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AN OPEN ECONOMY MODEL OF THE EURO AREA AND THE US

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An open economy model of the euro area and the US*

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Abstract

Taking stock of the recent developments in the New Open Macroeconomics literature, we build a two country Dynamic Stochastic General Equilibrium (DSGE) model of the euro area and the US, with nominal rigidities and imperfect exchange rate passthrough. The model is calibrated using parameters found in the literature. In order to illustrate the model's dynamics we simulate its response to a number of shocks.

JEL Classification: E5, F4.

Keywords: DSGE model; open economy; simulation.

1 Introduction

In this paper we build a medium sized open-economy DSGE model of the euro area and the US. We take stock of recent developments of the so-called New Open Economic Macroeconomics. The model presented here thus shares a number of common features with other models, namely models developed in other policy institutions (like the Global Economy Model (GEM) at the IMF) as well as other central banks (for instance, with the New Area Wide Model of the ECB).

The closed economy setup seems inadequate for the study of policy issues in the euro area. Even though a two-country setup is also a simplification, it allows us to study a number of issues that are not possible in a closed economy setting. Actually, Adolfson et al. (2005) compare the empirical properties of a closed and an open economy model of the euro area and, even though they don't find fundamental differences in the estimated parameters they do find differences in the transmission mechanism of monetary policy between the two types of models. They also find that open economy shocks are of high relevance in explaining the fluctuations in output and inflation in the short to medium term.

Even though the open economy setup seems more appropriate to deal with the euro area, any model is not without caveats. In respect to the model presented in this paper, one potentially important feature that we have left out in a first stage is the existence of tradable and non-tradeables goods or of a distribution sector (as in Corsetti and Dedola, 2005 or Corsetti, Dedola and Leduc, 2006). These features are important to model the exchange rate pass-through to domestic prices, namely to reduce the tendency in these models for changes in exchange rates or foreign prices to be transmitted more quickly to domestic prices than is usually found in the data. However, the intention of estimating the model in a follow-up study made such exclusion necessary as data

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for this sectoral breakdown is particularly difficult to find. Nevertheless, we have resorted to an alternative mechanism, namely the introduction of import adjustment costs, in order to slow down the pass-through.

The model presented here consists of two countries, the euro area (EA) and the United States (US). The two countries may have a different size but they share the same structure. The model features a number of frictions that have become quite standard in the related literature (e.g. as in the closed economy models by Christiano, Eichenbaum and Evans, 2005, or Smets and Wouters, 2003). These include price and wage rigidities, investment adjustment costs, variable capital utilization and imperfect exchange rate pass-through. At this stage the model is calibrated mainly on the basis of other similar studies for the euro area.

The paper is organised as follows. In the next section we present the model. In section 3 we discuss the calibration. In section 4 we analyse the impulse response functions to several shocks. Section 5 concludes. Appendices A and B show all the relevant equations of the model.

2 The model

The general structure of the model is summarised in Figure 1.

In each country, the representative household derives utility from consumption (assuming internal habit persistence) and money and disutility from the amount of hours worked. Households decide on how much to consume/spend and also set wages. We follow Erceg, Henderson and Levin (2000) and assume that, in each period, households face a constant probability of not being able to reoptimise their wage. When households are not reoptimising they update wages as a function of past inflation, the inflation objective and a compensation for trend productivity growth. Households own and rent capital to the intermediate firms. We assume there are adjustment costs in investment. We also allow for variable capital utilization (with adjustment costs).

Regarding firms, in each country there are firms producing intermediate goods sold both in the domestic and the foreign market. In the model only the intermediate goods are traded internationally. Markets are segmented and firms are local currency pricers. The production technology is Cobb-Douglas, combining capital services with domestic labour. We allow for technological progress (by introducing a technology shock following a unit root) and assume that firms set their prices à la Calvo. As for the final good sector, there is a single final good produced in each country that can be used both for consumption (private and public) and for investment. The final good sector is perfectly competitive and merely buys the bundle of domestically produced intermediate goods and the bundle of imported intermediate goods and combines them into the final good. The technology used to combine these inputs is a Constant Elasticity of Substitution (CES) production function. A quadratic adjustment cost to changing the composition of the final good is introduced with the purpose of slowing down the pass-through of foreign production prices.

The financial intermediaries included in the model have a rather passive role as in Christiano, Eichenbaum and Evans (2005). Intermediate firms borrow the wage bill from the financial intermediary which creates a demand for funds. In turn, the supply of funds stems from the deposits of households in the financial intermediary and the increase of the money supply.

The model includes a simple government sector. The model does not include any fiscal rule. The government in each country buys the final good, makes nominal transfers to households and receives taxes from households (both on payrolls and consumption expenditures). The government budget is balanced every period. As for the monetary authority, the central bank is assumed to follow a Taylor rule.

Finally, international financial markets are incomplete and foreign bond holdings are subject

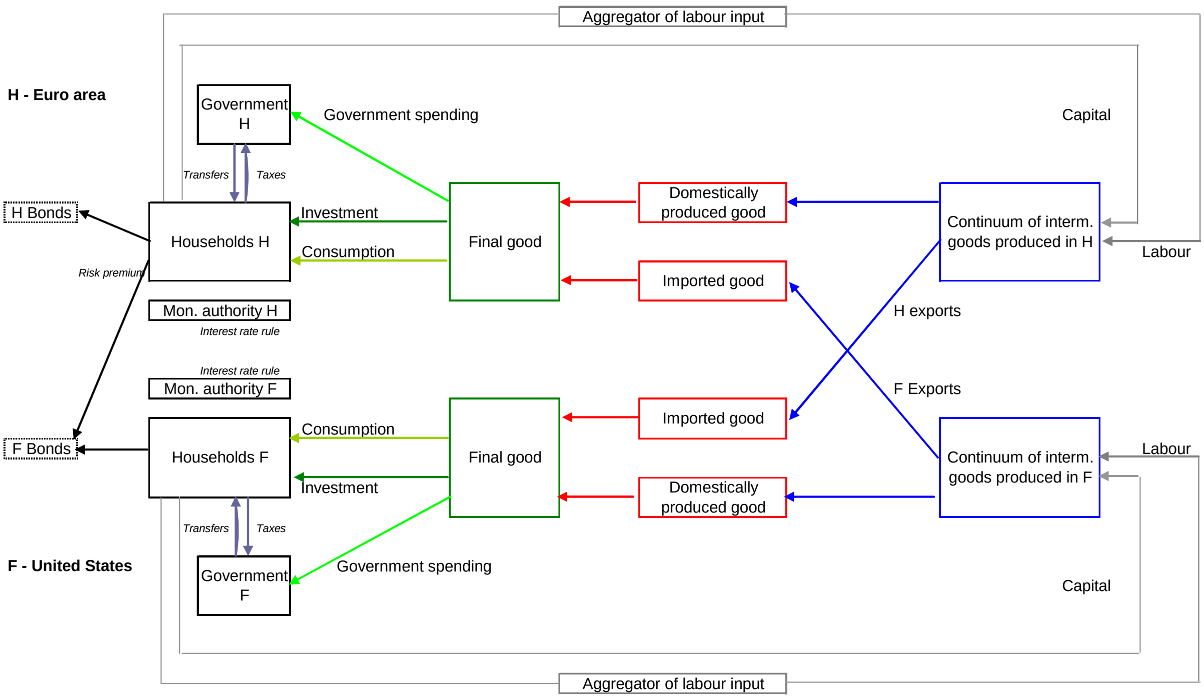

Figure 1: Structure of the model.

to a risk-premium, following Benigno (2001). The risk-premium ensures that Net Foreign Assets (NFA) are stabilised.

In the next section we provide some details on the structure of the model. Given that the two countries are symmetric, in the description we will primarily focus on the euro area.

2.1 Firms

2.2 Goods producing firms

There is one final good produced in each country (which is not traded internationally). This good serves for consumption purposes (both private and public) and investment purposes. The final good sector is perfectly competitive and merely combines a bundle of domestically produced intermediate goods ($Y^{EA}_{EA,t}$) and a bundle of imported intermediate goods ($Y^{EA}_{US,t}$) into the final good ($Y^{F}_{EA,t}$). The technology used to produce the final good is a CES production function:

$$Y^F_{EA,t} = \left[(d_F)^{\frac{\lambda_F}{1+\lambda_F}} \left(Y^{EA}_{EA,t}\right)^{\frac{1}{1+\lambda_F}} + (1-d_F)^{\frac{\lambda_F}{1+\lambda_F}} \left(\zeta_t Y^{EA}_{US,t}\right)^{\frac{1}{1+\lambda_F}} \right]^{1+\lambda_F}, \ 0 < d_F < 1$$

where $\frac{1+\lambda_F}{\lambda_F}$ is the elasticity of substitution between domestic goods and imports and d_F is a parameter that governs the home bias in the final goods production. Additionally,

$$\zeta_t = 1 - \frac{\zeta}{2} \left(1 - \frac{\frac{Y^{EA}_{US,t}}{Y^{EA}_{EA,t}}}{\frac{Y^{EA}_{US,t-1}}{Y^{EA}_{EA,t-1}}} \right)^2$$

is an adjustment cost (the firm incurs in a cost when varying the use of the bundle of imported intermediate goods in the production of the final good). This cost serves the purpose of slowing down the pass-through of foreign production price changes. $P_{EA,t}$ is the aggregate price index for $Y^F_{EA,t}$. Given the presence of adjustment costs, the final good producer chooses how much of the domestic intermediate goods to use ($Y^{EA}_{EA,t}$) and how much to import ($Y^{EA}_{US,t}$) in order to maximise its discounted stream of profits[1]:

$$\underset{Y^{EA}_{EA,t},Y^{EA}_{US,t}}{Max}\; E_t\beta^j\Lambda_{t+j}\left[P_{EA,t+j}Y^F_{EA,t+j} - P^{EA}_{EA,t+j}Y^{EA}_{EA,t+j} - P^{EA}_{US,t+j}Y^{EA}_{US,t+j}\right]$$

The bundle of domestically produced intermediate goods is merely an aggregator that combines the variety of differentiated intermediate goods produced by domestic firms and sold in the domestic market, namely:

$$Y^{EA}_{EA,t} = \left[\left(\frac{1}{n}\right)^{\frac{\lambda_{D,t}}{1+\lambda_{D,t}}}\int_0^n \left(Y^{EA}_{EA,t}(i)\right)^{\frac{1}{1+\lambda_{D,t}}} di\right]^{1+\lambda_{D,t}}$$

where $\frac{1+\lambda_{D,t}}{\lambda_{D,t}}$ is the elasticity of substitution between varieties of goods produced domestically, in the euro area.

Profit maximization implies the following demand function:

$$Y^{EA}_{EA,t}(i) = \left[\frac{P^{EA}_{EA,t}}{P^{EA}_{EA,t}(i)}\right]^{\frac{1+\lambda_{D,t}}{\lambda_{D,t}}}\frac{Y^{EA}_{EA,t}}{n}$$

The aggregate price index, denominated in the currency of the market where the goods are sold (i.e. in euros in this case) is therefore:

$$P^{EA}_{EA,t} = \left[\frac{1}{n}\int_0^n \left(P^{EA}_{EA,t}(i)\right)^{\frac{-1}{\lambda_{D,t}}} di\right]^{-\lambda_{D,t}}$$

As for the bundle of imported intermediate goods, it is a combination of the varieties of differentiated intermediate goods produced abroad, namely:

$$Y^{EA}_{US,t} = \left[\left(\frac{1}{1-n}\right)^{\frac{\lambda_{M,t}}{1+\lambda_{M,t}}}\int_0^{1-n} \left(Y^{EA}_{US,t}(i^*)\right)^{\frac{1}{1+\lambda_{M,t}}} di^*\right]^{1+\lambda_{M,t}}$$

where $\frac{1+\lambda_{M,t}}{\lambda_{M,t}}$ is the elasticity of substitution between varieties of imported goods in the euro area.

Profit maximization implies the following demand function:

$$Y^{EA}_{US,t}(i^*) = \left[\frac{P^{EA}_{US,t}}{P^{EA}_{US,t}(i^*)}\right]^{\frac{1+\lambda_{M,t}}{\lambda_{M,t}}}\frac{Y^{EA}_{US,t}}{1-n}$$

where $P^{EA}_{US,t}$ is the aggregate price index of the bundle (denominated in the currency of the market where the goods are sold, i.e. in euros in this case) and $P^{EA}_{US,t}(i^*)$ is the price of the intermediate good i^*. Given the above stated Dixit-Stiglitz aggregator, the aggregate price index of imported goods in the euro area is equal to:

[1] Λ_{t+j} is the Lagrange multiplier for money in the households optimization problem.

$$P_{US,t}^{EA} = \left[\frac{1}{1-n} \int_0^{1-n} \left(P_{US,t}^{EA} \left(i^* \right) \right)^{\frac{-1}{\lambda_{M,t}}} di^* \right]^{-\lambda_{M,t}}$$

In the euro area, there is also a continuum of firms producing intermediate goods that are sold both in the domestic market and in the foreign market. These firms are monopolist suppliers of the intermediate goods, indexed by $i \in [0, n]$ and are local currency pricers. Intermediate firms rent domestic capital, which is owned by households, and hire domestic labour (from a labour aggregator that sets wages) and since they have to pay in advance their wage bill, they borrow it from the domestic financial intermediary and repay at the end of the period at the gross nominal interest rate $R_{EA,t}$. Intermediate goods are produced with a Cobb-Douglas production function combining domestic capital services $(K_{EA,t}^s (i))$ with domestic labour $(L_{EA,t} (i))$:

$$Y_{EA,t} (i) = \varepsilon_{EA,t}^N \left[K_{EA,t}^s (i) \right]^\alpha \left[z_{EA,t} L_{EA,t} (i) \right]^{1-\alpha}$$

where $\varepsilon_{EA,t}^N$ is a neutral technology shock (stationary) and $z_{EA,t}$ is the level of technological progress. The gross growth rate of technological progress is denoted by $\mu_{z_{EA},t} (= z_{EA,t}/z_{EA,t-1})$ and it is assumed exogenous, namely:[2]

$$\log \mu_{z_{EA},t} = (1 - \rho^{\mu_z}) \rho^{\mu_z} \log \mu_{z_{EA}} + \log \mu_{z_{EA},t-1} + e_{EA,t}^{\mu_z}$$

Due to the existence of technological progress, a number of variables are non-stationary. To stationarise these variables, all quantities are divided by the trend level of technology $(z_{EA,t})$ with the exception of the Lagrange multiplier which is multiplied by $z_{EA,t}$.[3]

Cost minimization by the intermediate goods producing firms (given the price of the intermediate good $Y_{EA,t} (i)$) leads to the demand functions for the inputs used in the production process, namely capital and labour. These yield the equation for the equilibrium real rental rate of capital, $r_{EA,t}^K$, namely

$$r_{EA,t}^K = \frac{R_{EA,t}^K}{P_{EA,t}} = \mu_{z_{EA},t} \frac{\frac{L_{EA}^D}{n}}{u_{EA,t} k_{EA,t-1}} R_{EA,t} \omega_{EA,t}^{\otimes} \frac{\alpha}{1-\alpha}$$

where

$$\omega_{EA,t}^{\otimes} = \frac{W_{EA,t}}{z_{EA,t} P_{EA,t}}$$

is the stationarised real wage and $R_{EA,t}$ is the nominal gross interest rate.

It can be shown that the marginal costs are equalized across firms within a country. The real marginal cost is then :

$$RMC_{EA,t} = \frac{MC_{EA,t}}{P_{EA,t}} = \frac{1}{\varepsilon_{EA,t}^N} \left(\frac{1}{\alpha} \right)^\alpha \left(\frac{1}{1-\alpha} \right)^{1-\alpha} \left(R_{EA,t} \omega_{EA,t}^{\otimes} \right)^{1-\alpha} \left(r_{EA,t}^K \right)^\alpha$$

Following Calvo (1983) we assume that, in each period, intermediate firms face a constant probability of being able to reoptimize their prices in the domestic market equal to $1 - \xi_D$. All the firms reoptimising in each period will choose the same price, $P_{EA,t}^{EA,0}$. Those that don't reoptimize update prices according to the following scheme

$$P_{EA,t}^{EA} (i) = \left[\pi_{EA,t-1}^{EA} \right]^{\gamma_D} \left[\overline{\pi}_{EA,t} \right]^{1-\gamma_D} P_{EA,t-1}^{EA} (i) = a_{EA,t}^{EA} P_{EA,t-1}^{EA} (i)$$

[2]The steady state gross growth rate of technological progress in the euro area is $\mu_{z_{EA}}$. We will assume it is equal to the US growth.

[3]Let small letter variables denote stationary variables, for example $y_{EA,t}^F = \frac{Y_{EA,t}^F}{z_{EA,t}}$.

where $\pi_{EA,t-1}^{EA}$ is the previous period rate of change in the prices of domestic goods and $\overline{\pi}_{EA,t}$ is the central bank's inflation objective for the euro area and γ_D is an indexation parameter. So, intermediate goods producers maximise the following expected stream of profits with respect to $P_{EA,t}^{EA,0}$:

$$E_t \sum_{j=0}^{\infty} (\beta\xi_D)^j \Lambda_{t+j} \left[P_{EA,t}^{EA,0} A_{EA,t+j}^{EA} Y_{EA,t+j}^{EA}(i) - MC_{EA,t+j} Y_{EA,t+j}^{EA}(i) \right]$$

This implies the following first order condition:

$$E_t \sum_{j=0}^{\infty} (\beta\xi_D)^j \Lambda_{t+j} (P_{EA,t+j}^{EA})^{\frac{1+\lambda_{D,t+j}}{\lambda_{D,t+j}}} \frac{Y_{EA,t+j}^{EA}}{n} \left[\begin{array}{c} \frac{-1}{\lambda_{D,t+j}} A_{EA,t+j}^{EA} \left(P_{EA,t}^{EA,0} A_{EA,t+j}^{EA} \right)^{-\frac{1+\lambda_{D,t+j}}{\lambda_{D,t+j}}} + \\ A_{EA,t+j}^{EA} \frac{1+\lambda_{D,t+j}}{\lambda_{D,t+j}} (P_{EA,t}^{EA,0} A_{EA,t+j}^{EA})^{-\frac{1+\lambda_{D,t+j}}{\lambda_{D,t+j}}-1} MC_{EA,t+j} \end{array} \right] = 0$$

where $A_{EA,t+j}^{EA} = \prod_{k=0}^{j} a_{EA,t+j}^{EA} P_{EA,t+j-1}^{EA}(i)$ and $\lambda_{D,t+j}$ is a stochastic net price markup. This shows that the price will be a markup over a weighted sum of present and future marginal costs.

Log-linearising the above equation, yields the Philips curve relation for the goods sold domestically:

$$\begin{aligned} \widehat{\pi}_{EA,t}^{EA} &= \frac{\gamma_D}{1+\beta\gamma_D} \widehat{\pi}_{EA,t-1}^{EA} + \frac{\beta}{1+\beta\gamma_D} E_t \widehat{\pi}_{EA,t+1}^{EA} + \frac{1-\gamma_D}{1+\beta\gamma_D} \widehat{\overline{\pi}}_{EA,t} - \frac{\beta(1-\gamma_D)}{1+\beta\gamma_D} \widehat{\overline{\pi}}_{EA,t+1} + \\ &+ \frac{(1-\beta\xi_D)(1-\xi_D)}{(1+\beta\gamma_D)\xi_D} \left[(\widehat{1+\lambda_{D,t+j}}) + \widehat{RMC}_{EA,t}^{EA} \right] \end{aligned}$$

where hatted variables denote variables in log-deviations from the steady state.

Focusing now on the export market, the bundle of exported goods by the euro area (i.e. imported by the US) is defined identically to the bundle of domestic goods, but with an elasticity of substitution equal to $\frac{1+\lambda_{M,t}^{*}}{\lambda_{M,t}^{*}}$. Intermediate firms are local currency pricers, so euro area firms set export prices in USD. In each period, intermediate firms face a constant probability of being able to reoptimize their prices in the export market equal to $1-\xi_X$. The firms that don't reoptimize update prices according to

$$P_{EA,t}^{US}(i) = \pi_{EA,t-1}^{US} P_{EA,t-1}^{US}(i) = a_{EA,t}^{US} P_{EA,t-1}^{US}(i)$$

The Phillips curve for euro area exports is:

$$\begin{aligned} \widehat{\pi}_{EA,t}^{US} &= \frac{1}{1+\beta} \widehat{\pi}_{EA,t-1}^{US} + \frac{\beta}{1+\beta} E_t \widehat{\pi}_{EA,t+1}^{US} - \frac{\beta(1-\xi_X)}{1+\beta} E_t \widehat{\Delta S}_{t+1} + \\ &+ \frac{(1-\beta\xi_X)(1-\xi_X)}{(1+\beta)\xi_X} \left[(\widehat{1+\lambda_{M,t}^{*}}) + \widehat{RMC}_{EA,t}^{US} \right] \end{aligned}$$

2.3 Financial intermediary

Firms borrow from a financial intermediary to finance the wage bill in advance. This corresponds to the demand for funds. The supply of funds comes from the deposits $(M_{EA,t} - Q_{EA,t})$ by households and the exogenous increase in money supply .

The equilibrium in financial markets is obtained when the wage bill equals the supply of funds from the deposits:

$$W_{EA,t}L_{EA,t} = n\left[\mu_{m_{EA},t}M_{EA,t-1} - Q_{EA,t}\right]$$

where it is assumed that money grows at the gross rate $\mu_{m_{EA},t} = \frac{M_{EA,t}}{M_{EA,t-1}}$ and that, in steady state this growth rate equals the nominal growth rate of the economy (i.e $\mu_{m_{EA}} = \mu_{z_{EA}}\pi_{z_{EA}}$).

2.4 Households

There is a continuum of households in each country, which gain utility from consumption, leisure and cash balances. Households residing in the EA are indexed by $h \in [0, n]$, and households residing in the US are indexed by $h^* \in (n, 1]$. Households derive utility from consumption, leisure and money balances. In particular, the period utility function is assumed to take the following form:

$$\begin{aligned} U_{EA,t} &= \varepsilon^{C}_{EA,t+j}\frac{1}{1-\sigma_C}\left(C_{EA,t+j}(h) - b\ C_{EA,t+j-1}(h)\right)^{1-\sigma_C} - \sigma_0\ \varepsilon^{L}_{EA,t+j}\frac{1}{1+\sigma_L}\left(L_{EA,t+j}(h)\right)^{1+\sigma_L} + \\ &+\sigma_1\ \varepsilon^{Q}_{EA,t+j}\frac{1}{1-\sigma_Q}\left(\frac{Q_{EA,t+j}(h)}{P_{EA,t+j}z_{EA,t+j}}\right)^{1-\sigma_Q} \end{aligned}$$

In each period households decide their current level of consumption ($C_{EA,t}(h)$), their real holdings of cash ($\frac{Q_{EA,t}(h)}{P_{EA,t}}$), the amount of hours they worked ($L_{EA,t}(h)$) and their holdings of bonds (both domestic, $B^{EA}_{EA,t}(h)$, and foreign, $B^{EA}_{US,t}(h)$) and their domestic bank deposits ($M_{EA,t-1}(h) - Q_{EA,t}(h)$). Following Christiano, Eichenbaum and Evans (2005) we assume that the level of capital services rented to firms ($K^{s}_{EA,t}(h) \equiv u_{EA,t}(h)\,K_{EA,t-1}(h)$) is decided by the households. Households can increase their capital stock ($K_{EA,t}(h)$) by investing in physical capital ($I_{EA,t}(h)$) and they can vary the capacity utilization rate ($u_{EA,t}(h)$). Changing the capacity utilization rate implies a cost to households ($\phi(u_{EA,t}(h))$ per unit of physical capital), which is measured in units of investment goods. Capital depreciates at rate δ and given that there are investment adjustment costs, the capital evolution equation is:

$$K_{EA,t} = (1-\delta)\,K_{EA,t-1} + \varepsilon^{I}_{EA,t}\left[1 - H\left(\frac{I_{EA,t}}{I_{EA,t-1}}\right)\right]I_{EA,t}$$

and function $H()$ satisfies $H'(1) = 0$ and $H''(1) > 0$.

Regarding income, households receive income from working ($W_{EA,t}(h)\,L_{EA,t}(h)$), from renting capital to firms ($R^{k}_{EA,t}u_{EA,t}(h)\,K_{EA,t-1}(h)$), they receive dividends from firms ($Div_{EA,t}$) and lump-sum transfers from the government ($TR_{EA,t}$). Households pay taxes to the government, both on their labour income (at the tax rate $\tau_{W,t}$) and on their consumption expenditures (at the tax rate $\tau_{C,t}$). Within each country households are potentially different because we assume that not all of them can reoptimize their wages in each period, so they can work a different amount of hours and they may earn different wages. To avoid this heterogeneity within each country we assume that there exists a market for contingent securities ($A_{EA,t}(h)$) that ensures that in equilibrium all households are homogeneous with respect to consumption and asset holdings but heterogeneous regarding their wage and the amount of hours they work.

Households receive dividends from firms ($Div_{EA,t}(h)$), interest on deposits (at the gross nominal interest rate $R_{EA,t}$), income from renting capital services (at the gross nominal rental rate of capital $R^{k}_{EA,t}$) and interest on their bond holdings (at the gross nominal interest rates $R_{EA,t}$ and $R_{US,t}$).

Each household maximizes an intertemporal utility function given by:

$$E_t \sum_{j=0}^{\infty} \beta^j U \left(C_{EA,t+j}(h), C_{EA,t+j-1}(h), L_{EA,t+j}(h), \frac{Q_{EA,t+j}(h)}{P_{EA,t+j} z_{EA,t+j}}, \varepsilon^C_{EA,t+j}, \varepsilon^L_{EA,t+j}, \varepsilon^Q_{EA,t+j} \right)$$

where β is the discount factor and $\varepsilon^C_{EA,t+j}$, $\varepsilon^L_{EA,t+j}$ and $\varepsilon^Q_{EA,t+j}$ are shocks, subject to its budget constraint:

$$\begin{aligned} M_{EA,t}(h) &= R_{EA,t}\left(M_{EA,t-1}(h) - Q_{EA,t}(h)\right) + Q_{EA,t}(h) + Div_{EA,t} + \\ &+ W_{EA,t}(h) L_{EA,t}(h) + R^k_{EA,t} u_{EA,t}(h) K_{EA,t-1}(h) + A_{EA,t}(h) + \\ &+ TR_{EA,t} + B^{EA}_{EA,t-1}(h) + \left(\frac{B^{EA}_{US,t-1}(h)}{S_t} \right) - \frac{B^{EA}_{EA,t}(h)}{R_{EA,t}} - \frac{B^{EA}_{US,t}(h)}{S_t R_{US,t} \Xi_t} + \\ &- P_{EA,t}\phi\left(u_{EA,t}(h)\right) K_{EA,t-1}(h) - \tau_{W,t} W_{EA,t}(h) L_{EA,t}(h) - \tau_{C,t} P_{EA,t} C_{EA,t}(h) + \\ &- P_{EA,t} C_{EA,t}(h) - P_{EA,t} I_{EA,t}(h) \end{aligned}$$

Following Benigno, P. (2001), we assume that there is only one country, namely the US, that issues a bond that is traded internationally. Households in the euro area can invest both in national and in foreign bonds while US households only invest in US bonds. Euro area households face a positive risk premium on foreign bond holdings (Ξ_t), which depends on the real holdings of foreign-currency denominated assets of the entire economy.[4] Hence individual agents take the function Ξ_t as given when choosing the level of foreign currency denominated bonds. The risk premium increases when the euro area real holdings of foreign-currency denominated bonds are above the steady-state level (say b^{EA}_{US}, scaled for technology progress) and decreases when the euro area real holdings of foreign-currency denominated bonds are below the steady-state level. This guarantees that in steady state, when the gross rates of return on domestic and foreign bonds are equal, agents on aggregate hold only the exogenously determined steady state level of foreign currency denominated bonds[5]. The function Ξ_t is assumed to to satisfy:

$$\begin{aligned} \Xi_t() &> 0 \\ \Xi'_t() &= \chi'_t() < 0 \\ \Xi_t(b^{EA}_{US}, 1) &= 1 \end{aligned}$$

We now state the first order conditions of the households' optimization problem.

1. With respect to consumption:[6]

$$\varepsilon^C_{EA,t} \left[c_{EA,t} - b c_{EA,t-1} \frac{1}{\mu_{z_{EA,t}}} \right]^{-1} - b\beta \varepsilon^C_{EA,t+1} \left[c_{EA,t+1} \mu_{z_{EA,t+1}} - b c_{EA,t} \right]^{-1} - \lambda^z_{EA,t}(1 + \tau_{C,t}) = 0$$

where

$$\log \varepsilon^C_{EA,t} = \rho^Q \log \varepsilon^C_{EA,t-1} + e^C_{EA,t}$$

[4] S_t is the nominal exchange rate expressed in USD/€.

[5] The intermediation cost in the foreign bond market ensures that the level of foreign bond holdings relative to consumption is stationary. This allow us to log-linearise around a well defined steady state (the level of foreign bond holdings grows at the same rate as output and therefore $b^{EA}_{US} = \frac{B^{EA}_{US,t}}{S_t P_{EA,t} z_{EA,t}}$ is constant at the steady state).

[6] Let $P_{EA,t+1} z_{EA,t+1} \Lambda_{EA,t+1} = \lambda^z_{EA,t+1}$.

2. With respect to money:

$$-\lambda^z_{EA,t} + \beta E_t(\frac{1}{\mu_{z_{EA,t+1}}\pi_{EA,t+1}}\lambda^z_{EA,t+1}R_{EA,t+1}) = 0$$

3. With respect to cash holdings $Q_{EA,t}$ (let $q_{EA,t} = \frac{Q_{EA,t}}{P_{EA,t}z_{EA,t}}$):

$$q_{EA,t} = \left[\frac{1}{\sigma_1 \varepsilon^Q_{EA,t}}\lambda^z_{EA,t}(R_{EA,t}-1)\right]^{-\frac{1}{\sigma_Q}}$$

where

$$\log \varepsilon^Q_{EA,t} = \rho^Q \log \varepsilon^Q_{EA,t-1} + e^Q_{EA,t}$$

4. With respect to bonds:

The first order conditions with respect to domestic and foreign bonds yield the modified uncovered interest rate parity condition (let $b^{EA}_{US,t} = \frac{B^{EA}_{US,t}}{S_t P_{EA,t} z_{EA,t}}$):

$$E_t \frac{\lambda^z_{EA,t+1}R_{EA,t}}{\mu_{z_{EA,t+1}}\pi_{EA,t+1}} = E_t \frac{\lambda^z_{EA,t+1}}{\mu_{z_{EA,t+1}}\pi_{EA,t+1}}\frac{R_{US,t}}{\Delta S_{t+1}}\left[\chi\left(b^{EA}_{US,t}\right)\times \varepsilon^S_t\right]$$

5. With respect to investment (let $\rho^k_{EA,t} = \frac{v_{EA,t}}{P_{EA,t}\Lambda_{EA,t}}$):

$$\lambda^z_{EA,t} = E_t \left\{ \begin{array}{c} \rho^k_{EA,t}\varepsilon^I_{EA,t}\lambda^z_{EA,t}\left[1 - H\left(\frac{i_{EA,t}\mu_{z_{EA,t}}}{i_{EA,t-1}}\right) - \frac{i_{EA,t}\mu_{z_{EA,t}}}{i_{EA,t-1}}H'\left(\frac{i_{EA,t}\mu_{z_{EA,t}}}{i_{EA,t-1}}\right)\right] + \\ +\beta\lambda^z_{EA,t+1}\rho^k_{EA,t+1}\frac{1}{\mu_{z_{EA,t+1}}}\varepsilon^I_{EA,t+1}\left(\frac{i_{EA,t+1}\mu_{z_{EA,t+1}}}{i_{EA,t}}\right)^2 H'\left(\frac{i_{EA,t+1}\mu_{z_{EA,t+1}}}{i_{EA,t}}\right) \end{array} \right\}$$

where

$$\log \varepsilon^I_{EA,t} = \rho^I \log \varepsilon^I_{EA,t-1} + e^I_{EA,t}$$

6. With respect to capital

$$\rho^k_{EA,t}\lambda^z_{EA,t} = \beta E_t\left\{\frac{\lambda^z_{EA,t+1}}{\mu_{z_{EA,t+1}}}\left\{\left[r^k_{EA,t+1}u_{EA,t+1} - \phi(u_{EA,t+1})\right] + (1-\delta)\rho^k_{EA,t+1}\right\}\right\}$$

7. With respect to capital utilisation:

$$r^k_{EA,t} = \phi'(u_{EA,t})$$

8. Wage decision

Each household is a monopoly supplier of a differentiated labour service to firms in the domestic market (i.e. labour is completely immobile across countries). Therefore households are price setters in the labour market. As in Erceg, Henderson and Levin (2000), we assume that households sell their type of labour to an aggregator that transforms households' labour into a homogeneous input. The labour aggregator is in perfect competition and uses the following technology to produce the euro area labour aggregate:

$$L_{EA,t} = \left[\left(\frac{1}{n}\right)^{\frac{\lambda_{W,t}}{1+\lambda_{W,t}}}\int_0^n \left(L_{EA,t}(h)^{\frac{1}{1+\lambda_{W,t}}}\,dh\right)\right]^{1+\lambda_{W,t}}$$

where $\lambda_{W,t}$ is a stochastic net wage markup shock.

Therefore, each household in the EA faces the following labour demand:

$$L_{EA,t}(h) = \left[\frac{W_{EA,t}}{W_{EA,t}(h)}\right]^{\frac{1+\lambda_{W,t}}{\lambda_{W,t}}} \frac{L_{EA,t}}{n}$$

and the aggregate wage rate is

$$W_{EA,t} = \left[\frac{1}{n}\int_0^n W_{EA,t}(h)^{-\frac{1}{\lambda_{W,t}}} dh\right]^{-\lambda_{W,t}}$$

Following Calvo (1983), households face a constant and (exogenous) probability of being able to reoptimize wages in each period, equal to $1-\xi_W$. The fraction of households that cannot reoptimize (ξ_W) sets wages according to the following scheme:

$$\begin{aligned} W_{EA,t}(h) &= \left(\pi^{EA}_{EA,t-1}\right)^{\gamma_W} \left(\overline{\pi}_{EA,t}\right)^{1-\gamma_W} \mu_{z_{EA},t} W_{EA,t-1}(h) = \\ &= a^W_{EA,t}\mu_{z_{EA},t}W_{EA,t-1}(h) \end{aligned}$$

where $\overline{\pi}_{EA,t}$ is the central bank's objective for inflation.

So, each household chooses $W^0_{EA,t}$ that solves the following optimization problem (note that every household reoptimising in each period will choose the same wage):

$$\underset{W^0_{EA,t}}{Max}\ E_t \sum_{j=0}^{\infty} (\beta\xi_W)^j \left[\Lambda_{t+j}\left(1-\tau_{W,t+j}\right) W_{EA,t+j}(h) L_{EA,t+j}(h) + U\left(L_{EA,t+j}(h)\right)\right]$$

So we obtain the following first order condition:

$$E_t \sum_{j=0}^{\infty} (\beta\xi_W)^j \left[\begin{array}{c} -\frac{1}{\lambda_{W,t+j}}\Lambda_{t+j}\left(1-\tau_{W,t+j}\right)\left(W^0_{EA,t}\right)^{\frac{-1}{\lambda_{W,t+j}}-1} A^W_{EA,t+j}\frac{z_{EA,t+j}}{z_{EA,t}} \times \\ \times \left(z_{EA,t}P_{EA,t}\omega^{\otimes}_{EA,t+j}X_{t,j}\right)^{\frac{1+\lambda_{W,t+j}}{\lambda_{W,t+j}}} \frac{L_{EA,t+j}}{n} \\ +\frac{1+\lambda_{W,t+j}}{\lambda_{W,t+j}}\varepsilon^L_{t+j}f'\{\}\left(z_{EA,t}P_{EA,t}\omega^{\otimes}_{EA,t+j}X_{t,j}\right)^{\frac{1+\lambda_{W,t+j}}{\lambda_{W,t+j}}}\left(W^0_{EA,t}\right)^{-\frac{1+\lambda_{W,t+j}}{\lambda_{W,t+j}}-1}\frac{L_{EA,t+j}}{n} \end{array}\right] = 0$$

where $X_{t,j} = \frac{P_{EA,t+j}}{P_{EA,t}A^W_{EA,t+j}}$ and

$$\log \varepsilon^L_{EA,t} = \rho^L \log \varepsilon^L_{EA,t-1} + e^L_{EA,t}$$

2.5 Government

The government in each country buys final domestic goods $(G_{EA,t})$[7], makes nominal transfers $(TR_{EA,t})$ to the households (which are not household specific) and receives taxes from households, both taxes on payrolls ($\tau_{W,t}W_{EA,t}\frac{L_{EA,t}}{n}$) and taxes on consumption expenditures ($\tau_{C,t}P_{EA,t}C_{EA,t}$). Therefore the government budget constraint is:

$$P_{EA,t}G_{EA,t} + TR_{EA,t} = \tau_{C,t}P_{EA,t}C_{EA,t} + \tau_{W,t}W_{EA,t}\frac{L_{EA,t}}{n}$$

[7] We assume that the government consumption is exogenous, namely that it follows an autoregressive process.

2.6 Monetary authority

The monetary authority is assumed to follow a Taylor-type interest rule. We assume the following (log-linearized) rule:

$$\begin{aligned}\widehat{R}_{EA,t} &= \phi_R \widehat{R}_{EA,t-1} + (1-\phi_R)\left[\widehat{\overline{\pi}}_{EA,t} + \phi_\Pi\left(\widehat{\pi}_{EA,t} - \widehat{\overline{\pi}}_{EA,t}\right) + \phi_Y\left(\widehat{gdp}^F_{EA,t}\right)\right] \\ &\quad + \phi_{\Delta\pi}(\widehat{\pi}_{EA,t} - \widehat{\pi}_{EA,t-1}) + \phi_{\Delta Y}\left(\widehat{gdp}^F_{EA,t} - \widehat{gdp}^F_{EA,t-1}\right) + \widehat{\varepsilon}^R_{EA,t}\end{aligned}$$

where $\widehat{\varepsilon}^R_{EA,t}$ is an i.i.d. Normal shock and

$$\widehat{\overline{\pi}}_{EA,t} = \rho^{\overline{\pi}} \widehat{\overline{\pi}}_{EA,t-1} + e^{\overline{\pi}}_{EA,t}$$

This rule implies that the central bank sets interest rates as a function of past interest rates, deviations of inflation from the objective and deviations of GDP from steady state. Two additional terms are included (as in Smets and Wouters, 2003) namely changes in inflation and changes in the output deviations from steady state.

2.7 Market clearing

The final goods market is in equilibrium if production equals demand. So, in equilibrium

$$P_{EA,t}Y^F_{EA,t} = n\left(P_{EA,t}C_{EA,t} + P_{EA,t}I_{EA,t} + P_{EA,t}\phi_{EA,t}\left(u_{EA,t}\right)K_{EA,t-1} + P_{EA,t}G_{EA,t}\right)$$

The capital market is in equilibrium when the demand for capital by the intermediate goods producers equals the supply by households. And the labour market is in equilibrium if the demand for labour by firms equals labour supply at the wage rate set by households.

2.8 Balance of payments

Equilibrium in the euro area balance of payments implies

$$\frac{S_t^{-1}P^{US}_{EA,t}}{P_{EA,t}}\frac{Y^{US}_{EA,t}}{n} - \frac{P^{EA}_{US,t}}{P_{EA,t}}\frac{Y^{EA}_{US,t}}{n} = \frac{B^{EA}_{US,t}}{S_t R_{US,t}\Xi_t P_{EA,t}} - \frac{B^{EA}_{US,t-1}}{S_t P_{EA,t}}$$

3 Calibration

The model is calibrated for the euro area and the US at a quarterly frequency. Most parameters are obtained from the calibrated version of the New Area Wide Model of Coenen McAdam and Straub (2007) who in turn largely rely on the estimated closed economy model for the euro area of Smets and Wouters (2003). The remaining parameters are implicitly obtained. The only exception is the risk premium parameter which is obtained from Adolfson et al. (2007). In the assumptions made we have closely followed the literature. In addition, we keep the differences between the two economies as small as possible i.e., we chose different parameter values for the two economies only when we found evidence strongly favouring that choice. Table 1 summarises the calibration made indicating the sources of the parameter values.

The two countries are of slightly different size, namely the euro area stands for 42 per cent of total population (i. e. the euro area plus the US). The utility function parameter values are the same in both economies, namely the habit persistence parameter (b) is set to 0.6, the inverse of the wage elasticity of work (σ_L) is set to 2, the inverse of the intertemporal elasticity of substitution (σ_C) is set to 1 (meaning we have log utility in consumption - as in Christiano, Eichenbaum and Evans, 2005). The values of these parameters are within the 90 per cent range estimated in Smets and Wouters (2003). The inverse semi-elasticity of money demand (σ_Q) is set to 6 which, in the case of the euro area, is the same as used in Christiano, Motto, Rostagno (2005). In both countries we set the discount factor of consumers (β) to around 0.99 and the per capita gross growth rate of technology ($\mu_{z_{EA}}$) to 1.004 quarterly (i.e. 1.6 per cent in terms of the annual rate). Together with an annual gross inflation rate of 1.02 this implies a long run gross nominal interest rate of 1.0165 quarterly in both economies. We calibrate the depreciation rate (δ) to 0.025 quarterly. The inverse of the elasticity of capital utilisation with respect to the rental rate is 6 in both economies and the parameter of the investment adjustment cost function (H'') is set to 3 in the euro area and the US.

Regarding the production function, the Cobb-Douglas parameter α is set to 0.3 in both countries while the CES function parameter (λ_F) is set to 2 both in the euro area and the US, which implies an intratemporal elasticity of substitution between home and foreign goods of 1.5. The consumption to output ratio is calibrated to be 0.6 in the euro area and 0.62 in the US.

As for price setting, the average duration of price contracts is set to 10 quarters in the domestic sector (ξ_D=0.9) and 1.4 quarters in the export sector sector (ξ_X=0.3). The degree of price indexation (γ_D) is set to 0.5 in both economies. The price markup is set to 0.3 both in the domestic and the import sector in the two economies (λ_D and λ_M).

Wage contracts last on average 4 quarters (ξ_W=0.75) and the degree of wage indexation is set to 0.75 (γ_W) in the two countries. The wage markup is set to 0.3 (λ_W). Per capita hours worked ($\frac{L_{EA}}{n}$) are calibrated so that households spend roughly 30 per cent of their time working.

The import adjustment cost parameter ζ is set to 2.5 in both economies and the parameter of the risk premium function (i.e the first derivative of the risk premium), χ, is calibrated to -0.1 following the estimates of Adolfson et al. (2007). The share of imports on domestic output is set to 18 per cent in the euro area while for the case of the US it is derived from the other parameters of the model resulting in a share of imports of 13 per cent. d_F and d_F^* are determined by solving a non-linear system and using the known values of the other model parameters (see Alves, Gomes and Sousa, 2007).

The tax rate on consumption is 0.183 in the euro area and 0.077 in the US. The tax rate on labour income (including social security contributions) is 0.46 in the euro area and 0.3 in the US. The inverse of the semi-elasticity of money demand is set to 1.5. The share of cash in money was calibrated to 8.6 per cent in the euro area and 10.4 per cent in the US. In both economies these shares correspond to the weight of currency in circulation on the monetary aggregate M2 in July 2007.

We follow Smets and Wouters in specifying the Taylor rule. The parameters assumed in the monetary policy rule are close to those estimated in Smets and Wouters (2003), namely a coefficient of 1.5 on inflation and coefficients of 0.1 on output, changes in inflation and changes in output. Following Coenen, McAdam, Straub, we chose a parameter of 0.9 for the interest rate smoothing parameter which is close to the value estimated in Smets and Wouters (2003).

As for the autoregressive coefficients in the shock processes, we have assumed a high degree of persistence for technology, labour supply, consumer preference, government spending and risk premium shocks and no persistence for the remaining shocks.

Table 1 - Calibrated parameters and ratios					
	EA		US		Source
Population size	n	0.42	$1-n$	0.58	CMS
Inflation rate (gross)	π_{EA}	1.02^0.25	π_{US}	1.02^0.25	Assumption
Nominal interest rate (gross)	R_{EA}	1.0165	R_{US}	1.0165	Implicit
Per capita hours	$\frac{L_{EA}}{n}$	0.285	$\frac{L_{US}}{1-n}$	0.285	Assumption
Consumption-output ratio	$\frac{c_{EA}}{y^F_{EA/n}}$	0.6	$\frac{c_{US}}{y^F_{US/(1-n)}}$	0.62	CMS
Share of government spending	$\frac{gs_{EA}}{y^F_{EA/n}}$	0.21	$\frac{gs_{US}}{y^F_{US/(1-n)}}$	0.20	Implicit (US)
Share of investment	$\frac{is_{EA}}{y^F_{EA/n}}$	0.188	$\frac{is_{US}}{y^F_{US/(1-n)}}$	0.179	Implicit (US)
Share of imports	$\frac{y^{EA}_{US}}{y^F_{EA/n}}$	0.18	$\frac{y^{US}_{EA}}{y^F_{US/(1-n)}}$	0.13	Implicit (US)
Productivity growth (gross)	$\mu_{z_{EA}}$	1.016^0.25	$\mu_{z_{US}}$	1.016^0.25	Assumption
Discount factor	β	1.03^-0.25	β^*	1.03^-0.25	CMS
Depreciation rate	δ	0.025	δ^*	0.025	Assumption
Tax rate on consumption	τ_C	0.183	τ^*_C	0.077	CMS
Tax rate on labour income	τ_W	0.459	τ^*_W	0.296	CMS
Share of capital income in value added	α	0.3	α^*	0.3	Assumption
Habit persistence parameter	b	0.6	b^*	0.6	CMS
Import adjustment cost	ζ	2.5	ζ^*	2.5	CMS
CES parameter of imported and domestic interm. goods	λ_F	2	λ^*_F	2	CMS
CES parameter of imported and domestic interm. goods	d_F	0.83	d^*_F	0.87	Implicit
Goods markup	λ_D		λ^*_D		
Wage markup	λ_W	0.3	λ^*_W	0.3	CMS
Import price markup	λ_M		λ^*_M		
Degree of price indexation	γ_D	0.5	γ^*_D	0.5	CMS
Degree of wage indexation	γ_W	0.75	γ^*_W	0.75	CMS
Calvo setting	ξ_D	0.9	ξ^*_D	0.9	
(Domestic goods, Exports,	ξ_X	0.3	ξ^*_X	0.3	CMS
Wages)	ξ_W	0.75	ξ^*_W	0.75	
	ϕ_R	0.9	ϕ^*_R	0.9	
	ϕ_Π	1.5	ϕ^*_Π	1.5	
Taylor rule parameters	ϕ_Y	0.1	ϕ^*_Y	0.1	Assumption
	$\phi_{\Delta\Pi}$	0.1	$\phi^*_{\Delta\Pi}$	0.1	
	$\phi_{\Delta Y}$	0.1	$\phi^*_{\Delta Y}$	0.1	
Share cash balances in money	$\frac{q_{EA}}{m_{EA}}$	0.086	$\frac{q_{US}}{m_{US}}$	0.104	Statistics
Inv. semi-elast. money demand	σ_Q	1.5	σ^*_Q	1.5	CMS
Investment adjustment cost	$H^{"}_H$	3	$H^{"}_F$	3	CMS
Inv. elasticity of capital utiliz. to capital rental rate	σ_a	6	σ^*_a	6	CMS

Table 1(continued)

Shock Processes					
	Euro area		US		Source
Shock AR, consumption	ρ_C	0.9	ρ_C^*	0.9	Assumption
Shock AR, money demand	ρ_Q	0	ρ_Q^*	0	Assumption
Shock AR, labour	ρ_L	0.9	ρ_L^*	0.9	Assumption
Shock AR, investment	ρ_I	0	ρ_I^*	0	Assumption
Shock AR, interest rate	ρ_R	0	ρ_R^*	0	Assumption
Shock AR, government	ρ_G	0.9	ρ_G^*	0.9	Assumption
Shock AR, technological	ρ_{μ_z}	0.9	$\rho_{\mu_z}^*$	0.9	Assumption
Shock AR, money growth	ρ_{μ_m}	0	$\rho_{\mu_m}^*$	0	Assumption
Shock AR, Inflation target	$\overline{\pi}_{EA}$	0	$\overline{\pi}_{US}$	0	Assumption

	Other		Source
Stationary holdings of US bonds	b_{US}^{EA}	0	Assumption
Relative US/EA price	p_{US}	1	Implicit
Risk premium	$\chi'()$	-0.1	Adolfson, et.al. (2005)
Shock AR, exchange rate	ρ_S	0.9	Assumption

CMS-Coenen, McAdam and Straub (2007).

4 Model responses to shocks

In this section we illustrate the properties of the model by comparing the impulse responses of a number of variables of the model to standard shocks[8]. In particular we show the responses of GDP, consumption, investment, hours worked, the real wage, the short-term interest rate (annualised), exports and imports. The shocks we consider are monetary policy shocks, technology shocks, a government spending shock and a risk premium shock.

4.1 Monetary policy shock

Figure 2 displays the dynamic responses of several variables to a one-period monetary policy shock i.e. an exogenous change in $\widehat{\varepsilon}^{R}_{EA,t}$ which is i.i.d. The shock is calibrated so that the annualised interest rate in the euro area falls on impact by 25 basis points. Once the shock hits the economy, the nominal interest rate is determined endogenously by the monetary policy rule.

According to the model, the policy rate remains below its steady state level for almost two years. At the same time, the decrease in the interest rate stimulates demand. The monetary policy shock leads to a hump-shaped increase in real GDP, real consumption and real investment in the euro area. As expected, real investment responds more strongly than consumption. The open economy framework introduces a new channel for the transmission of monetary policy shocks, namely the exchange rate channel. The decrease in the euro area interest rate, together with a muted response to the shock by the US monetary authority, leads to a real exchange rate depreciation. In fact, the real exchange rate depreciates on impact and then returns to its steady state value, implying consequently a gain of competitiveness. This is translated into a decline in imports and, initially, a rise in exports that is later reversed.

Following the shock, hours worked increase, as firms want to produce more to satisfy increased demand. Higher demand for labour puts upward pressure on nominal wages. The effect on real wages will depend on the nominal rigidities (on both wages and prices), on the degree of workers' market power and also on the utility parameters (governing the disutility from work). In the model, following a surprise decline in interest rates, real wages increase which is in line with the stylised facts following an unanticipated monetary policy shock in the euro area (Peersman and Smets, 2001, Alves *et al.,* 2006). Note that the increase in hours worked and in the real wage contribute to the expansion in consumption. As regards inflation, the annual rate increases following the shock and, after peaking a year after the shock, gradually returns to the steady-state.

[8] All the results are obtained with Dynare, a matlab toolbox aimed at simulating and estimating DSGE models. The Dynare code used for solving and simulating the model is available from the authors.

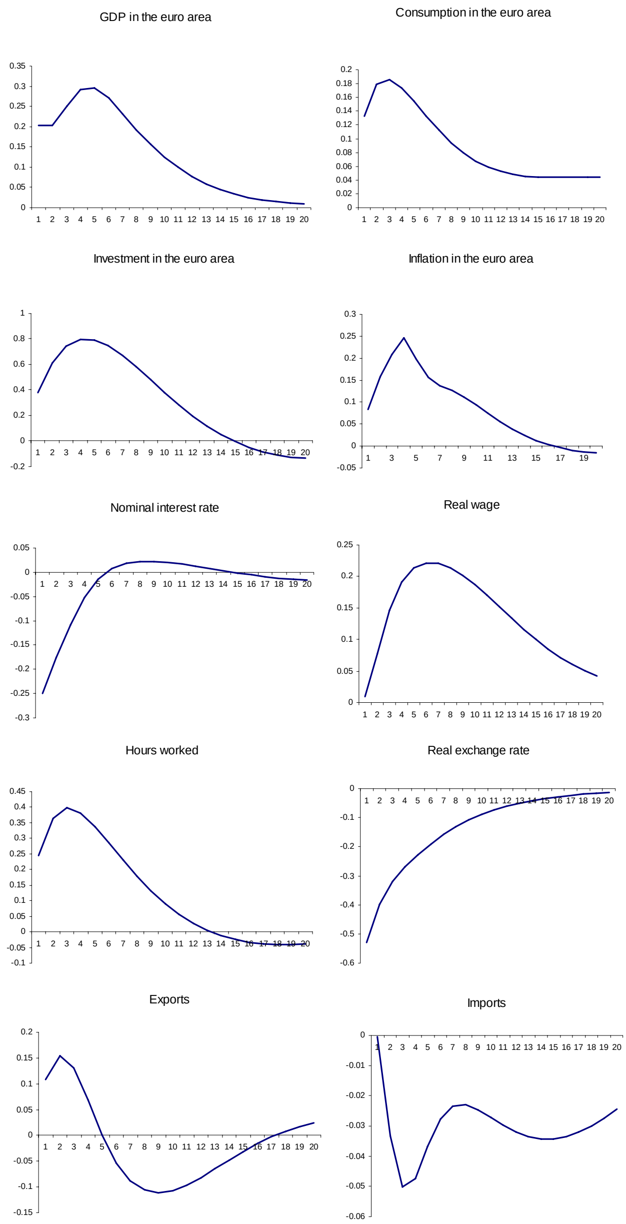

Figure 2: Impulse responses to a monetary policy shock.

4.2 Technology shock

Figure 3 depicts the impulse responses to a transitory, though persistent, technology shock. The shock is calibrated such that real GDP in the euro area increases one per cent (in deviations from the steady state), not necessarily on impact.

The impulse responses of the model to a positive technological shock show that both consumption and investment rise after the shock. Hours worked fall initially which is a result similar to the one found in Smets and Wouters (2003) and Alves, et. al. (2006). One explanation for this fall is that the technology shock, by increasing labour productivity, makes it possible for firms to produce more with the same or even a lower amount of labour. As the real wage increases it may be more profitable for firms to use less labour. Given the general equillibrium setup, this also corresponds to the optimal decision of households given the constraints they face.

The technology shock expands temporarily the production capacity of the economy and therefore lowers the marginal cost of production. Therefore, firms want to lower their prices but, given that only a fraction of the firms are re-optimizing in each period, this will happen only gradually. The decline in inflation explains why the short-term interest rate declines while GDP is increasing. The real exchange rate appreciates but then falls and returns to the steady-state from below. The real exchange rate appreciation explains the rise in imports. Given that we also see an expansion in the foreign country, euro area exports also increase.

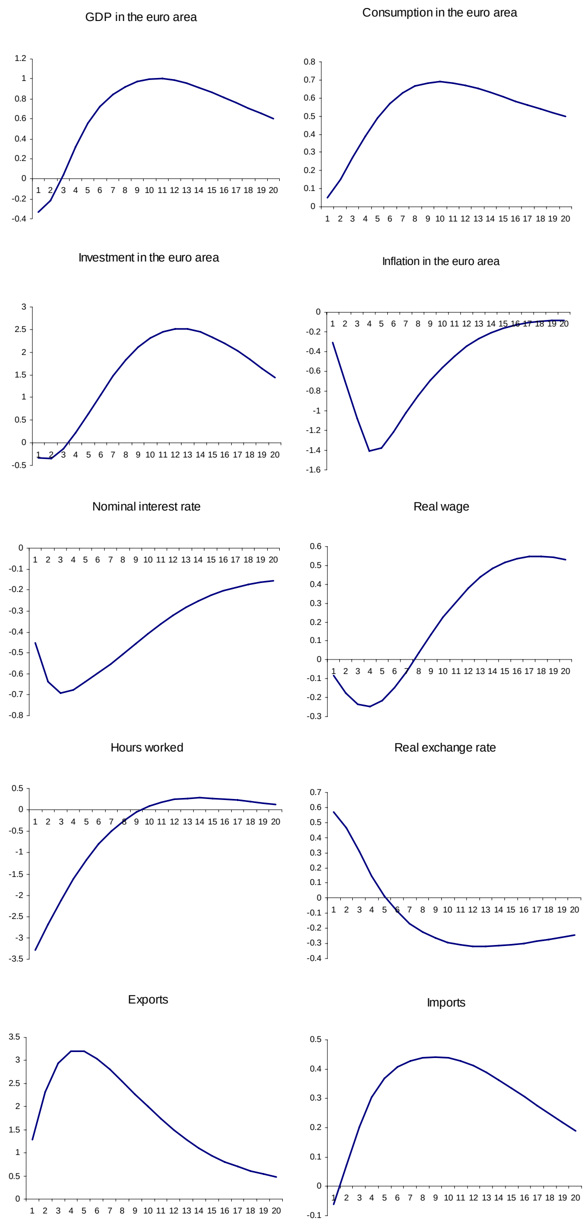

Figure 3: Impulse responses to a technology shock.

4.3 Government spending shock

The government spending shock is calibrated so that the government spending-to-output ratio increases by one percentage point on impact. Government spending is modelled as an autoregressive process with an autoregressive coefficient of 0.9. The increase in government spending leads to an initial rise in GDP but crowds out investment and consumption (see Figure 4). Even though the effect on consumption is at odds with the results in the VAR literature (where usually consumption either does not react or rises following an unanticipated increase in government spending, see Adão and Brito, 2006, for example), this result is found in New-Keynesian models with Ricardian agents. The explanation for this behaviour is that the increase in government spending lowers the present value of after tax income and therefore generates a negative wealth effect that induces the fall in consumption. Additionally, the shock implies an increase in the number of hours worked and a initial rise in the real wage that is later reversed. The euro depreciates slightly in real effective terms. There is a small decline in exports and an increase in imports, which is later reversed. Inflation increases slightly which, together with higher GDP, leads to a tightening of monetary policy.

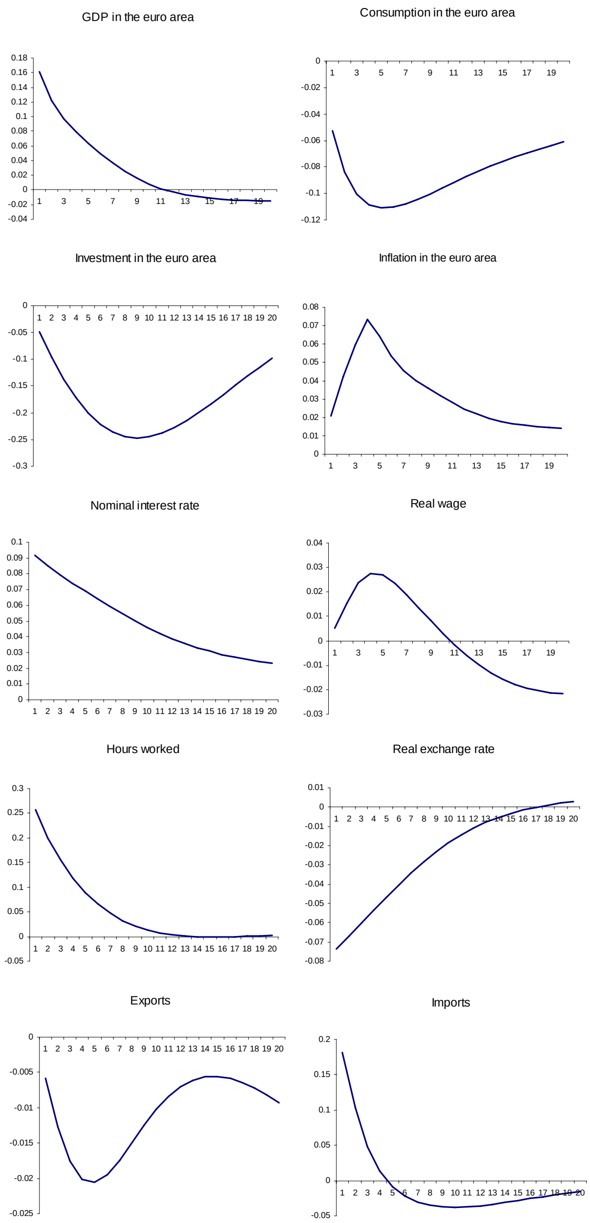

Figure 4: Impulse responses to a government spending shock.

4.4 UIP shock

The risk premium shock is a shock to the modified uncovered interest rate parity equation. This open-economy shock is defined so that the euro real exchange rate depreciates by 1 per cent on impact, as can be seen in Figure 5. Initially, the real exchange rate depreciation, by generating a negative wealth effect associated with the deterioration of the terms of trade, leads to a drop in consumption and in investment in the euro area. At the same time the real depreciation leads to a shift in demand towards domestic goods. Therefore euro area exports increase while imports fall. GDP increases above its steady state value following the shock, as a result of the improved contribution from net external demand. The increased demand for euro area goods by the US is translated into an increase in hours worked. The real wage initially declines but recovers after a period of around one year. Given the increase in inflation the monetary authority reacts by rising interest rates.

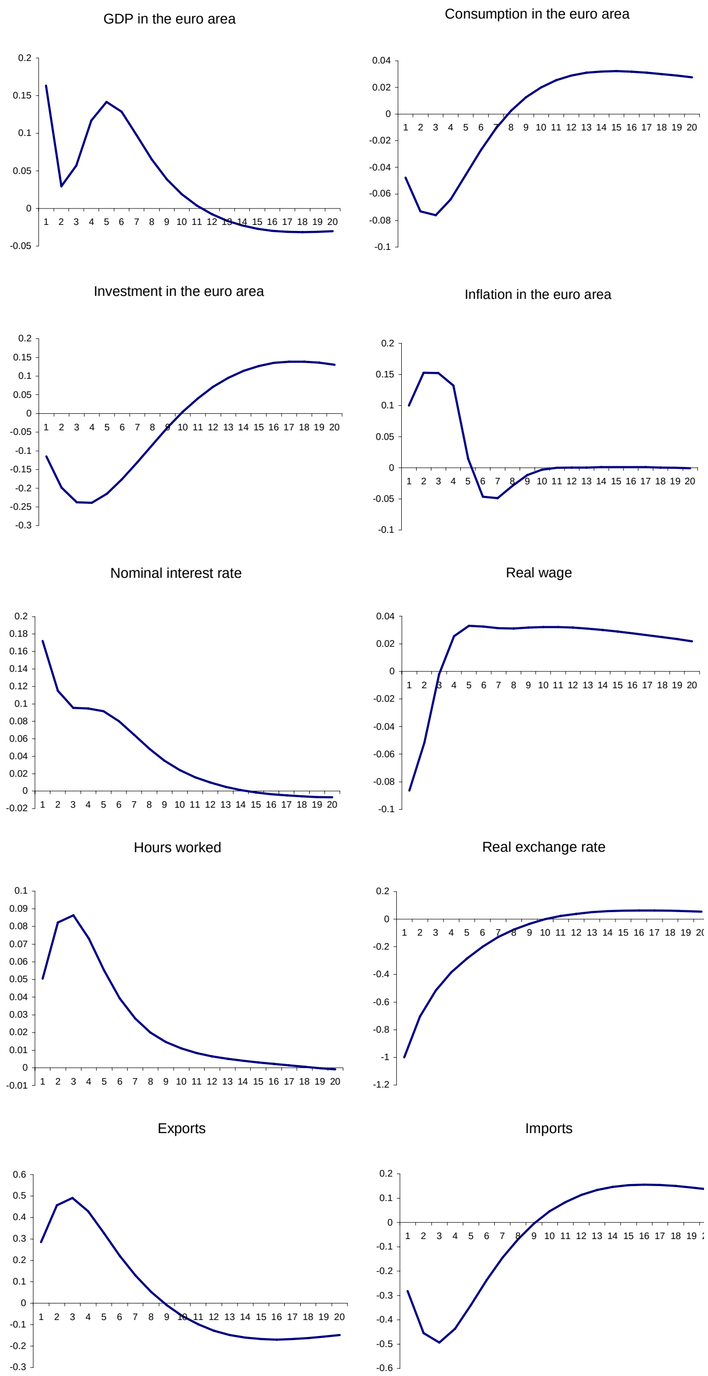

Figure 5: Impulse responses to an uncovered interest rate parity shock.

5 Concluding remarks

In this paper we build and simulate an open economy DSGE model of the euro area and the US, calibrating it with parameters obtained from other papers.

The two-country setup is preferable to the closed economy one as it allows the simulation of a much larger number of shocks and takes into account more channels of monetary policy transmission. The results suggest that the open economy feature is indeed important, in particular for assessing the impact of monetary policy shocks. A follow up study will formally estimate the model for the euro area and the US in order to test whether the results obtained still apply. Further refinements of the model for introducing other channels of transmission of shocks in the economy could also be envisaged (for instance more detailed open economy features, richer government or financial sectors, frictions in the labour market to allow for unemployment and allowing for non-zero net foreign assets in steady state).

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Appendix A. The steady-state model

The steady state system has 52 equations.

$$\mu_{z_{EA}} = \mu_{z_{US}} = \mu_z$$

$$R_{EA} = \frac{\mu_z \pi_{EA}}{\beta}$$

$$R_{EA} = R_{US}$$

$$\frac{\mu_z \pi_{EA}}{\beta} = \frac{\mu_z \pi_{US}}{\beta^*} \Leftrightarrow \frac{\beta^*}{\beta} \pi_{EA} = \pi_{US}$$

$$\mu_{m_{EA}} = \mu_z \pi_{EA}$$

$$\mu_{m_{US}} = \mu_z \pi_{US}$$

$$\rho^k_{EA} = 1$$

$$\rho^k_{US} = 1$$

$$\phi'(1) = r^k_{EA} = \frac{\mu_z}{\beta} - (1 - \delta)$$

$$\phi^{*\prime}(1) = r^k_{US} = \frac{\mu_z}{\beta^*} - (1 - \delta^*)$$

$$r^K_{EA} = \mu_z \frac{\frac{L_{EA}}{n}}{k_{EA}} R_{EA} \omega^{\otimes}_{EA} \frac{\alpha}{1 - \alpha} \Rightarrow \left[\frac{\mu_z}{\beta} - (1 - \delta) \right] = \mu_z \frac{\frac{L_{EA}}{n}}{k_{EA}} R_{EA} \omega^{\otimes}_{EA} \frac{\alpha}{1 - \alpha}$$

$$r^K_{US} = \mu_z \frac{\frac{L_{US}}{1-n}}{k_{EA}} R_{US} \omega^{\otimes}_{US} \frac{\alpha^*}{1 - \alpha^*} \Rightarrow \left[\frac{\mu_z}{\beta^*} - (1 - \delta^*) \right] = \mu_z \frac{\frac{L_{US}}{1-n}}{k_{US}} R_{US} \omega^{\otimes}_{US} \frac{\alpha^*}{1 - \alpha^*}$$

$$\begin{aligned} p^{EA}_{EA} &= (1 + \lambda_D) \left(\frac{1}{\alpha} \right)^{\alpha} \left(\frac{1}{1 - \alpha} \right)^{1-\alpha} \left[\frac{\mu_z \pi_{EA}}{\beta} \omega^{\otimes}_{EA} \right]^{1-\alpha} \left[\frac{\mu_z}{\beta} - (1 - \delta) \right]^{\alpha} \\ p^{US}_{EA} &= \frac{(1 + \lambda^*_M)}{(1 + \lambda_D)} p^{EA}_{EA} \end{aligned}$$

$$\begin{aligned} p^{US}_{US} &= (1 + \lambda^*_D) \left(\frac{1}{\alpha^*} \right)^{\alpha^*} \left(\frac{1}{1 - \alpha^*} \right)^{1-\alpha^*} \left[\frac{\mu_z \pi_{US}}{\beta^*} \omega^{\otimes}_{US} \right]^{1-\alpha^*} \left[\frac{\mu_z}{\beta^*} - (1 - \delta^*) \right]^{\alpha^*} \\ p^{EA}_{US} &= \frac{(1 + \lambda_M)}{(1 + \lambda^*_D)} p^{US}_{US} \end{aligned}$$

$$1 = \left[(d_F)^{\frac{\lambda_F}{1+\lambda_F}}\left(\frac{y_{EA}^{EA}}{y_{EA}^F}\right)^{\frac{1}{1+\lambda_F}} + (1-d_F)^{\frac{\lambda_F}{1+\lambda_F}}\left(\frac{y_{US}^{EA}}{y_{EA}^F}\right)^{\frac{1}{1+\lambda_F}}\right]^{1+\lambda_F}$$

$$1 = \left[(d_F^*)^{\frac{\lambda_F^*}{1+\lambda_F^*}}\left(\frac{y_{US}^{US}}{y_{US}^F}\right)^{\frac{1}{1+\lambda_F^*}} + (1-d_{*F})^{\frac{\lambda_F^*}{1+\lambda_F^*}}\left(\frac{y_{EA}^{US}}{y_{US}^F}\right)^{\frac{1}{1+\lambda_F^*}}\right]^{1+\lambda_F^*}$$

$$\frac{y_{EA}^{EA}}{y_{EA}^F} = d_F\left(p_{EA}^{EA}\right)^{-\frac{1+\lambda_F}{\lambda_F}}$$

$$\frac{y_{US}^{EA}}{y_{EA}^F} = (1-d_F)\left(p_{US}^{EA}\right)^{-\frac{1+\lambda_F}{\lambda_F}}$$

$$\frac{y_{US}^{US}}{y_{US}^F} = d_F^*\left(p_{US}^{US}\right)^{-\frac{1+\lambda_F^*}{\lambda_F^*}}$$

$$\frac{y_{EA}^{US}}{y_{US}^F} = (1-d_F^*)\left(p_{EA}^{US}\right)^{-\frac{1+\lambda_F^*}{\lambda_F^*}}$$

$$p_{EA}^{US}\frac{y_{EA}^{US}}{y_{US}^F}\frac{y_{US}^F}{y_{EA}^F} - p_{US}^{EA}\frac{y_{US}^{EA}}{y_{EA}^F} = n\frac{b_{US}^{EA}}{y_{EA}^F}\frac{1}{R_{EA}}\left(1-\frac{1}{\beta}\right)$$

$$1 = \frac{c_{EA}}{\frac{y_{EA}^F}{n}} + \frac{i_{EA}}{\frac{y_{EA}^F}{n}} + \frac{g_{EA}}{\frac{y_{EA}^F}{n}}$$

$$1 = \frac{c_{US}}{\frac{y_{US}^F}{1-n}} + \frac{i_{US}}{\frac{y_{US}^F}{1-n}} + \frac{g_{US}}{\frac{y_{US}^F}{1-n}}$$

$$\frac{i_{EA}}{\frac{y_{EA}^F}{n}} = \left[1-\frac{(1-\delta)}{\mu_z}\right]\frac{k_{EA}}{\frac{y_{EA}^F}{n}}$$

$$\frac{i_{US}}{\frac{y_{US}^F}{1-n}} = \left[1-\frac{(1-\delta^*)}{\mu_z}\right]\frac{k_{US}}{\frac{y_{US}^F}{1-n}}$$

$$\frac{y_{EA}^{EA}}{y_{EA}^F} + \frac{y_{EA}^{US}}{y_{US}^F}\frac{y_{US}^F}{y_{EA}^F} = \frac{(\mu_z)^{-\alpha}\left(\frac{k_{EA}}{L_{EA}/n}\right)^{\alpha} L_{EA}}{y_{EA}^F}$$

$$\frac{y_{US}^{US}}{y_{US}^F} + \frac{y_{US}^{EAS}}{y_{EA}^F}\frac{y_{EA}^F}{y_{US}^F} = \frac{(\mu_z)^{-\alpha^*}\left(\frac{k_{US}}{L_{US}/(1-n)}\right)^{\alpha^*} L_{US}}{y_{US}^F}$$

$$
\begin{aligned}
\frac{c_{EA}}{\frac{y^F_{EA}}{n}} &= c_{EA} \times \frac{y^F_{EA}}{n} \\
\frac{c_{US}}{\frac{y^F_{US}}{1-n}} &= c_{US} \times \frac{y^F_{US}}{1-n} \\
g_{EA} &= \frac{g_{EA}}{\frac{y^F_{EA}}{n}} \times \frac{y^F_{EA}}{n} \\
g_{US} &= \frac{g_{US}}{\frac{y^F_{US}}{1-n}} \times \frac{y^F_{US}}{1-n}
\end{aligned}
$$

$$
\begin{aligned}
\lambda^z_{EA} &= \frac{\mu_z - b\beta}{(\mu_z - b)(1+\tau_C)} \frac{1}{c_{EA}} \\
\lambda^z_{US} &= \frac{\mu_z - b^*\beta^*}{(\mu_z - b^*)(1+\tau^*_C)} \frac{1}{c_{US}} \\
m_{EA} &= \frac{1}{1 - shareq_{EA}} \omega^{\otimes}_{EA} \frac{L_{EA}}{n} \\
q_{EA} &= shareq_{EA} \times m_{EA} \\
m_{US} &= \frac{1}{1 - shareq_{US}} \omega^{\otimes}_{US} \frac{L_{US}}{n} \\
q_{US} &= shareq_{US} \times m_{US}
\end{aligned}
$$

$$
\begin{aligned}
\sigma_0 &= \frac{\omega^{\otimes}_{EA}}{c_{EA}} \frac{(\mu_z - b\beta)(1-\tau_W)}{(\mu_z - b)(1+\tau_C)(1+\lambda_W)} \left(\frac{L_{EA}}{n}\right)^{-\sigma_L} \\
\sigma^*_0 &= \frac{\omega^{\otimes}_{US}}{c_{US}} \frac{(\mu_z - b^*\beta^*)(1-\tau_W)}{(\mu_z - b^*)(1+\tau^*_C)(1+\lambda^*_W)} \left(\frac{L_{US}}{1-n}\right)^{-\sigma^*_L}
\end{aligned}
$$

$$
\begin{aligned}
\sigma_1 &= (q_{EA})^{\sigma_Q} \frac{\mu_z - b\beta}{c_{EA}(\mu_z - b)(1+\tau_C)} \left(\frac{\mu_z \pi_{EA}}{\beta} - 1\right) \\
\sigma^*_1 &= (q_{US})^{\sigma_Q} \frac{\mu_z - b\beta}{c_{US}(\mu_z - b^*)(1+\tau^*_C)} \left(\frac{\mu_z \pi_{US}}{\beta^*} - 1\right)
\end{aligned}
$$

$$
\begin{aligned}
tr_{EA} &= \tau_C c_{EA} + \tau_W \omega^{\otimes}_{EA} \frac{L_{EA}}{n} - g_{EA} \\
tr_{US} &= \tau^*_C c_{US} + \tau^*_W \omega^{\otimes}_{US} \frac{L_{US}}{1-n} - g_{US}
\end{aligned}
$$

$$
\pi^{EA}_{EA} = \pi_{EA} \quad \pi^{US}_{US} = \pi_{US}
$$
$$
\pi^{US}_{EA} = \pi_{EA} \quad \pi^{EA}_{US} = \pi_{US}
$$

$$
p_{US} = 1 \quad \widetilde{z} = 1
$$

Appendix B. The log-linearised model

Firms

- Financial intermediary (clearing in the loan market):

$$\left[1-\underbrace{\frac{q_{EA}}{m_{EA}}}_{shareQ_{EA}}\right](\widehat{\omega}^{\otimes}_{EA,t}+\widehat{L}_{EA,t})=\widehat{\mu}_{m_{EA},t}+\widehat{m}_{EA,t-1}-\widehat{\mu}_{z_{EA},t}-\widehat{\pi}_{EA,t}-\underbrace{\frac{q_{EA}}{m_{EA}}}_{shareQ_{EA}}\widehat{q}_{EA,t}$$

$$\widehat{m}_{EA,t}=\widehat{\mu}_{m_{EA},t}+\widehat{m}_{EA,t-1}-\widehat{\mu}_{z_{EA},t}-\widehat{\pi}_{EA,t}$$

- Price setting equations:

Euro area domestic production:

$$\begin{aligned}\widehat{\pi}^{EA}_{EA,t} &= \frac{\gamma_D}{1+\beta\gamma_D}\widehat{\pi}^{EA}_{EA,t-1}+\frac{\beta}{1+\beta\gamma_D}E_t\widehat{\pi}^{EA}_{EA,t+1}+\frac{1-\gamma_D}{1+\beta\gamma_D}\widehat{\bar{\pi}}_{EA,t}-\frac{\beta(1-\gamma_D)}{1+\beta\gamma_D}\widehat{\bar{\pi}}_{EA,t+1}+\\ &+\frac{(1-\beta\xi_D)(1-\xi_D)}{(1+\beta\gamma_D)\xi_D}\left[(\widehat{1+\lambda_{D,t}})+\widehat{RMC}^{EA}_{EA,t}\right]\end{aligned}$$

where

$$\widehat{RMC}^{EA}_{EA,t}=\widehat{R}_{EA,t}+\widehat{\omega}^{\otimes}_{EA,t}-\widehat{p}^{EA}_{EA,t}-\alpha\left[\widehat{u}_{EA,t}+\widehat{k}_{EA,t-1}-\widehat{\mu}_{z_{EA,t}}-\widehat{L}_{EA,t}\right]-\widehat{\varepsilon}^{N}_{EA,t}$$

Euro area export production:

$$\begin{aligned}\widehat{\pi}^{US}_{EA,t} &= \frac{1}{1+\beta}\widehat{\pi}^{US}_{EA,t-1}+\frac{\beta}{1+\beta}E_t\widehat{\pi}^{US}_{EA,t+1}+\frac{\beta(1-\xi_X)}{1+\beta}E_t\widehat{\Delta S_{t+1}}+\\ &+\frac{(1-\beta\xi_X)(1-\xi_X)}{(1+\beta)\xi_X}\left[(\widehat{1+\lambda^*_{M,t}})+\widehat{RMC}^{US}_{EA,t}\right]\end{aligned}$$

where

$$\widehat{RMC}^{US}_{EA,t}=\widehat{R}_{EA,t}+\widehat{\omega}^{\otimes}_{EA,t}-\widehat{p}^{US}_{EA,t}-\alpha\left[\widehat{u}_{EA,t}+\widehat{k}_{EA,t-1}-\widehat{\mu}_{z_{EA,t}}-\widehat{L}_{EA,t}\right]-\widehat{\varepsilon}^{N}_{EA,t}$$

US domestic production:

$$\begin{aligned}\widehat{\pi}^{US}_{US,t} &= \frac{\gamma^*_D}{1+\beta^*\gamma^*_D}\widehat{\pi}^{US}_{US,t-1}+\frac{\beta^*}{1+\beta^*\gamma^*_D}E_t\widehat{\pi}^{US}_{US,t+1}+\frac{1-\gamma^*_D}{1+\beta^*\gamma^*_D}\widehat{\bar{\pi}}_{US,t}-\frac{\beta(1-\gamma^*_D)}{1+\beta^*\gamma^*_D}\widehat{\bar{\pi}}_{US,t+1}+\\ &+\frac{(1-\beta^*\xi^*_D)(1-\xi^*_D)}{(1+\beta^*\gamma^*_D)\xi^*_D}\left[(\widehat{1+\lambda^*_{D,t}})+\widehat{RMC}^{US}_{US,t}\right]\end{aligned}$$

where

$$\widehat{RMC}^{US}_{US,t}=\widehat{R}_{US,t}+\widehat{\omega}^{\otimes}_{US,t}-\widehat{p}^{US}_{US,t}-\alpha\left[\widehat{u}_{US,t}+\widehat{k}_{US,t-1}-\widehat{\mu}_{z_{US,t}}-\widehat{L}_{US,t}\right]-\widehat{\varepsilon}^{N}_{US,t}$$

US export production:

$$\widehat{\pi}_{US,t}^{EA} = \frac{1}{1+\beta^*}\widehat{\pi}_{US,t-1}^{EA} + \frac{\beta^*}{1+\beta^*}E_t\widehat{\pi}_{US,t+1}^{EA} - \frac{\beta^*\left(1-\xi_X^*\right)}{1+\beta^*}E_t\widehat{\Delta S_{t+1}} + + \frac{\left(1-\beta^*\xi_X^*\right)\left(1-\xi_X^*\right)}{\left(1+\beta^*\right)\xi_X^*}\left[\widehat{(1+\lambda_{M,t})} + \widehat{RMC}_{US,t}^{EA}\right]$$

where

$$\widehat{RMC}_{US,t}^{EA} = \widehat{R}_{US,t} + \widehat{\omega}_{US,t}^{\otimes} - \widehat{p}_{US,t}^{EA} - \alpha^*\left[\widehat{u}_{US,t} + \widehat{k}_{US,t-1} - \widehat{\mu}_{z_{US,t}} - \widehat{L}_{US,t}\right] - \widehat{\varepsilon}_{US,t}^{N}$$

- Production functions[9]

$$\widehat{y}_{EA,t}^{F} = \left(d_F\right)^{\frac{\lambda_F}{1+\lambda_F}}\left(\frac{y_{EA}^{EA}}{y_{EA}^{F}}\right)^{\frac{1}{1+\lambda_F}}\widehat{y}_{EA,t}^{EA} + \left(1-d_F\right)^{\frac{\lambda_F}{1+\lambda_F}}\left(\frac{y_{US}^{EA}}{y_{EA}^{F}}\right)^{\frac{1}{1+\lambda_F}}\left(\widehat{y}_{US,t}^{EA} + \widehat{\widehat{z}}_t\right)$$

$$\widehat{y}_{US,t} = \left(d_F^*\right)^{\frac{\lambda_F^*}{1+\lambda_F^*}}\left(\frac{y_{US}^{US}}{y_{US}}\right)^{\frac{1}{1+\lambda_F^*}}\widehat{y}_{US,t}^{US} + \left(1-d_F^*\right)^{\frac{\lambda_F^*}{1+\lambda_F^*}}\left(\frac{y_{EA}^{US}}{y_{US}}\right)^{\frac{1}{1+\lambda_F^*}}\left(\widehat{y}_{EA,t}^{US} - \widehat{\widehat{z}}_t\right)$$

$$\frac{y_{EA}^{EA}}{y_{EA}^{EA}+y_{EA}^{US}}\widehat{y}_{EA,t}^{EA} + \frac{y_{EA}^{US}}{y_{EA}^{EA}+y_{EA}^{US}}\widehat{y}_{EA,t}^{US} = \widehat{\varepsilon}_{EA,t}^{N} + \alpha\left(\widehat{u}_{EA,t} + \widehat{k}_{EA,t-1} - \widehat{\mu}_{z_{EA,t}}\right) + (1-\alpha)\,\widehat{L}_{EA,t}$$

$$\frac{y_{US}^{US}}{y_{US}^{US}+y_{US}^{EA}}\widehat{y}_{US,t}^{US} + \frac{y_{US}^{EA}}{y_{US}^{US}+y_{US}^{EA}}\widehat{y}_{US,t}^{EA} = \widehat{\varepsilon}_{US,t}^{N} + \alpha^*\left(\widehat{u}_{US,t} + \widehat{k}_{US,t-1} - \widehat{\mu}_{z_{US,t}}\right) + (1-\alpha^*)\,\widehat{L}_{US,t}$$

- Demand functions

$$\widehat{p}_{EA,t}^{EA} = \frac{\lambda_F}{1+\lambda_F}\left(\widehat{y}_{EA,t}^{F} - \widehat{y}_{EA,t}^{EA}\right) + \frac{\left(1-d_F\right)^{\frac{\lambda_F}{1+\lambda_F}}\left(y_{US}^{EA}\right)^{\frac{1}{1+\lambda_F}}}{\left(d_F\right)^{\frac{\lambda_F}{1+\lambda_F}}\left(y_{EA}^{EA}\right)^{\frac{1}{1+\lambda_F}}}\zeta\left[\begin{array}{c}\widehat{y}_{US,t}^{EA} - \widehat{y}_{EA,t}^{EA} - \widehat{y}_{US,t-1}^{EA} + \widehat{y}_{EA,t-1}^{EA} + \widehat{\mu}_{z_{US,t}} - \widehat{\mu}_{z_{EA,t}} - \\ -\beta\left(\widehat{y}_{US,t+1}^{EA} - \widehat{y}_{EA,t+1}^{EA} - \widehat{y}_{US,t}^{EA} + \widehat{y}_{EA,t}^{EA} + \widehat{\mu}_{z_{US,t+1}} - \widehat{\mu}_{z_{EA,t+1}}\right)\end{array}\right]$$

$$\widehat{p}_{US,t}^{EA} + \widehat{p}_{US,t} = \frac{\lambda_F}{1+\lambda_F}\left(\widehat{y}_{EA,t}^{F} - \widehat{y}_{US,t}^{EA} - \widehat{\widehat{z}}_t\right) - -\zeta\left[\begin{array}{c}\left(\widehat{y}_{US,t}^{EA} - \widehat{y}_{EA,t}^{EA} - \widehat{y}_{US,t-1}^{EA} + \widehat{y}_{EA,t-1}^{EA} + \widehat{\mu}_{z_{US,t}} - \widehat{\mu}_{z_{EA,t}}\right) - \\ -\beta\left(\widehat{y}_{US,t+1}^{EA} - \widehat{y}_{EA,t+1}^{EA} - \widehat{y}_{US,t}^{EA} + \widehat{y}_{EA,t}^{EA} + \widehat{\mu}_{z_{US,t+1}} - \widehat{\mu}_{z_{EA,t+1}}\right)\end{array}\right]$$

$$\widehat{p}_{US,t}^{US} = \frac{\lambda_F^*}{1+\lambda_F^*}\left(\widehat{y}_{US,t}^{F} - \widehat{y}_{US,t}^{US}\right) + \frac{\left(1-d_F^*\right)^{\frac{\lambda_F^*}{1+\lambda_F^*}}\left(y_{EA}^{US}\right)^{\frac{1}{1+\lambda_F^*}}}{\left(d_F^*\right)^{\frac{\lambda_F}{1+\lambda_F}}\left(y_{US}^{US}\right)^{\frac{1}{1+\lambda_F^*}}}\zeta^*\left[\begin{array}{c}\widehat{y}_{EA,t}^{US} - \widehat{y}_{US,t}^{US} - \widehat{y}_{EA,t-1}^{US} + \widehat{y}_{US,t-1}^{US} + \widehat{\mu}_{z_{EA,t}} - \widehat{\mu}_{z_{US,t}} - \\ -\beta^*\left(\widehat{y}_{EA,t+1}^{US} - \widehat{y}_{US,t+1}^{US} - \widehat{y}_{EA,t}^{US} + \widehat{y}_{US,t}^{US} + \widehat{\mu}_{z_{EA,t+1}} - \widehat{\mu}_{z_{US,t+1}}\right)\end{array}\right]$$

[9] $\widehat{y}_{US,t} = \left(d_F^*\right)^{\frac{\lambda_F^*}{1+\lambda_F^*}}\left(\frac{y_{US}^{US}}{y_{US}}\right)^{\frac{1}{1+\lambda_F^*}}\widehat{y}_{US,t}^{US} + \left(1-d_F^*\right)^{\frac{\lambda_F^*}{1+\lambda_F^*}}\left(\frac{y_{EA}^{US}}{y_{US}}\right)^{\frac{1}{1+\lambda_F^*}}\left(\widehat{y}_{EA,t}^{US} - \widehat{\widehat{z}}_t\right)$

$$\widehat{p}^{US}_{EA,t} - \widehat{p}_{US,t} = \frac{\lambda^*_F}{1+\lambda^*_F}\left(\widehat{y}^{F}_{US,t} - \widehat{y}^{US}_{EA,t} + \widehat{\widehat{z}}_t\right) - \zeta^* \left[\begin{array}{c} \widehat{y}^{US}_{EA,t} - \widehat{y}^{US}_{US,t} - \widehat{y}^{US}_{EA,t-1} + \widehat{y}^{US}_{US,t-1} + \widehat{\mu}_{z_{EA,t}} - \widehat{\mu}_{z_{US,t}} - \\ -\beta^* \left(\widehat{y}^{US}_{EA,t+1} - \widehat{y}^{US}_{US,t+1} - \widehat{y}^{US}_{EA,t} + \widehat{y}^{US}_{US,t} + \widehat{\mu}_{z_{EA,t+1}} - \widehat{\mu}_{z_{US,t+1}}\right) \end{array} \right]$$

- Shadow rental rate of capital

$$\widehat{r}^{K}_{EA,t} - \widehat{\omega}^{\otimes}_{EA,t} - \widehat{R}_{EA,t} - \widehat{L}_{EA,t} + \widehat{u}_{EA,t} + \widehat{k}_{EA,t-1} - \widehat{\mu}_{z_{EA,t}} = 0$$

Households

- Consumption Euler equation

$$\begin{aligned} & \left[c_{EA} - bc_{EA}\frac{1}{\mu_{z_{EA}}}\right]^{-1}\widehat{\varepsilon}^{C}_{EA,t} - \left[c_{EA} - bc_{EA}\frac{1}{\mu_{z_{EA}}}\right]^{-2}\left[c_{EA}\widehat{c}_{EA,t} - \frac{bc_{EA}}{\mu_{z_{EA}}}\widehat{c}_{EA,t-1} + \frac{bc_{EA}}{\mu_{z_{EA}}}\widehat{\mu}_{z_{EA,t}}\right] \\ & -b\beta\left[c_{EA}\mu_{z_{EA}} - bc_{EA}\right]^{-1}E_t\widehat{\varepsilon}^{C}_{EA,t+1} \\ & +b\beta\left[c_{EA}\mu_{z_{EA}} - bc_{EA}\right]^{-2}\left[c_{EA}\mu_{z_{EA}}(\widehat{c}_{EA,t+1} + \widehat{\mu}_{z_{EA,t+1}}) - bc_{EA}\widehat{c}_{EA,t}\right] \\ & -\lambda_{z_{EA}}(1+\tau_C)\left[\widehat{\lambda}^{z}_{EA,t} + \widehat{(1+\tau_{C,t})}\right] \\ = {} & 0 \end{aligned}$$

- Money demand

$$\widehat{q}_{EA,t} = -\frac{1}{\sigma_Q}\left(-\widehat{\varepsilon}^{Q}_{EA,t} + \widehat{\lambda}^{z}_{EA,t} + \frac{\mu_z\pi_{EA}}{\mu_z\pi_{EA} - \beta}\widehat{R}_{EA,t}\right)$$

- Monetary base first order condition:

$$E_t\left[-\widehat{\lambda}^{z}_{EA,t} + \widehat{\lambda}^{z}_{EA,t+1} + \widehat{R}_{EA,t+1} - \widehat{\pi}_{EA,t+1} - \widehat{\mu}_{z_{EA},t+1}\right] = 0$$

- Investment Euler equation

$$\widehat{\rho}^{k}_{EA,t} = \begin{array}{c} -\widehat{\varepsilon}^{I}_{EA,t} + H''()(\mu_z)^2\left[\widehat{i}_{EA,t} - \widehat{i}_{EA,t-1} + \widehat{\mu}_{z_{EA,t}}\right] - \\ -\beta H''()(\mu_z)^2 E_t\left(\widehat{i}_{EA,t+1} - \widehat{i}_{EA,t} + \widehat{\mu}_{z_{EA,t+1}}\right) \end{array}$$

- Capital evolution equation

$$\widehat{k}_{EA,t} = \frac{(1-\delta)}{\mu_{z_{EA}}}\left[\widehat{k}_{EA,t-1} - \widehat{\mu}_{z_{EA,t}}\right] + \left[1 - \frac{(1-\delta)}{\mu_z}\right](\widehat{i}_{EA,t} + \widehat{\varepsilon}^{I}_{EA,t})$$

- Capital Euler equation

$$\frac{\mu_z}{\beta}E_t\left(\widehat{\lambda}^z_{EA,t} + \widehat{\rho}^k_{EA,t} + \widehat{\mu}_{z_{EA,t+1}} - \widehat{\lambda}^z_{EA,t+1}\right) = \left(\frac{\mu_z}{\beta} - (1-\delta)\right)E_t\widehat{r}^k_{EA,t+1} + (1-\delta)E_t\widehat{\rho}^k_{EA,t+1}$$

- Capital utilisation

$$\widehat{r}^k_{EA,t} - \sigma_a\widehat{u}_{EA,t} = 0$$

$$\sigma_a = \frac{\phi''(u_{EA})}{\phi'(u_{EA})}$$

- Wage equation

$$\begin{aligned} & \eta_0\widehat{\omega}^{\otimes}_{EA,t-1} + \eta_1\widehat{\omega}^{\otimes}_{EA,t} + \eta_2 E_t\widehat{\omega}^{\otimes}_{EA,t+1} + \eta_3\widehat{\pi}_{EA,t-1} + \eta_4\widehat{\pi}_{EA,t} + \eta_5 E_t\widehat{\pi}_{EA,t+1} + \\ & +\eta_6\frac{\widehat{L}_{EA,t}}{n} + \eta_7\widehat{\lambda}^z_{EA,t} + \eta_8\widehat{\overline{\pi}}_{EA,t} + \eta_9 E_t\widehat{\overline{\pi}}_{EA,t+1} + \eta_{10}(\widehat{1+\lambda_{W,t}}) + \eta_{11}\widehat{\varepsilon}^L_t + \eta_{12}(\widehat{1-\tau_{W,t}}) \\ = \; & 0 \end{aligned}$$

$$\eta = \begin{pmatrix} -b_W\xi_W \\ b_W(1+\beta\xi^2_W) - \sigma_L(1+\lambda_W) \\ -b_W\xi_W\beta \\ -b_W\xi_W\gamma_W \\ b_W\xi_W\left(1+\beta\gamma_W\right) \\ -b_W\beta\xi_W \\ -\lambda_W\sigma_L \\ \lambda_W \\ -b_W\xi_W(1-\gamma_W) \\ b_W\beta\xi_W(1-\gamma_W) \\ -\lambda_W \\ -\lambda_W \\ -\lambda_W \end{pmatrix} = \begin{pmatrix} \eta_0 \\ \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \\ \eta_5 \\ \eta_6 \\ \eta_7 \\ \eta_8 \\ \eta_9 \\ \eta_{10} \\ \eta_{11} \\ \eta_{12} \end{pmatrix}$$

$$b_W = \frac{\lambda_W + (1+\lambda_W)\sigma_L}{(1-\beta\xi_W)(1-\xi_W)}$$

- Modified uncovered interest rate parity

$$E_t\left(\Delta\widehat{S}_{t+1}\right) = \widehat{R}_{US,t} - \widehat{R}_{EA,t} + \chi\prime()\widehat{b}^{EA}_{US,t} + \widehat{\varepsilon}^S_t$$

Government

$$
\begin{aligned}
&\frac{g_{EA}}{y_{EA}^F/n}\widehat{g}_{EA,t}+\frac{tr_{EA}}{y_{EA}^F/n}\widehat{tr}_{EA,t}=\\
=\ &\frac{c_{EA}}{y_{EA}^F/n}\left((1+\tau_C)\,(\widehat{1+\tau_{C,t}})+\tau_C\widehat{c}_{EA,t}\right)+\frac{\omega_{EA}^{\otimes}\frac{L_{EA}}{n}}{y_{EA}^F/n}\left((\tau_W-1)\,(\widehat{1-\tau_{W,t}})+\tau_W\left(\widehat{\omega}_{EA,t}^{\otimes}+\widehat{L}_{EA,t}\right)\right)
\end{aligned}
$$

Monetary Authority

$$
\begin{aligned}
\widehat{R}_{EA,t} &= \phi_R\widehat{R}_{EA,t-1}+(1-\phi_R)\left[\widehat{\overline{\pi}}_{EA,t}+\phi_\Pi\left(\widehat{\pi}_{EA,t}-\widehat{\overline{\pi}}_{EA,t}\right)+\phi_Y\left(\widehat{gdp}_{EA,t}^F\right)\right]+\\
&\quad+\phi_{\Delta\pi}(\widehat{\pi}_{EA,t}-\widehat{\pi}_{EA,t-1})+\phi_{\Delta Y}\left(\widehat{gdp}_{EA,t}^F-\widehat{gdp}_{EA,t-1}^F\right)+\widehat{\varepsilon}_{EA,t}^R
\end{aligned}
$$

Final good market clearing

$$
\begin{aligned}
\widehat{y}_{EA,t}^F &= \frac{c_{EA}}{y_{EA}^F/n}\widehat{c}_{EA,t}+\frac{i_{EA}}{y_{EA}^F/n}\widehat{i}_{EA,t}+\frac{g_{EA}}{y_{EA}^F/n}\widehat{g}_{EA,t}+\frac{\overbrace{\phi_{EA}'(1)}^{=r_{EA}^k=\frac{\mu_{z_{EA}}-\beta(1-\delta)}{\beta}}}{\mu_{z_{EA}}}\frac{i_{EA}}{y_{EA}^F/n}\left[1-\frac{(1-\delta)}{\mu_z}\right]^{-1}\widehat{u}_{EA,t}\Leftrightarrow\\
\widehat{y}_{EA,t}^F &= \frac{c_{EA}}{y_{EA}^F/n}\widehat{c}_{EA,t}+\frac{i_{EA}}{y_{EA}^F/n}\widehat{i}_{EA,t}+\frac{g_{EA}}{y_{EA}^F/n}\widehat{g}_{EA,t}+\frac{\mu_z-\beta(1-\delta)}{\beta\left(\mu_{z_{EA}}-(1-\delta)\right)}\frac{i_{EA}}{y_{EA}^F/n}\widehat{u}_{EA,t}
\end{aligned}
$$

Balance of payments[10]

$$
p_{EA}^{US}y_{EA}^{US}\left(\widehat{p}_{EA,t}^{US}+\widehat{y}_{EA,t}^{US}\right)-p_{US}^{EA}p_{US}y_{US}^{EA}\left(\widehat{p}_{US,t}^{EA}+\widehat{p}_{US,t}+\widehat{y}_{US,t}^{EA}+\widehat{\widetilde{z}}_t\right)=
$$

$$
=n\frac{1}{\mu_{z_{EA}}\pi_{EA}}\left[\begin{array}{c}\beta\widehat{b}_{US,t}^{EA}-\widehat{b}_{US,t-1}^{EA}-\\ -\beta b_{US}^{EA}\left(\widehat{R}_{US,t}+\chi'\widehat{b}_{US,t}^{EA}+\widehat{\varepsilon}_t^S\right)+b_{US}^{EA}\left(\widehat{\Delta S}_t+\widehat{\mu}_{z_{EA,t}}+\widehat{\pi}_{EA,t}\right)\end{array}\right]
$$

[10] $\widetilde{z}=1$.

Definition equations

$$
\begin{aligned}
\pi_{EA,t}^{EA} &= \frac{p_{EA,t}^{EA}}{p_{EA,t-1}^{EA}}\pi_{EA,t} \Rightarrow \widehat{\pi}_{EA,t}^{EA} - \widehat{\pi}_{EA,t} = \widehat{p}_{EA,t}^{EA} - \widehat{p}_{EA,t-1}^{EA} \\
\pi_{EA,t}^{US} &= \frac{p_{EA,t}^{US}}{p_{EA,t-1}^{US}}\Delta S_t \pi_{EA,t} \Rightarrow \widehat{\pi}_{EA,t}^{US} - \widehat{\pi}_{EA,t} = \widehat{p}_{EA,t}^{US} - \widehat{p}_{EA,t-1}^{US} + \widehat{\Delta S}_t \\
\pi_{US,t}^{US} &= \frac{p_{US,t}^{US}}{p_{US,t-1}^{US}}\pi_{US,t} \Rightarrow \widehat{\pi}_{US,t}^{US} - \widehat{\pi}_{US,t} = \widehat{p}_{US,t}^{US} - \widehat{p}_{US,t-1}^{US} \\
\pi_{US,t}^{EA} &= \frac{p_{US,t}^{EA}}{p_{US,t-1}^{EA}}\left(\Delta S_t\right)^{-1}\pi_{US,t} \Rightarrow \widehat{\pi}_{US,t}^{EA} - \widehat{\pi}_{US,t} = \widehat{p}_{US,t}^{EA} - \widehat{p}_{US,t-1}^{EA} - \widehat{\Delta S}_t \\
p_{US,t} &= \frac{\pi_{US,t}}{\pi_{EA,t}} p_{US,t-1} \Rightarrow \widehat{p}_{US,t} - \widehat{p}_{US,t-1} = \widehat{\pi}_{US,t} - \widehat{\pi}_{EA,t} \\
\widetilde{z}_t &= \frac{z_{US,t}}{z_{EA,t}} = \frac{\mu_{z_{US,t}}}{\mu_{z_{EA,t}}}\widetilde{z}_{t-1} \Rightarrow \widehat{\widetilde{z}}_t - \widehat{\widetilde{z}}_{t-1} = \widehat{\mu}_{z_{US,t}} - \widehat{\mu}_{z_{EA,t}}
\end{aligned}
$$

Shocks

$$\widehat{\varepsilon}_{EA,t}^{C} = \rho^{C}\widehat{\varepsilon}_{EA,t-1}^{C} + e_{EA,t}^{C}$$

$$\widehat{\varepsilon}_{EA,t}^{Q} = \rho^{Q}\widehat{\varepsilon}_{EA,t-1}^{Q} + e_{EA,t}^{Q}$$

$$\widehat{\varepsilon}_{EA,t}^{L} = \rho^{L}\widehat{\varepsilon}_{EA,t-1}^{L} + e_{EA,t}^{L}$$

$$\widehat{\varepsilon}_{EA,t}^{I} = \rho^{I}\widehat{\varepsilon}_{EA,t-1}^{I} + e_{EA,t}^{I}$$

$$\widehat{\varepsilon}_{EA,t}^{N} = \rho^{N}\widehat{\varepsilon}_{EA,t-1}^{N} + e_{EA,t}^{N}$$

$$\widehat{\varepsilon}_{EA,t}^{R} = \rho^{R}\widehat{\varepsilon}_{EA,t-1}^{R} + e_{EA,t}^{R}$$

$$\widehat{\overline{\pi}}_{EA,t} = \rho^{\overline{\pi}}\widehat{\overline{\pi}}_{EA,t-1} + e_{EA,t}^{\overline{\pi}}$$

$$\widehat{g}_{EA,t} = \rho^{G} g_{EA,t-1}^{G} + e_{EA,t}^{G}$$

$$(\widehat{1+\lambda_{W,t}}) = \rho^{\lambda_W}(\widehat{1+\lambda_{W,t-1}}) + e_t^{\lambda_W}$$

$$(\widehat{1+\lambda_{D,t}}) = \rho^{\lambda_D}(\widehat{1+\lambda_{D,t-1}}) + e_t^{\lambda_D}$$

$$(\widehat{1+\lambda_{M,t}}) = \rho^{\lambda_M}(\widehat{1+\lambda_{M,t-1}}) + e_t^{\lambda_M}$$

$$\widehat{(1+\tau_{C,t})} = \rho^{\tau C}\widehat{(1+\tau_{C,t-1})} + e_t^{\tau_C}$$

$$\widehat{(1+\tau_{W,t})} = \rho^{\tau W}\widehat{(1+\tau_{W,t-1})} + e_t^{\tau_W}$$

$$\widehat{\mu}_{z_{EA,t}} = \rho^{\mu_z}\widehat{\mu}_{z_{EA,t-1}} + e_{EA,t}^{\mu_z}$$

$$\widehat{\varepsilon}_t^S = \rho^S\widehat{\varepsilon}_{t-1}^S + e_t^S$$

Foreign counterparts

All the above equations have a foreign counterpart, except for the modified UIP condition (and the risk-premium definition as well as the $\widehat{\varepsilon}_t^S$ shock) and the definition equation for $\widetilde{z}_t$.

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