} & 0 & 0 & 0 \\ b_{pi} & b_{pp} & b_{py} & b_{pe} \\ b_{yi} & b_{yp} & b_{yy} & b_{ye} \\ b_{ei} & b_{ep} & b_{ey} & b_{ee} \end{bmatrix} \begin{bmatrix} i_{t-1} \\ \hat{p}_{4,t-1} \\ \hat{y}_{t-1} \\ \Delta \ln e_{t-1} \end{bmatrix} + \mathrm{K} \begin{bmatrix} 1 \\ DERM_t \\ D924_t \end{bmatrix} + \begin{bmatrix} e_{i,t} \\ e_{p,t} \\ e_{y,t} \\ e_{e,t} \end{bmatrix}$$

This is a restricted VAR that is estimated using OLS.[25] We also impose $b_{pi} = b_{pe} = 0$, which ensures that the inflation equation does not exhibit a 'price puzzle' in response to a monetary policy shock.[26] These restrictions are not rejected by the data: the *p*-value of the log-likelihood test is 0.90. In addition, we impose the restriction that the long-run response of the interest rate to inflation is greater than one. We find that the restriction $a_{ip}/(1-b_{ii}) = 1.01$ is not rejected by the data

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[22] The measure is equal to the percentage point difference between the expected 24-month depreciation of the sterling ERI (derived from the responses of survey participants) and the two-year nominal interest rate differential.
[23] Measured as the deviation from a Hodrick-Prescott trend.
[24] The target rate of inflation is derived in the same way as in Batini and Nelson (2001).
[25] The estimated coefficients are available on request.
[26] The 'price puzzle' occurs when inflation rises in response to a monetary contraction (a positive shock to the interest rate equation). This reaction is driven by a statistically significant negative coefficient on the lagged interest rate in the inflation equation.

(p-value=0.07) and we impose this on the interest rate equation.[27] Ignoring the constant term, the estimated monetary policy rule is:

$$i_t = 0.681 i_{t-1} + 0.322 \hat{p}_{4,t} + 0.075 \hat{y}_t - 0.014 \Delta \ln e_t - 0.003 DERM_t - 0.004 D924_t + e_{i,t} \quad \textbf{(31)}$$
$$(9.37) \qquad (3.65) \qquad (1.93) \qquad (2.49) \qquad (3.59)$$

where i is the average interbank lending rate expressed in quarterly units, $e_{i,t}$ is the residual, and t-statistics are in brackets. We embed this in the estimated model and examine the impulse responses of the variables under a shock to $e_{i,t}$. This methodology essentially follows Ericsson, Hendry and Mizon (1998).

We use this identification approach because it allows us to derive an estimated equation for the nominal interest rate in which it depends only on contemporaneous values of inflation, output and changes in the exchange rate, plus a lagged interest rate term. Such an estimated rule can be directly compared with a standard Taylor-type rule in which the nominal interest rate responds to current-dated deviations of output from trend and inflation from target. If we were, instead, to use a standard Cholesky decomposition to identify the monetary policy shock, our estimated rule would imply that interest rates feed back from contemporaneous and lagged values of all the variables in the VAR. Alternatively, adopting the approach of Rotemberg and Woodford (1997) — leading the other variables in the VAR (inflation and output in their case) in order to, in effect, estimate a VAR with a vector of endogenous variables equal to $[i_t, p_{4,t+1}, \hat{y}_{t+1}, \Delta \ln e_{t+1}]$ — would yield a similar dynamic specification of the policy rule. But, even though this gives an estimated equation for the interest rate that responds to contemporaneous realisations of output and inflation (as we would like), it implies very restricted dynamic specifications for the other variables in the model: one in which the leads of inflation and output depend only on lags of the interest rate and not also on the level of the interest rate at time t.

Since the endogenous variables in the estimated model feature as deviations from their respective long-run values — or enter as first differences — they are comparable to variables in the log-linearised first-order approximation version of the theoretical model described in Section 2. Chart 2 shows the responses of output, inflation and the nominal interest rate to a unit shock to the monetary policy rule **(31)** over 30 periods (calendar quarters). The solid line depicts the theoretical model's responses and the dashed line gives the estimated model's responses. The shaded areas show confidence intervals for the responses in the estimated model.[28]

The responses of both the estimated and the theoretical model broadly agree with conventional wisdom: following a temporary rise in the interest rate, output declines, but ultimately reverts to base, and inflation also falls. However, the error bands around the estimated model's impulse responses are generally quite wide, indicating that these effects cannot be estimated with great precision. So, the comparison of the two sets of responses should not be taken too literally.

Panel 1 indicates that, in our theoretical model, output falls on impact by around 0.25%, following an unanticipated 100 basis point rise in the nominal interest rate: the same order of magnitude as that of

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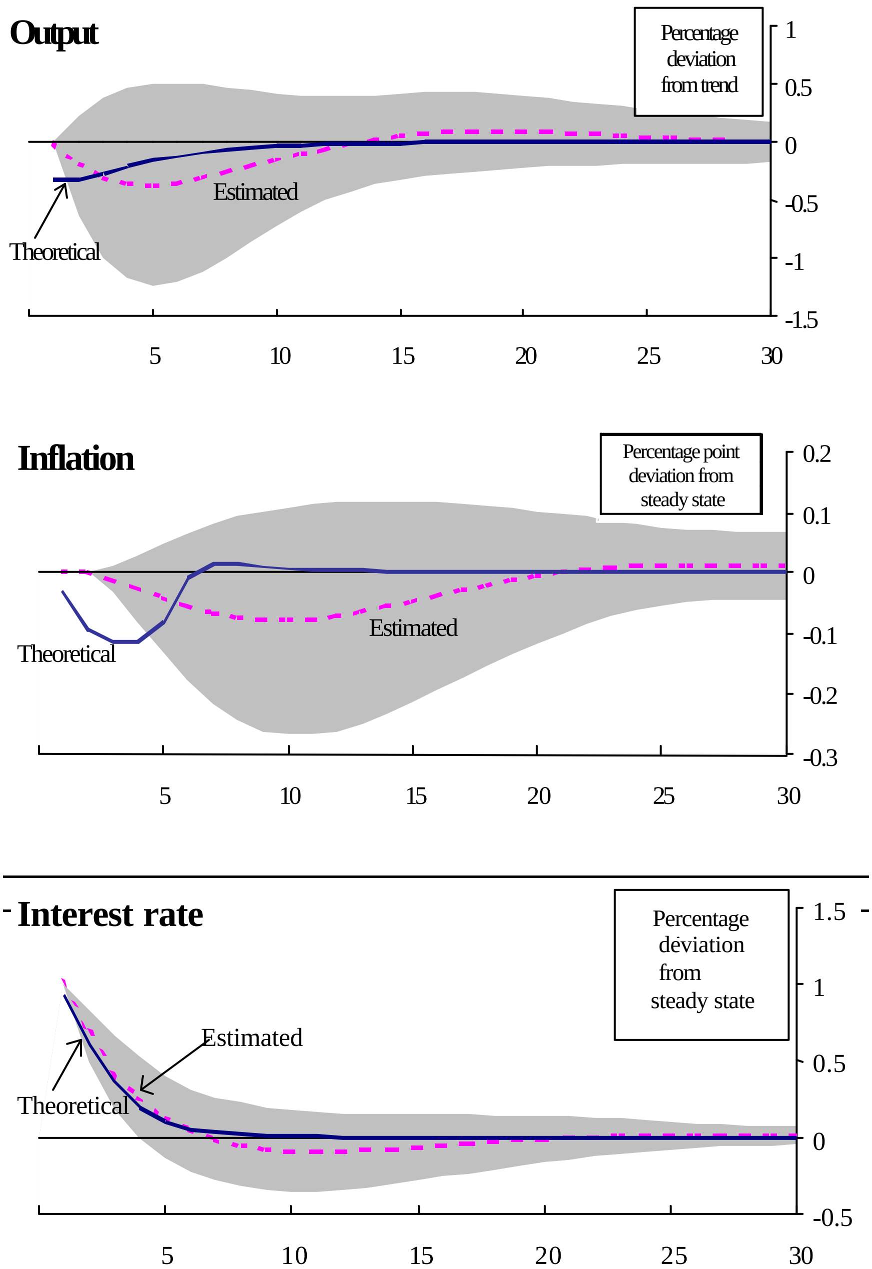
(27) The fact that the p-value for this restriction is not particularly high may reflect changes in the coefficients of the monetary reaction function over different subsamples. (See Nelson (2000).)

(28) These were computed by conducting 100 simulations. In each simulation the coefficients of the model were drawn from the distribution implied by our estimation procedure and the associated impulse response functions were recorded. The shaded area represents the range covered by two standard deviations of the simulated impulse responses either side of the mean response.

the estimated model. The policy shock response in the estimated model is slightly more sluggish than that in the theoretical model and the trough in output following the shock occurs later in the estimated model than in the theoretical model. The speedier response of output in the theoretical model reflects the rapid response of the net trade component of aggregate output in that model. The theoretical model does exhibit a sluggish and 'hump-shaped' consumption response, reflecting the high value of the habit formation parameter (x). This result accords with the findings of Fuhrer (2000).

Chart 2: Impulse responses following a 100 basis point monetary policy shock



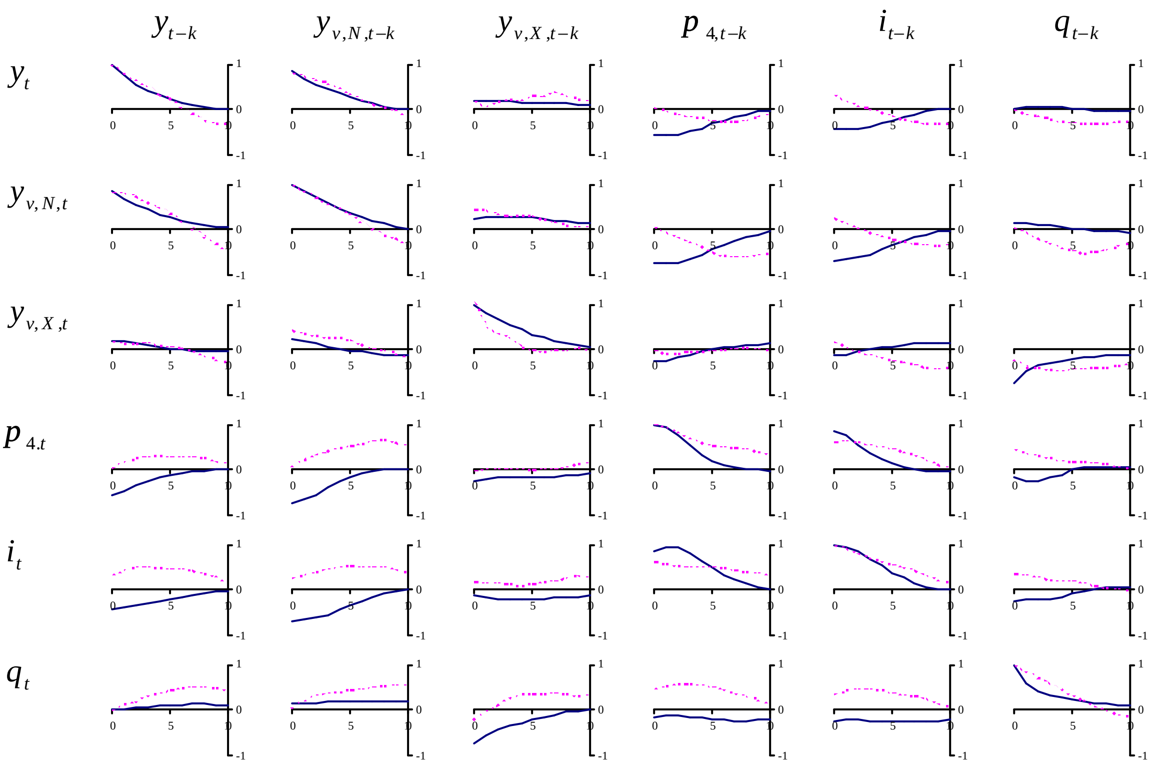
Panel 2 compares the inflation responses of the theoretical and estimated models. In the theoretical model, inflation responds earlier and more intensely than the estimated model. There, inflation touches its *nadir* around ten quarters after the shock, and returns smoothly back over a period of about two to three years. The difference between the two responses reflects the fact that the theoretical model, even accounting for the built-in persistence, is forward-looking. This means that output and inflation can 'jump' immediately in response to a shock. In contrast, inflation and output in the estimated model are entirely backward-looking.

Panel 3 depicts how the (nominal) interest rate responds. While it rises by a full 1% in the estimated model, the nominal interest rate rises by slightly less in the theoretical model. Again, this reflects the fact that output and inflation jump immediately in response to the shock in the theoretical model. So a shock to the monetary policy rule manifests itself in the form of changes in output and inflation as well as a change in the nominal interest rate. In the estimated model, the output and inflation equations are entirely backward-looking so that shocks to the monetary policy rule can only affect the nominal interest rate.

A second way of evaluating the correspondence between UK data and our model is to compare the dynamic cross-correlations of key variables from the data with those from the model.[29] Chart 3 shows this comparison for (log deviations of) aggregate output (y), value added sectoral outputs ($y_{v,N}$ and $y_{v,X}$), annual CPI inflation (p_4), the nominal interest rate (i) and the real exchange rate (q). In each of the 36 panels, the solid line illustrates the theoretical cross-correlation function and the dashed line the cross-correlation function from the data.

Chart 3 indicates that our model seems to account for the autocorrelations of the data to a reasonable extent (see charts on the diagonal). In particular, our model can in part replicate the degree of persistence of inflation seen in the data, although this is mainly driven by persistence in the exogenous shocks. The model is perhaps less successful at capturing cross-correlations: for example, the dynamic relationship between the real exchange rate and some of the other variables in the panel.

Chart 3: Cross-correlations of selected endogenous variables



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[29] For the model, the cross-correlations were computed using a variant of the Hansen and Sargent (1998) doubling algorithm also used by Williams (1999).

5 A comparison of alternative simple rules

In this section we present results from the model when it is closed with alternative monetary policy rules. In what follows we assume that deviations of the nominal interest rate from base are a linear function of deviations of endogenous variables (current, lagged or expected) from base. So we consider rules of the form:

$$i_t = Rg_t \qquad \textbf{(32)}$$

where g is the set of feedback variables in the rule (a subset of all the endogenous and exogenous variables in the model) and R is a row vector of coefficients.[30] A simple rule therefore consists of two components, the vector of feedback variables, g, and the vector of coefficients, R. We define generic classes of rules by the g vector, ie, by the set of feedback variables.

To carry out the comparison, we consider simple 'optimised' rules. In this case, the R vectors are those that minimise the policy-maker's loss function for each rule. The specification of the rules is the one originally suggested for those rules, ie, the set of feedback variables, g, corresponds to the set initially proposed by the rule's first advocate.[31] By contrast, as anticipated, in our family of open-economy simple rules, we vary the vectors of feedback variables, g, relative to those implied by existing rules, to better account for the exchange rate channel of monetary transmission.

5.1 Two alternative welfare criteria

For the policy-maker's loss function, we chose a standard function in which the loss was quadratic in asymptotic variances of inflation deviations from target and output deviations from potential. This is often used as a metric for capturing policy-makers' preferences in studies that attempt to evaluate the trade-off between inflation variability and output variability, under alternative specifications of the interest rate rule (see Taylor (1999)). Algebraically, the loss, L_1, can be written as:

$$L_1(p, y, i) = w_p AVar(4p) + w_y AVar(y) + w_i AVar(\Delta 4i) \qquad \textbf{(33)}$$

which is a linear combination of the asymptotic variances ($AVar$) of annualised inflation and output, and the change in the (annualised) nominal interest rate. Following Batini and Nelson (2001) we set $w_p = w_y = 1$. Of course, policy-makers are often interested in the behaviour of annual inflation, rather than the annualised quarterly inflation rate. However, it greatly simplifies the analysis to work with quarterly inflation in equation **(33)** and the choice is unlikely to affect the relative performance of the various rules.

The inclusion of a term in the variability of the nominal interest rate is designed to address the fact that optimised coefficients for simple rules often imply very aggressive policy responses. In practice, this would lead to large movements in the policy instrument. Casual empiricism suggests that policy-makers prefer stability in the instrument, which implies that nominal interest rate variability should be

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(30) Note that by using lag and lead identities within the model, the set of variables that could be included in the rule is large.

(31) For example, an output gap and an inflation gap (deviations of actual inflation from its target or equilibrium value) for the Taylor (1993a) rule; and an expected inflation gap (deviations of future expected inflation from an inflation target) and an interest rate smoothing term for the inflation-forecast-based rule.

included in the loss function.[32] Perhaps more importantly, when taken literally, aggressive policy rules often imply that policy-makers should set a negative nominal interest rate, despite the general presumption that nominal rates cannot fall below zero (see McCallum (2000) and Goodfriend (2000)). This issue is discussed in Williams (1999).

Including a term in the loss function is one way to ensure that rules with optimised coefficients do not imply that there is a high probability that the zero bound on the nominal interest rate is violated. The choice of the weight w_i depends on the model being used. Following Rudebusch and Svensson (1999), Batini and Nelson (2001) set $w_i = 0.5$. We set $w_i = 0.25$, which ensures that there is a relatively low probability of violating the zero bound for the optimised rules we consider. We discuss this further below.

Turning to the vector of 'optimised' coefficients ($\tilde{R}$), this is chosen as follows:

$$\tilde{R} = \arg\min_{R} L_1(p, y, i) \qquad \textbf{(34)}$$

To derive it, we employ a simplex search method based on the Nelder-Mead algorithm.[33]

In addition to loss L_1 upon which we optimise to get coefficients in the $\tilde{R}$ vector, we consider a second measure of loss, ie, a utility-based loss function, which we denote L_2. However, we do not derive a second vector of optimal coefficients from this loss. Rather, we use it as a metric to measure the amount of utility loss associated with each rule when the authorities derive coefficients for the rules by optimising a set of preference described by the first, standard quadratic loss function L_1. In this sense, we can still use this second metric to assess which rules are successful at minimising (the sum of) the inefficiencies present in our model, although the rules we consider will not be specifically designed to that end. The reason why we opt to choose coefficients optimising on L_1 rather than L_2 is that, in the absence of *ad hoc* added interest rate variability terms the latter suggests unplausibly aggressive coefficients for our battery of rules. Adding an *ad hoc* interest rate variability term defies the same rationale for using utility-based losses. On the other hand excluding it leaves us with results that are difficult to compare with much of the literature on optimised simple rules.

Following Woodford (2001), we derive L_2 by taking a second-order log-linearisation of the utility function **(1)** around the steady state. The derivation is very similar to that of Erceg *et al* (2000).[34] We ignore the constant and first-order terms (the latter are zero in unconditional expectation) and focus on the unconditional expectation of the second-order terms. The result is shown in equation **(35)**, below. This shows that this measure of loss depends on a number of factors. The first line gives the loss associated with variations in consumption and real money balances. The term in the (asymptotic) first-order autocovariance of consumption appears because of the habit formation assumption. The rest of the loss function evaluates the loss due to heterogeneous labour supply. The terms in the variances of prices, non-traded goods inflation and wages are analogous to those in Erceg *et al* (2000). The remaining terms reflect the fact that, in our model, labour is purchased by exporters as well as by non-traded producers.

[32] The fact that the interest rate smoothing term in the estimated rule – equation **(31)** – is high and significant, suggests that – historically – interest rates have not responded aggressively in the United Kingdom.
[33] The method is contained in the MATLAB Optimization Toolbox and detailed by Lagarias *et al* (1998).
[34] The derivation is available on request.

$$
\begin{aligned}
L_2 = {} & \frac{x}{(1-x)^2} AVar(\hat{c}_t) - \frac{x}{(1-x)^2} ACov(\hat{c}_t, \hat{c}_{t-1}) + \frac{c(\frac{\Omega}{P})^{1-e}}{2} \frac{1-e}{e} AVar(\hat{w}_t) \\
& + \frac{dh}{2(1-h)^2} \frac{1+q_N}{q_N} \frac{f_N}{(1-f_N)^2} AVar(\hat{p}_{N,t}) \\
& + \frac{dh}{2(1-h)} \left[\frac{q_W}{1+q_W} + \frac{h}{(1-h)} \right] \left(\frac{1+q_W}{q_W} \right)^2 \frac{f_W}{(1-f_W)^2} AVar(\Delta \hat{W}_t) \\
& + \frac{dh_X^2}{2(1-h)^2 h} AVar(\hat{h}_{X,t}) + \frac{dh_N^2}{2(1-h)^2 h} \{AVar(\hat{y}_{N,t}) + AVar(\hat{w}_t - \hat{p}_{N,t})\} \\
& + \frac{dh_X h_N}{(1-h)^2 h} \{ACov(\hat{h}_{X,t}, \hat{y}_{N,t}) - ACov(\hat{h}_{X,t}, \hat{w}_t - \hat{p}_{N,t})\} \\
& - \frac{dh_N^2}{(1-h)^2 h} ACov(\hat{y}_{N,t}, \hat{w}_t - \hat{p}_{N,t})
\end{aligned}
\qquad \textbf{(35)}
$$

The terms that appear in equation **(35)** are directly related to the distortions present in our model. Specifically, the welfare of the representative consumer is adversely affected by variability in non-traded price inflation, nominal wage inflation and the impact of wage rigidity on the allocation of labour between the export and non-traded sectors. Terms in the variability of price inflation and nominal wage inflation appear in closed-economy models, such as Erceg *et al* (2000). But equation **(35)** shows that, in a two-sector economy, agents care also about the co-movement of output and employment in the two sectors. Since an open economy like ours typically has at least two sectors (ie the traded and non-traded goods sectors) this aspect is plausibly a constant feature of utility-based losses in open-economy models.

Since this loss function is derived from the utility of the households, it seems to be a good way of judging the welfare effects of monetary policy rather than using an arbitrary loss function —such as L_1 — as has been common in this literature.[(35)] However, it is not necessarily ideal as it requires us to make some judgments about how to measure welfare in a model with heterogeneous households.

Finally, to obtain the asymptotic variances in equations **(33)** and **(35)**, we again used the doubling algorithm of Hansen and Sargent (1998).

5.2 A battery of rules

We evaluate the relative performance of the following classes of rules: (i) the estimated policy rule (see Section 4); (ii) a Taylor rule; (iii) an inflation forecast-based (IFB) rule; (iv) a naïve MCI-based rule; (v) Ball's (1999) rule; and (vi) a family of alternative 'open-economy' rules. This battery of rules encompasses the mainstream of the literature on simple policy rules for both closed and open economies, but adds a series of new simple rules that slightly modify existing rules in the attempt to better suit monetary policy in open economies.

The estimated rule enables us to assess the remaining rules *vis-à-vis* history, and to infer whether, using these other rules, it may have been possible to do better than historically. The Taylor rule was devised for a closed economy (the United States), where the exchange rate channel of monetary

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(35) Note that, because we characterise the economy using a log-linear approximation, there is no clear advantage to evaluating an exact utility function; see Woodford (2001, page 5).

transmission has a negligible role in the propagation of monetary impulses. IFB rules imply that the interest rate should respond to deviations of expected, rather than current, inflation from target.[36]

A naïve simple rule based on a MCI is one that entails adjusting the nominal interest rate to ensure that real monetary conditions are unchanged over time. Ball's (1999) rule is a less naïve specification of a MCI-based rule where policy-makers alter a combination of interest and exchange rates in response to deviations of (an exchange-rate-adjusted or 'long-run' measure of) inflation from target and output from potential.

Finally, we look at a set of alternative open-economy rules. As anticipated, these rules are designed for an economy that is open.

Ideally, following Ball (1999), we want these rules to do two things. First, alongside the standard output gap channel, the rules should also exploit the exchange rate channel of monetary transmission. In other words, they should take account of the fact that changes in the nominal interest rate in an open economy affect not just demand via the consumers' Euler equation, but also overseas goods prices in domestic currency terms via the changes it elicits in the exchange rate. This should make policy more effective since it ensures that the amount of adjustment imposed on each sector after a shock is a function of both the degree of nominal inertia in the sector and the extent to which each sector is affected by the various types of monetary impulses. Second, they should only augment closed-economy rules (eg, Taylor (1993a) and Henderson and McKibbin (1993)) in a parsimonious way. This is because, both on credibility and monitorability grounds, there is a clear merit in having a rule that is simple to compute — ie a rule that does not introduce any extra uncertainty in the measurement of its arguments —and that can be easily understood by the public.

For this purpose we consider four different rules, which account for the openness of the economy in various ways. The first rule in the family (OE1) instead, is a modification of the inflation-forecast-based rule of Batini and Haldane (1999), which adds to that rule an explicit response to the real exchange rate (again contemporaneous and lagged, unrestricted). In principle, an IFB rule already accounts for the exchange rate channel of monetary transmission, inasmuch as this underlies the equations that inform the forecast for inflation. So evaluating this rule enables us to understand whether incorporating a separate exchange rate term in an IFB rule provides information over and above that already contained in the inflation forecast.[37] The remaining rules we look at are variants of Ball's (1999) rule. More specifically, the first variant (OE2) adds to the standard feedback terms in Ball's rule a term responding to the balance of trade. The second variant (OE3) replaces aggregate output with output gaps in the two sectors; this takes explicit account of the fact that components of GDP differ in their international exposure. And the third variant (OE4) has the interest rate responding to the same variables as in Ball (1999), but imposes a restriction on the contemporaneous and lagged real exchange rate terms, so that their coefficients are equal and opposite. In practice, this implies that the policy-makers respond to time *t* changes in the real exchange rate rather than levels of it.

Table A lists exact specifications of rules (i)-(vi). Throughout the table, i_t denotes the percentage point deviation of the short-term nominal interest rate from steady state; p_t and y_t are log-deviations

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[36] See Batini and Haldane (*op cit*).
[37] See also Batini and Nelson (2000) for a comprehensive study of this issue using a small-scale structural model of the UK economy.

of inflation and GDP from base; $E_t p_{t+k}$ is inflation expected at $t + k$; q_t is the real exchange rate, Δq_t represents changes in the real exchange rate; BT_t is the balance of trade; Δe_t indicates changes in the nominal exchange rate; $y_{n,N,t}$ and $y_{n,X,t}$ are sectoral output gaps (of the non-traded and export sectors, respectively); and, finally, $\hat{p}_{4,t}$ and $\hat{y}_t$ are defined in Section 4.

Table A: A battery of rules

Rule's specification	**Name**	**Author**	**Author's suggested coefficients**
$i_t = l_i i_{t-1} + l_p \hat{p}_{4,t} + l_y \hat{y}_t + l_e \Delta e_t$	Estimated rule	Section 4 of this paper	$l_y = 0.075$, $l_p = 0.322$, $l_i = 0.68$ and $l_e = -0.014$.
$i_t = l_p p_t + l_y y_t$	Taylor rule	Taylor (1993a)	Taylor (1993a): $l_p = 1.5$; $l_y = 0.125$. Henderson-McKibbin (1993): $l_p = 2$; $l_y = 0.5$.
$i_t = l_i i_{t-1} + l_p E_t p_{t+j}$	IFB rule	Batini and Haldane (1999), among others	$j = 5$, $l_i = 0.5$ and $l_p = 5$
$i_t = p_t - m q_t$	Naïve MCI rule	-	$m = 1/3$
$i_t = l_y y_t + l_p p_t + l_{q1} q_t + l_{q2} q_{t-1}$	Ball's rule	Ball (1999)	$l_y = 1.93$, $l_p = 2.51$, $l_{q1} = -0.43$ and $l_{q2} = 0.3$.
$i_t = l_i i_{t-1} + l_p E_t p_{t+j} + l_{q1} q_t + l_{q2} q_{t-1}$	OE1	This paper	See Table B below
$i_t = l_y y_t + l_p p_t + l_{q1} q_t + l_{q2} q_{t-1} + l_{BT} BT_t$	OE2	This paper	See Table B below
$i_t = l_{yN} y_{n,N,t} + l_{yX} y_{n,X,t} + l_p p_t + l_{q1} q_t + l_{q2} q_{t-1}$	OE3	This paper	See Table B below
$i_t = l_y y_t + l_p p_t + l_{\Delta q} \Delta q_t$	OE4	This paper	See Table B below

5.3 Results

Table B below contains values of the two loss functions (L_1 and L_2) and asymptotic second-order moments of inflation, output, the nominal interest rate, sectoral outputs and the real exchange rate. These are reported for the Taylor (and Henderson and McKibbin) rule(s), the IFB rule, the naïve MCI-based rule, Ball's rule and for the OE1, OE2, OE3 and OE4 rules when coefficients are set optimally with respect to loss function L_1. This table also reports coefficients for the corresponding optimised rules. Finally, Table C offers a test for relative robustness, by showing the same statistics for each rule when the model is hit by individual shocks rather than by a combination of shocks.

5.3.1 Results under an 'all shocks' scenario

The optimisation indicates that Taylor and Henderson-McKibbin rules for the UK economy, as modelled here, require stronger weights on inflation relative to output than those originally suggested for the United States by Taylor (1993a) and Henderson and McKibbin (1993). This suggests that a mechanical application of the Taylor and/or Henderson and McKibbin rules in the UK context with coefficients designed for the United States is not ideal. Moreover, our model seems to favour a stronger weight on inflation relative to output.

Table B: Comparison of simple monetary policy rules (optimised coefficients)

		Taylor/ H-McK	IFB	MCI	Ball	OE1	OE2	OE3	OE4
Coeffs:	p_t	5.6807	-	**1**	4.8420	-	3.5505	4.8334	5.6821
	y_t	0.2155	-	-	-0.0296	-	0.0912	-	0.2127
	i_{t-1}	-	0.9196	-	-	0.9321	-	-	-
	$E_t p_{t+1}$	-	0.8158	-	-	1.0817	-	-	-
	q_t	-	-	-0.2048	-0.1104	-0.0099	-0.0654	-0.0780	-
	q_{t-1}	-	-	-	-0.0377	-0.0272	-0.0469	-0.0340	-
	$y_{v,N,t}$	-	-	-	-	-	-	-0.0445	-
	$y_{v,X,t}$	-	-	-	-	-	-	0.1033	-
	Δq_t	-	-	-	-	-	-	-	-0.0379
	BT_t	-	-	-	-	-	6.7952	-	-
Welfare	L_1	2.2131	1.6431	3.5920	2.1217	1.5665	2.0658	2.1130	2.1757
	L_2	4.9114	2.6926	4.8373	4.1151	2.5432	3.5975	4.1803	4.9068
Avars	p	0.0250	0.0238	0.1663	0.0264	0.0238	0.0292	0.0253	0.0243
	y	1.2390	1.2022	0.4100	1.1397	1.1090	1.0908	1.1671	1.2525
	Δi	0.1433	0.0150	0.1305	0.1399	0.0191	0.1271	0.1354	0.1337
	$y_{v,N}$	2.4457	2.3549	0.7936	2.2438	2.1879	2.1832	2.2922	2.4733
	$y_{v,X}$	1.1274	1.1027	0.7918	1.0737	1.0509	1.0564	1.0634	1.1199
	c	2.1791	2.2063	0.9487	2.0477	2.0851	2.0269	2.0971	2.2047
	i	0.5204	0.1372	0.2274	0.4929	0.1614	0.4402	0.4905	0.5131
	q	5.2046	4.5376	2.0166	4.3948	3.8913	4.1440	4.3808	5.0811
Prob($i < 0$), %		1.88	0.00	0.08	1.63	0.01	1.19	1.61	1.81

Similarly, for our model economy, the optimal coefficient for the MCI-based rule is smaller than one third — the value commonly used in the MCI literature — suggesting that a greater weight than that used in practice should be placed on interest rates *vis-à-vis* the exchange rate when altering monetary conditions.

Looking at the stabilisation properties of each rule, the first thing to notice is that the IFB rule performs well. In the presence of transmission lags, IFB rules have the benefit of aligning the policy instrument with the target variable (ie, is said to be ‘lag-encompassing’), which minimises the output costs of inflation stabilisation relative to more myopic rules.(38) Along this intuition, under this rule, the interest rate moves solely to correct low-frequency changes in inflation. The asymptotic variance of changes in the nominal interest rate for this rule is, in fact, around a tenth of that under all other rules if we exclude the OE1 rule, a modification of the IFB. This explains why the IFB rule is extremely successful at controlling inflation volatility for a level of output volatility that is comparable to that of

(38) Clarida, Galí and Gertler (1998) report that estimated output-gap-augmented IFB rules offer a good portrait of the behaviour of actual short-term nominal interest rates in G3 countries in the 1980s and 1990s.

other rules in the table. These results are in line with the findings in Batini and Haldane (1999) based on a small-scale, open-economy model of the UK economy. The optimal horizon of just one period may seem surprisingly low. This result is likely to be highly model-dependent, however, reflecting the low persistence in the model (see Chart 2) as well as our use of quarterly, rather than annual, inflation in the loss function. A model with more complex dynamics and/or the use of an objective function defined over annual inflation would be likely to generate an optimal horizon of more than one period ahead. Exploration of this conjecture is left for future work.

Second, Ball's rule provides a lower-than-average variability of output when compared with Taylor/Henderson-McKibbin and with the IFB rule. Relative to them, it also reduces the disparity between output volatilities in the two sectors, other things being equal. However, it produces more interest rate, exchange rate and ultimately inflation variability than the IFB rule because it implies that the nominal interest rate reacts to current, rather than expected, inflation and, hence, is moved more aggressively. This rule is, unsurprisingly, more efficient than the simplistic MCI-based rule, which seems unsuited to cope with inflationary shocks that do not originate from a shock to the exchange rate.

More generally, the naïve MCI-based rule is the worst rule in the set. By construction, the naïve MCI implies a level for the interest rate conditional on the existing level of the exchange rate, when the latter can change as a result of shocks to which the central bank may not wish to respond.[(39)] For this reason, the performance of MCI-based rules tends to be shock-specific, doing poorly in the face of shocks that affect the exchange rate but do not ask for a compensating change in interest rates (eg, shocks to the real exchange rate).

When we look at our 'family' of open-economy rules, we find that, in general, parsimonious modifications of either Ball's or the IFB rule do not provide substantial gains in terms of inflation or output control. The reduction in the value of L_1 is indeed modest and almost certainly ascribable to the fact that rules in the OE family typically react to more endogenous variables. By construction, this gives them a performance 'bonus' relative to non-OE rules. By the same logic, the opposite is true of rule OE4 — a restricted version of Ball's rule — which hence does worse than Ball's rule itself.

If we use L_1 to rank the rules, OE1 is the best rule in Table B. Compared with the Taylor/Henderson-McKibbin and Ball rules, OE1 gives considerably lower output, exchange rate and interest rate variability. Abstracting from the naïve-MCI (which performs badly in terms of inflation variability), OE1 produces the minimum disparity between the volatility of the output gap in the two sectors. This is because it takes explicit account of the fact that in an open economy there are multiple channels of monetary transmission that can be simultaneously exploited in an effective way. Because they reduce the volatility of the policy instrument, IFB and OE1 rules also give the lowest probability of hitting a zero bound with the nominal interest rate.

These results on the relative performance of the rules are confirmed by our second measure of loss, the utility-based loss function L_2. According to this metric, households would be better off if policy-makers followed an OE1 rule or an IFB rule (with coefficients optimised over the objective function L_1) rather than the other rules that we consider. This means that even if designed so as to optimise a proxy of the utility-based loss function (namely L_1), in practice these rules achieve the result of

(39) In general, this criticism would also apply to a rule responding to the output gap, when it is unclear whether this has moved because actual output changed or rather because potential output did.

reducing the microeconomic distortions implied by that function. The worse possible rule according to L_2 is instead the Taylor/Henderson-McKibbin.

The intuition for this result is that the superior inflation stabilisation of the IFB rule also results in more effective stabilisation of non-traded price inflation and nominal wage inflation. These variables appear in the utility-based loss function given by equation **(35)**. Moreover, adding a term in the real exchange rate (OE1) reduces the disparity between output in the non-traded and export sectors further and — as **(35)** would suggest — reduces the utility-based loss. However, the resulting reduction in (utility-based) loss is only marginal. This reflects the fact that the 'sectoral disparity' terms in the utility-based loss function have a small weight compared with the terms in non-traded inflation and nominal wage inflation. This implies that optimal policy (using equation **(35)** as the metric of loss) is broadly similar in our two-sector open economy to the optimal policy in a one-sector closed economy such as that modelled by Erceg *et al* (2000). This accords with the (analytical) results of Clarida, Galí and Gertler (2001) who demonstrate that, for a simple model, the optimal policy in an open economy is isomorphic to optimal policy in a closed economy.

5.3.2 Robustness analysis to individual shocks

To provide more intuition about why certain rules perform better than others, we now re-assess the performance of the rules assuming that the economy was hit by one type of shock at a time. In particular, we are looking to see which rules produce 'sensible' responses to each of the shocks and analyse whether or not the rules that perform well do so because they are robust to many different shocks. In each case, the coefficients in the rules are again those optimally derived for the 'all-shocks' case (shown in Table B), so this is a test of robustness of the exact rule specification.[40] Results from this experiment are summarised in Tables Ca and Cb below.

The tables suggest that the OE1 (ie the modified IFB) rule and the IFB rule itself are still the 'best' rules under most shocks. The OE1 (and to some extent also the original IFB) rule seems to perform particularly well in the face of shocks from overseas. However, both the OE1 and the IFB rules are outperformed by the OE4 (restricted Ball) rule and by their 'closed-economy' counterparts under productivity shocks to the export sector.[41] This is because a shock to export sector productivity affects both export prices and output. Since export prices do not enter the calculation of CPI inflation, rules like OE1 or IFB that respond only to consumer price inflation will not perform well because they fail to respond to the first-round effects of this shock. This is in line with the general intuition that a simple rule can be a good guide for policy in the face of some — but not all — shocks.

Crucially, however, the IFB and the OE1 rules seem more robust to different shocks than the naïve MCI-based rule or Ball's rule. This is particularly evident for overseas shocks (eg foreign interest rate shocks and shocks to the risk premium), but also to shocks to the relative foreign price of intermediate inputs and to shocks to world output and inflation. In the case of Ball's rule, this is also true for shocks to productivity in both the export sector and the non-traded goods sector.

A comparison of the losses associated with each shock reveals that the most costly shock is that which affects intermediates prices. This is because this shock not only has a higher variance than other shocks but also because this shock feeds through to other overseas forcing processes.

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[40] To perform this test, we have re-derived losses and asymptotic second moments of the variables of interest by setting the variances of the remaining shocks to zero.

[41] The OE1 and IFB rules are also inferior to OE4 under shocks to non-traded sector productivity, but this is less severe than in the case of a shock to productivity to the export sector.

Moreover, intermediate prices are a large proportion of unit costs in both sectors. Since non-traded producers set prices as a function of unit costs (as well as expected future inflation), changes in these prices feed into non-traded price inflation. On the other hand, shocks to the export sector seem to be relatively unimportant given the size of this sector and the openness of the economy. This is because shocks to this sector are largely absorbed by the price of exports which is not a component of CPI inflation.

Given that a shock to intermediate prices is the most costly of our shocks, a good monetary policy rule should generate the appropriate response to this shock. In particular, we know that policy-makers would want to absorb the first-round effects of this shock but would want to make sure that there was no long-run effect on inflation. A standard rule that feeds back off current inflation may lead to a tightening of policy that causes a dramatic fall in output. By contrast, the IFB and OE1 rules act to stabilise future rather than current inflation: exactly the policy response that seems appropriate for this type of shock.

The results of this section suggest that OE1 and IFB rules manage to dominate all other rules in an 'all-shocks' scenario because they are efficient at stabilising the economy in the face of overseas shocks (among which are, notably, shocks to intermediate prices).

Table Ca: Comparison of simple monetary policy rules (individual shocks)

		Taylor/ H-McK	IFB	MCI	Ball	OE1	OE2	OE3	OE4
Non-traded productivity shock									
Loss	L_1	0.01762	0.01769	0.02153	0.02108	0.01760	0.02158	0.02112	0.01756
	L_2	0.0164	0.0148	0.0700	0.0155	0.0170	0.0119	0.0192	0.0163
Avars	p	3.03E-5	1.97E-5	4.75E-4	3.76E-5	3.45E-5	5.60E-5	6.10E-5	2.99E-5
	y	0.0168	0.0174	0.0135	0.0178	0.0170	0.0194	0.0174	0.0168
	Δi	7.31E-5	2.97E-6	9.86E-5	6.62E-4	4.94E-6	3.13E-4	6.86E-4	5.97E-5
	$y_{v,N}$	0.0049	0.0054	6.05E-4	0.0051	0.0047	0.0100	0.0043	0.0049
	$y_{v,X}$	0.0118	0.0120	0.0099	0.0121	0.0118	0.0128	0.0119	0.0118
	c	0.0019	0.0022	2.13E-5	0.0018	0.0017	0.0053	0.0014	0.0019
	i	1.09E-4	6.63E-5	3.83E-4	4.96E-4	1.03E-4	5.93E-4	5.72E-4	1.03E-4
	q	4.42E-3	0.0053	1.20E-4	0.0070	0.0048	0.0080	0.0063	4.40E-3
Export productivity shock									
Loss	L_1	0.0439	0.0454	0.0434	0.0462	0.0452	0.0559	0.0491	0.0433
	L_2	0.0238	0.0248	0.0267	0.0252	0.0248	0.0412	0.0275	0.0238
Avars	p	2.94E-5	2.46E-6	2.78E-5	5.72E-6	2.48E-6	4.07E-4	2.17E-5	2.96E-5
	y	0.0400	0.0453	0.0429	0.0461	0.0452	0.0290	0.0483	0.0400
	Δi	8.72E-4	1.01E-6	1.28E-6	9.53E-6	1.33E-6	0.0051	1.15E-4	7.11E-4
	$y_{v,N}$	9.72E-5	3.69E-4	1.96E-5	5.12E-4	3.33E-4	0.0023	8.23E-4	9.77E-5
	$y_{v,X}$	0.0546	0.0506	0.0510	0.0507	0.0507	0.0634	0.0493	0.0545
	c	1.08E-4	1.46E-4	6.00E-6	2.20E-4	1.23E-4	0.0022	4.02E-4	1.09E-4
	i	4.50E-4	4.88E-6	2.42E-5	3.39E-5	6.45E-6	0.0026	6.20E-5	3.77E-4
	q	0.0019	2.05E-4	5.31E-6	3.28E-4	1.87E-4	0.0202	8.26E-4	0.0018
FX risk premium shock									
Loss	L_1	0.1243	0.0226	0.2562	0.1471	0.0166	0.1236	0.1407	0.1075
	L_2	0.0174	0.0047	0.0036	0.0105	0.0252	0.0095	0.0116	0.0216
Avars	p	7.52E-4	0.0011	8.55E-4	5.23E-4	6.05E-4	6.00E-4	5.60E-4	9.38E-4
	y	0.0015	0.0020	0.0010	7.99E-4	0.0035	9.28E-4	8.83E-4	0.0018
	Δi	0.0277	0.0008	0.0604	0.0345	0.0009	0.0283	0.0327	0.0227
	$y_{v,N}$	9.37E-4	1.04E-4	1.27E-4	5.05E-4	0.0048	4.06E-4	5.58E-4	0.0013
	$y_{v,X}$	0.0435	0.0553	0.0367	0.0352	0.0454	0.0381	0.0361	0.0419
	c	4.75E-4	2.87E-4	3.10E-4	4.35E-4	0.0056	3.25E-4	4.25E-4	5.56E-4
	i	0.0251	0.0010	0.0454	0.0421	0.0023	0.0334	0.0398	0.0274
	q	1.1342	1.4475	0.9594	0.9175	1.1886	0.9921	0.9405	1.0937
Preference shock									
Loss	L_1	0.1329	0.1281	0.1369	0.1303	0.1287	0.1389	0.1319	0.1298
	L_2	0.5264	0.5483	0.5666	0.5521	0.5491	0.5704	0.5559	0.5263
Avars	p	7.28E-5	4.70E-6	7.33E-5	1.59E-5	7.09E-6	8.28E-5	2.54E-5	7.38E-5
	y	0.1149	0.1281	0.1357	0.1299	0.1286	0.1370	0.1315	0.1149
	Δi	0.0042	5.37E-7	1.76E-5	2.28E-5	1.06E-6	1.47E-4	2.08E-6	0.0034
	$y_{v,N}$	0.1724	0.1901	0.2013	0.1929	0.1909	0.2029	0.1951	0.1723
	$y_{v,X}$	4.16E-4	2.72E-5	1.36E-6	1.99E-5	2.50E-5	7.42E-6	1.01E-5	3.97E-4
	c	0.1866	0.2037	0.2148	0.2066	0.2045	0.2162	0.2087	0.1865
	i	0.0021	1.03E-5	5.88E-5	3.82E-5	1.65E-5	7.07E-5	2.07E-5	0.0017
	q	0.0114	7.70E-4	1.93E-5	5.34E-4	6.99E-4	1.98E-4	2.64E-4	0.0110

Table Cb: Comparison of simple monetary policy rules (individual shocks)

		Taylor/ H-McK	IFB	MCI	Ball	OE1	OE2	OE3	OE4
Relative (world) intermediates price shock									
Loss	L_1	1.0825	0.8944	1.8820	1.0447	0.8955	1.0369	1.0296	1.0805
	L_2	2.8650	1.2035	1.2147	2.2677	1.1890	1.7939	2.2541	2.8525
Avars	p	0.0193	0.0197	0.0978	0.0210	0.0180	0.0224	0.0192	0.0184
	y	0.5730	0.5306	0.1428	0.5026	0.5410	0.4636	0.5231	0.5823
	Δi	0.0503	0.0122	0.0434	0.0515	0.0168	0.0537	0.0497	0.0510
	$y_{v,N}$	1.2521	1.1802	0.3849	1.1185	1.1981	1.0443	1.1581	1.2713
	$y_{v,X}$	0.1258	0.0619	0.0326	0.1093	0.0666	0.0962	0.1109	0.1244
	c	1.1449	1.1684	0.4739	1.0474	1.1824	1.0001	1.0830	1.1629
	i	0.3957	0.1114	0.1213	0.3574	0.1335	0.3201	0.3533	0.3830
	q	1.6504	0.3685	0.2794	1.3141	0.4574	1.0543	1.3471	1.6081
World inflation shock									
Loss	L_1	0.3778	0.1803	0.2196	0.4004	0.1577	0.4218	0.4259	0.3818
	L_2	0.6303	0.3414	0.1253	0.6231	0.2582	0.7140	0.6854	0.6388
Avars	p	2.88E-3	2.83E-3	6.62E-3	2.59E-3	2.31E-3	3.51E-3	2.81E-3	2.90E-3
	y	0.1558	0.1278	0.0506	0.1674	0.1126	0.1895	0.1803	0.1580
	Δi	0.0440	0.0018	0.0158	0.0479	0.0021	0.0440	0.0502	0.0443
	$y_{v,N}$	0.3155	0.2583	0.1141	0.3367	0.2312	0.3757	0.3603	0.3197
	$y_{v,X}$	0.0120	0.0220	0.0163	0.0110	0.0193	0.0129	0.0110	0.0115
	c	0.3118	0.2677	0.1354	0.3335	0.2447	0.3692	0.3550	0.3156
	i	0.0797	0.0106	0.0187	0.0836	0.0095	0.0742	0.0878	0.0826
	q	0.3190	0.5600	0.2990	0.3015	0.4451	0.3948	0.3130	0.3096
World interest rate shock									
Loss	L_1	0.0960	0.0863	0.4647	0.1133	0.0797	0.1316	0.1214	0.0955
	L_2	0.1294	0.0759	1.0228	0.1486	0.0954	0.1515	0.1667	0.1247
Avars	p	0.0012	0.0011	0.0230	0.0022	9.77E-4	0.0036	0.0027	0.0013
	y	0.0531	0.0668	0.0048	0.0405	0.0585	0.0289	0.0361	0.0523
	Δi	0.0058	6.61E-4	0.0231	0.0092	0.0014	0.0113	0.0104	0.0057
	$y_{v,N}$	0.1058	0.1323	0.0076	0.0823	0.1164	0.0614	0.0742	0.1045
	$y_{v,X}$	0.1661	0.1674	0.1183	0.1611	0.1676	0.1537	0.1592	0.1654
	c	0.0733	0.0954	0.0094	0.0558	0.0819	0.0415	0.0498	0.0724
	i	0.0241	0.0040	0.0452	0.0356	0.0099	0.0381	0.0391	0.0240
	q	0.2962	0.3714	0.2076	0.2510	0.3400	0.2065	0.2371	0.2912
World output shock									
Loss	L_1	0.2556	0.1418	0.2722	0.1744	0.0818	0.1228	0.1451	0.2371
	L_2	0.2910	0.1350	1.2340	0.1350	0.0884	0.1014	0.1246	0.2942
Avars	p	0.0025	0.0050	0.0149	0.0013	0.0036	0.0010	0.0010	0.0024
	y	0.0619	0.0490	0.0296	0.0377	0.0159	0.0315	0.0329	0.0625
	Δi	0.0384	0.0034	0.0010	0.0290	0.0023	0.0186	0.0242	0.0340
	$y_{v,N}$	0.1332	0.0935	0.0669	0.0903	0.0412	0.0796	0.0835	0.1347
	$y_{v,X}$	0.6591	0.7242	0.5813	0.6489	0.6750	0.6398	0.6370	0.6566
	c	0.0857	0.0566	0.1250	0.0652	0.0420	0.0635	0.0655	0.0874
	i	0.0820	0.0155	0.0027	0.0581	0.0104	0.0503	0.0559	0.0819
	q	1.2509	1.6314	0.6059	1.1346	1.2341	1.0623	1.0533	1.2369

6 Conclusions

In existing rules devised for closed economies, like that advocated by Taylor (1993a), the central bank only responds to inflation deviations from target and output deviations from potential. In this paper we have explored alternative simple monetary policy rules for an economy that is open like the United Kingdom. To do so we considered existing rules for open economies like a naïve MCI-based rule and Ball's (1999) rule. We also looked at parsimonious modifications of these and 'closed-economy' rules that account for the openness of the economy in various ways.

We concluded that a good rule in this respect is an inflation-forecast-based rule (IFB), ie a rule that reacts to deviations of expected inflation from target, when the horizon is chosen appropriately. This rule is associated with a lower-than-average variability of inflation when compared to the alternative open and closed-economy rules. Adding a separate response to the level of the real exchange rate (contemporaneous and lagged) appears to reduce further the difference in adjustment between output gaps in the two sectors of the economy, but this improvement is only marginal.

These results on the relative performance of the rules are broadly confirmed by results obtained comparing the utility losses faced by the households in our model economy under each rule. This reflects the fact that the distortions in our economy are broadly similar to those that are modelled in existing closed-economy models — price and wage stickiness. The distinctive feature of our two-sector open-economy model is that the utility-based loss function includes terms that capture disparities between the non-traded and export sectors. But because the weight on these terms is relatively small, augmenting simple rules with terms in the real exchange rate has only a modest effect on their performance when measured by the utility-based loss function.

Importantly, an IFB rule, with or without exchange rate adjustment, appears quite robust to different shocks, in contrast to naïve MCI-based rules or Ball's rule. Finally, relative to other open and closed-economy rules that we have analysed, an IFB rule (and OE1, an exchange-rate-adjusted IFB rule) seems to reduce the probability of hitting a zero bound with nominal interest rates, and thereby may increase the chances of policy remaining operational under particularly severe deflationary shocks.

Technical annexes

Annex A: First-order conditions

Following the discussion of the model in Sections 2.1-2.3 of the main text, here we consider the problems facing agents in each sector in turn.

Households

Household $j \in (0,1)$ solves the following problem:

$$\text{Max } E_0 \sum_{t=0}^{\infty} b^{t} \left(\exp(n_t) \ln(c_t(j) - x_c c_{t-1}(j)) + d \ln(1 - h_t(j)) + \frac{c}{1-e} \left(\frac{\Omega_t(j)}{P_t} \right)^{1-e} \right)$$

Subject to

$$\begin{aligned} & M_t(j) + B_t(j) + \frac{B_{f,t}(j)}{e_t(j)} + P_t \int r_t(s) b_t(s,j)\,ds = \\ & M_{t-1}(j) + (1+i_{t-1})B_{t-1}(j) + (1+i_{f,t-1})\frac{B_{f,t-1}(j)}{e_t} + P_t \int b_{t-1}(s,j)\,ds + W_t(j)h_t(j) + D_t + T_t - P_t c_t(j) \end{aligned} \qquad \textbf{(A1)}$$

$$\Omega_t(j) = M_{t-1}(j) + T_t + (1+i_{t-1})B_{t-1}(j) + (1+i_{f,t-1})\frac{B_{f,t-1}(j)}{e_t} - B_t(j) - \frac{B_{f,t}(j)}{e_t} \qquad \textbf{(A2)}$$

$$C_t = c^{g}_{M,t} c^{1-g}_{N,t} \qquad \textbf{(A3)}$$

$$P_t = \frac{P^{g}_{M,t} P^{1-g}_{N,t}}{g^{g}(1-g)^{1-g}} \qquad \textbf{(A4)}$$

where the variables are defined as in the text. The household chooses c_M, c_N , W, M, B, $b(s)$ and B_f to solve the maximisation problem.

To solve this problem we substitute the definitions of aggregate consumption and the aggregate price level into the utility function, the budget constraint and the definition of 'money' **(A2)**. We let the Lagrange multipliers on these two constraints be denoted l_1 and l_2 respectively. Suppressing the j index throughout, we differentiate to get:

$$\frac{g \exp(n_t)}{c_t - x c_{t-1}} \left(\frac{c_{N,t}}{c_{M,t}} \right)^{1-g} - l_{1,t} P_{M,t} = bgx \left(\frac{c_{N,t}}{c_{M,t}} \right)^{1-g} E_t \left(\frac{\exp(n_{t+1})}{c_{t+1} - x c_t} \right) \qquad \textbf{(A5)}$$

$$\frac{(1-g)\exp(n_t)}{c_t - x c_{t-1}} \left(\frac{c_{N,t}}{c_{M,t}} \right)^{g} - l_{1,t} P_{N,t} = b(1-g)x \left(\frac{c_{N,t}}{c_{M,t}} \right)^{g} E_t \left(\frac{\exp(n_{t+1})}{c_{t+1} - x c_t} \right) \qquad \textbf{(A6)}$$

$$l_{1,t} + l_{2,t} = b(1+i_t) E_t \left(l_{1,t+1} + l_{2,t+1} \right) \qquad \textbf{(A7)}$$

$$\frac{l_{1,t} + l_{2,t}}{e_t} = b(1+i_{f,t}) E_t \left(\frac{l_{1,t+1} + l_{2,t+1}}{e_{t+1}} \right) \qquad \textbf{(A8)}$$

$$l_{2,t} = \frac{c}{P_t}\left(\frac{\Omega_t}{P_t}\right)^{-e} \quad \textbf{(A9)}$$

$$l_{1,t} = bE_t\left(l_{1,t+1} + l_{2,t+1}\right) \quad \textbf{(A10)}$$

The choice of the nominal wage discussed in Section 2.3.2. The first-order condition is:

$$E_t\sum_{s=0}^{\infty}(b\,f_W)^s\left[\frac{(1+p)^s W_t(j)}{P_{t+s}}\Lambda_{1,t+s} - (1+q_W)\frac{d}{1-h_{t+s}(j)}\right]h_{t+s}(j) = 0\,. \quad \textbf{(A11)}$$

Equation **(A12)** features the real marginal utility of consumption, Λ_1, which is related to the marginal utility of nominal consumption in a simple manner: $\Lambda_1 = P\,l_1$. This is discussed in more detail below.

Non-traded sector

As described in Section 2.3.1 producer $k \in (0,1)$ in the non-traded sector choose prices to solve the following problem.

$$\max\ E_t\sum_{j=0}^{\infty}(b\,f_N)^j\,\Lambda_{1,t+j}\left(\frac{(1+p)^j P_{N,t}(k)}{P_{t+j}} - V_{t+j}\right)y_{N,t+j}(k)$$

subject to $y_{N,t+j}(k) = \left(\frac{(1+p)^j P_{N,t+j}(k)}{P_{N,t+j}}\right)^{-\frac{(1+q_N)}{q_N}} y_{N,t+j}$

The first-order condition is:

$$E_t\sum_{j=0}^{\infty}(b\,f_N)^j\,\Lambda_{1,t+j}\left(\frac{-q_N(1+p)^j P_{N,t}(k)}{P_{t+j}} + (1+q_N)V_{t+j}\right)y_{N,t+j}(k) = 0 \quad \textbf{(A12)}$$

The real unit cost (in units of final consumption), V, can be defined in terms of unit factor demands (denoted with a 'U' superscript):

$$P_tV_t = \min\left\{W_t h^U_{N,t+s} + P_{I,t+s} I^U_{N,t+s}\right\} \text{ subject to } A_{N,t+s}(h^U_{N,t+s})^{a_N}(I^U_{N,t+s})^{1-a_N} = 1$$

The minimised unit cost for all firms in the non-traded sector is found to be:

$$V_t = \frac{1}{a_N^{a_N}(1-a_N)^{1-a_N}}\frac{W_t^{a_N}(P_{I,t})^{1-a_N}}{A_{N,t}P_t} \quad \textbf{(A13)}$$

Similarly, the unit factor demands are given by:

$$h^U_{N,t} = A^{-1}_{N,t}\left[\frac{a_N}{1-a_N}\frac{P_{I,t}}{W_t}\right]^{1-a_N},$$

and

$$I^U_{N,t} = A^{-1}_{N,t}\left[\frac{1-a_N}{a_N}\frac{W_t}{P_{I,t}}\right]^{a_N}$$

These unit factor demands are common across all firms, so this allows us to write total factor demands as:

$$h_{N,t} \equiv \int_{k=0}^{1} h_{N,t}(k)dk = h_{N,t}^{U} \int_{k=0}^{1} y_{N,t}(k)dk = h_{N,t}^{U} y_{N,t} \int_{k=0}^{1} \left[\frac{P_{N,t}(k)}{P_{N,t}} \right]^{-\frac{1+q_N}{q_N}} dk \tag{A14}$$

and

$$I_{N,t} \equiv \int_{k=0}^{1} I_{N,t}(k)dk = I_{N,t}^{U} \int_{k=0}^{1} y_{N,t}(k)dk = I_{N,t}^{U} y_{N,t} \int_{k=0}^{1} \left[\frac{P_{N,t}(k)}{P_{N,t}} \right]^{-\frac{1+q_N}{q_N}} dk \tag{A15}$$

Export sector

As described in Section 2.2.2, exports are produced using a Cobb-Douglas technology:

$$y_{X,t} = A_{X,t} h_{X,t}^{a_X} I_{X,t}^{1-a_X} \tag{A16}$$

Efficient production implies that factor demands are given by:

$$\frac{W_t}{P_{X,t}} = a_X A_{X,t} \left(\frac{I_{X,t}}{h_{X,t}} \right)^{1-a_X} \tag{A17}$$

$$\frac{P_{I,t}}{P_{X,t}} = (1-a_X) A_{X,t} \left(\frac{h_{X,t}}{I_{X,t}} \right)^{a_X} \tag{A18}$$

Export demand is:

$$X_t = \left(\frac{e_t P_{X,t}}{P_t^*} \right)^{-h} y_{f,t}^{b} \tag{A19}$$

Intermediate goods sector

Producers in both the non-traded and export sectors purchase imported intermediates from retailers who solve a pricing problem described in Section 2.3.1. The first-order condition is:

$$E_{t-1} \sum_{s=0}^{\infty} (b f_I)^s \Lambda_{1,t+s} \left(\frac{-q_I (1+p)^s P_{I,t}(k)}{P_{t+s}} + (1+q_I) \frac{P_{I,t+s}^*}{e_{t+s} P_{t+s}} \right) y_{I,t+s}(k) = 0 \tag{A20}$$

Final imports sector

The first-order condition for the pricing problem of retailers of final imported goods is given by:

$$E_{t-1}\sum_{s=0}^{\infty}(b\,f_M)^s\Lambda_{1,t+s}\left(\frac{-q_M(1+p)^s P_{M,t}(k)}{P_{t+s}}+(1+q_M)\frac{P^*_{t+s}}{e_{t+s}P_{t+s}}\right)y_{M,t+s}(k)=0\,. \qquad \textbf{(A21)}$$

Government

The government operates monetary policy by setting nominal interest rates according to a rule (described below) and prints as much money as is demanded at this level of nominal interest rates. Any seignorage revenue is distributed as a lump-sum transfer to consumers. For simplicity, we assume a zero supply of domestic bonds. Hence:

$$M_t - M_{t-1} = T_t - t_t \qquad \textbf{(A22)}$$

Market clearing

We have the following market-clearing conditions in factor markets, goods markets and asset markets:

$$h_t = h_{X,t} + h_{N,t} \qquad \textbf{(A23)}$$

$$c_{N,t} = y_{N,t} \qquad \textbf{(A24)}$$

$$X_t = y_{X,t} \qquad \textbf{(A25)}$$

$$\int\int b_t(s,j)\,ds\,dj = 0 \qquad \textbf{(A26)}$$

Net foreign assets

The evolution of net foreign assets can be found by evaluating the household's budget constraint **(A2)** at market equilibrium and then aggregating across households. As discussed in Section 2.4, the net foreign asset position (under our assumptions this is equal to the domestic holdings of foreign bonds) is non-stationary. To deal with this problem we do not include this equation in our system. Instead we use the equation to substitute foreign bond holdings out of the definition of 'money' **(A3)**.

Annex B: Flexible-price steady state

We use the following notation. Variables without time subscripts are the steady-state values. Lower-case letters represent nominal variables expressed relative to the CPI (we also define the real value of foreign bond holdings as $b_f = B_f / eP$). We express nominal variables relative to the general price level in order to solve for steady state variables that are not trended (in steady state all nominal variables will follow the same trend path). In addition, the Lagrange multipliers l_1 and l_2 are homogenous of degree -1 so we scale them by the CPI, to give stationary multipliers $\Lambda_1 = P l_1$ and $\Lambda_2 = P l_2$. Throughout we use the real exchange rate definition, $q_t = \frac{e_t P_t}{P_t^*}$.

To construct a steady state, we first assume that all domestic nominal variables are growing at an annual rate of 2.5%. This means that, in steady state, the government is meeting an inflation target of 2.5%. For simplicity, we also assume that the steady state growth of foreign nominal variables is 2.5%. The implied steady state value of nominal interest rates at home and abroad will be given by:

$$i = i_f = \frac{1+p}{b} - 1$$

In what follows, we use equations **(A23)** and **(A27)** before evaluating the steady state. We assume that steady-state taxes are set to exactly offset steady state dividends. Finally, we choose a flexible-price equilibrium so that, although price setters retain some monopoly power, they simply set prices as a mark-up over unit costs.

Then, the first-order conditions imply the following equations defining steady-state values of the variables:

$$l_1 p_M = \frac{(1-bx)g}{(1-x)c}\left(\frac{c_N}{c_M}\right)^{1-g} \quad \textbf{(A27)}$$

$$l_1 p_N = \frac{(1-bx)(1-g)}{(1-x)c}\left(\frac{c_M}{c_N}\right)^{g} \quad \textbf{(A28)}$$

$$c w^{-e} = l_2 \quad \textbf{(A29)}$$

$$l_1 = \frac{b(l_1 + l_2)}{1+p} \quad \textbf{(A30)}$$

$$l_1 w = \frac{(1+q_W)d}{(1-h)} \quad \textbf{(A31)}$$

$$\frac{1-b}{b} b_f = p_X X - p_M c_M - p_I (I_X + I_N) \quad \textbf{(A32)}$$

$$w = m + \frac{1-b}{b} b_f \quad \textbf{(A33)}$$

$$c = c_M^g c_N^{1-g} \quad \textbf{(A34)}$$

$$p_N^{1-g} p_M^{g} = g^{g}(1-g)^{1-g} \qquad \textbf{(A35)}$$

$$p_N = (1+q_N)v \qquad \textbf{(A36)}$$

$$\frac{w}{p_I} = \frac{a_N}{1-a_N}\frac{I_N}{h_N} \qquad \textbf{(A37)}$$

$$y_N = A_N h_N^{a_N} I_N^{1-a_N} \qquad \textbf{(A38)}$$

$$v = \frac{w^{a_N} p_I^{1-a_N}}{a_N^{a_N}(1-a_N)^{1-a_N}} \qquad \textbf{(A39)}$$

$$y_X = A_X h_X^{a_X} I_X^{1-a_X} \qquad \textbf{(A40)}$$

$$\frac{w}{p_X} = a_X A_X \left(\frac{I_X}{h_X}\right)^{1-a_X} \qquad \textbf{(A41)}$$

$$\frac{p_I}{p_X} = (1-a_X)A_X \left(\frac{h_X}{I_X}\right)^{a_X} \qquad \textbf{(A42)}$$

$$X = \left(\frac{q}{p_X}\right)^{h} y_f^{b} \qquad \textbf{(A43)}$$

$$p_I = (1+q_I)\frac{p_I^*}{q} \qquad \textbf{(A44)}$$

$$p_M = (1+q_M)\frac{1}{q} \qquad \textbf{(A45)}$$

$$c_N = y_N \qquad \textbf{(A46)}$$

$$h = h_N + h_X \qquad \textbf{(A47)}$$

$$X = y_X \qquad \textbf{(A48)}$$

Annex C: A log-linear representation of the model

To solve the model we log-linearise the first-order conditions of the model around the non-stochastic steady state defined by equations **(A27)** to **(A48)**. As described in the main text we use **(A2)** evaluated at market equilibrium to substitute foreign bond holdings out of the model. As in Annex B, we also substitute out for taxes, transfers and dividends. Log-linearising the consumers' first-order conditions (equations **(A5)** to **(A10)**) gives us:

$$E_t\left(\frac{bx}{(1-bx)(1-x)}\hat{c}_{t+1}-\frac{bx}{1-bx}n_{t+1}\right)=\hat{\Lambda}_{1,t}+\hat{p}_{M,t}-\frac{1}{1-bx}n_t+\hat{c}_{M,t}-\left(1-\frac{1+bx^2}{(1-bx)(1-x)}\right)\hat{c}_t-\frac{x}{(1-bx)(1-x)}\hat{c}_{t-1} \quad \textbf{(A49)}$$

$$E_t\left(\frac{bx}{(1-bx)(1-x)}\hat{c}_{t+1}-\frac{bx}{1-bx}n_{t+1}\right)=\hat{\Lambda}_{1,t}+\hat{p}_{N,t}-\frac{1}{1-bx}n_t+\hat{c}_{N,t}-\left(1-\frac{1+bx^2}{(1-bx)(1-x)}\right)\hat{c}_t-\frac{x}{(1-bx)(1-x)}\hat{c}_{t-1} \quad \textbf{(A50)}$$

$$E_t\left(\hat{p}_{t+1}-\frac{\Lambda_1}{\Lambda_1+\Lambda_2}\hat{\Lambda}_{1,t+1}-\frac{\Lambda_2}{\Lambda_1+\Lambda_2}\hat{\Lambda}_{2,t+1}\right)=(i_t-i)-\frac{\Lambda_1}{\Lambda_1+\Lambda_2}\hat{\Lambda}_{1,t}-\frac{\Lambda_2}{\Lambda_1+\Lambda_2}\hat{\Lambda}_{2,t} \quad \textbf{(A51)}$$

$$E_t\left(\hat{p}^*_{t+1}+\hat{q}_{t+1}-\frac{\Lambda_1}{\Lambda_1+\Lambda_2}\hat{\Lambda}_{1,t+1}-\frac{\Lambda_2}{\Lambda_1+\Lambda_2}\hat{\Lambda}_{2,t+1}\right)=(i_{f,t}-i_f)+\hat{q}_t-\frac{\Lambda_1}{\Lambda_1+\Lambda_2}\hat{\Lambda}_{1,t}-\frac{\Lambda_2}{\Lambda_1+\Lambda_2}\hat{\Lambda}_{2,t}+z_t \quad \textbf{(A52)}$$

$$\hat{\Lambda}_{2,t}+e\hat{w}_t=0 \quad \textbf{(A53)}$$

$$E_t\left(\hat{p}_{t+1}-\frac{\Lambda_1}{\Lambda_1+\Lambda_2}\hat{\Lambda}_{1,t+1}-\frac{\Lambda_2}{\Lambda_1+\Lambda_2}\hat{\Lambda}_{2,t+1}\right)=\hat{\Lambda}_{1,t} \quad \textbf{(A54)}$$

where for any variable x, $\hat{x}=\ln\left(\frac{x_t}{x}\right)$ where x is its steady-state value and z is an exogenous 'foreign exchange risk premium' shock.

The definition of W (equation **(A3)**) becomes:

$$\hat{w}_t-\frac{m}{w}\hat{m}_t+\frac{wh}{w}\hat{h}_t+\frac{wh}{w}\hat{w}_t-+\frac{c}{w}\hat{c}_t=0 \quad \textbf{(A55)}$$

The definitions of consumption and the price indices are:

$$\hat{c}_t = g\hat{c}_{M,t} + (1-g)\hat{c}_{N,t} \tag{A56}$$

$$0 = g\hat{p}_{M,t} + (1-g)\hat{p}_{N,t} \tag{A57}$$

Wage-setting is given by the following two equations (the derivation follows Erceg *et al* (1999, page 25)).

$$\Delta\hat{W}_t = bE_t\Delta\hat{W}_{t+1} + \frac{(1-f_W)(1-bf_W)h}{f_W(1-h)[1+\frac{h(1+q_W)}{q_W(1-h)}]}\hat{h}_t - \frac{(1-f_W)(1-bf_W)}{f_W[1+\frac{h(1+q_W)}{q_W(1-h)}]}\hat{\Lambda}_{1,t} - \frac{(1-f_W)(1-bf_W)}{f_W[1+\frac{h(1+q_W)}{q_W(1-h)}]}\hat{w}_t \tag{A58}$$

$$\hat{w}_t = \hat{w}_{t-1} + \Delta\hat{W}_t - \hat{p}_t \tag{A59}$$

Pricing decisions by non-traded goods producers are described by:

$$\Delta\hat{P}_{N,t} = bE_t\Delta\hat{P}_{N,t+1} + \frac{(1-f_N)(1-bf_N)}{f_N}\hat{v}_t - \frac{(1-f_N)(1-bf_N)}{f_N}\hat{p}_{N,t} \tag{A60}$$

$$\hat{p}_{N,t} = \hat{p}_{N,t-1} + \Delta\hat{P}_{N,t} - \hat{p}_t \tag{A61}$$

$$\hat{v}_t = a_N\hat{w}_t + (1-a_N)\hat{p}_{I,t} - \hat{A}_{N,t} \tag{A62}$$

Factor demands from non-traded producers are:

$$\hat{h}_{N,t} = -\hat{A}_{N,t} + (1-a_N)\hat{p}_{I,t} - (1-a_N)\hat{w}_t + \hat{y}_{N,t} \tag{A63}$$

$$\hat{I}_{N,t} = -\hat{A}_{N,t} + a_N\hat{w}_t - a_N\hat{p}_{I,t} + \hat{y}_{N,t} \tag{A64}$$

The first-order conditions for export producers become:

$$\hat{w}_t - \hat{p}_{X,t} - \hat{A}_{X,t} - (1-a_X)\hat{I}_{X,t} + (1-a_X)\hat{h}_{X,t} = 0 \tag{A65}$$

$$\hat{p}_{I,t} - \hat{p}_{X,t} - \hat{A}_{X,t} + a_X\hat{I}_{X,t} + a_X\hat{h}_{X,t} = 0\,. \tag{A66}$$

Export production is given by:

$$\hat{y}_{X,t} - \hat{A}_{X,t} - a_X\hat{h}_{X,t} - (1-a_X)\hat{I}_{X,t} = 0\,. \tag{A67}$$

Export demand can be written as:

$$\hat{X}_t + h\hat{q}_t + h\hat{p}_{X,t} - b\hat{y}_{F,t} = 0 \tag{A68}$$

Pricing of intermediates is described by:

$$\Delta\hat{P}_{I,t} = bE_{t-1}\Delta\hat{P}_{I,t+1} + \frac{(1-f_I)(1-bf_I)}{f_I}E_{t-1}\hat{p}^{*}_{I,t} - \frac{(1-f_I)(1-bf_I)}{f_I}E_{t-1}\hat{q}_t - \frac{(1-f_I)(1-bf_I)}{f_I}E_{t-1}\hat{p}_{I,t} \qquad \textbf{(A69)}$$

$$\hat{p}_{I,t} = \hat{p}_{I,t-1} + \Delta\hat{P}_{I,t} - \hat{p}_t \qquad \textbf{(A70)}$$

Pricing of final imports is described by:

$$\Delta\hat{P}_{M,t} = bE_{t-1}\Delta\hat{P}_{M,t+1} - \frac{(1-f_I)(1-bf_I)}{f_I}E_{t-1}\hat{q}_t \qquad \textbf{(A71)}$$

$$\hat{p}_{M,t} = \hat{p}_{M,t-1} + \Delta\hat{P}_{M,t} - \hat{p}_t \qquad \textbf{(A72)}$$

The relevant market-clearing conditions can be written as:

$$\frac{h_X}{h}\hat{h}_{X,t} + \frac{h_N}{h}\hat{h}_{N,t} - \hat{h}_t = 0 \qquad \textbf{(A73)}$$

$$\hat{c}_{N,t} - \hat{y}_{N,t} = 0 \qquad \textbf{(A74)}$$

$$\hat{X}_t - \hat{y}_{X,t} = 0 \qquad \textbf{(A75)}$$

Together with some obvious lag identities and log-linearised definitions (for example the GDP identity) the model can be cast in the form of equations **(22)** and **(23)** in the main text. The calibration of the forcing processes is described in Section 3.2 of the main text.

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