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AND RAF WOUTERS

March 2002

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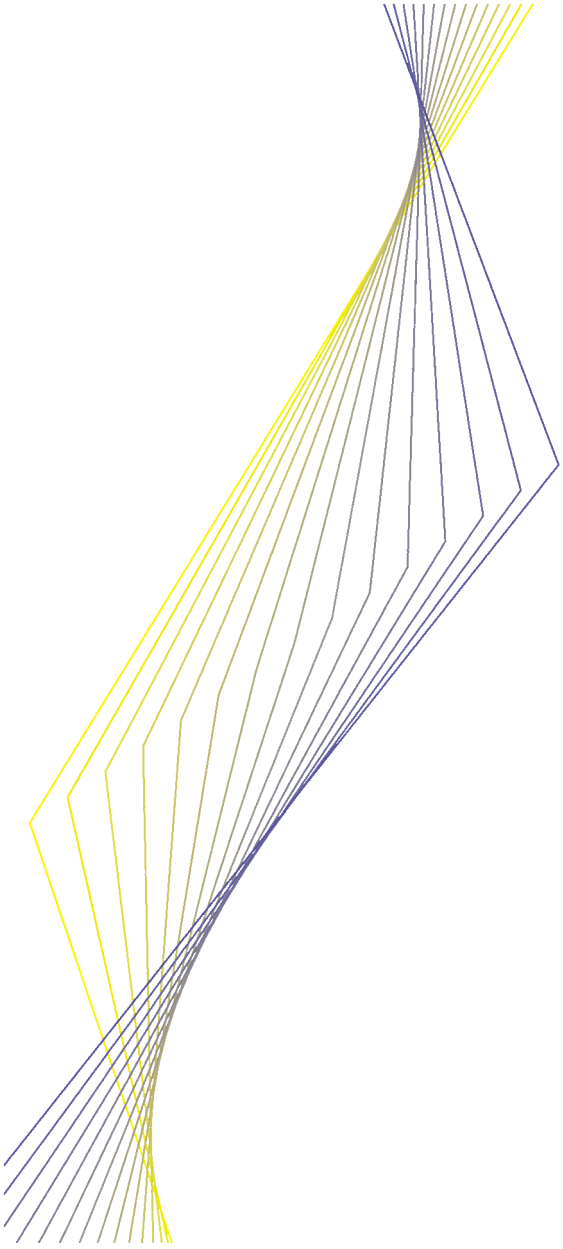

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OPENNESS, IMPERFECT EXCHANGE RATE PASS-THROUGH AND MONETARY POLICY

BY FRANK SMETS*
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* *Corresponding author: Frank Smets, Directorate General Research, European Central Bank, D-60311 Frankfurt am Main, Germany; Telephone: +49 69 1344 6550; Fax: +49 69 1344 8553; Email: frank.smets@ecb.int*

** *National Bank of Belgium, B-1000 Brussels, Belgium*

Address	**Kaiserstrasse 29** **D-60311 Frankfurt am Main** **Germany**
Postal address	**Postfach 16 03 19** **D-60066 Frankfurt am Main** **Germany**
Telephone	**+49 69 1344 0**
Internet	**http://www.ecb.int**
Fax	**+49 69 1344 6000**
Telex	**411 144 ecb d**

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Contents

Abstract

This paper analyses the implications of imperfect exchange rate pass-through for optimal monetary policy in a linearised open-economy dynamic general equilibrium model calibrated to euro area data. Imperfect exchange rate pass through is modelled by assuming sticky import price behaviour. The degree of domestic and import price stickiness is estimated by reproducing the empirical identified impulse response of a monetary policy and exchange rate shock conditional on the response of output, net trade and the exchange rate. It is shown that a central bank that wants to minimise the resource costs of staggered price setting will aim at minimising a weighted average of domestic and import price inflation.

Key words: monetary policy, open economies; exchange rate pass-through

JEL: E58-F41

Non-technical summary

Over the last six years a large literature (the so-called "New Open Economy Macroeconomics, NOEM") has developed, examining the optimal conduct of monetary policy in a class of open-economy dynamic general equilibrium models that feature imperfect competition and nominal rigidities. One of the striking findings in the benchmark models of this literature is that the welfare results obtained in the basic closed-economy New-Keynesian model carry over to its open-economy counterpart. Welfare optimising monetary policy results in a complete stabilisation of the price level of domestically produced goods. There is no trade-off between domestic price stability and output gap stabilisation and there is no need for an explicit consideration of the exchange rate.

One feature that characterises those models is the assumption of perfect exchange rate pass-through. There is, however, a lot of empirical evidence that changes in nominal exchange rates affect import prices only gradually. Recent research shows that in most OECD countries complete pass-through of exchange rate changes to import prices can be rejected in the short run, while long-run pass-through elasiticities are generally closer to one. One explanation of the gradual exchange rate pass-through is that import prices are sticky due to, for example, menu costs.

In this paper, we explore the implications of sticky import prices and imperfect exchange rate pass-through for optimal monetary policy. This is done in three steps. In the first step, we develop a completely micro-founded model for an open economy with sticky domestic and import prices, which takes the international interest rate, prices and output as given. This model differs from the benchmark models in two important ways. First, we introduce a monopolistically competitive import goods sector with sticky prices. Firms in this sector import a homogenous foreign good at a given world price and produce a differentiated import good for the domestic market. Capturing the presence of menu costs, import firms are only allowed to change their price when they receive a random price signal. In line with the empirical evidence discussed above, the assumption of sticky import prices implies a gradual adjustment of import prices to the level implied by the law of one price. Second, we introduce Blanchard-Yaari-type overlapping generations. This allows us to derive a well-defined stationary steady-state for consumption, the terms of trade and net foreign assets, around which the model can be linearised. It also allows for a potentially important role of the current account and net foreign assets in the dynamics of the economy, which we do not further explore in this paper.

In the second step, we calibrate a linearised version of the model using euro area data. As our analysis focuses on the implications of imperfect pass-through for optimal monetary policy, our calibration exercise concentrates on estimating the degree of price stickiness in the domestic and imported goods sectors. In order to do so, we use a new estimation

methodology. Using a VAR on euro area data, we estimate the effects of a monetary policy shock on domestic and import prices and on the three variables that drive those prices: output, net exports and the exchange rate. Conditional on the response of the three driving variables and on other structural parameters of the model, we can then estimate the degree of price stickiness in the domestic and imported goods sector by minimising a measure of the distance between the empirical and the model-based impulse responses of domestic and import price inflation to the monetary policy shock. The results of this exercise suggest two conclusions. First, there is a considerable degree of price stickiness in euro area import prices, consistent with the findings mentioned above. Second, the degree of stickiness in import prices is not significantly different from that in domestic prices.

In the third and final step, we then analyse the implications of sticky import prices for optimal monetary policy in the calibrated model. We assume that the central bank's mandate is to minimise the distortions that arise from staggered price setting in the domestic and imported goods sector. We show that the output cost of these distortions is proportional to the relative price variability in the respective sectors, which in turn is proportional to the variance of price inflation in that sector. The resulting loss function can therefore be written as a weighted average of the variance of domestic and import price inflation, where the relative weight depends on the degree of openness of the economy (or the relative importance of both sectors in consumption and production) and the relative degree of price stickiness. As import price inflation will depend on the gap between the sticky import price and the foreign price denominated in local currency, one important implication of this analysis is the introduction of an explicit reason for the stabilisation of the nominal exchange rate in response to other shocks than those that affect foreign prices. The reason is that such movements in the nominal exchange rate create relative price distortions in the imported goods sector. Depending on the relative degree of stickiness in domestic and import good prices, the results can also be interpreted as providing a justification for targeting consumer price inflation rather than domestically generated inflation. Another important implication is that the combination of sticky domestic and import prices makes the achievement of the flexible price outcome no longer feasible, even if the central bank only cares about domestic inflation stabilisation. The reason is that imperfect exchange rate pass-through makes the exchange rate channel less effective. As a result more of the adjustment needs to be born by the domestic interest rate channel which primarily affects domestic demand. As an illustration, we discuss the optimal policy response to a domestic productivity shock, a world demand shock and an exchange rate shock. Overall, the results show that an exclusive focus on the stabilisation of prices of domestically produced goods is no longer optimal, when import prices are sticky and the exchange rate pass-through is gradual.

1. Introduction

Over the last six years a large literature (the so-called "New Open Economy Macroeconomics, NOEM") has developed examining the optimal conduct of monetary policy in a class of open-economy dynamic general equilibrium models that feature imperfect competition and nominal rigidities.[1] One of the models that recently has attracted a lot of attention is the one of Gali and Monacelli (2000). This model combines the open economy features of the NOEM, with the elegance of the benchmark New-Keynesian closed economy model as, for example, analysed in Woodford (1999b). One of the striking findings in Gali and Monacelli (2000) is that the welfare results obtained in the basic New-Keynesian model carry over to its open economy counterpart. Welfare optimising monetary policy results in a complete stabilisation of the domestic price level. In particular, there is no trade off between output gap stabilisation and domestic price stability and there is no need for an explicit consideration of the exchange rate.[2] This result has proven to be relatively robust with respect to certain extensions of the model. For example, in a two-country set-up Benigno and Benigno (2001) have shown that a policy pursuing domestic price stability can be considered as the optimal outcome in a Nash game between the monetary authorities in two countries. Similarly, Obstfeld and Rogoff (2000b) have rejected the necessity of a new international compact on the basis of the argument that policies geared at domestic price stability deliver outcomes that are close to the first best. In another extension, Benigno (2001) shows that achieving domestic price stability continues to characterise the optimal monetary policy when international financial markets are incomplete.

One feature that characterises all the models discussed above is the assumption of perfect exchange rate pass-through. There is, however, a lot of empirical evidence that changes in nominal exchange rates affect import prices only gradually. Recently, Campa and Goldberg (2001) estimated pass-through equations for 25 OECD countries over the period 1975 to 1999. They find that they can reject the hypothesis of complete short-run pass-through in 22 of the 25 countries. In contrast, long-run elasiticities are generally closer to one; Campa and Goldberg (2001) reject long-run pass-through equal to one in only 9 of the 25 countries.[3] Based on an empirical analysis of international prices for two magazines, Ghosh and Wolf (2001) argue that sticky prices or menu costs are a better explanation for imperfect pass-through than strategic pricing or international product differentiation. Consistently with the findings of Campa and Goldberg (2001), they find complete long-run pass-through, which typically holds in theories based on sticky prices, but does not hold in theories of international product differentiation.

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1 The seminal publications in the area are Obstfeld and Rogoff (1995, 1996). Other notable contributions include Betts and Devereux (1997,1998), Kollmann (2000a,b), Gali and Monacelli (2000), Ghironi (2000a,b), Benigno and Benigno (2000), Chari, Kehoe and McGrattan (2000), McCallum and Nelson (1999), Corsetti and Pesenti (2000, 2001). This literature parallels an abundant literature on optimal monetary policy in closed economy dynamic general equilibrium models. See, for example, the volume edited by Taylor (1999).

2 See Woodford (1999b) for a clear and thorough analysis of this result. The seminal papers are King and Wolman (1999), Goodfriend and King (1997) and Rotemberg and Woodford (1997).

3 Other recent evidence on imperfect exchange rate pass-through can be found in McCarthy (1999).

In this paper, we explore the implications of sticky import prices and imperfect exchange rate pass-through for optimal monetary policy. This is done in three steps. In the first step, we develop a completely micro-founded model for an open economy with sticky domestic and import prices, which takes the international interest rate, prices and output as given. This model differs from the benchmark model in Gali and Monacelli (2000) in two important ways. First, as in Monacelli (1999), we introduce a monopolistically competitive import goods sector with sticky prices. Firms in this sector import a homogenous foreign good at a given world price and produce a differentiated import good for the domestic market. Following Calvo (1983) and capturing the presence of menu costs, import firms are only allowed to change their price when they receive a random price signal. In line with the empirical evidence discussed above, the assumption of sticky import prices implies a gradual adjustment of import prices to the level implied by the law of one price. In addition, following the suggestion by McCallum and Nelson (2001), we allow imported goods to be used both in consumption and production. Second, following Ghironi (2000b), we introduce Blanchard-Yaari-type overlapping generations into the Gali and Monacelli (2000) model.[4] This allows us to derive a well-defined stationary steady-state for consumption, the terms of trade and net foreign assets, around which the model can be linearised. It also allows for a potentially important role of the current account and net foreign assets in the dynamics of the economy, which we do not further explore in this paper.[5]

In the second step, we calibrate a linearised version of the model using euro area data. As our analysis focuses on the implications of imperfect pass-through for optimal monetary policy, our calibration exercise concentrates on estimating the degree of price stickiness in the domestic and imported goods sectors. In order to do so, we use a new estimation methodology. Using a VAR on euro area data, we estimate the effects of a monetary policy shock on domestic and import prices and on the three variables that drive those prices: output, net exports and the exchange rate. Conditional on the response of the three driving variables and on other structural parameters of the model, we can then estimate the degree of price stickiness in the domestic and imported goods sector by minimising a measure of the distance between the empirical and the model-based impulse responses of domestic and import price inflation to the monetary policy shock. The results of this exercise suggest two conclusions. First, there is a considerable degree of price stickiness in euro area import prices, consistent with the findings mentioned above. Second, the degree of stickiness in import prices is not significantly different from that in domestic prices.

In the third and final step, we then analyse the implications of sticky import prices for optimal monetary policy in the calibrated model. We assume that the central bank's mandate is to minimise the distortions that arise from staggered price setting in the domestic and imported goods sector. Following Woodford (1999b), we show that the output cost of these distortions is proportional to the relative price variability in the respective sectors, which in turn is proportional to the variance of price inflation in that sector. The

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4 More specifically, we use the discrete-time version developed in Frenkel and Razin (1987).

5 For a thorough discussion of this point, see Ghironi (2000b).

resulting loss function can therefore be written as a weighted average of the variance of domestic and import price inflation, where the relative weight depends on the degree of openness of the economy (or the relative importance of both sectors in consumption and production) and the relative degree of price stickiness. As import price inflation will depend on the gap between the sticky import price and the foreign price denominated in local currency, one important implication of this analysis is the introduction of an explicit reason for the stabilisation of the nominal exchange rate in response to other shocks than those that affect foreign prices. The reason is that such movements in the nominal exchange rate create relative price distortions in the imported goods sector. Another important implication is that the combination of sticky domestic and import prices makes the achievement of the flexible price outcome no longer feasible, even if the central bank only cares about domestic inflation stabilisation. The reason is that imperfect exchange rate pass-through makes the exchange rate channel less effective. As a result more of the adjustment needs to be born by the domestic interest rate channel which primarily affects domestic demand. These findings echo the analysis in Erceg, Henderson and Levin (2000), who come to similar conclusions focusing on the trade-off between the stabilisation of sticky price and wage inflation in a closed economy. We discuss the optimal policy response to a domestic productivity shock, a world demand shock and an exchange rate shock. Overall, the results show that an exclusive focus on the stabilisation of domestic prices is no longer optimal, when import prices are sticky and the exchange rate pass-through is gradual.

A number of papers have analysed monetary policy behaviour in the presence of imperfect exchange rate pass-through. For example, Devereux and Engel (2000) examine the implications of local currency pricing in the context of the Obstfeld-Rogoff model and argue that in contrast to the findings of Obstfeld and Rogoff (2000b) in this case optimal monetary policy in response to real shocks is fully consistent with fixed exchange rates. Other papers are Monacelli (1999), Batini, Harrison and Millard (2000), Devereux (2000) and Adolfson (2001). Those papers analyse the performance of simple monetary policy rules in the presence of imperfect exchange rate pass-through. However, they do not consider the costs of imperfect pass-through and as such ignore the explicit role for exchange rate stabilisation that it implies. This partly explains why the conclusions are sometimes different. For example, Devereux (2000) finds that a rule that stabilises non-traded goods price inflation performs the best, in particular when pass-through is limited. However, the welfare judgement is based on an ad hoc examination of the volatility of output, consumption and inflation. As we show in this paper, in the presence of sticky prices in both the domestic and the imported goods sector, the response of output and consumption will indeed be less than in the flexible price outcome when a productivity shock hits. However, this response is sub-optimal. Another example is Adolfson (2001), who analyses the impact of incomplete exchange rate pass-through when the central bank minimises a standard loss function in inflation, the output gap and interest rate changes. Adolfson (2001) finds that lower pass-through leads to higher exchange rate volatility. However, also this result depends on the fact that exchange rate stabilisation does not explicitly enter the loss function.

Our results are most similar to those obtained by Corsetti and Pesenti (2000). In a model with predetermined domestic and foreign prices based on Corsetti and Pesenti (2001), they show that the

optimal policy is to minimise the expected value of a CPI-weighted average of mark-ups charged in the domestic market by domestic and foreign producers. The reasons for doing so are different from those in our model. In Corsetti and Pesenti (2000), risk-averse producers respond to the variability of profits from a specific market by increasing the ex-ante price charged in that market. Policy makers can defend domestic consumers' welfare by committing to stabilise producers' profits around their equilibrium flex-price level. Corsetti and Pesenti (2000) also find that a low degree of pass-through severely constrains the ability of monetary policy to move the economy towards the flexible price allocation.[6]

The remainder of the paper is organised as follows. In Section 2 we develop the theoretical model, derive its steady state and a log-linearised version. In Section 3, we derive and discuss the loss function of the central bank, which is based on a minimisation of the resource cost of inefficient relative price variability in the domestic and imported goods sector. Section 4 presents the calibration of the model. We first estimate a VAR using synthetic euro area data over the period 1977-1999. This VAR is used to derive the empirical impulse response function of a monetary policy shock and an exchange rate shock on the euro area economy (Section 4.1). In Section 4.2 the structural parameters of the price setting processes are estimated. Section 5 analyses the optimal monetary policy response under discretion to a productivity, world demand and exchange rate shock. Finally, we make some concluding remarks in Section 6.

2. An open-economy model with sticky domestic and imported goods prices

In this section, we develop a dynamic, micro-founded model for an open economy with sticky domestic and import prices that takes the foreign interest rate, prices and output as given. The domestic monopolistically competitive goods market is modelled as in the closed-economy models of Rotemberg and Woodford (1997) and Clarida, Gali and Gertler (1999). The consumption and savings decisions, on the other hand, are derived along the lines of the discrete-time version of the Blanchard-Yaari overlapping-generations model as developed by Frenkel and Razin (1989).[7] Using an overlapping-generations framework allows us to derive a stationary steady-state for consumption, the terms of trade and net foreign assets in an economy which takes the world real interest rate as given.[8] Imperfect exchange rate pass-through is modelled as the result of sticky import price setting rather than from an explicit model of optimal price differentiation.

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[6] Sutherland (2001) shows that these results are to some extent dependent on the linear specification of leisure in the utility function.

[7] See Blanchard (1985).

[8] See, for example, Ghironi (2000a) for an application of the Blanchard-Yaari framework to an open economy with price rigidities. Alternative approaches to obtaining a stationary steady state in a small open economy are discussed in Schmitt-Grohe and Uribe (2001).

2.1 Consumption and labour supply decisions

2.1.1 The households' consumption and labour supply decisions

The objective of the representative household of generation *i* is to maximise the expected utility flow derived from consumption and from providing labour services:[9]

$$\sum_{j=0}^{\infty} \beta^j \vartheta^j \left[\frac{1}{1-\sigma} \left(C_{t+j}^i \right)^{1-\sigma} - \frac{\kappa}{1+\omega} \left(L_{t+j}^i \right)^{1+\omega} \right] \tag{1}$$

where β is the discount factor, ϑ is the constant probability of households to survive, C_t^i is the consumption of the aggregate consumption basket by household *i*, L_t^i is the labour services provided by the household *i*, $(1/\sigma)$ is the intertemporal elasticity of substitution in consumption and ω is the elasticity of marginal disutility with respect to labour supply. As in Frenkel and Razin (1989), households have a finite life expectation. A perfect insurance market inherits consumers' financial wealth contingent on their death and redistributes this in proportion to financial wealth. As a result the effective cost of borrowing or returns on savings relevant for individual decisions is multiplied by $1/\vartheta$.

Household *i*'s intertemporal budget constraint is given by:

$$\frac{e_t F_t^i}{(1+R_t^*)} + \frac{B_t^i}{(1+R_t)} = \frac{1}{\vartheta} \left[e_t F_{t-1}^i + B_{t-1}^i + W_t L_t^i - P_t C_t^i + Div_t^D + Div_t^F - T_t^i \right] \tag{2}$$

where B_t represent the holdings of domestic one-period government bonds issued on a discount basis with an interest rate R_t, F_t denote the holdings of one-period bonds issued by the rest of the world in foreign currency with an interest rate, R_t^*, Div_t^D and Div_t^F are respectively the dividends distributed by the domestic goods producers and the import sector, T_t^i is a lump-sum government tax. It is assumed that international markets are incomplete, i.e. there is no perfect international risk sharing.

Maximising the household's expected utility flow with respect to C_t^i, L_t^i, B_t^i and F_t^i subject to this budget constraint, gives the familiar first-order conditions which can be expressed as the uncovered interest rate parity (UIRP) condition and generation *i*'s consumption Euler equation and labour supply function:[10]

$$\frac{1+R_t}{1+R_t^*} = \frac{e_{t+1}}{e_t} \tag{3}$$

$$\left[\frac{C_{t+1}^i}{C_t^i} \right]^{\sigma} = \beta \frac{(1+R_t)}{P_{t+1}/P_t} \tag{4}$$

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[9] For simplicity, we do not analyse money demand which could be introduced by putting money in the utility function. Given separability, the resulting money demand function would be completely recursive to the rest of the model discussed.

[10] As we will eventually linearise the model, we analyse the model under the assumption of certainty equivalence and leave out the expectations operators from the start.

$$\left(L_t^i\right)^{\omega} = \frac{1}{\kappa}\left(C_t^i\right)^{-\sigma}\frac{W_t}{P_t} \tag{5}$$

Using the UIRP condition (3) and the following expressions for financial wealth (A_t^i), and human wealth (H_t^i),

$$A_t^i = e_t F_{t-1}^i + B_{t-1}^i, \tag{6}$$

$$H_t^i = h_t^i + \Sigma_{j=1}^{\infty}\vartheta^j\left(\prod_{k=0}^{j-1}\frac{1}{(1+R_{t+k})}\right)h_{t+j}^i, \tag{7}$$

where h_t^i is total household non-interest income and defined as $h_t^i = W_t L_t^i + Div_t^D + Div_t^F - T_t^i$,

the budget constraint can be written as

$$A_{t+1}^i = \frac{1+R_t}{\vartheta}\left[h_t^i - P_t C_t^i + A_t^i\right]. \tag{8}$$

Solving equation (8) forward and using equation (4), consumption of household *i* can also be written as a fraction of total wealth:

$$P_t\, C_t^i = \Phi_t\left[H_t^i + A_t^i\right] \tag{9}$$

where the propensity to consume out of wealth, defined as

$$\Phi_t = \left[1 + \Sigma_{j=1}^{\infty}\vartheta^j\beta^{\frac{j}{\sigma}}\left[\prod_{k=0}^{j-1}(1+RR_{t+k})^{\frac{1-\sigma}{\sigma}}\right]\right]^{-1}, \tag{10}$$

is constant over generations and RR_t is the ex-ante real interest rate, given by:

$$RR_t = \frac{(1+R_t)}{P_{t+1}/P_t} \tag{11}$$

For logarithmic preferences the propensity to consume is constant and equals $1-\beta\vartheta$. For more general iso-elastic preferences it is a function of the expected real return on financial wealth.

2.1.2 Aggregation

Aggregating equations (8) and (9) over the generations alive at time t, yields the macro-economic consumption and wealth equations:[11]

$$P_t C_t = \Phi_t\left[H_t + A_t\right] \tag{12}$$

$$A_{t+1} = (1+R_t)\left[h_t - P_t C_t + A_t\right], \tag{13}$$

from which the following macro-economic consumption function can be derived

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[11] An aggregate variable, X_t, is defined as $X_t = (1-\vartheta)\sum_{i=0}^{\infty}\vartheta^i X_t^i$, where *i* refers to the generation born at period *t-i*.

$$C_t = \frac{1}{(\beta RR_t)^{1/\sigma}}\left[C_{t+1} + \frac{(1-\vartheta)}{\vartheta}\Phi_{t+1}\frac{A_{t+1}}{P_{t+1}}\right], \tag{14}$$

Equation (14) shows that due to the overlapping-generations nature of our model, aggregate consumption is a function not only of expected consumption, but also of the real stock of financial wealth. The interest rate effect remains nevertheless unchanged. In the remainder of the paper, we will assume that the government debt B_t always equals zero in equilibrium. This implies that in every period the government expenditures on subsidies to firms equal net transfers to households.

Aggregation of the labour supply equation (5) yields the following relationship:

$$\left(L_t\right)^{\omega} = \frac{1}{\kappa}\left[(1-\vartheta)\sum_{i=0}^{\infty}\vartheta^i\left(C_t^i\right)^{-\frac{\sigma}{\omega}}\right]^{\omega}\frac{W_t}{P_t} \tag{15}$$

In general, aggregate labour supply will depend on the distribution of consumption over the different generations and thus on the wealth distribution. However, as in the steady state that we will describe below all generations have zero net foreign assets and as a result the same steady state consumption, the linearised version of this expression will only depend on aggregate variables (see section 2.4).

2.1.3 The demand for domestic and imported goods

The overall consumption basket is a CES aggregate of the domestic and import good bundles:

$$C_t = \left[(1-\alpha_C)\left(C_{D,t}\right)^{\frac{\eta-1}{\eta}} + \alpha_C\left(C_{F,t}\right)^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}} \tag{16}$$

where η is the elasticity of substitution between domestic and foreign goods and α_C determines the steady state share of imported goods in total consumption.

The demand for the domestic and imported composite good derived from expenditure minimisation is given by:[12]

$$C_{D,t} = (1-\alpha_C)\left(\frac{P_{D,t}}{P_t}\right)^{-\eta}C_t \tag{17}$$

$$C_{F,t} = \alpha_C\left(\frac{P_{F,t}}{P_t}\right)^{-\eta}C_t \tag{18}$$

where the aggregate price index is defined as:

$$P_t = \left[(1-\alpha_C)\left(P_{D,t}\right)^{1-\eta} + \alpha_C\left(P_{F,t}\right)^{1-\eta}\right]^{\frac{1}{1-\eta}} \tag{19}$$

[12] Here we suppress the index i since the individual and aggregate demand equations are identical.

Each composite good is itself a bundle of differentiated goods:

$$C_{k,t} = \left[\int C_{k,t}^{\iota} \frac{\theta-1}{\theta} d\iota \right]^{\frac{\theta}{\theta-1}} \quad \text{for } k=D,F. \tag{20}$$

The elasticity of substitution between any two differentiated goods, θ, is assumed to be greater than one.

The demand for each differentiated good ι is then given by:

$$C_{k,t}^{\iota} = \left(\frac{P_{k,t}^{\iota}}{P_{k,t}} \right)^{-\theta} C_{k,t} \tag{21}$$

where

$$P_{k,t} = \left[\int \left(P_{k,t}^{\iota} \right)^{1-\theta} d\iota \right]^{\frac{1}{1-\theta}} \tag{22}$$

and $P_{k,t}^{\iota}$ is the price of the differentiated good for $k=D,F$.

2.2 Production and price-setting decisions

2.2.1 Firms producing domestic goods

In the domestic good producing sector, firm ι transforms homogenous labour and the import good bundle into a differentiated domestic output good.[13] Following a Leontief-technology, the imported intermediate good is used in a fixed proportion, α_Y, of output:

$$Y_{D,t}^{\iota} = \min\left(\frac{\upsilon_t L_t^{\iota}}{1-\alpha_Y}, \frac{I_{F,t}^{\iota}}{\alpha_Y} \right) \tag{23}$$

where υ_t is an aggregate productivity shock and $I_{F,t}$ is an index over differentiated imported goods used in production:

$$I_{F,t} = \left[\int_0^1 \left(I_{F,t}^{m} \right)^{1-\theta} dm \right]^{\frac{1}{1-\theta}} \tag{24}$$

Cost minimisation implies that:

$$Y_{D,t}^{\iota} = \frac{\upsilon_t L_t^{\iota}}{1-\alpha_Y} = \frac{I_{F,t}^{\iota}}{\alpha_Y} \tag{25}$$

Nominal profits of firm ι are then given by:

[13] For a thorough discussion of the importance of allowing for intermediate imported inputs in open economy models, see McCallum and Nelson (2001).

$$\Xi^{\iota}_{H,t} = (P^{\iota}_{D,t} - MC_t)\, Y^{\iota}_{D,t} \tag{26}$$

where the marginal cost is a function of aggregate productivity and the factor costs, the wage and the import price. Moreover, the marginal cost is identical across firms:

$$MC_t = (1-\alpha_Y)\frac{W_t}{\upsilon_t} + \alpha_Y P_{F,t}\,. \tag{27}$$

The demand for good ι is the sum of demand by domestic consumers and the demand by the competitive export sector which bundles the differentiated domestic goods into a homogenous export good:

$$Y^{\iota}_{D,t} = C^{\iota}_{D,t} + C^{\iota *}_{D,t} = \left[\frac{P^{\iota}_{D,t}}{P_{D,t}}\right]^{-\theta} \left[C_{D,t} + X_t\right] \tag{28}$$

Following Calvo (1983), firms are not allowed to change their prices unless they receive a random "price-change signal". The probability that a given price can be re-optimised in any particular period is constant and is given by $(1-\xi_D)$. Following Christiano et al (2001), prices of firms that do not receive a price signal are imperfectly indexed to last period's inflation rate in domestic good prices. The degree of indexation is given by the parameter γ_D $(0 \le \gamma_D \le 1)$.

$$P^{\iota}_{D,t} = \left(\frac{P_{D,t-1}}{P_{D,t-2}}\right)^{\gamma_D} P^{\iota}_{D,t-1} \tag{29}$$

Profit optimisation by producers that are "allowed" to re-optimise their prices at time t results in the following first-order condition:

$$P^{N}_{D,t} = \frac{\theta}{(1-\tau)(\theta-1)} \frac{\Sigma^{\infty}_{j=0}\left(\frac{1}{\prod^{j-1}_{k=0}(1+R_{t+k})}\right)\xi^{j}_{D} Y^{\iota}_{D,t+j} MC_{t+j}}{\Sigma^{\infty}_{j=0}\left(\frac{1}{\prod^{j-1}_{k=0}(1+R_{t+k})}\right)\xi^{j}_{D} Y^{\iota}_{D,t+j}\left(\frac{P_{D,t-1+j}}{P_{D,t-1}}\right)^{\gamma_D}} \tag{30}$$

Equation (30) shows that the new price set by firm ι, at time t, is a mark-up over the expected future marginal costs. If prices are perfectly flexible $(\xi_D = 0)$, the mark-up is a constant and equal to $\frac{\theta}{(1-\tau)(\theta-1)}$. We will assume that firms are subsidised (τ) in such a way that in steady state the mark-up is zero. With sticky prices the mark-up becomes variable over time when the economy is hit by exogenous shocks.

The definition of the price index in equation (22) implies that its law of motion is given by:

$$\left(P_{D,t}\right)^{1-\theta} = \xi_D \left(P_{D,t-1}\left(\frac{P_{D,t-1}}{P_{D,t-2}}\right)^{\gamma_D}\right)^{1-\theta} + (1-\xi_D)\left(P^{N}_{D,t}\right)^{1-\theta} \tag{31}$$

Aggregating equation (28) over the monopolistic domestic goods producers and using equation (17) and the equivalent equation for exported goods yields the overall domestic goods market equilibrium equation:

$$Y_{D,t} = \delta_{P,t}\left[\left(\frac{P_{D,t}}{P_t}\right)^{-\eta}(1-\alpha_C)C_t + X_t\right], \tag{32}$$

where $\delta_{P,t} = \int\left(\frac{P^{\iota}_{D,t}}{P_{D,t}}\right)^{-\theta} d\iota$ is a measure of relative price dispersion in the domestic good sector. Equation (32) illustrates the real resource cost of relative price dispersion in the domestic goods sector. As the measure of relative price dispersion will always be greater than or equal to one (which is its steady-state value when all prices of the differentiated goods are equal) and rise with the variance of domestic prices, it shows that higher variability implies that for given aggregate output there will be less aggregate consumption.

2.2.2 Firms importing foreign goods

The import sector consists of firms that import a homogenous good produced abroad and turn it into a differentiated import good for the home market using a linear production technology. As in the domestic good sector, import firms are only allowed to change their price in response to a change in the exchange rate or the foreign price when they receive a random price-change signal. The constant probability of receiving such a signal is $(1-\xi_F)$. As before, we also assume that prices of import firms that do not receive a price signal are indexed to last period's inflation rate in import goods prices.

When an importing firm *m* is allowed to change its import price, it does so to optimise the present discounted value of its profit flow subject to the demand constraint:

$$Y^m_{F,t} = \left[\frac{P^m_{F,t}}{P_{F,t}}\right]^{-\theta} Y_{F,t} = \left[\frac{P^m_{F,t}}{P_{F,t}}\right]^{-\theta}\left(C_{F,t} + I_{F,t}\right) \tag{33}$$

For simplicity, we assume the same elasticity of substitution between differentiated goods in the domestic good and import sector.

As in the case of the domestic good producers, this results in an expression for the optimal setting of the new import price:

$$P^N_{F,t} = \frac{\theta}{(1-\tau\ )(\theta-1)}\frac{\Sigma^{\infty}_{j=0}\left(\frac{1}{\prod^{j-1}_{k=0}(1+R_{t+k})}\right)\xi^j_F Y^{\iota}_{F,t+j}\left[P^*_{F,t+j}\,e_{t+j}\right]}{\Sigma^{\infty}_{j=0}\left(\frac{1}{\prod^{j-1}_{k=0}(1+R_{t+k})}\right)\xi^j_F Y^{\iota}_{F,t+j}\left(\frac{P_{F,t-1+j}}{P_{F,t-1}}\right)^{\gamma_F}} \tag{34}$$

Again we assume that the subsidy rate, τ, is set such that the mark-up is zero in steady state. With flexible import prices ($\xi_F = 0$), the importing firms simply set the domestic sales price equal to the marginal cost, which in turn equals the foreign currency price translated in domestic currency:

$$P_{F,t} = P^*_{F,t}\, e_t \tag{35}$$

This situation is equivalent to the traditional assumption of Producer Currency Pricing (PCP). Sticky import prices lead to an imperfect pass-through of changes in the exchange rate and the foreign output price on import prices.

The aggregate domestic import price becomes:

$$\left(P_{F,t}\right)^{1-\theta} = \xi_F \left(P_{F,t-1} \left(\frac{P_{F,t-1}}{P_{F,t-2}} \right)^{\gamma_F} \right)^{1-\theta} + (1-\xi_F)\left(P^N_{F,t}\right)^{1-\theta} \tag{36}$$

In order to preserve symmetry, we also assume that foreign import firms use the domestic export good to produce a differentiated export good for the foreign market. The export demand for the domestic good is given by:

$$X_t = \left(\frac{P^*_{D,t}}{P^*_{F,t}} \right)^{-\eta} C^*_t \tag{37}$$

where C^*_t is foreign consumption and $P^*_{D,t}$ is the price of the composite export good abroad. With perfect exchange rate pass-through, the foreign export price equals the domestic price in foreign currency, $P^*_{D,t} = P_{D,t} e_t$. With imperfect exchange rate pass-through due to sticky export prices, the foreign export price will adjust only gradually to deviations from the law of one price.

2.3 The steady-state analysis

In this section, we analyse the non-stochastic steady-state of the model in which domestic and import prices are stabilised. It is easy to show that this steady-state is also the flexible price non-stochastic steady state. Below we will use this steady state as the point around which to linearise the model.

First, assuming that the foreign and domestic real interest rate equal the inverse of the rate of time preference ($\beta = 1/R\bar{R}$) and that inflation is stabilised at zero, the propensity to consume out of wealth is given by:

$$\bar{\Phi} = 1 - \vartheta\beta^{\frac{1}{\sigma}} R\bar{R}^{\frac{1-\sigma}{\sigma}} = 1 - \vartheta\beta \tag{38}$$

Using the aggregate consumption equation (14), the definition of wealth and the law of motion for human wealth, steady-state consumption can be derived as a function of the steady-state terms of trade ($T\overline{O}T = \overline{P}_D / \overline{P}_F$) and output:[14]

$$\overline{C} = \overline{\Phi}\frac{\overline{H}}{\overline{P}} = \overline{\Phi}\frac{R\overline{R}}{R\overline{R} - \vartheta}(1-\alpha_Y \frac{\overline{P}_F}{\overline{P}_D})\frac{\overline{P}_D}{\overline{P}}\overline{Y} = (1-\alpha_Y \frac{\overline{P}_F}{\overline{P}_D})\frac{\overline{P}_D}{\overline{P}}\overline{Y}\,, \tag{39}$$

The second equality follows from the fact that in steady state non-interest income equals the steady state wage bill, which in turn equals the steady state value of output minus the value of imported intermediate goods. The last equality follows from the assumption that $\beta = 1/R\overline{R}$. In steady state, higher potential output and an improved terms of trade increase consumption. The assumption that $\beta = 1/R\overline{R}$ also implies that the real trade balance and the real net foreign asset position are equal to zero in steady state.

Next, we examine the steady state relationship between output and the terms of trade from the demand side. From equation (32) and (37), the following steady-state relationship can be derived:

$$\overline{Y} = \frac{\overline{P}_D}{\overline{P}}^{-\eta}(1-\alpha_C)\overline{C} + \frac{\overline{P}_D}{\overline{P}_F}^{-\eta}\overline{C}^*. \tag{40}$$

Using equation (39), a negative relationship between the steady-state terms of trade and steady-state output follows:

$$\overline{Y} = \frac{\left(\frac{\overline{P}_D}{\overline{P}_F}\right)^{-\eta}}{1-(1-\alpha_C)(1-\alpha_Y T\overline{O}T^{-1})\left(\frac{\overline{P}_D}{\overline{P}}\right)^{1-\eta}}\overline{C}^* \tag{41}$$

Finally, in order to characterise the steady-state output and terms-of-trade, we also need to consider the supply side. In a steady state with constant prices, no stochastic shocks and an appropriate subsidy to production, all prices set domestically will equal marginal cost. Moreover, the assumption that $\beta = 1/R\overline{R}$ also implies that consumption will be equal across generations. As a result, in steady state the labour supply equation (15) will equal:

$$\overline{W} = \kappa\overline{P}\overline{L}^{\omega}\overline{C}^{\sigma}. \tag{42}$$

Combining this with the aggregate production function derived from (25), the steady state versions of equations (27) and (30), the expression for steady state consumption derived above, gives the following steady-state supply equation:

$$\kappa\overline{Y}^{\sigma+\omega} = \left(\frac{\overline{v}}{1-\alpha_Y}\right)^{1+\omega}\left(\left(1-\alpha_Y T\overline{O}T^{-1}\right)\frac{\overline{P}_D}{\overline{P}}\right)^{1-\sigma}. \tag{43}$$

[14] Note that $\overline{P}_D/\overline{P}$ is a monotonic positive function of the terms of trade. When $\eta = 1$, $\overline{P}_D/\overline{P} = T\overline{O}T^{\alpha_C}$.

In this open economy there are three effects of an increase in the terms of trade on the supply of domestic output. First, an increase in the price of domestic goods versus foreign goods has a direct negative impact on the marginal cost as imported intermediate goods become cheaper. This has a positive impact on steady-state output. Second, an increase in the price of domestic goods relative to imported goods will also reduce producer wages for given consumption wages and thereby reduce the real marginal cost. Also this effect on output is positive. Third, an improvement in the terms of trade also leads to increased consumption through its positive effect on real wealth. This reduces the marginal utility of an additional unit of consumption and leads workers to reduce their supply of labour. This has a positive effect on the marginal cost and a negative one on output. The overall terms-of-trade effect will depend on the coefficient of relative risk aversion. If $\sigma > 1$, then the supply curve will have a negative slope. However, it can also be shown that the slope of the steady-state supply curve will be steeper than that of the steady-state demand curve. Also note that an increase in productivity (i.e. a rise in $\overline{\upsilon}$) shifts the supply curve to the right. If $\sigma = 1$, the supply curve is vertical. In that case, a permanent increase in world demand leads to an improvement of the terms of trade, while output remains constant. A permanent increase in productivity leads to a rise in output and a fall in the terms of trade.

The steady-state discussed in this section characterises both the steady state under flexible prices and the one under sticky prices when inflation is completely stabilised. In what follows we will analyse small deviations around this steady state.

2.4 The linearised open-economy model

In this section we linearise the model discussed in Section 2.1-2.2 around the steady state discussed in Section 2.3. In addition, we normalise the steady state terms of trade to be one.

Linearisation of equation (3) yields the following uncovered interest rate parity condition:

$$\hat{e}_t = \hat{e}_{t+1} + \hat{R}_t - \hat{R}_t^*, \tag{44}$$

where the last term captures stochastic deviations around the world real interest rate. In the rest of the paper, this shock will be interpreted as a temporary change in the risk premium on domestic currency assets.

Linearisation of equation (11) yields a version of the Fisher equation:

$$R\hat{R}_t = \hat{R}_t - \left[\hat{P}_{t+1} - \hat{P}_t\right] \tag{45}$$

Around a steady state with $\beta R\overline{R} = 1$ and zero net wealth, the linearisation of the consumption function yields:

$$\hat{C}_t = -\frac{1}{\sigma} R\hat{R}_t + \hat{C}_{t+1} + \frac{(1-\vartheta)}{\vartheta}\overline{\Phi}\tilde{a}_{t+1}, \tag{46}$$

where $\tilde{a}_t = d(A_t/P_t)/\overline{C}$ is the deviation of real net foreign assets from steady state as a percentage of steady state consumption. Variations in the propensity to consume are of second order around this steady

state and can therefore be neglected. The corresponding net foreign asset accumulation equation is given by:

$$\tilde{a}_{t+1} = (1+\overline{R}\overline{R})\left(\tilde{a}_t + \hat{Y}_t - \hat{C}_t + \left(\alpha_C + \frac{\alpha_Y}{1-\alpha_Y}\right)\left(\hat{P}_{D,t} + e_t\right)\right). \tag{47}$$

The linearisation of the aggregate labour supply function (15) and the production function (25) yields:

$$\hat{W}_t = \hat{P}_t + \omega\hat{Y}_t + \sigma\hat{C}_t - \omega\hat{\upsilon}_t \tag{48}$$

Substituting equations (48) in the linearised domestic price setting equations result in the following expression for domestic price inflation ($\hat{\pi}_{D,t} = \hat{P}_{D,t} - \hat{P}_{D,t-1}$):

$$\begin{aligned}\hat{\pi}_{D,t} = &\frac{\beta}{1+\beta\gamma_D}\hat{\pi}_{D,t+1} + \frac{\gamma_D}{1+\beta\gamma_D}\hat{\pi}_{D,t-1} - \frac{(1-\beta\xi_D)(1-\xi_D)}{(1+\beta\gamma_D)\xi_D}\times \\ &\left[(1-(1-\alpha_Y)(1-\alpha_C))(\hat{P}_{D,t} - \hat{P}_{F,t}) - (1-\alpha_Y)((\omega+\sigma)\hat{Y}_t - \sigma(\hat{Y}_t - \hat{C}_t)) + (1-\alpha_Y)(1+\omega)\hat{\nu}_t\right]\end{aligned} \tag{49}$$

Domestic inflation depends on past and expected future inflation and the current real marginal cost, which itself is a function of output, the trade balance, the price of imported inputs relative to the price of domestic goods and the productivity shock. When $\gamma_D = 0$, this equation reverts to the standard purely forward-looking Phillips curve. In other words, the degree of indexation determines how backward looking the inflation process is. The elasticity of inflation with respect to changes in the marginal cost depends mainly on the degree of price stickiness.

Similarly, import price inflation ($\hat{\pi}_{F,t} = \hat{P}_{F,t} - \hat{P}_{F,t-1}$) is determined by:

$$\hat{\pi}_{F,t} = \frac{\beta}{1+\beta\gamma_F}\hat{\pi}_{F,t+1} + \frac{\gamma_F}{1+\beta\gamma_F}\hat{\pi}_{F,t-1} - \frac{1}{1+\beta\gamma_F}\frac{(1-\beta\xi_F)(1-\xi_F)}{\xi_F}\left[\hat{P}_{F,t} + \hat{e}_t\right], \tag{50}$$

where we have assumed that the foreign price level is constant.

Linearisation of the goods market equilibrium equation yields:

$$\begin{aligned}\hat{Y}_t = &-\eta\alpha_C(1-\alpha_C)(1-\alpha_Y)(\hat{P}_{D,t} - \hat{P}_{F,t}) + (1-\alpha_C)(1-\alpha_Y)\hat{C}_t \\ &-\eta(\alpha_Y + (1-\alpha_Y)\alpha_C)\hat{P}^*_{D,t} + (1-(1-\alpha_C)(1-\alpha_Y))\hat{C}^*_t\end{aligned}. \tag{51}$$

Finally, the consumer price level is given by:

$$\hat{P}_t = (1-\alpha_C)\hat{P}_{D,t} + \alpha_C\hat{P}_{F,t} \tag{52}$$

With perfect exchange rate pass-through in the foreign market, the foreign export price will be equal to the domestic price in foreign currency: $\hat{P}^*_{D,t} = \hat{P}_{D,t} + \hat{e}_t$. In the simulations reported in Section 5 we will assume imperfect exchange rate pass-through in foreign export prices (in analogy with the imported goods sector). In that case export price inflation ($\hat{\pi}_{X,t} = \hat{P}^*_{D,t} - \hat{P}^*_{D,t-1}$) is given by:

$$\hat{\pi}_{X,t} = \frac{\beta}{1+\beta\gamma_F}\hat{\pi}_{X,t+1} + \frac{\gamma_F}{1+\beta\gamma_F}\hat{\pi}_{X,t-1} - \frac{1}{1+\beta\gamma_F}\frac{(1-\beta\xi_F)(1-\xi_F)}{\xi_F}\left[\hat{P}^*_{D,t} - \hat{P}_{D,t} - \hat{e}_t\right] \tag{53}$$

Adding a policy reaction function for the nominal interest rate closes the system. The linear model containing equations (45) to (53) can be further reduced to a dynamic system in six variables: the real exchange rate, the terms of trade, consumption, net foreign assets, domestic price inflation and imported price inflation. The stochastics depends on three exogenous shocks: a productivity shock, a foreign demand shock and an exchange rate risk premium shock.

Before discussing optimal monetary policy in the calibrated open economy model of Section 4, it may be worth discussing the various transmission channels of monetary policy in this economy. In the closed economy model of Rotemberg and Woodford (1997) the only channel of monetary policy is the intertemporal substitution effect of changes in the interest rate on spending. This channel is also presented in this model. In the open-economy model discussed in this section, there are additional transmission channels that work through the effects of changes in the exchange rate on the terms of trade. Combining equations (49) and (51), one can show that changes in the terms of trade have two important effects on real marginal cost and thus inflation. First, an improvement of the terms of trade will reduce both domestic and foreign demand for domestically produced goods. This will have a negative impact on domestic output and reduce the marginal cost of producing an additional unit of output. The reduction in marginal cost will be reflected in a fall in domestic inflation. Second, an improvement in the terms of trade has a direct negative effect on the real marginal cost through the price of imported intermediate goods and because it increases producer prices relative to consumption prices which affect the nominal cost of producing an additional unit. The size of this effect will of course depend on the degree of openness of the economy. It is easy to show that this effect is similar whether imported goods are used as intermediate or final consumption goods.

Finally, changes in the terms of trade also have a wealth effect on consumption which is enhanced through the effect on net foreign assets. As can be seen from equation (47), an improvement in the terms of trade will lead to an accumulation of net foreign assets which enter the consumption function because of the overlapping generations structure. Higher consumption will in turn have a positive impact on prices both through its direct impact on labour supply and through its impact on the demand for domestic products. When the intertemporal elasticity of substitution is small enough, this effect may dominate the other negative terms of trade effects.

3. The central bank´s loss function

In this section we discuss the central bank's objective function that we will use to analyse optimal monetary policy. Rather than assuming the standard quadratic loss function in inflation and the output gap as is done in a large part of the literature on optimal monetary policy, we want to relate the central bank's objective function to the underlying model and the welfare of the consumers.

Because of the overlapping generations structure a full-blown derivation of the central bank's loss function from consumers' utility as in Rotemberg and Woodford (1997) is rather complicated.[15] We will therefore assume a more limited mandate for the central bank. In our model with staggered prices in both sectors, both domestic and imported price inflation give rise to resource misallocation across monopolistic competitive sectors that are otherwise similar. We will assume that the central bank aims at minimising those distortions that arise from inflation.

To derive the loss function of the central bank we proceed in three steps. First, we first derive a measure of the resource cost that is due to relative price variability. Then we show that these resource costs are proportional to the variability of prices in the monopolistic domestic and import good sectors. Finally, we relate the variability of prices to the variance of inflation and the change in inflation as in Woodford (1999), Steinsson (2001) and Amato and Laubach (2000).

In order to illustrate the resource cost of relative price variability, it is useful to start from expression (16) for the aggregate consumption bundle and relate the consumption bundle to the real resource cost in terms of units of output and net imports that are needed to produce it. This can be done by substituting the aggregation of equation (28) and (33) into equation (16). This yields:

$$C_t = \left[(1-\alpha_C)\left(\frac{Y_t}{\delta_{D,t}} - X_t \right)^{\frac{\eta-1}{\eta}} + \alpha_C \left(\frac{M_t}{\delta_{F,t}} - I_{F,t} \right)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}} \tag{54}$$

where $\delta_{D,t} = \int \left[\frac{P_{D,t}^i}{P_{D,t}} \right]^{-\theta} di$ and $\delta_{F,t} = \int \left[\frac{P_{F,t}^i}{P_{F,t}} \right]^{-\theta} di$ denote the resource cost of relative price variability in the domestic and imported good sectors respectively. Both measures are one in steady state, when all prices are stabilised and equal to the average price in the sector, and become greater than one when individual prices deviate from the average price. Equation (54) illustrates that for given units of output produced at home and foreign goods imported, aggregate consumption will be higher, the lower these measures of relative price variability.

In what follows, we will assume that the central bank tries to minimise a weighted average of the resource costs due to relative price variability in the domestic and imported good sectors. The relative weight is assumed to be proportional to the relative elasticity of aggregate consumption with respect to a change in the two resource costs (δ). Taking the derivatives of equation (54) with respect to $\delta_{D,t}$ and $\delta_{F,t}$ and evaluating them at the steady state, the following elasticities are derived:

$$w_D = 1 \text{ and } w_F = \alpha_C + \frac{\alpha_Y}{1+\alpha_Y}. \tag{55}$$

[15] For a derivation of a welfare based loss function in a similar OLG model without sticky prices, see Ghironi (2000c). Benigno (2001) is an example of a full-blown welfare analysis in a two-country model.

The weights depend solely on the parameters characterising the openness of the economy. The higher the share of imported goods in consumption and in production, the greater the weight on relative price variability in the imported good sector in the central bank's loss function.

In the next step, we can link the resource cost δ to the variability of relative prices in the monopolistic sector by taking a second-order Taylor expansion around the steady state. This yields:

$$\hat{\delta}_{k,t} = \frac{1}{2}(1+\theta^2) \;\; Var_i \hat{P}^i_{k,t} \qquad \text{for } k = D, F \,. \tag{56}$$

A higher relative price variability increases the resource cost; by how much depends on the degree of monopolistic competition. The higher the degree of competition or the lower the market power of firms (the lower the mark-up), the higher the resource cost. The intuitive reason for this is that the higher the degree of substitutability between differentiated goods, the more demand and output will respond to changes in relative prices that arise from inflation. As the efficient allocation is one where equal quantities of the differentiated goods are produced and consumed, this is indicative of a worse resource misallocation. However, as we have assumed the same degree of substitutability between differentiated goods in the domestic and import sector, the degree of monopolistic competition will not feature in the weights at the end of this section.

Finally, following Woodford (1999), Amato and Laubach (2000) and Steinsson (2001), we can relate the unconditional variance of relative prices in both sectors to the unconditional variance of the inflation rate and its change, as follows:

$$Var_i P^i_{k,t} = \frac{\xi_k (1-\gamma_k)(1-\xi_k \gamma_k)}{(1-\xi_k)^2} Var\pi_{k,t} + \frac{\xi_k \gamma_k (\xi_k (\gamma_k - 1) + 1)}{(1-\xi_k)^2} Var\Delta\pi_{k,t} \;\; \text{for } k = D, F \tag{57}$$

Equation (57) shows that the weight on inflation in the domestic and imported goods sector will depend on the degree of price stickiness (ξ) and the degree of price indexation (γ). A higher degree of price stickiness will increase the weight on inflation in that sector.[16] The degree of price indexation primarily determines the relative weight of the level of inflation as opposed to the change in the inflation rate. Without indexation, $\gamma_k = 0$, only the variance of inflation matters:

$$Var_i P^i_{k,t} = \frac{\xi_k}{(1-\xi_k)^2} Var\pi_{k,t} \,. \tag{58}$$

With perfect indexation to past inflation, $\gamma_k = 1$, only the change in inflation needs to be stabilised:

$$Var_i P^i_{k,t} = \frac{\xi_k}{(1-\xi_k)^2} Var\Delta\pi_{k,t} \,. \tag{59}$$

[16] This result was highlighted by Benigno (1999), who argued that targeting a weighted average of sectoral inflation where the weights depend on the degree of price stickiness came close to achieving the first-best outcome. See also Benigno and Lopez-Salido (2001) for an empirical application to the euro area.

In summary, in the rest of this paper we will assume that the central bank minimises the following weighted average of the variance in inflation and the change in inflation in both domestic price and import price inflation:

$$L = w_{\pi_D} Var\pi_{D,t} + w_{\Delta\pi_D} Var\Delta\pi_{D,t} + \left[\alpha_C + \frac{\alpha_Y}{1-\alpha_Y}\right]\left[w_{\pi_F} Var\pi_{F,t} + w_{\Delta\pi_F} Var\Delta\pi_{F,t}\right] \quad (60)$$

where the weights are determined by those in equation (57).

4. Empirical calibration of the open-economy model

In order to analyse the optimal policy response to the shocks affecting the economy, we need to calibrate the parameters of the model. Given that the weights in the objective function of the central bank are crucially dependent on the parameters governing the domestic and import inflation process, we concentrate the empirical calibration of the model on these parameters. This calibration is done on the basis of euro area macro-economic data.

In the literature, there are basically two ways of estimating the parameters of price stickiness (ξ_D, ξ_F) and indexation (γ_D, γ_F) featuring in equations (49) and (50). One way is due to Rotemberg and Woodford (1997) and Christiano et al (2001) and consists of estimating the effects of a monetary policy shock using an empirical methodology such as identified VARs and estimating/calibrating a subset of the structural parameters such that the theoretical impulse responses match as closely as possible the empirical ones. For example, using this methodology, Rotemberg and Woodford (1997) calibrate the Calvo parameter of price stickiness to be 0.66 in US data.[17] One problem with this methodology is that the estimation of the parameters of interest will depend on the full structure of the model. This point is highlighted by Christiano et al (2001).[18] These authors show that the estimated degree of price stickiness crucially depends on how the real economy and in particular the marginal cost is modelled. They show that the estimated degree of price stickiness falls quite considerably and is not significantly different from zero if nominal wages are modelled as being sticky. Even allowing for sticky wages, the estimated degree of price stickiness varies from 0.34 to 0.54 depending on how the rest of the economy is modelled regarding habit formation in consumption, adjustment costs in investment and variable capital utilisation. As combining the open economy features of the model in this paper with a realistic modelling of the persistence in the rest of the economy is beyond the scope of this paper, using this methodology in the current model would naturally bias our estimates upward.

A second way of estimating the price parameters is to estimate equations (49) and (50) directly using instrumental variable techniques as in Gali and Gertler (2000) and Sbordone (1998). For example, using GMM methods, Gali, Gertler and Lopez-Salido (2001) find that the degree of price stickiness in the euro

[17] In a previous version of this paper, we applied the same methodology to an open economy model for the euro area. See Smets and Wouters (2000).

[18] See also Dotsey and King (2001).

area lies between 0.79 and 0.92 depending on the specification of technology. This methodology works quite well for the pricing equation estimated in those papers because under the assumptions of the model the real marginal cost can be measured by the wage share and is therefore directly observable. However, under more general conditions this may not be the case. Moreover, for other prices such as wages or import prices, such a straightforward empirical counterpart to the driving factors may not easily be found. In such a case, one needs to take a stand on how to measure the unobservable variables that enter the driving variables, such as, for example, preference shocks. For example, Sbordone (2001) assumes that preference shocks follow a random walk. Such an assumption regarding the nature of the preference shock appears to be quite arbitrary and is likely to affect the results considerably.

In this paper we use a methodology to calibrate the price parameters, which combines features of both methods. As in Rotemberg and Woodford (1997) and Christiano et al (2001), we use empirical impulse response functions of domestic and import price inflation to a monetary policy shock to calibrate the stickiness parameters. However, as in Sbordone (2001) we take the process driving the fundamental factors entering the pricing equations as given. That is, in estimating the stickiness parameters we take the response of output, net trade and the exchange rate as given and minimise the squared difference between the implied theoretical response of domestic and import price inflation to the shock and its empirical counterpart. This methodology alleviates the criticism of the first methodology that the estimated stickiness will depend crucially on how the real side of the economy is modelled, by taking the response of the driving factors as given. It also alleviates the difficulties of the second methodology with the identification and measurement of unobserved shocks, by doing the analysis conditional on an identified structural shock (in our case a monetary policy).

Of course, this methodology does not solve all problems. First, the results may depend on the identification of the monetary policy shock. To check the sensitivity we also examine the sensitivity of the results to an alternative exchange rate shock. Second, the form of the error-correction term that appears in equations (49) and (50) does depend on certain assumptions regarding technologies and preferences.

The rest of this section reports the results of this calibration exercise. In the next subsection, we estimate an unrestricted VAR and discuss the identification method for obtaining the impulse response functions of the two structural shocks: a monetary policy shock and an exchange rate shock. In Section 4.2. we calibrate the model of Section 2 and estimate the price stickiness parameters using the methodology discussed above.

4.1. A VAR model estimated on synthetic euro area data

From the three pricing equations, (49), (50) and (52), it is clear that three variables are driving the vector of prices: output, net trade and the exchange rate. In order to estimate the stickiness parameters, in a first step we therefore estimate a 6x6 VAR system for the euro area over the period 1977:1 to 1999:4 containing real GDP, net trade as a percentage of GDP, domestic CPI inflation, a short-term nominal

interest rate, the real effective exchange rate (re_t) and import price inflation.[19] The US-dollar 3-month interest rate, US GDP and CPI-inflation rate and world commodity-prices enter the VAR as exogenous variables in order to control for world conditions.[20] As in much of the literature on the effects of monetary policy using VARs (see, for example, Christiano, Eichenbaum and Evans (1999)), the impulse-response of the endogenous variables to a monetary policy shock and an exchange rate shock are identified by using a Choleski decomposition. The implicit identifying assumption is that changes in monetary policy have only a lagged effect on output and domestic prices, but may have an immediate impact on the exchange rate and therefore import prices. The immediate impact effect of a monetary policy shock through import prices on CPI-inflation is assumed to be negligible. The exchange rate shock is identified as the shock to the exchange rate equation.

Insert Figure 1
Estimated response to a monetary policy shock
(Euro area data: 1977-1999)

The empirical impulse responses for a monetary policy are given by the solid lines in Figure 1. The bounds represent two times the standard error of a bootstrap exercise. The estimated impulse response functions appear to broadly conform with other evidence on the transmission mechanism in the euro area.[21] The effects of the exchange rate shock are shown in Figure 2.

Insert Figure 2
Estimated response to an exchange rate shock
(Euro area data: 1977-1999)

Both impulse responses contain significant information on how inflation in import and consumer prices reacts to the two shocks. This information allows us to estimate the relative stickiness in the theoretical price equations, using the impulse responses of the other macro-economic variables that were identified by the model as the driving forces behind the price dynamics.

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[19] The synthetic euro area variables are constructed in Fagan et al (2000). One problem with the import price series is that it also includes intra euro area trade prices which accounts for about half of gross imports. This will tend to bias the degree of price stickiness in import prices upward.

[20] The VAR is estimated with quarterly dummies, but without a time trend. Two lags appear to be sufficient to make the residuals white noise.

[21] See, for example, Peersman and Smets (2001).

4.2. Estimating the price stickiness parameters

In order to estimate the parameters that determine the stickiness of domestic and imported prices ($\xi_D, \xi_F, \gamma_D, \gamma_F$), we first need to calibrate the other parameters that appear in the pricing equations (49) and (50): the labour supply elasticity (ω), the intertemporal elasticity of substitution (σ), the share of intermediate imports in production (α_Y), the share of imports in final consumption (α_C) and the rate of time preference (β).

As in many other papers, we calibrate the rate of time preference to be equal to 0.99, which implies a 4 percent steady state real interest rate given the assumed quarterly frequency of the model. The share of total imports in GDP ($\approx \alpha_C + \alpha_Y$) is calibrated to be approximately equal to its historical average for the euro area, which is about 15%.[22] In a recent paper, McCallum and Nelson (2001) have argued that treating imports as intermediate inputs rather than final consumption goods improves the empirical fit (in particular regarding the cross-correlations between the exchange rate and prices) of open economy models. As we do not have input/output data that allow us to determine how much of the imports is used as an intermediate good in production and how much is used for consumption, we take the assumption that all imports are used in intermediate production as our benchmark (i.e. $\alpha_C = 0$).

For the intertemporal elasticity of substitution, we assume log utility, which implies an elasticity of one. This elasticity is close to the one estimated by Casares (2000) on euro area data on the basis of a structural consumption equation.[23] The most difficult parameter to calibrate is the elasticity of labour supply. It is well known that in models without sticky wages or other frictions that cause a slow and gradual response of the marginal cost to output, the labour supply elasticity has to be quite small in order to match the variability of real wages and their correlation to changes in economic activity. Here, we assume an elasticity of 0.25 which is in between the very low estimate that we obtained in a previous paper (0.05) (Smets and Wouters, 2000) and the estimate obtained for the United States by Rotemberg and Woodford (1997) (0.47).

Given the calibrated parameters discussed above, we estimate the four price parameters by minimising the distance between the impulse-response functions of consumer and import price inflation to a monetary policy shock implied by equations (49), (50) and (52) and their empirical impulse-response functions. To check robustness, we also perform this exercise for the exchange rate shock. More formally, we follow Christiano et al (2001) in minimising the following distance function:

$$J(\Psi) = \left[vec(\hat{\varsigma}) - vec(\varsigma(\Psi))\right]' W^{-1} \left[vec(\hat{\varsigma}) - vec(\varsigma(\Psi))\right] \tag{61}$$

where $\Psi = \left[\xi_D \quad \xi_F \quad \gamma_D \quad \gamma_F\right]$ is the vector of structural parameters to be estimated, $\varsigma(\Psi)$ is the matrix of impulse responses of the monetary policy (exchange rate) shock generated by the structural model for consumer and imported price inflation given the response of the driving variables (output, net trade and the exchange rate) and the calibrated parameters, $\hat{\varsigma}$ is the corresponding matrix of the

[22] This is also close to the number that is obtained when we include this parameter in the estimation.

[23] Casares (2001) estimates an inverse elasticity of substitution of 1.25.

estimated empirical impulse response functions and W is a weighting matrix with the variance of these estimates on the diagonal.[24] Twelve quarters of the impulse response functions are used in the estimation.

Table 1 reports the results under the benchmark calibration of the other parameters discussed above. The implied impulse response functions are shown in Figures 1 and 2 (dashed lines), together with the empirical estimates.

Insert Table 1

Estimation results of the price stickiness parameters

A number of observations can be made. First, as can be seen from the third row in Figures 1 and 2, the model seems to be able to track the response of consumer and import price inflation quite well. The theoretical responses expected on the basis of the behaviour of the driving factors (given by the dashed lines) generally lie quite close to the empirical responses and fall well within the confidence band of the empirical impulse response functions. The last row in Figures 1 and 2 plot the inverse of the real marginal cost and the deviation of the law of one price together with predicted domestic and import inflation. Clearly, the foreign price gap responds quickly and strongly to both shocks reflecting the significant exchange rate response in both cases. In contrast, the response of the domestic price gap is much slower, but more persistent reflecting the persistent fall in output.

Second, Table 1 shows that there seems to be considerable evidence of Calvo-stickiness in both domestic and import prices. More surprisingly, the degree of stickiness in import prices is in most cases very similar to that of domestic prices. In contrast, we do not find evidence in favour of strong indexation. While inflation clearly responds in a very persistent way to both shocks, the persistence in the factors driving those prices appears to be sufficient to explain that persistence. This evidence seems to be consistent with recent findings of Gali and Gertler (1999) and Gali, Gertler and Lopez-Salido (2001). The latter paper finds a very similar degree of price stickiness (with a Calvo parameter of 0.90) in euro area data, when marginal costs are assumed to be the same for all firms as we have assumed here.[25] Third, the estimated degree of price stickiness depends to a considerable extent on which identified shock is used in the estimation. Price stickiness is estimated to be much larger when a monetary policy shock is used rather than the exchange rate shock. [26] This points to a weakness of the methodology that

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[24] If $\hat{\varsigma}$ is normally distributed, J has a chi-squared distribution with N-m degrees of freedom with N the total number of observations on the impulse-response functions (the number of elements in $\mathrm{vec}(\hat{\varsigma})$) and m the number of coefficients (the number of elements in Ψ): $T * J(\Psi) = \chi^2(N-m)$ if $\sqrt{T}\, vec(\hat{\varsigma} - \varsigma) \xrightarrow{d} N(0, W)$.

[25] Gali, Gertler and Lopez-Salido (2001) show that when one allows for upward-sloping marginal cost curves, the estimated Calvo-parameters will be lower.

[26] McCallum (2001) has argued against using impulse response functions to calibrate SDGE models.

the reliability of the estimates will depend on the reliability of the identification of the structural shocks.[27]

In conclusion, the analysis in this section suggests three broad conclusions that are of interest for the analysis of optimal monetary policy in the next section. First, there is evidence of considerable price stickiness in import prices. This evidence is consistent with recent papers (Campa and Goldberg, 2001 and Ghosh and Wolf, 2001), that have documented the imperfect pass through of exchange rate changes into domestic prices for many countries. Second, in general we find that the degree of price stickiness in import prices is very similar to that found in domestic prices, suggesting that differences in the degree of stickiness are not a dominant reason for putting different weights on domestic versus import price inflation in the central bank's loss function. Finally, the degree of indexation to past inflation is relatively limited. In the calibration, we therefore assume that $\xi_D = \xi_F = 0.85$ and that $\gamma_D = \gamma_F = 0$. In addition, we calibrate the probability of survival to be 0.99 and the substitution elasticity between domestic and foreign goods to be 1.5. The latter is also the parameter used by Gali and Monacelli (2000).

5. Optimal monetary policy

5.1 The flexible price economy

Before analysing optimal monetary policy in the calibrated model, it is useful to discuss briefly the flexible price analogue of the open-economy model. This provides a useful benchmark for the analysis of optimal monetary policy with sticky prices in the next section.

When domestic and import prices are flexible, equations (49) and (50) need to be replaced by the condition that prices equal marginal cost in both goods markets. This implies:

$$\hat{P}^f_{D,t} - \hat{P}^f_{F,t} = \alpha_1 \hat{C}^f_t + \alpha_2 \hat{C}^*_t - \alpha_3 \hat{\upsilon}_t \tag{62}$$

$$\hat{P}^f_{F,t} = -\hat{e}^f_t \tag{63}$$

where $\alpha_1 = \dfrac{\omega\alpha_Y(1-\alpha_Y)}{\alpha_Y + \eta\omega\alpha_Y(1-\alpha_Y)}$, $\alpha_2 = \dfrac{(1-\alpha_Y)(\sigma+\omega(1-\alpha_Y))}{\alpha_Y + \eta\omega\alpha_Y(1-\alpha_Y)}$, $\alpha_3 = \dfrac{(1+\omega)(1-\alpha_Y))}{\alpha_Y + \eta\omega\alpha_Y(1-\alpha_Y)}$

and the superscript *f* denotes a flexible price outcome. Together with equations (44), (46) and (47) this can be used to solve for the flexible price equilibrium. The response of the flexible price economy to each of the three structural shocks is discussed in the next section.

In analogy with the analysis in Erceg, Henderson and Levin (2000), who focus on the trade-off between the stabilisation of price and wage inflation in a closed economy, one can easily see that, when either the

[27] We also checked the sensitivity of these results with respect to the calibrated parameters. Overall, the estimates turn out to be quite robust. Not surprisingly, it turns out that the larger σ and ω, the higher the estimated degree of stickiness. In particular in response to an exchange rate shock, the model appears to prefer a rather high share of imports in production. This result points to a more general finding highlighted by Huang and Liu (1999) that the combination of Calvo pricing and multi-stage production can substantially increase the persistence of output and inflation in response to shocks.

domestic goods or the import goods sector has flexible prices, the central bank can achieve the flexible price equilibrium by targeting inflation in the sticky price sector. To see this, note that if the central bank only targets the domestic inflation rate, it will be able to stabilise domestic prices perfectly by setting the interest rate in such a way that domestic prices always equal marginal cost. In this case, equation (62) will always hold. If imported prices are flexible, also equation (63) will hold, and as a result the flexible price economy will be replicated. In this case, there is no conflict between domestic inflation stabilisation and stabilising output, consumption or the terms of trade around their flexible price outcome. Similarly, if domestic prices are flexible, then according to equation (64) it is optimal for the central bank to stabilise import price inflation. The central bank can do so perfectly by setting the interest rate in such a way that the import prices always equal marginal cost (equation (63) holds). In the absence of foreign price shocks, the central bank could achieve this by perfectly stabilising the nominal exchange rate. Also in this case the central bank will replicate the flexible-price equilibrium.

These two extreme cases illustrate that when both domestic and import prices are sticky, there will be a trade-off between stabilising domestic inflation by stabilising the domestic real marginal cost and stabilising imported price inflation by stabilising the nominal exchange rate. In general, the flexible price outcome can no longer be replicated. The reason is simple. Take, for example, the effect of a positive productivity shock. In order to stabilise domestic inflation in the presence of sticky domestic prices, the central bank will want to easy monetary policy so as to accommodate the rise in supply with a depreciation of the exchange rate. Sticky import prices then have two consequences. First, movements in the exchange rate will create import price inflation and distortions in the imported goods sector. Second, a given change in the exchange rate will no longer have the same effects on the equilibrium outcome if it only gradually leads to changes in imported goods prices. As a result the flexible price outcome is no longer feasible. The exchange rate will have to fall by more to achieve the same effect on the domestic output gap and as a result, the allocation of demand between domestic consumption and world demand will have to be different. In the following section, we systematically compare the response of the flexible price economy with the response when both domestic and import prices are sticky and the central bank aims at stabilising inflation. Of course, in the previous discussion we have abstracted from the question whether the flexible price outcome is Pareto-efficient. If this is not the case due to the presence of other distortions (such as the monopolistic competition distortion or distortions arising from incomplete markets), there may still be a trade-off between stabilising sticky prices and alleviating those distortions even in the case where there is only one source of price stickiness.

5.2 The response of the economy under optimal monetary policies

In this Section we discuss the response of the economy to each of the three structural shocks under the assumption that the central bank minimises the loss function derived in Section 3 under discretion.[28] Under the calibrated parameters this loss function simplifies to:

[28] In order to avoid extreme interest rate movements in the optimal policy case, we also introduce a small relative weight of 0.001 on the variance of the nominal interest rate.

$$L = Var\pi_{D,t} + \frac{\alpha_Y}{1-\alpha_Y} Var\pi_{F,t} \tag{64}$$

We systematically compare this outcome with the outcome under flexible prices and the outcome under domestic inflation targeting.[29] The first comparison allows us to analyse the emergence of an output, consumption or terms-of-trade gap when both domestic and import prices are sticky. The latter comparison gives us an idea of the empirical importance of the trade-off between stabilising domestic and imported price inflation in our calibrated model.

5.2.1 The response to a productivity shock

Figure 3a plots the responses of the economy to a 1% positive productivity shock which decays with an autoregressive coefficient of 0.9. As a result, productivity is close to baseline towards the end of the simulation period (i.e. after 5 years). The responses in the flexible-price economy are qualitatively very similar to the responses derived in the model of Gali and Monacelli (2000). A positive productivity shock leads to an easing of monetary conditions as indicated by a fall in the real interest rate of about 35 basis points and a depreciation of the real exchange rate by about 100 basis points. This easing of monetary conditions is necessary in order to increase both consumption and output in response to the positive productivity shock. The real marginal cost is stabilised. Reflecting the sharp depreciation, the rise in output is stronger than that in consumption. As in Gali and Monacelli (2000), the real trade balance improves in response to a positive productivity shock. Exports rise by more than imports, due to the expenditure switching effects of the sharp depreciation of the terms of trade. However, real net foreign assets fall as the terms-of-trade effects dominate the net import effect.

When domestic and import prices are sticky, the response of the terms of trade is much more gradual and hump-shaped as noted by Monacelli (1999). As a result, output and consumption rise by less. Price stickiness leads to a negative output and consumption gap (defined as the deviation from the flexible price outcome) in response to a positive productivity shock. As a result, domestic inflation falls by 14 basis points.

From the graph, it is clear that the central bank faces a trade-off between falling domestic prices and rising import prices. This prevents her from easing monetary policy too much. This trade-off is also clear from the comparison with the domestic inflation targeting case. In that case, the central bank eases policy by more, which leads to a smaller output gap and a stronger depreciation. Domestic prices are much better stabilised, but import prices rise by more. However, perfect stabilisation is not possible, because the different policy mix between the interest rate and the exchange rate channel leads to a different composition of demand. In particular, because the exchange rate channel works only gradually the easing works primarily through the interest rate channel and domestic demand, rather than through net exports. As a result, net foreign assets fall by more. It is interesting to note that in contrast to the flexible price outcome, a positive productivity shock leads to an initial deterioration of the real trade balance, because

[29] See Soederlind (1999) for a discussion of solution methods.

the expenditure switching effects take time to materialise, while imports rise immediately with increased domestic demand.

Insert Figure 3a

The response to a positive productivity shock.

5.2.2 The response to a positive demand shock in the rest of the world

Figure 3b shows the response to a 1% positive shock in world demand. Because of the relatively small share of exports in domestic production, this has a relatively small impact on the domestic economy. In this case, a similar trade-off arises between stabilising domestic and imported price inflation. With flexible prices, output, consumption and net exports rise in response to a positive foreign demand shock. Monetary conditions tighten as the real exchange rate and the real interest rate increase. The gradual, but persistent rise in consumption is underpinned by a rise in net foreign assets.

With sticky domestic and import prices, the terms of trade can adjust only gradually to dampen the rise in foreign demand and as a result a positive output gap emerges, domestic inflation rises, while import price inflation falls. Somewhat surprisingly, under the optimal monetary policy, the nominal and real interest rate initially falls in response to a positive foreign demand shock, boosting domestic demand even more than in the flexible price outcome. The reason appears to be that a tighter monetary policy would lead to an even stronger real exchange rate appreciation and greater distortions in the imported goods sector. Again, this trade off can be easily seen when comparing the optimal monetary policy outcome with the domestic inflation targeting case. In the latter case, the central bank can by tightening monetary policy, stabilise domestic prices quite effectively. As a result, consumption falls initially before rising in the medium-term and the output gap is more than halved. However, the cost is that the foreign price gap is larger and the fall in imported price inflation is greater.

Insert Figure 3b

The response to a positive foreign demand shock.

5.2.3 The response to an exchange rate appreciation

Finally, Figure 3c shows the response of a 0.2% reduction of the risk premium, which results in a 1.5% appreciation of the real exchange rate. In the flexible price economy, the appreciation of the exchange rate is counteracted by a drop in the domestic real interest rate of about 12 basis points. The terms of trade improvement has a positive effect on consumption, but a negative effect on net exports. Overall, the latter dominates, so that output falls.

Again, with sticky domestic and import prices, the terms of trade responds much more gradually. As a result net exports fall by much less, whereas consumption increases by more. The latter effect dominates, so that a positive output gap emerges which leads to domestic price inflation. The main reason for this surprising result is that with an elasticity of substitution of one, the consumption effects of a terms-of-trade improvement dominate the direct negative effects on the marginal cost. If the central bank only cares about domestic inflation stabilisation, it pursues a relatively tighter monetary policy, thereby considerably reducing the consumption boom and stabilising domestic inflation.

Insert Figure 3c

The response to a fall in the exchange rate risk premium.

Overall, these impulse responses show that the introduction of sticky import prices has two important effects. First, it makes the achievement of the flexible price outcome infeasible, even if the central bank only cares about domestic inflation stabilisation. The reason is that imperfect exchange rate pass-through makes the exchange rate channel less effective. As a result more of the adjustment needs to be born by the domestic interest rate channel which primarily affects domestic demand. Second, stickiness in import prices gives a rationale for stabilising those prices and implicitly the exchange rate. This creates a trade-off between domestic and imported price inflation in response to all shocks that affect the exchange rate. Indeed, we find that the exchange responds stronger to each of the shocks when the central bank only cares about domestic inflation stabilisation. These differences would be even clearer in a more open economy for which the distortions in the import sector are relatively more important or if the degree of price stickiness turned out to be stronger in the import sector.

Whether imperfect pass-through increases or reduces exchange rate volatility compared to the flexible price economy is ambiguous and will depend on the type of shocks that hit the economy. In the case of the three shocks we considered in this paper, there are two offsetting effects. On the one hand, imperfect pass-through reduces the effectiveness of the exchange rate channel and thereby increases the need for larger exchange rate movements to stabilise the economy. This is the effect emphasised by Adolfson (2001). On the other hand, in the presence of imperfect pass-through, changes in the exchange rate carry a cost due to the relative price variability it creates in the import sector. This will reduce the incentive for the central bank to actively use the exchange rate channel.

6. Conclusions

In this paper we have analysed the implications of imperfect exchange rate pass-through for optimal monetary policy in a completely micro-founded open economy model in which foreign interest rates, prices and output are assumed to be exogenous. The model used may be of interest by itself, as in contrast to many of the existing open economy models, it has a well-defined steady state and incorporates a non-trivial role for the current account and net foreign asset accumulation. The empirical evidence on

gradual exchange rate pass-through into import prices, is captured by assuming Calvo-type staggered price setting in the imported goods sector, similar to that in the domestic goods sector. Using euro area data, we show that import prices appear to exhibit the same degree of price stickiness as domestic prices. As discussed in the introduction, a number of papers have recently examined monetary policy behaviour with incomplete exchange rate pass-through and have noted that imperfect pass-through reduces the effectiveness of the exchange rate channel. However, none of these papers have derived the policy implications of the welfare costs that arise because of staggered import price setting. We show that the minimisation of those costs introduces a motive for exchange rate stabilisation in the central bank's loss function. Similar to the analysis in Benigno (1999), the weight on the stabilisation of imported price inflation depends on the degree of openness and the relative degree of price stickiness in the imported goods sector. This cost of exchange rate variability will provide a counterweight to attempts by the central bank to engineer larger exchange rate movements in order to overcome the ineffectiveness of the exchange rate channel.

In the light of the central bank's loss function that we derived, it would be interesting to examine how simple policy rules perform in the presence of imperfect exchange rate pass-through. Another interesting issue is to see what the net effect is of imperfect pass-through on exchange rate volatility. For those questions we need to calibrate the processes driving each of the structural shocks. We leave that for future research.

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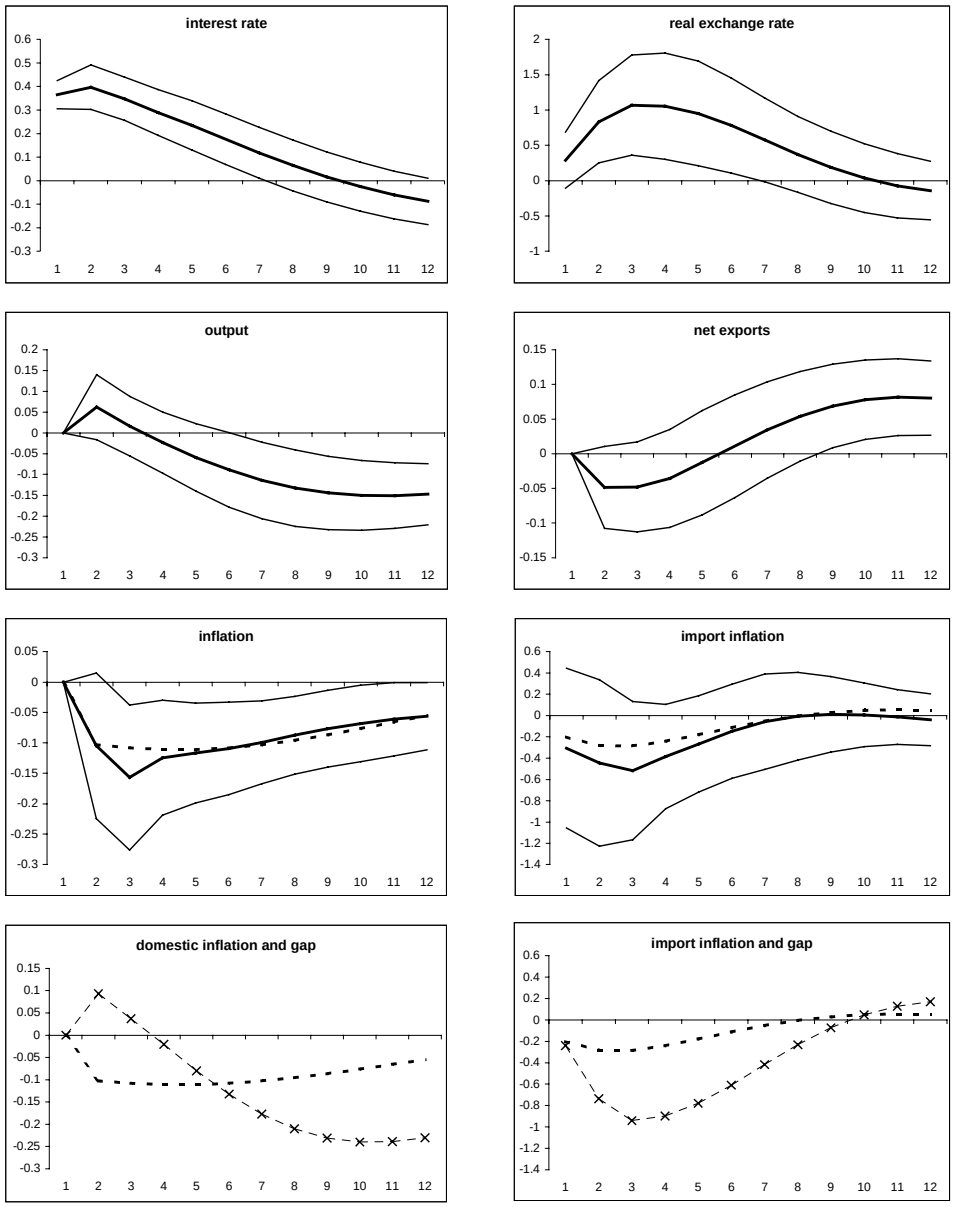
Table 1: Estimation results of the price stickiness parameters

	Monetary policy shock	
	Estimate	Standard error
$1-\xi_D$	0.90	0.01
$1-\xi_F$	0.90	0.03
γ_D	0.00	-
γ_F	0.45	0.37
	Exchange rate shock	
	Estimate	Standard error
$1-\xi_D$	0.72	0.01
$1-\xi_F$	0.73	0.02
γ_D	0.00	-
γ_F	0.03	0.09

Notes: In the case of a monetary policy shock, the function value is 3.26 with a probability of 0.99. In the case of the exchange rate shock the function value is 14.0 with a probability of 0.78. The probabilities are calculated using a Chi-Squared distribution with 19 degrees of freedom. Standard errors are calculated as the square root of the diagonal elements of the inverted Hessian matrix resulting from the optimisation of the objective function.

Figure 1

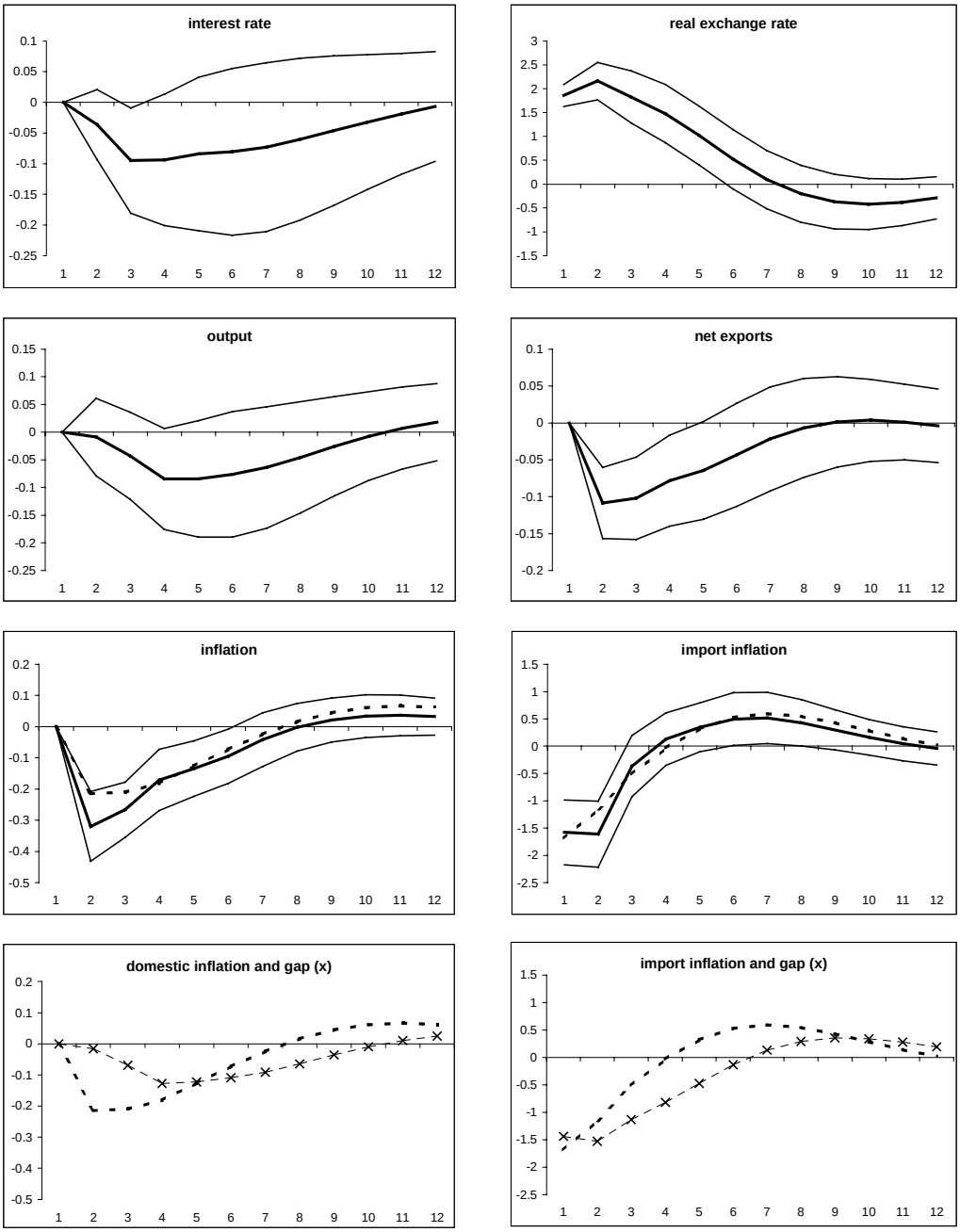
The estimated response to a monetary policy shock



Notes: The horizontal axis is in quarters. The solid lines are the impulse responses of a monetary policy shock in an identified VAR and their 95% confidence band. The broken lines in the third row are the theoretical impulse responses of inflation and import price inflation under the estimated price stickiness parameters and conditional on the empirical responses of output, net trade and the exchange rate. The gaps (denoted by x) in the last row are respectively the inverse of the real marginal cost and the deviation from the law of one price. Estimation is done using euro area data from 1977:1 till 1999:4 from Fagan et al (2001).

Figure 2

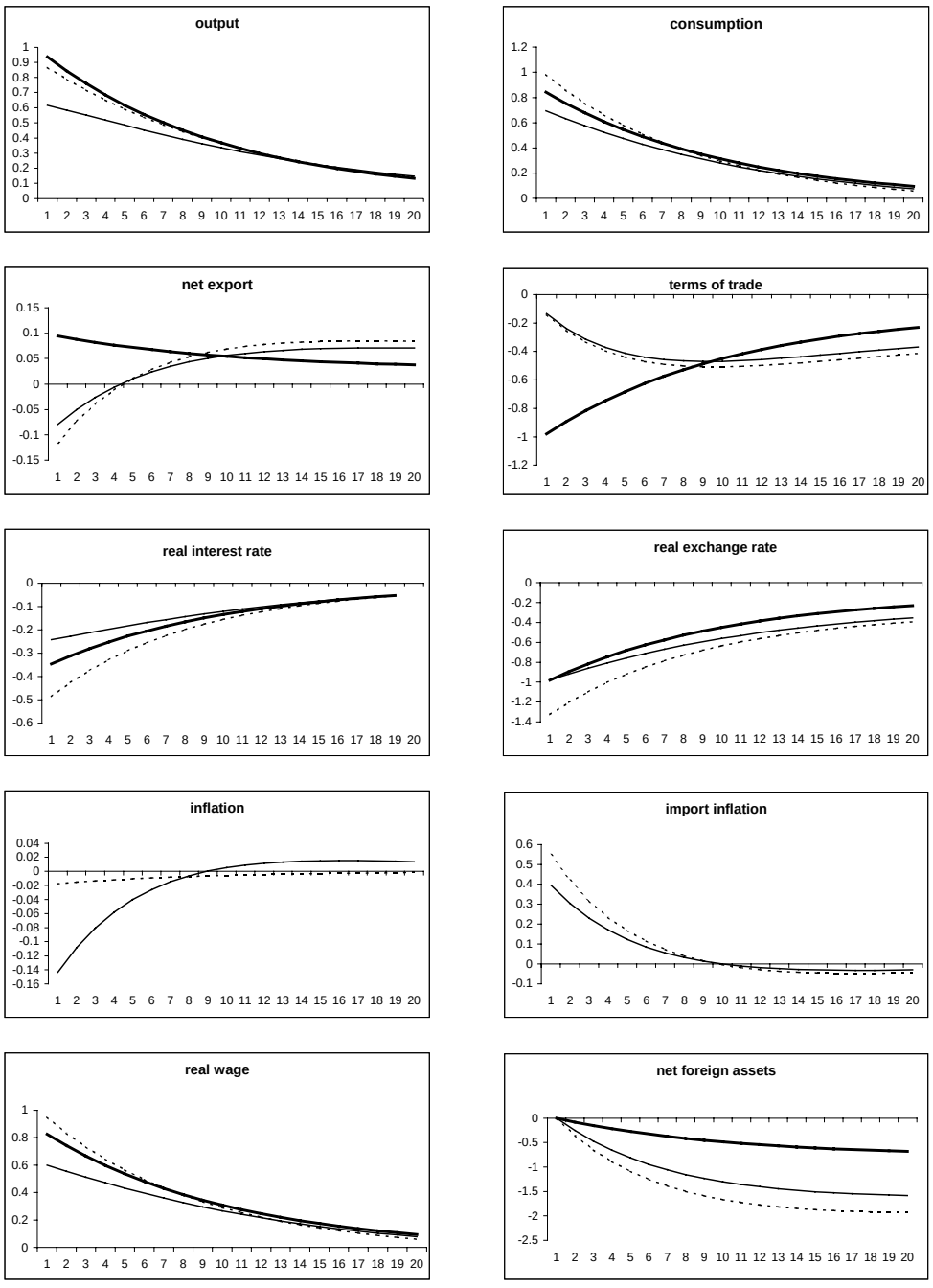
The estimated response to an exchange rate shock



Notes: The horizontal axis is in quarters. The solid lines are the impulse responses of an exchange rate shock in an identified VAR and their 95% confidence band. The broken lines in the third row are the theoretical impulse responses of inflation and import price inflation under the estimated price stickiness parameters and conditional on the empirical responses of output, net trade and the exchange rate. The gaps (denoted by x) in the last row are respectively the inverse of the real marginal cost and the deviation from the law of one price. Estimation is done using euro area data from 1977:1 till 1999:4 from Fagan et al (2001).

Figure 3a

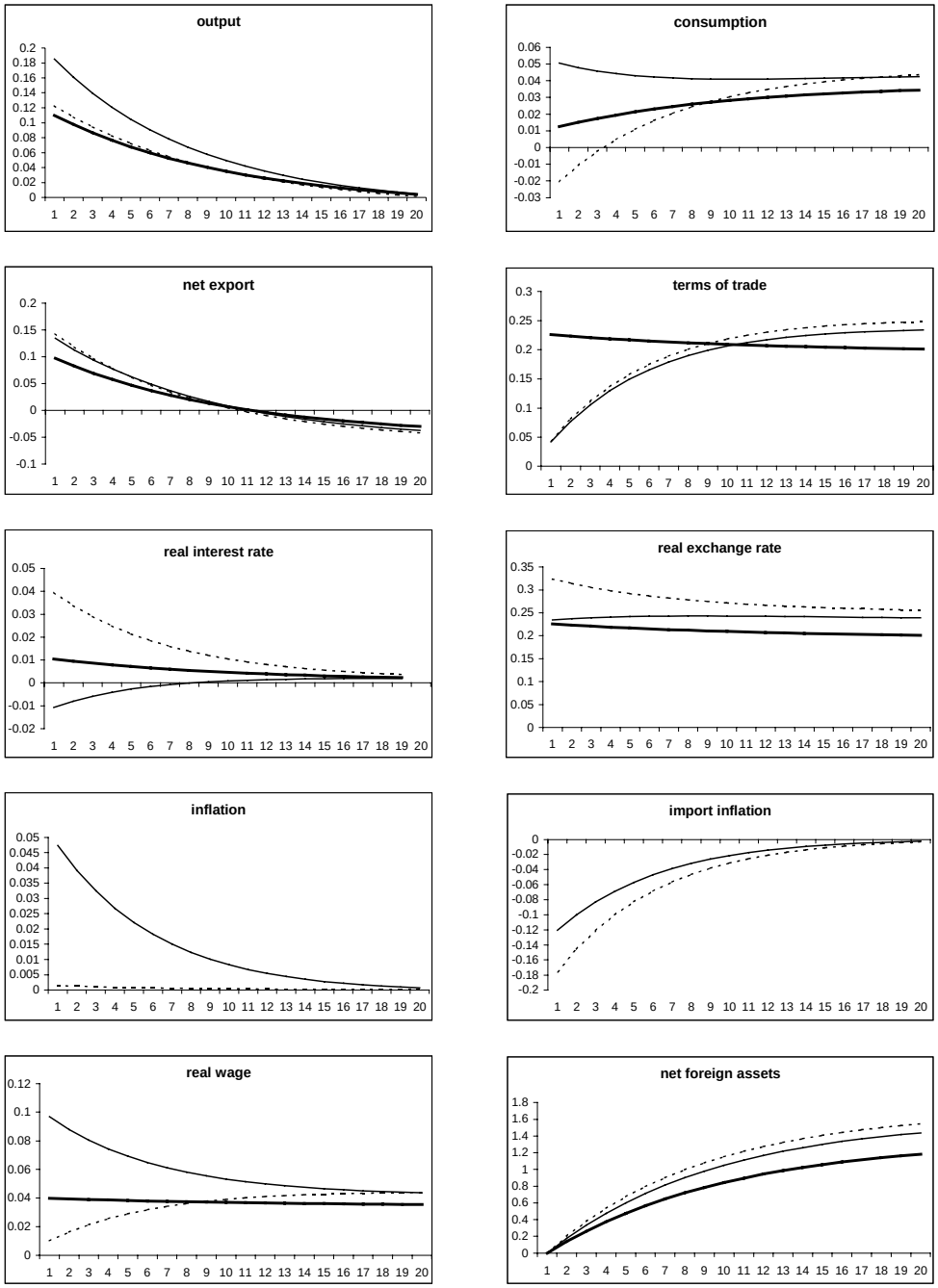
The response to a positive productivity shock



Note: The thick solid line corresponds to the response of the flexible price economy; the thin solid line corresponds to the sticky price economy with optimal discretionary policy; the broken line corresponds to the sticky price economy with domestic inflation targeting.

Figure 3b

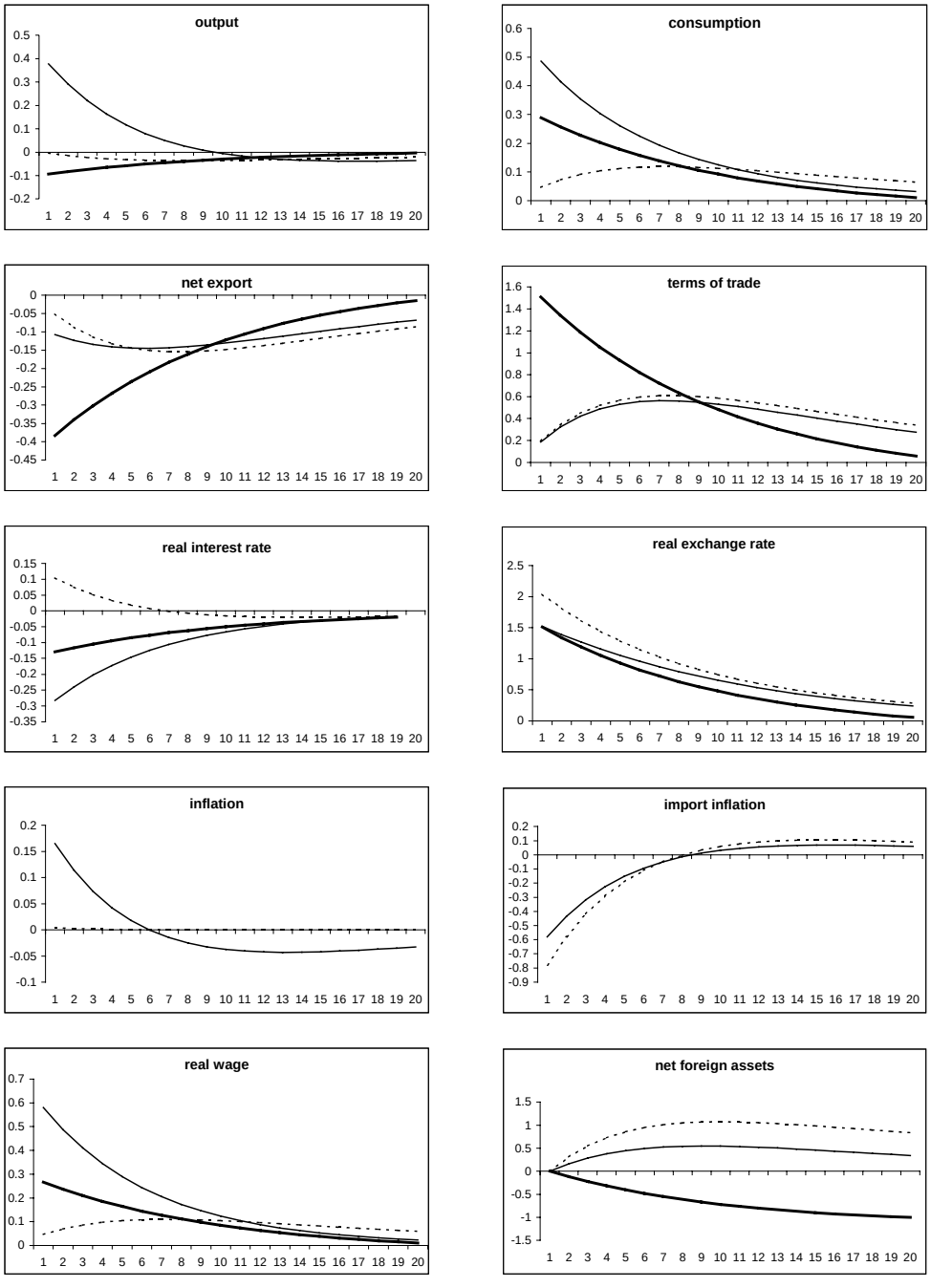
The response to a positive foreign demand shock



Note: The thick solid line corresponds to the response of the flexible price economy; the thin solid line corresponds to the sticky price economy with optimal discretionary policy; the broken line corresponds to the sticky price economy with domestic inflation targeting.

Figure 3c

The response to a fall in the exchange rate risk premium



Note: The thick solid line corresponds to the response of the flexible price economy; the thin solid line corresponds to the sticky price economy with optimal discretionary policy; the broken line corresponds to the sticky price economy with domestic inflation targeting.

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