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Tovonony Razafindrabe

UMR 7235

Université de Paris Ouest Nanterre La Défense
(bâtiment G)
200, Avenue de la République
92001 NANTERRE CEDEX

Tél et Fax : 33.(0)1.40.97.59.07
Email : nasam.zaroualete@u-paris10.fr

université Paris Ouest Nanterre La Défense

A multi-country DSGE model with incomplete Exchange Rate Pass-through: application for the Euro area.

Tovonony Razafindrabe*

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*EconomiX, Université Paris Ouest Nanterre la Défense.

Abstract

This paper develops an estimated multi-country open economy dynamic stochastic general equilibrium (DSGE) model with incomplete Exchange Rate Pass-Through (ERPT) for the Euro-area. It is designed to model global international linkages and to assess international transmission of shocks under an endogenous framework and incomplete ERPT assumption. On the one hand, we relax the small open economy framework (SOEF) but derive a canonical representation of the equilibrium conditions to maintain analytical tractability of the complex international transmission mechanism underlying the model. Namely, the model considers economies of different size that are open and endogenously related. On the other hand, in order to take into account international linkages, possible cointegration relationships within domestic variables and between domestic and foreign variables, and the role of common unobserved and observed global factors such as the oil price, we use the Global VAR model to estimate the steady state of observed endogenous variables of the multi-country DSGE model. Namely, steady states are computed as long-horizon forecasts from a reduced-form cointegrating GVAR model. ERPT analysis conducted from the estimated multi-country DSGE model for the Euro-area in relation with its five main trade partners which are the United Kingdom, the United States, China, Japan and Switzerland yields the following results. First, exchange rate volatility contributes to a large part of import price inflation variation of the Euro-area in contrast to foreign mark-up shocks. Second, deviation from inflation objective of the foreign trade partners contributes to another source of the Euro-area import price variability. Third, nominal rigidity induces a persistent but a lower impact of the exchange rate changes on import inflation.

1 Introduction

This paper develops a multi-country open economy dynamic stochastic general equilibrium (DSGE) model with incomplete exchange rate pass-through (ERPT) assumption for the Euro-area. The latter assumption is introduced, following Monacelli (2003), by the means of nominal import price rigidity. That is, there exists a continuum of monopolistic importing firms that buy homogeneous goods in international market and sell it to domestic consumers. Optimal mark-up problem of the importing firms, namely by using staggered price setting framework à la Calvo, leads to deviation from the law of one price assumption and, hence, to incomplete ERPT. Hence, and as detailed in Burstein and Gopinath (2013), we assume a normative perspective in choosing this framework.[1]

The main focus of this study is to model global international linkages under an endogenous framework and to highlight the important role of the incomplete ERPT assumption on the international transmission of shocks. For these purposes, first, we relax the small open economy framework (SOEF) and consider economies of different sizes that are open and endogenously related.[2] However, we maintain analytical tractability of the complex international transmission mechanism underlying the model by deriving a canonical representation of the model equilibrium solutions. Second, to model explicitly the direct and indirect link between domestic and foreign variables, but also the possible cointegration relationships within domestic variables and between domestic and foreign variables, we estimate the steady state of variables as the long-horizon forecasts from a reduced-form cointegrating Global VAR. This approach permits to give steady states an economic interpretation and, thus, to circumvent the "black box" paradigm, in the sens of Garratt et al. (2006), that arises from the use of pure statistical filtering procedure. Moreover, the important role of the oil price that is considered as common observable global factor and the United States' financial variables in the world economy are handled through the specification of the GVAR model. Third, structural parameters of the model are estimated using variables measured as deviation from their estimated GVAR steady states and Bayesian estimation methodology.

It is admitted that incomplete ERPT phenomenon modified the traditional Keynesian international transmission channel such the expenditure swtiching effects, consumption risk sharing and the law of one price assumption (Betts and Devereux (2000), and Engel(2002b)), and the conduct of monetary policy (Gagnon and Ihrig (2001) and Monacelli (2003)). De-

[1] One can cite among others Obstfeld and Rogoff (2000) and Smets and Wouters (2002) for theoretical studies that support the normative issue. At the empirical side, one can cite the work of Campa and Goldberg (2002), Campa et al. (2005), and Campa and Minguez (2006). Normative issue is commonly known as the Producer Currency Pricing (PCP) literature.

[2] It is worth noting that it is common in the open economy DSGE model literature to assume domestic economy as small relative to the rest of the world. Among others, one can cite the work of Adolfson et al. (2007) and Christoffel et al. (2008). Under the SOEF assumption, domestic variables have negligible effects on foreign variables which are taken as exogenous and usually assessed using a vector autoregressive model. This assumption is mainly adopted, as is the case in Gali and Monacelli (2005), to have isomorphism between the closed and open economy version of the model equilibrium solutions.

parture from the SOEF framework permits to handle some important features of the open economy model under the assumption of incomplete ERPT. First, the multi-country open economy model considers economies of different sizes that are open and endogenously related. As regards to ERPT analysis, this has stark implications. It permits to have endogenously foreign producers' cost-push shocks in the import price law of motion in contrast to other models in the literature that have exogenous shocks that measure a shift in the elasticity of substitution among imported goods. Second, it permits asymmetric trade flows and diversification of foreign trade for each economy. For ERPT analysis, it renders the role of import market share and currency invoicing more relevant. On the one hand, economies are endogenously linked by international trade and the importance of a trade partner is measured by the means of the import and export share. Hence, the extent to which trade partners' variables influence domestic variables depends mainly on their respective market share. One the other hand, the multi-country specification permits to handle the important role of currency invoicing in influencing the extent of ERPT under a multi-currency analysis.[3] It leads to a distinction that has to be made between pass-through that arises from bilateral and multilateral or effective exchange rate movements. Moreover, it highlights the role of currency invoicing in international trade. Namely, we found that the Pound bilateral exchange rate drives to a larger extent the variability of the Euro-area import price inflation and thus confirms the important role played by the United Kingdom as trade partner.

Focusing our interpretation on the ERPT analysis, we find the following results. First, the variance decomposition analysis permits to conclude that exchange rate volatility contributes to a large part of the import price inflation volatility. More precisely, it accounts for 70.83% upon the impact of the shock. Such evidence supports the relevance of the normative approach in contrast to the positive one that supports the declining value of the extent of ERPT over time.[4] Second, foreign mark-up shocks have a reduced impact on the variability of the import price inflation. Along with the traditional arguments such as the presence of international competitive market and the weight attributed to foreign goods in the domestic consumption basket, it is mainly explained by the fact that foreign mark-up shocks' impact on foreign inflation, and to a certain extent on foreign marginal cost, is limited and short-lived. This is again an argument in favor of the Producer Currency Pricing (PCP) behavior rather than the LCP-PTM at the export side. Third, we found that deviation from inflation objective, namely in the foreign trade partners, contributes to another important part of the Euro-area import price variability. More precisely, it accounts for 12.47% of the volatility. If one assumes without loss of generality that foreign marginal cost follows the same dynamics as foreign inflation, an assumption generally adopted in the empirical literature of pass-through, we found that the United Kingdom marginal cost variability contributes to a large part, more precisely 6.28%, in the volatility of the Euro-area import inflation. Fourth, and most importantly, nominal

[3] See de Bandt and Razafindrabe (2014) for a comprehensive revue of the link between currency invoicing and ERPT.

[4] See for example Marazzi and Sheets (2007), Bouakez and Rebei (2008) and Gust et al. (2010). Positive issue is commonly known as the Local Currency Pricing - Pricing to Market (LCP-PTM) literature.

rigidity induces a persistent but a lower impact of the exchange rate changes on import price inflation. This has a stark implication for the conduct of the monetary policy. Reinforced by the presence of home consumption bias and the trade-off between output and law of one price gap stabilization generated by the new independent channel of monetary policy arising from incomplete pass-through assumption, the monetary authority could pursue a stable inflation target with less action, as far as ERPT is concerned. Namely, this finding is supported by the low estimate value of the law of one price gap in the interest rate rule.

The rest of the paper is organized as follows: section 2 develops the multi-country open economy DSGE model; section 3 summarizes the equilibrium solutions of the model into the standard canonical representation; section 4 describes the estimation procedure and the data; section 5 reports the results; and section 6 concludes.

2 Multi-country open economy DSGE

The world economy is considered as a set of N open economy countries indexed by $i \in \{1, \ldots, N\}$ which are supposed to be different from one another with regard to their population size, degree of openness related to the share of imports and exports on gross domestic product and international portfolio diversification in world asset market. There are four types of agents in each country i: a continuum of monopolistic competitive firms in the unit interval $[0, 1]$ indexed by f_i, a continuum of monopolistic competitive importing firms also, without loss of generality, in the unit interval $[0, 1]$ indexed by l_i, households $h \in [0, \mathcal{P}_i]$ which are supposed to be a monopolistic supplier of their individual labor indexed by $L_i(h)$ and where $\mathcal{P}_i$ is the number of population in country i, and finally a central bank.

All goods are tradable. Following Monacelli (2003), we assume that the law of one price holds "*at the dock*" for any international trade. However, deviation from the law of one price is generated by the optimal pricing behavior of monopolistic importing firms. For simplicity, and without loss of generality, each single firm uses only labor as input factor to produce one type of goods which will be consumed at home as well as exported abroad. It has a monopoly power over its single good but faces competition from other substitutable goods produced by other home and foreign firms. Each household consumes and supplies monopolistically a distinctive variety of its labor to home firms. Retailers import goods and sell it without any transformation to domestic consumers. Finally, central bank conducts monetary policy using nominal interest rate as instrument.

Within each country i, we assume **symmetry** so that households and firms share respectively the same preference and technology. However, across countries, technology and preference over different types of home and foreign goods may differ. It is assumed that households have access to a **complete** set of nominal contingent claims traded internationally.

Concerning notation, lower case letters indicate the natural logarithm of variables, while upper case letters indicate level. Hatted lower case letters indicate log-deviation of variables from their respective steady state values.[5]

2.1 Nominal and real exchange rate

Among N countries around the world indexed by $i \in \{1, \ldots, N\}$, country 1 is chosen, without loss of generality, as a numeraire. It is the Euro-area in this study.[6] Denote E_{ijt} the **nominal bilateral** exchange rate between country i and j expressed as country i's currency price of one unit of foreign country j's currency. By choosing country 1 as a numeraire, bilateral exchange rate between country i and numeraire country E_{i1t} is, henceforth, denoted E_{it}. This allows to write the **bilateral** exchange rate E_{ijt} in log-linear term as:

$$\hat{e}_{ijt} = \hat{e}_{it} - \hat{e}_{jt}$$

Therefore, effective real exchange rate will be given by

$$\mathfrak{q}_{it} = (\hat{e}_{it} - \hat{p}_{it}) - \sum_{j=1}^{N} \alpha_{ij} (\hat{e}_{jt} - \hat{p}_{jt}) \tag{1}$$

where $\hat{p}_{it}$ represents the consumption-based price index (CPI) of country i. Parameter α_{ij}, where $\alpha_{ij} > 0$ and $\sum_{j=1}^{N} \alpha_{ij} = 1$, in turn represents the share of imported goods from country j on the consumption basket of the representative household in country i.

It is worth noting that we assume **home consumption bias** which is formally represented by the following condition:

$$\max_{i \neq j} \alpha_{ij} < \alpha_{ii} < 1 \ \forall i \in \{1, \ldots, N\}$$

and that each economy is open.[7]

2.2 Terms of trade and inflation

Bilateral terms of trade between country i and j is defined to be the price of foreign country j's imported goods in terms of domestic country i's goods. That is in log-linear deviation terms,

$$\hat{s}_{ijt} = \hat{p}_{ijt} - \hat{p}^{d}_{it} \tag{2}$$

[5] For a variable X_t, $x_t = \log(X_t)$ and $\hat{x}_t = \log(X_t) - \log(\bar{X}) = x_t - \bar{x}$, where $\bar{X}$ is the steady state value of X_t.

[6] The choice of numeraire country is irrelevant and does not alter the equilibrium of the model.

[7] As shown by Chudik and Straub (2010), no group of countries is isolated from the rest of the world if and only if

$$rank\,(I_N - \mathbf{M}) = N - 1$$

where I_N is a NxN identity matrix and $\mathbf{M}$ is the (NxN) import share matrix where its (i, j)-th element equals α_{ij}.

where $\hat{p}_{ijt}$ denotes the home-currency (country i) price index of goods imported from country j and $\hat{p}^d_{it}$ the domestic producer price index. Using the definition of country i's aggregate consumer price index (19) and that of import price index (20), effective terms of trade is given by:

$$\hat{s}_{it} = \hat{p}^f_{it} - (1 - \alpha_{ii})\hat{p}^d_{it} = \hat{p}_{it} - \hat{p}^d_{it} \tag{3}$$

In terms of inflation, defined as the rate of change in price index, CPI, IPI and producer price index (PPI) are linked according to:

$$\hat{\pi}_{it} = \hat{\pi}^f_{it} + \alpha_{ii}\hat{\pi}^d_{it} \tag{4}$$

where, for latter use, import inflation index (IPI) is defined as:

$$\hat{\pi}^f_{it} = \sum_{\substack{j=1 \\ j\neq i}}^{N} \alpha_{ij}\left(\hat{p}_{ijt} - \hat{p}_{ijt-1}\right) = \sum_{\substack{j=1 \\ j\neq i}}^{N} \alpha_{ij}\hat{\pi}^{jf}_{it} \tag{5}$$

2.3 Incomplete pass-through

Following Monacelli (2003), let

$$\psi_{ij,t} = \hat{e}_{ijt} + \hat{p}^d_{jt} - \hat{p}_{ijt} \tag{6}$$

be the **bilateral** *law-of-one price gap* (hereafter l.o.p gap) between country i and j that measures the difference between foreign prices and domestic currency prices of imports, and

$$\Psi_{it} = \sum_{\substack{j=1 \\ j\neq i}}^{N} \alpha_{ij}\psi_{ij,t} = \sum_{j=1}^{N} \alpha_{ij}\psi_{ij,t}$$

be the effective l.o.p gap. The domestic currency price of imports $\hat{p}_{ijt}$ is set by monopolistic importing firms as a result of an optimal markup problem. Namely, import prices are set in a staggered fashion à la Calvo. Hence, *incomplete pass-through* arises due to a fraction of firms that do not adjust their prices. That is, changes in the exchange rate are not entirely transmitted into domestic price of imports due to nominal price rigidity, implying a deviation from the law of one price assumption.

Using the definition of the effective real exchange rate (1) and that of the effective terms of trade (3), one obtains:

$$\Psi_{it} = \mathfrak{q}_{it} - \sum_{j=1}^{N} \alpha_{ij}\hat{s}_{jt} \tag{7}$$

This last equation indicates that there are two sources of deviation from the purchasing power parity assumption, the relative price variations captured by the effective terms of trade and the deviation from the law of one price assumption captured by the effective l.o.p gap. Therefore, under the assumption of Calvo price setting, nominal rigidity generates gradual and persistent deviation from the law of one price assumption, hence incomplete pass-through, which in turn yields a persistent deviation from the purchasing power parity assumption.

2.4 CPI and PPI index

Combining country i's aggregate CPI, IPI, PPI, home-currency price index of good from country j (21), and the definition of effective l.o.p gag, yields a relationship between CPI and PPI index. That is,

$$\hat{p}_{it} - \hat{e}_{it} = \sum_{j=1}^{N} \alpha_{ij} \left(\hat{p}^d_{jt} - \hat{e}_{jt} \right) - \Psi_{it}$$

which in matrix form yields:

$$\hat{\mathbf{e}}_t - \hat{\mathbf{p}}_t = \mathbf{M} \left(\hat{\mathbf{e}}_t - \hat{\mathbf{p}}^d_t \right) + \mathbf{\Psi}_t \tag{8}$$

where $\hat{\mathbf{p}}_t = (\hat{p}_{1t}, \ldots, \hat{p}_{Nt})'$, $\hat{\mathbf{e}}_t = (0, \hat{e}_{2t}, \ldots, \hat{e}_{Nt})'$, $\hat{\mathbf{p}}^d_t = \left(\hat{p}^d_{1t}, \ldots, \hat{p}^d_{Nt}\right)'$, $\mathbf{\Psi}_t = (\Psi_{1t}, \ldots, \Psi_{Nt})'$, and $\mathbf{M}$ is the $(N\text{x}N)$ import share matrix where its (i,j)-th element equals α_{ij}.

Using this relationship, the real effective exchange rate (1) can be written in function of relative prices and effective l.o.p gap in matrix form as:

$$\mathbf{q}_t = (\mathbf{I}_N - \mathbf{M}) \mathbf{M} \left(\hat{\mathbf{e}}_t - \hat{\mathbf{p}}^d_t \right) + (\mathbf{I}_N - \mathbf{M}) \mathbf{\Psi}_t \tag{9}$$

where $\mathbf{q}_t = (\mathfrak{q}_{1t}, \ldots, \mathfrak{q}_{Nt})'$ and $\mathbf{I}_N$ is an $(N\text{x}N)$ identity matrix.

2.5 International risk sharing condition

Under the assumption of complete asset markets, households share risk internationally. Consumption index between two countries is therefore linked for all t according to:[8]

$$(C_{it} - H_{it}) = \vartheta_i (C_{jt} - H_{jt}) Q_{ijt} \tag{10}$$

where ϑ_i is a constant that depends on initial conditions and $H_{it} = hC_{it-1}$ is an external habit taken as exogenous by households. Without loss of generality, we assume that:

$$\vartheta_i = 1 \; \forall i \in \{1, \ldots, N\}$$

Log-linearized version of the international risk sharing condition yields:

$$\hat{c}_{it} - h\hat{c}_{it-1} = \hat{c}_{jt} - h\hat{c}_{jt-1} + (1-h)\hat{q}_{ijt} \tag{11}$$

[8] For a formal derivation of this risk sharing condition, see Gali and Monacelli (2005).

That is, through its impact on the real exchange rate, equation (9) and (11) clearly show that the l.o.p gap generates a deviation from the consumption risk sharing condition. Therefore, incomplete exchange rate pass-through distorts the traditional Keynesian effects of exchange rate changes such as the consumption risk sharing and the expenditure switching effect. Betts and Devereux (2000) get to the same conclusion using the class of new open economy model (NOEM). Intuitively, nominal depreciation of the home currency i generates a competitive gain for home producers. This will increase domestic revenue and, hence, consumption. However, demand of imported goods is not altered by the depreciation due to import price nominal rigidity. At the extreme case of zero pass-through, foreign firms will also benefit from the increase in home revenue which yields an increase in the foreign revenue, a departure from the expenditure switching effect. In the foreign country j, incomplete pass-through prevents decrease in the foreign price of home exported goods. Thus, consumption will not increase as is the case under complete pass-through. This will generate, combined with the rise in home consumption, a deviation from risk sharing condition. Moreover, the international risk sharing condition (11) indicates that rise in home consumption (country i) relative to foreign, due for instance to a rise in home output, necessitates a real exchange rate depreciation to attain equilibrium. The latter can be achieved through terms of trade deterioration (a rise in $\hat{s}_{it}$ through a fall in the price of domestic goods $\hat{p}^d_{it}$) or deviation from the law of one price assumption (a rise in the l.o.p gap through a nominal exchange rate depreciation).

2.6 Uncovered interest parity

Under the assumption of complete asset markets, the uncovered interest parity condition between country i and j

$$E_t \left\{ \Delta \hat{e}_{ijt+1} \right\} = \hat{r}^n_{it} - \hat{r}^n_{jt} \tag{12}$$

is obtained using households optimal condition (25) and international risk sharing condition (11). $\hat{r}^n_{it}$ denotes the nominal interest rate of country i.

3 Canonical representation

To conclude the presentation of the model, let us resume the equilibrium conditions into the standard canonical representation. This permits to have tractability in the interpretation and to see what our specification brings compared to the standard small open economy framework. Typically, the latter can be represented, as in the closed economy setup, by three well know equations which are the new Keynesian Phillips curve, the dynamic investment-saving equation and the monetary policy rule. However, the inclusion of the incomplete pass-through assumption will add in this canonical representation another equation that characterizes the law of motion of the import price inflation.

3.1 Phillips curve

Substituting the real marginal cost (49) into the domestic inflation dynamics (40) yields the **new keynesian hybrid Phillips curve:**

$$\begin{aligned}\hat{\pi}^d_{it} &= \frac{\gamma_{id}}{1+\gamma_{id}\beta}\hat{\pi}^d_{it-1} + \frac{\beta}{1+\gamma_{id}\beta}E_t\left\{\hat{\pi}^d_{it+1}\right\} + \omega_i \hat{y}_{it} - \frac{\lambda^d_i h}{1-h}\hat{y}_{it-1} \\ &\quad - \frac{\lambda^d_i h}{1-h}\Phi_{it} + \lambda^d_i \hat{\mu}^w_{it} - \lambda^d_i (1+\psi)\,\hat{a}_{it} + \lambda^d_i \varepsilon^p_{it}\end{aligned}$$

where $\omega_i = \lambda^d_i (1+\psi(1-h))\,/\,(1-h)$. Hence, the producer price inflation $\hat{\pi}^d_{it}$ is driven by its past value through inflation indexation and its future discounted path. Moreover, it depends positively on the current value of output $\hat{y}_{it}$ and negatively on productivity shock $\hat{a}_{it}$. A rise in output induces a rise in domestic goods inflation through its positive impact on marginal cost whereas a rise in productivity shock induces a decrease in domestic goods inflation through its negative impact on marginal cost, namely the labor productivity. Apart from these variables that typically characterize the new Keynesian Phillips curve, there are additional frictions that arise from the model specification. First, the habit formation leads domestic goods inflation to depend negatively on past output and real interest rate differential Φ_{it} through international risk sharing condition and optimal allocation of expenditures. Second, labor market friction $\hat{\mu}^w_{it}$ induced by the households' monopolistic wage setting behavior has a positive impact on domestic goods inflation. It acts as households' mark-up that raise the marginal cost of producing domestic goods using labor. Finally, domestic goods inflation rises with the cost-push shock ε^p_{it}.

3.2 Import price law of motion

Aggregating bilateral import price inflation across foreign partners j and using import inflation index (5) yield the aggregate import inflation law of motion. That is,

$$\hat{\pi}^f_{it} = \frac{\gamma_{if}}{1+\gamma_{if}\beta}\hat{\pi}^f_{it-1} + \frac{\beta}{1+\gamma_{if}\beta}E_t\left\{\hat{\pi}^f_{it+1}\right\} + \lambda^f_i\left(\Psi_{it} + \varepsilon^{fp}_{it}\right) \tag{13}$$

where Ψ_{it} is the country i's effective l.o.p gap defined in (7) and $\varepsilon^{fp}_{it} = \sum_{j=1,j\neq i}^{N}\alpha_{ij}\varepsilon^p_{jt}$. This last equation deserves some comments. At the aggregate level, import price inflation varies positively with the effective l.o.p gap and the effective foreign cost-push shock. On the one hand, under the assumption that the law of one price holds at the dock, the foreign price of imported goods $(\hat{e}_{ijt} + \hat{p}^d_{jt})$ can be interpreted as the importing firm marginal cost. Therefore, nominal depreciation of the home currency i triggers an increase in marginal cost that takes the form of an increase in the l.o.p gap. The extent to which, however, this depreciation is passed-through import price inflation depends on the degree of import price nominal rigidity θ_{iF} contained in the coefficient λ^f_i. On the other hand, the multi-country specification allows the import price inflation to depend on foreign cost-push shocks. However, the latter differ from the importing firms markup shocks usually obtained in the open economy DSGE model incorporating import block and that are generally interpreted as a shift in the elasticity of substitution among imported goods. Here, ε_{it}^{fp} represents a weighted average of **trading partners** cost-push or markup shocks.

It is worth noting that the impact on the aggregate import price inflation of bilateral exchange rate movements and cost-push shocks between home country i and foreign country j will depend both on the degree of import price nominal rigidity θ_{iF} and the share of imported goods α_{ij}. That is, bilateral analysis shows how market share plays an important role in the exchange rate pass-through issue.

3.3 Dynamic IS-equation

Substituting the link between consumption and output (53) into the Euler equation (25) yields the following dynamic IS-equation in matrix notation:

$$\begin{aligned}\mathbf{M}\hat{\mathbf{y}}_t &= \frac{1}{1+h}\mathbf{M}E_t\left\{\hat{\mathbf{y}}_{t+1}\right\} + \frac{h}{1+h}\mathbf{M}\hat{\mathbf{y}}_{t-1} + \frac{1-h}{1+h}E_t\left\{\Delta\mathbf{\Psi}_{t+1}\right\} \\ &\quad -\frac{h}{1+h}\mathbf{M}E_t\left\{\Delta\mathbf{\Phi}_{t+1}\right\} - \frac{1-h}{1+h}\left(\hat{\mathbf{r}}_t^n - E_t\left\{\hat{\boldsymbol{\pi}}_{t+1}\right\}\right)\end{aligned} \tag{14}$$

Thus, assumptions adopted in the model introduce new variables in the dynamics of the demand compared to the standard canonical representation. First, the introduction of the habit formation in the model leads output to depend negatively on the expected changes in the effective real interest rate differential. Second, expected value of the output and that of changes in the l.o.p gap are negatively linked. As will be explained below, this indicates a trade-off between the stabilization of output gap and l.o.p gap that the monetary authority has to face due to the introduction of incomplete exchange rate pass-through assumption.

3.4 Monetary policy

To close the model, let us assume that monetary authority follows an instrument rule rather than optimizing a specific loss function. Monetary authority adjusts nominal interest rate in response to deviation of CPI inflation from its target, to output gap $\tilde{y}_{it} = \hat{y}_{it} - \hat{y}_{it}^n$ and to l.o.p gap. Following Smets and Wouters (2003), policy maker adopts the following interest rate rule:

$$\begin{aligned}\hat{r}_{it}^n &= \rho_{ir}\hat{r}_{it-1}^n + (1-\rho_{ir})\left(\bar{\pi}_{it} + r_{\pi_i}\left(\hat{\pi}_{it-1} - \bar{\pi}_{it}\right) + r_{y_i}\tilde{y}_{it} + r_{\psi_i}\Psi_{it}\right) \\ &\quad + r_{\Delta\pi_i}\Delta\hat{\pi}_{it} + r_{\Delta y_i}\Delta\tilde{y}_{it} + \varepsilon_{r_{it}}\end{aligned} \tag{15}$$

with $\bar{\pi}_{it}$ being a persistent shock to the CPI inflation objective which is assumed to follow a first-order autoregressive process $\bar{\pi}_{it} = \rho_{\pi_i}\bar{\pi}_{it-1} + \eta_t^{\pi_i}$ where $\eta_t^{\pi_i}$ is an inflation targeting shock, whereas $\varepsilon_{r_{it}}$ is a monetary policy shock.

To see how the introduction of the incomplete exchange rate pass-through assumption affects the conduct of monetary policy, namely by the introduction of the effective l.o.p gap in the interest rate rule, let us first discuss to what extent different specifications adopted in this model break the standard canonical representation obtained with the small open economy framework in Gali and Monacelli (2005). First, some specifications adopted in the model in order to generate nominal and real rigidity break the standard canonical representation. Namely, the external habit formation leads to the presence of the real interest rate differential Φ_{it} and the lagged value of the output $\hat{y}_{it-1}$ in the dynamic IS equation and the Phillips curve. The monopolistic wage setting behavior of the households in turn leads the labor market friction $\hat{\mu}^w_{it}$ to enter the Phillips curve. Second, the multi-country approach allows the model to depart from the small open economy assumption. Namely, there exists a number of trading partners that are no longer taken as exogenous for domestic economy. This specification leads to the matrix representation of the dynamic IS equation where outputs are linked by the means of the import matrix share. However, it does not break the isomorphism between the closed and open economy model. The important implication of this assumption, namely for the exchange rate pass-through analysis, is that trading partners cost-push shocks weighted by their respective import market share enter endogenously the import price inflation dynamics and hence that of CPI inflation. Third, the assumption of incomplete exchange rate pass-through breaks the traditional aggregate demand and supply channel of monetary policy through the existence of independent channel by the means of the l.o.p gap variables in the dynamic IS and import inflation (and hence the CPI inflation) equation.

Suppose now that the monetary authority reacts to a contraction of the output gap by lowering interest rate. Through the dynamic IS equation, the real interest rate therefore decreases. It leads to a rise in output and hence, the output gap. However, lowering interest rate yields a nominal depreciation that in turn raises the l.o.p gap. In turn, if the monetary authority raises interest rate to stabilize a rise in the l.o.p gap, this leads to a contraction of the activity. Therefore, and as argued by Monacelli (2003), apart from the traditional trade off faced by the monetary authority between stabilizing inflation and output gap, this example illustrates how the assumption of the incomplete pass-through leads to another trade off between stabilizing output and l.o.p gap. The introduction of the l.o.p gap variable in the interest rate rule aims at capturing this new trade-off and treating endogenously the deviation from the law of one price.

4 Estimation

We estimate structural parameters of the model using Bayesian methodology which formal description can be found in An and Schorfheide (2007). It is worth noting that it is common in the literature to take the rest of the world as a fictional exogenous economy in order to reduce the curse of dimensionality. The multi-country assumption therefore does not permit a shrinkage of the data in this study. Therefore, inference of the structural parameters is done by block in order to reduce the curse of dimensionality and to attain convergence more rapidly. Structural parameters are classified into three blocks that are behavioral, nominal friction from wage and price setting problems, and monetary policy parameters.[9]

For each country i, the log-linearized version of the equilibrium conditions contain five observable endogenous variables such as output $\hat{y}_{it}$, nominal interest rate $\hat{r}^n_{it}$, domestic price inflation $\hat{\pi}^d_{it}$, import price inflation $\hat{\pi}^f_{it}$ and real wage $\widehat{wr}_{it}$, five non-observable endogenous variables such as the law of one price gap Ψ_{it}, real interest rate differential Φ_{it}, wage mark-up $\hat{\mu}^w_{it}$ and natural output $\hat{y}^n_{it}$, and finally two exogenous processes of bilateral nominal exchange rate $\hat{e}_{it}$ (observable) and technology $\hat{a}_{it}$ (non-observable). The stochastic behavior of the model is mainly driven by seven exogenous shocks such as exchange rate shock ε_{e_it}, idiosyncratic technology shock ε_{a_it}, monetary policy shock $\varepsilon_{r_{it}}$, inflation targeting shock $\eta^{\pi_i}_t$, wage mark-up shock ε^w_{it}, domestic price mark-up shock ε^p_{it} and preference shock ε^g_{it}.[10]

4.1 Data

The multi-country model that is estimated includes the Euro-area and its five main trade partners which are the United Kingdom, China, the United States, Japan and Switzerland. In order to estimate the model, we use quarterly data for the period 1998Q2 to 2011Q2. Note that we do not use data constructed by Fagan et al. (2001) as is commonly the case when estimating DSGE model for Euro-area given that the last update of the Area-Wide Model database includes dataset that ends in 2009Q4. Data used in this study comes mainly from national sources and the International Monetary Fund database.[11]

Estimation of the structural parameters are conducted using variables expressed in deviation from their respective steady states. In turn, steady states of observable variables are estimated as the long-horizon forecasts from a reduced-form cointegrating Global VAR. The use of GVAR to estimate the steady state is introduced by Dees et al. (2009) and used by Dees et al. (2010) to estimate structural parameters of multi-country new Keynesian model. It has the advantage of taking into account direct and indirect link between domestic and foreign variables, and possible cointegration within domestic variables and between domestic and foreign variables. This permits to give economic interpretation to the estimated steady state in contrast to pure statistical filtering procedures, qualified by Garratt et al. (2006) as a "black box", that are commonly used in the literature. Moreover, the GVAR specification permits to take into account the role of oil price that is considered as common observable

[9] Estimation is conducted using Dynare. It is a software platform for handling DSGE model. See Adjemian et al. (2011). Initial value of structural parameters is obtained using a posterior sample of 100,000 draws. Thereafter, posterior sample of each block of parameters is generated in sequence using 20,000 draws.

[10] Introduction of the preference is standard and straightforward. For the sake of clarity, we report interested readers in a supplement available upon request for details.

[11] Details of the sources and data transformation are given in a supplement available upon request. Moreover, output, real wage and nominal exchange rate are expressed in 100 times logarithm of the variable. In turn, inflation and interest rate are expressed in quarterly basis and in percentage.

global factor and the importance of Unites States financial variables in the world economy.[12]

As in Smets and Wouters (2003) and Christoffel et al. (2008), we proceed to some normalizations of structural shocks in the log-linearized version of the equilibrium solutions of the model before estimation. These are done in order to ease choice of the prior and to improve convergence of estimated structural parameters. First, we normalize coefficients affected to domestic price mark-up shock ε_{it}^{p} in the Phillips curve and wage mark-up shock ε_{it}^{w} in the real wage law of motion to be equal to unity. Second, we assume that foreign mark-up shock ε_{it}^{fp} follows a first order autoregressive process and normalize its coefficient to be equal to unity.

4.2 Priors

Some parameters are kept fixed throughout the estimation procedure. The discount factor β is calibrated to be equal to 0.99 which implies a quarterly steady-state real interest rate of 1%. The optimal allocation of expenditures between goods produced in different countries (23) gives the formal definition of the imported goods share. That is,

$$\alpha_{ij} = \frac{P_{ijt}C_{ijt}}{P_{it}C_{it}} \text{ and } \alpha_{ii} = \frac{P_{iit}C_{iit}}{P_{it}C_{it}}$$

$P_{ijt}C_{ijt}$ represents the nominal value of goods imported from country j that is proxied by the corresponding value of importation from country j. $P_{iit}C_{iit}$ represents consumption of domestic produced goods and is proxied by the value of domestic production which is not exported. Finally, $P_{it}C_{it}$ represents nominal consumption of country i and is assumed to be equal to $P_{ijt}C_{ijt} + P_{iit}C_{iit}$. The import matrix share is constructed by averaging the right hand side of the above expression during the period 1999-2011. This specification permits to respect the restriction imposed for α_{ij}. In turn, the expression of the export share of goods $\varkappa_{ij}$ in (44) is approximated by the share of nominal export from a given trade partner relative to the nominal value of domestic production.

Priors of structural parameters are set based on earlier studies that estimate DSGE model using Bayesian methods such as Smet and Wouters (2003), Adolfson et al. (2007), Walque et al. (2005) and Christoffel et al. (2008). Each parameter is given the same prior for all countries. Table C in the appendix reports prior distribution, mean and standard deviation or degree of freedom of the structural parameters. We assume that domestic price and wage nominal rigidity last in average one year. This is line with the findings of Alvarez et al. (2006). They provide a comprehensive revue of the literature concerning micro-data analysis of price stickiness for the Euro-area. More exactly, they report that Euro-area CPI and PPI price duration last respectively 13 and 10.8 months. In turn, we assume that price duration last 7 months for import prices. The fact that import price duration is assumed to be shorter than domestic price stems from the fact that exchange rate volatility contributes to frequent changes in import prices. Concerning the l.o.p gap coefficient in the interest rate rule, we set

[12] See apppendix B for detailed and formal derivation of the long-horizon forecast and the GVAR specification.

a low value of 0.05 and a relatively narrow range of parameters with a standard deviation that amounts to 0.05 for the prior given the trade-off that the monetary has to face between stabilizing output gap and l.o.p gap. Finally, prior mean of the volatility of exchange rate corresponds to the mean of the different currencies standard error obtained with an ordinary least square estimation of a first order autoregressive process.

5 Results

5.1 Posterior estimates

Results obtained with the Metropolis-Hasting algorithm are presented in Table C in the appendix. We report posterior mode of the structural parameters for two different specifications of the model as regards to the methodology used for computing steady state of variables. The first specification, labeled "model1" in the Table, uses deviation of variables from GVAR estimates of the steady state in order to estimate structural parameters of the model. In turn, the second specifiation, labeled "model2" in the Table, uses variables detrended by a linear trend and demeaned. This is the common filtering procedure used in the DSGE literature and, thus, will serve us as a benchmark throughout the analysis.

First, the estimate of the degree of habit formation is around 0.5. These estimated values are reasonable. For instance, Smet and Wouters (2003) found an estimate equal to 0.55. Walque et al. (2005) in turn have found a higher estimate equal to 0.74 for the Euro-area and 0.72 for the United States. The estimated value of the labor Frish elasticity is around 2 apart from that of the Euro-area and Japan for which it amounts respectively to 0.65 and 0.5.

Second, posterior mode of the persistence parameters amounts to around 0.9. However, estimates of the autoregressive coefficient in the inflation objective are more heterogeneous. Namely, it is lower for Japan and Switzerland, and amounts respectively to 0.70 and 0.63, but remains higher for the rest of countries.

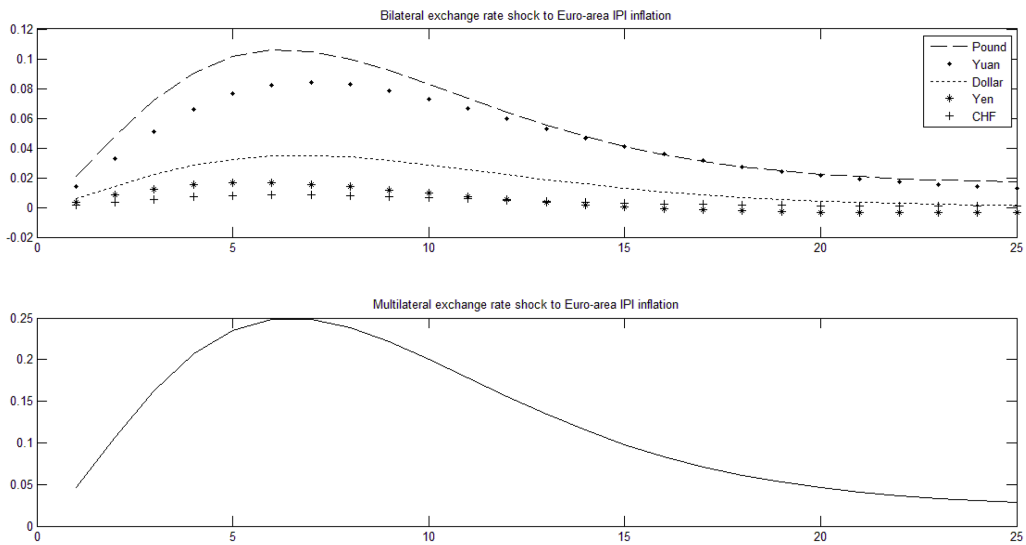
Third, concerning nominal price rigidity, posterior estimates of Calvo parameters for domestic prices amount to around 0.8. These correspond to an average price duration of 1.5 year. Domestic inflation indexation parameters are estimated to be around 0.4. These values are slightly higher compared to the estimated value of 0.21 found by Adolson et al. (2005) and Walque et al. (2005), but are in line with the estimated value of 0.42 found by Smet and Wouters (2003) and Christoffel et al. (2008). In turn, estimates of Calvo parameters for import prices are equal to around 0.7 which corresponds to an average duration of 3 quarters. It is worth noting however that nominal price rigidity is higher for the Euro area. Estimates of Calvo parameters for domestic and import prices amount respectively to 0.94 and 0.85. That is, higher persistence in the time varying inflation objective does not permit to have a lower price stickiness. One plausible explanation is the following. To match real exchange rate volatility and persistence, Chari et al. (2002) argue that the model needs price stickiness and inflation inertia by the means of Calvo and inflation indexation parameters. However, and as is argued by Justiniano and Preston (2004), the introduction of the habit formation has a drastic implication to parameter estimates. Increase in the degree of habit formation permits to match real exchange rate volatility by an increase of the output volatility. Thus, and however, to match real exchange rate persistence, price stickiness and inflation persistence have to increase. This increase may even overstate for that elasticities of substitution between domestic and foreign goods given by import share matrix coefficients are fixed in our study. That is, high estimate of inflation objective, inflation indexation and price stickiness parameters is necessary in order for the model to generate persistence in real exchange rate in presence of external habit.

Fourth, concerning monetary policy parameters, interest rate response to l.o.p gap is low except for the United Kingdom. It indicates that monetary authority reacts less to the deviation from the law of one price. There are two main reasons behind this finding. First, and as is explained above, stabilization of the l.o.p gap could be pursued but at the cost of the output gap deviation. That is, there is a trade-off between l.o.p gap and output gap stabilization. Second, nominal rigidity, and as far as exchange rate pass-through is concerned, induces a **persistent** but **low** changes in import price inflation following exchange rate changes that may stem from various shocks in the model. This will be further illustrated in the next section on impulse response function.

5.2 Impulse response

To start with the impulse response analysis, let us consider standard shocks that generate responses of nominal and real variables which are known to follow a given particular shape. This permits to have a general idea on the dynamic properties of the model. The dynamic effects of interest rate rate shock, interpreted as an unexpected monetary policy shock are given in Figure E.1 in the appendix. Responses of output, real wage and domestic inflation have the standard hump-shaped form as in closed economy model. However, response of real wage is much more persistent compared to those of output and inflation where they reach a peak within one year. Impulse responses following an inflation targeting shock are depicted in Figure E.2. It seems clear that a temporary and unexpected rise in inflation target induce a persistent rise in domestic inflation and real wage. The duration of the effect on output is heterogeneous across countries where it is more persistent for the Euro-area. In Figure E.3, preference shock induces a hump-shaped rise in output and a rather persistent rise in domestic inflation and real wage. Given the assumption of home consumption bias and fixed elasticity of substitution between home and foreign goods given by import share α_{ij}, preference shock has a reduced and non-persistent effect on consumption and, hence, on output. Finally, impulse responses to a domestic mark-up shock are given in Figure E.4. It induces a decrease in output and real wage. In turn, domestic inflation rise but the effect is short-lived. These findings give a support to a certain isomorphism between the dynamics of closed and open economy model. Namely, concerning monetary policy shock, even if one could not match exactly the response obtained under an identified structural VAR due to the presence of various shocks and new channel for monetary policy, the dynamics are very similar.

If we turn to exchange rate pass-through analysis. Impulse response of the Euro-area import price inflation following an exchange rate shock is given in the following figure.



It is worth noting that the extent of the response is different from exchange rate pass-through. The latter is driven by the degree of nominal rigidity but influence the extent of the import price inflation impulse response.[13] The top panel of the figure depicts the cumulative responses of the Euro-area aggregate import price changes following a bilateral nominal exchange rate shock, namely a depreciation of Euro which is formally defined as a decrease in $\hat{e}_{it}$. It is evident that depending on the currency, the extent of the effect is different. Namely, the highest impact stems from the Pound whereas the lowest from the Swiss Franc. The bottom panel in turn depicts the cumulative response of the Euro-area import price following a shock to Euro currency that induces a depreciation of the effective or multilateral nominal exchange rate. It is clear that the impact is higher than that of the bilateral shock. Therefore, these findings indicate that exchange rate pass-through analysis should make the distinction between bilateral and multilateral exchange rate changes. In this simple example, all bilateral nominal exchange rates are assumed to depreciate vis-à-vis the Euro. There are situations in which bilateral exchange rates move in opposite direction. In this case, separating bilateral effects would permits to avoid aggregation downward bias in the extent of pass-through.

[13] A formal way to obtain the extent of exchange rate pass-through is to evaluate change in import price (not import price inflation) in percentage of change in nominal exchange rate following an exchange rate shock. Moreover, it is worth noting that changes in exchange rate can stem from other shocks such as monetary policy (interest rate) shock, risk premium shock, ...

Moreover, the response of the import price inflation is hump-shaped and reach a peak roughly after 2 years. This indicates that nominal frictions generate a persistent impact on import price inflation. This is a key issue for the exchange rate channel of monetary policy analysis. As can be seen, import price inflation rise by 0.04% upon impact following an effective Euro depreciation. After 2 years, the cumulative sum of the impact amounts to 0.25%. That is, nominal import price rigidity, and hence incomplete exchange rate pass-through, generates a persistent but reduced impact of exchange rate changes on import price inflation. Therefore, and combined with the weight attributed to import price inflation into consumer price inflation, the monetary authority could pursue a stable inflation target with less action. The latter is reinforced by the presence of trade-off between output gap and law of one price gap. These explain the low estimated value of monetary policy parameters r_{ψ_i} that are affected to the l.o.p gap. This finding is in line with the extensive studies conducted by the Inflation Persistence Network (IPN) team in the European Central Bank.

5.3 Variance decomposition

Table D in the appendix reports conditional variance decomposition of the Euro-area aggregate import price. It permits to formally assess the contribution of different shocks to the variability of the variable of interest at different horizons. We choose to present decomposition of the import price inflation volatility of the Euro-area for eight quarters. The first quarter gives the contribution of shocks upon impact and can be considered as a short run decomposition. In the analysis of exchange rate pass-through, defining long term as two years is sufficient. Apart from foreign mark-up shock, we only report shocks that explain at least one percent of the variance of the import price. If one refer to the traditional exchange rate pass-through equation of Goldberg and Knetter (1997), movements in import price are explained by three major factors that are nominal exchange rate, mark-up and marginal cost. Other variables are also introduced to capture demand conditions, the degree of local market competition and market share. An important strand of the literature, which is the Pricing-to-Market (PTM) or Local Currency Pricing (LCP) literature, argues that incomplete pass-through arises due to adjustment of the mark-up following exchange rate movements in order to maintain market share. Results from variance decomposition presented below highlight some interesting findings.

First, if one consider decomposition upon the impact of shocks which is given in the first column, exchange rate movements contribute to 70.83% of the import price volatility. This confirms the fact that import prices are characterized with lower price stickiness than domestic producer prices. Moreover, it is possible with the multi-country specification to identify the role played by each nominal bilateral exchange rate vis-à-vis each trade partner. This leads to a distinction that has to be made between **bilateral** and **multilateral** (or effective) exchange rate pass-through. As one can see, a large part of the Euro-area import price volatility explained by exchange rate movements comes from the Pound bilateral exchange rate. Upon the impact, the latter explains 45% of the import price volatility. This confirms the important role played by the United Kingdom as trade partner for the Euro-area. Concerning the Chinese-Renminbi, the model reports that it explains 20% percent of the import price volatility upon impact. Nevertheless, care must be taken when interpreting this result. The fact that the Chinese-Renminbi explains such a large part of import price volatility comes more from its comovements with the US-Dollar than anything else. In fact, the Chinese authority allowed officially the use of the Chinese-Renminbi as invoicing currency in China's foreign trade only since 2005. Moreover, and despite this official decision, Chinese firms continue to price their goods generally in US-Dollar leading Chinese authorities to conduct in July 2009 a trial scheme where some enterprises are asked to invoice their trade in the Chinese-Renminbi as argued in Cui et al.(2009).[14] The US-Dollar explain 3% of the Euro-area import price volatility whereas only 1% and 0.25% are explained respectively by the Japanese-Yen and Swiss-Franc.

Second, foreign mark-up shock plays a minor role in explaining the volatility of the Euro-area import price. Its influence is less than 1% for all countries considered and conditional on all quarters. Under the assumption that international market is competitive and the law of one price holds at the dock, mark-up shocks have a reduced influence in international price of exported goods. Combined with price setting behavior of the monopolistic importing firms, they have a negligible impact on the volatility of import prices. This is an argument in favor of the Producer Currency Pricing (PCP) behavior rather than LCP-PTM at the export side.

Third, upon the impact, inflation objective shock explained 12.47% of the import price volatility. It is common in the empirical literature of pass-through to proxy marginal cost with CPI inflation of the trade partner. If one consider that the monetary authority follows an inflation target, deviation from this objective will impact the CPI inflation dynamics and hence the marginal cost. Therefore, one can interpret without lost of generality inflation objective shock as marginal cost shock. As is shown in the Table, the United Kingdom inflation objective shock explains 6.28% of the import price of the Euro-area volatility upon the impact. Under the context of regional interdependency, it is not surprising to have marginal cost dynamics influenced by that of the United Kingdom.

Fourth, although to a lesser extent, preference shock influences import price variability. On the one hand, the fact that domestic (Euro-area) shock has a negligible impact comes from the existence of home bias consumption. On the other hand, foreign preference shocks will have an influence to foreign inflation dynamics. This will influence foreign marginal cost and, hence, import price.

6 Conclusion

This study estimates a multi-country open economy DSGE model under the assumption of incomplete exchange rate pass-through. It builds on the seminal paper of Monacelli (2003)

[14]See Bacchetta and Van Wincoop (2005) and Goldberg and Tille (2008) for the role of currency-invoicing in the extent of exchange rate pass-through and the role played by a vehicle currency in international trade.

but relaxes the small open economy framework in order to capture some important features and dynamics of an open economy model where countries are endogenously related and where deviation from the law of one price generated by nominal price rigidity is allowed. Moreover, within a context of a multi-country analysis, one important issue that arises is the existence of a long term relationship between variables within the economy or between domestic and foreign variables. In this study, we use Global (GVAR) to model long-run international linkage between countries and calculate the steady state by the means of the long-horizon forecast.

First, and as regards to exchange rate pass-through analysis, we found that exchange rate pass-through still remains when firms adjust prices but its impact on the aggregate import prices is limited and delayed by the presence of nominal price rigidity. This model presents results in this direction, namely that exchange rate volatility accounts for a large part, more precisely 70%, of the Euro-area import price inflation variability whereas foreign mark-up shocks have a reduced impact. Second, it is more convenient to make distinction between exchange rate pass-through that stems from bilateral and multilateral exchange rate movements. This permits to take into account explicitly the role of currency invoicing and namely the role of a vehicle currency in the extent of pass-through. Third, the presence of incomplete exchange rate pass-through has a stark implication in the conduct of the monetary policy. It induces a new channel of the monetary policy and at the same time a trade-off between output gap and law of one price gap stabilization. Moreover, exchange rate changes have a reduced and persistent impact on import price inflation due to the presence of nominal rigidity. Combined with the home consumption bias assumption, less action is needed for the monetary authority to achieve a certain inflation target as far as exchange rate pass-through is concerned.

It is worth noting that the primary focus of this study is to obtain tractability of the complex mechanism underlying the model under the multi-country assumption. Nevertheless, this is achieved to a certain extent at the expense of some important features of the model such as the capital accumulation dynamics. This puts a pressure on the nominal rigidity parameters in order for the model to generate enough volatility to match the data. Though more complicated, it is interesting for future research to extend the model with more robust dynamics by introducing investment and various shocks such as the risk premium, equity premium and investment shocks. Moreover, using long horizon forecast of the GVAR to estimate steady state of variables permits to circumvent the "black box" property but, however, presents one major drawback. Indeed, steady state estimate values will depend on the GVAR specification. Therefore, it is also interesting for future research to take into account structural breaks, to mention only the 2007 global crisis, in the estimation of the steady states.

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A Model details

A.1 Households

Households h within a country i share the same preference technology. They maximize a string of discounted future value of utilities given by:

$$E_t \sum_{k=0}^{\infty} \beta^k U_{i,t+k}(h)$$

with period t felicity function defined as:

$$U_{i,t}(h) = \ln(C_{it} - H_{it}) - \frac{L_{it}^{1+\psi}(h)}{1+\psi} \tag{16}$$

where C_{it} and $L_{it}(h)$ represent respectively the consumption index and the individual labor supply (number of hours worked) of a representative home agent. H_{it} is an external habit taken as exogenous by the household and defined as $H_{it} = hC_{it-1}$. Positive parameter ψ represents the inverse of the intertemporal elasticity of labor supply.

Given that all goods are tradable, consumption bundles are composed of goods produced by home firms but also of goods imported from the rest of the world. We assume that consumption index is represented by the following Cobb-douglas preference:

$$C_{it} = \frac{\prod_{j=1}^{N} C_{ijt}^{\alpha_{ij}}}{\prod_{j=1}^{N} \alpha_{ij}^{\alpha_{ij}}} \tag{17}$$

where C_{ijt} represents country i individual households' consumption of goods imported from country j.

Following Smets and Wouters (2003), consumption of goods produced in country j is assumed to be a CES function defined as:

$$C_{ijt} = \left(\int_0^1 \ddot{C}_{i,t}(f_j)^{\frac{1}{1+\lambda_{jt}^p}} df_j \right)^{1+\lambda_{jt}^p} \tag{18}$$

where $\ddot{C}_{i,t}(f_j)$ is the consumption of individual good produced by an individual foreign firm $f_j \in [0,1]$ with $j \in \{1,\ldots,N\}$. The elasticity of substitution between varieties of products λ_{jt}^p is assumed to be random and is given by:

$$ln(1+\lambda_{jt}^p) = ln(1+\lambda_j^p) + \varepsilon_{jt}^p$$

It will turn out that $(1+\lambda_{jt}^p) = \lambda_j^{p\prime}$ is the time-varying markup of prices over marginal costs at the intermediate goods level. Thus, ε_{jt}^p is interpreted as a **good markup** or a **cost-push shock** with $E\left\{\varepsilon_{jt}^p\right\} = 0$ and $E\left\{(\varepsilon_{jt}^p)^2\right\} = \sigma_{\varepsilon_j^p}^2$.

A.1.1 Prices and demand

With consumption index preference (17), the overall home-currency consumption-based[15] price index (CPI) is given by:

$$P_{it} = \prod_{j=1}^{N} P_{ijt}^{\alpha_{ij}} \tag{19}$$

whereas the aggregate import price index (IPI) is defined as:

$$P_{it}^{f} = \prod_{\substack{j=1 \\ j \neq i}}^{N} P_{ijt}^{\alpha_{ij}} \tag{20}$$

where P_{ijt} denotes the home-currency (country i) price index of good imported from country j, which using the CES function (18) is defined as:

$$P_{ijt} = \left(\int_0^1 P_{ijt}(f_j)^{-1/\lambda_{jt}^p} df_j \right)^{-\lambda_{jt}^p} \tag{21}$$

with $P_{ijt}(f_j)$ being the consumer price of good f_j in country i.

The allocation of country i representative individual's demand across differentiated goods f_j produced within a country j is given by:

$$\ddot{C}_{i,t}(f_j) = \left(\frac{P_{ijt}(f_j)}{P_{ijt}} \right)^{-(1+\lambda_{jt}^p)/\lambda_{jt}^p} C_{ijt} \tag{22}$$

and finally, the optimal allocation of expenditures between goods produced in different countries $j \in \{1, \ldots, N\}$ is given by:

$$C_{ijt} = \alpha_{ij} \left(\frac{P_{ijt}}{P_{it}} \right)^{-1} C_{it} \tag{23}$$

Using this last equation and the property of import share coefficients $\sum_{j=1}^{N} \alpha_{ij} = 1$, one can derive total expenditure. That is,

$$P_{it} C_{it} = \sum_{j=1}^{N} P_{ijt} C_{ijt}$$

[15] As well explained in Obstfeld and Rogoff (1996), this is the price index defined as the minimal expenditure in terms of country i's domestic currency needed to purchase one unit of consumption index.

A.1.2 Household's optimization problem

Country i representative household has a budget constraint of the form:

$$P_{it}C_{it} + E_t\left(Q_{it+1}B_{it+1}\right) \leq B_{it} + W_{it}(h)L_{it}(h) + T_{it} \tag{24}$$

where B_{it+1} is the nominal payoff in period $t+1$ of portfolio held at the end of period t whereas Q_{it+1} is the asset market price of nominal bonds. $W_{it}(h)$ is the nominal wage and T_{it} denotes a lump-sum taxe or transfer. Formally,

$$Q_{it+1} = \frac{1}{R_{it}^n} = \frac{1}{1+i_{it}}$$

where i_{it} denotes country i's one period nominal interest rate that prevails on date t.

Representative household chooses a string of variables $\{C_{it+k}, L_{it+k}(h), B_{it+k+1}\}_{k=0}^{\infty}$ that maximize a string of discounted future value of its utilities given by:

$$E_t \sum_{k=0}^{\infty} \beta^k \left[\ln(C_{it+k} - H_{it+k}) - \frac{L_{it+k}^{1+\psi}(h)}{1+\psi}\right]$$

subject to budget constraint (24).

First order conditions to this optimization problem with respect to C_{it+k} and B_{it+k+1} yield the standard optimal stochastic Euler equation. In log-linear terms, it is given by:

$$\hat{c}_{it} = \frac{h}{1+h}\hat{c}_{it-1} + \frac{1}{1+h}E_t\left\{\hat{c}_{it+1}\right\} - \frac{1-h}{1+h}\left(\hat{r}_{it}^n - E_t\left\{\hat{\pi}_{it+1}\right\}\right) \tag{25}$$

A.1.3 Wage setting problem

Households supply monopolistically a distinctive variety of labor to home firms and set nominal wages in a staggered contracts fashion à la Calvo (1983). That is, individual household h resets its nominal wage only after receiving a random price-change signal with constant probability $1-\theta_{iW}$, so that $W_{it}(h) = \tilde{W}_{it}^o(h)$. However, whenever household is not allowed to adjust its contracts, wage is indexed to last period CPI inflation[16] rate according to the following **indexation** rule:

$$W_{it}(h) = \left(\frac{P_{it-1}}{P_{it-2}}\right)^{\gamma_{iw}} W_{it-1}(h) = \left(\Pi_{it-1}\right)^{\gamma_{iw}} W_{t-1}(h) \tag{26}$$

If $\gamma_{iw} = 0$ there is no indexation, whereas if $\gamma_{iw} = 1$ there is a perfect indexation of wage to past inflation. Therefore, wages remain fixed on average $1/\left(1-\theta_{iW}\right)$ periods. When setting

[16] We follow Erceg et al. (1999), Smets and wouters (2003), and Adolfson et al. (2007) when taking CPI inflation as wage indexation. Some open DSGE model such as the SIGMA model by Erceg et al. (2006) and that of Jacquinot et al. (2006) instead use wage inflation as indexation.

nominal wage, household chooses $W_{it}(h)$ to maximize:

$$E_t \sum_{k=0}^{\infty} (\beta\theta_{iW})^k \left[\ln(C_{it+k} - H_{it+k}) - \frac{L_{it+k}^{1+\psi}(h)}{1+\psi} \right]$$

subject to budget constraint (24), labor demand (36) and the equality $W_{it}(h) = \tilde{W}_{it}^{o}(h) X_{itk}^{w}$, where:

$$X_{itk}^{w} = \begin{cases} \Pi_{it}^{\gamma_{iw}}.\Pi_{it+1}^{\gamma_{iw}}.\cdots.\Pi_{it+k-1}^{\gamma_{iw}} \text{ for } k \geq 1 \\ 1 \text{ for } k = 0 \end{cases}$$

θ_{iW}^{k} is the probability that the wage $W_{it}(h)$ set at time t still holds k periods ahead. The first order condition to this optimization problem is standard. The log-linear version around steady state yields:

$$\begin{aligned} & \hat{w}_{it}^{o}(h) - \gamma_{iw}\hat{p}_{it-1} \\ = \; & (1-\beta\theta_{iW}) E_t \left\{ \sum_{k=0}^{\infty} (\beta\theta_{iW})^k \left[(\hat{w}_{it+k} - \gamma_{iw}\hat{p}_{it+k-1}) - \frac{1}{k_w}\hat{\mu}_{it+k}^{w} + \frac{1}{k_w}\varepsilon_{it}^{w} \right] \right\} \end{aligned} \tag{27}$$

where $k_w = 1 + \psi\left(1+\lambda_i^w\right)/\lambda_i^w$ and $\hat{\mu}_{it}^{w}$ denotes the **labor market friction** defined as the difference between the real wage and the marginal rate of substitution. That is,

$$\hat{\mu}_{it}^{w} = \hat{w}_{it} - \hat{p}_{it} - \psi\hat{l}_{it} - \frac{1}{1-h}\left(\hat{c}_{it} - h\hat{c}_{it-1}\right) \tag{28}$$

A.1.4 Aggregate home wage dynamics

Given that, on the one hand, all individual households that adjust in period t choose the same wage $\tilde{W}_{it}^{o}$, and on the other hand, the average wage of households that do not adjust is simply the last period wage level W_{it-1} indexed with past CPI inflation, we can rewrite the wage index (37) in terms of wage inflation defined as $\Pi_{it}^{w} = W_{it}/W_{it-1}$ and in log-linear deviation around steady state. That is,

$$\hat{\pi}_{it}^{w} = \theta_{iW}\gamma_{iw}\hat{\pi}_{it-1} + (1-\theta_{iW})\left(\hat{w}_{it}^{o} - \hat{w}_{it-1}\right) \tag{29}$$

Therefore, using wage inflation dynamics (29) and reset wage equation (27), we have an expression determining domestic country i's real wage law of motion as a function of labor market friction variable. That is,

$$\begin{aligned} \widehat{wr}_{it} \; = \; & \frac{1}{1+\beta}\widehat{wr}_{it-1} + \frac{\beta}{1+\beta}E_t\left\{\widehat{wr}_{it+1}\right\} + \frac{\gamma_{iw}}{1+\beta}\hat{\pi}_{it-1} \\ & - \frac{1+\beta\gamma_{iw}}{1+\beta}\hat{\pi}_{it} + \frac{\beta}{1+\beta}E_t\left\{\hat{\pi}_{it+1}\right\} - \delta_i^w\hat{\mu}_{it}^{w} + \delta_i^w\varepsilon_{it}^{w} \end{aligned} \tag{30}$$

where $\delta_i^w = \frac{(1-\theta_{iW})(1-\beta\theta_{iW})}{(1+\beta)\theta_{iW}k_w}$. Note that by definition, $\widehat{mc}_t^{w} = -\hat{\mu}_{it}^{w}$, where $\widehat{mc}_t^{w}$ is the (log-deviation from steady state) real marginal cost of supplying labor.

A.2 Domestic producers

In the domestic market i, there exists a *continuum* of monopolistic competitive firms, indexed by $f_i \in [0,1]$. Each firm produces a single good using a *variety* of labor as the only input factor. Let $Y_{it}(f_i)$ denotes the output of differentiated good of firm f_i and $L_{it}(h, f_i)$ its demand for labor input h. To obtain symmetry in the model, assume that the production function is given by:

$$Y_{it}(f_i) = A_{it} L_{it}(f_i) \tag{31}$$

with the composite labor $L_{it}(f_i)$ defined as:

$$L_{it}(f_i) = \left[(\mathcal{P}_i)^{-\frac{\lambda_{it}^w}{1+\lambda_{it}^w}} \int_0^{\mathcal{P}_i} L_{it}(h, f_i)^{\frac{1}{1+\lambda_{it}^w}} dh \right]^{1+\lambda_{it}^w} \tag{32}$$

where the degree of substitutability among different types of labor λ_{it}^w is assumed to be random and is given by:

$$ln(1+\lambda_{it}^w) = ln(1+\lambda_i^w) + \varepsilon_{it}^w$$

In the **flexible-wage** economy, $(1+\lambda_{it}^w) = \lambda_{it}^{w\prime}$ is the real wage mark-up over the usual ratio of marginal disutility of labor to the marginal utility of consumption. Thus, ε_{it}^w is interpreted as a **wage markup shock** with $E\{\varepsilon_{it}^w\} = 0$ and $E\left\{(\varepsilon_{it}^w)^2\right\} = \sigma^2_{\varepsilon_{it}^w}$.

We assume that the productivity follows a first order autoregressive process. That is,

$$\hat{a}_{it} = \rho_{a_i} \hat{a}_{it-1} + \varepsilon_{a_i t} \tag{33}$$

where $\left|\rho_{a_i}\right| < \rho < 1 \ \forall i \in \{1, \ldots, N\}$ and $\varepsilon_{a_i t}$ is the idiosyncratic productivity shock with $E(\varepsilon_{a_i t}) = 0$ and $E(\varepsilon_{a_i t}^2) = \sigma^2_{\varepsilon_{a_i}}$.

A.2.1 Cost minimization problem

Given the wage index W_{it}, each firm f_i chooses $L_{it}(f_i)$ to minimize its production cost:

$$\frac{W_{it}}{P_{i,t}^d} L_{it}(f_i)$$

subject to

$$A_{it} L_{it}(f_i) - \bar{Y}_i(f_i) \geq 0$$

where $P_{i,t}^d$ is the aggregate domestic producer price index defined as:[17]

$$P_{i,t}^d = \left(\int_0^1 P_{it}^d(f_i)^{-\frac{1}{\lambda_{it}^p}} df_i \right)^{-\lambda_{it}^p} \tag{34}$$

[17] Notice that $P_{it}^d = P_{iit}$, thus aggregate producer price index will be the same as (21) for $j = i$.

The log-linear version of the first order condition of this minimization problem yields the following standard equation of real marginal cost *expressed in terms of domestic producer price index* $P^d_{i,t}$:

$$\widehat{mc}_{it} = \hat{w}_{it} - \hat{p}^d_{i,t} - \hat{a}_{it} \tag{35}$$

Note that real marginal cost will be common across domestic firms because the right hand side of the equation does not depend on f_i.

A.2.2 Labor demand

Given the optimal aggregate level of labor $\bar{L}(f_i)$ chosen in the cost minimization problem above, firm f_i chooses the best combination of the different types of labor when setting its labor demand,

$$L_{it}(h) = \frac{1}{\mathcal{P}_i}\left[\frac{W_{it}(h)}{W_{it}}\right]^{-\frac{1+\lambda^w_{it}}{\lambda^w_{it}}} L_{it} \tag{36}$$

Substituting into the expression of $L_{it}(f_i)$ in (32) yields the expression of the aggregate wage index:

$$W_{it} = \left[\frac{1}{\mathcal{P}_i}\int_0^{\mathcal{P}_i} W_{it}(h)^{-\frac{1}{\lambda^w_{it}}} dh\right]^{-\lambda^w_{it}} \tag{37}$$

A.2.3 Price setting

Domestic firm f_i faces a downward slopping demand from domestic households and foreign households via retailers that import goods where the law of one price holds "*at the dock*". That is,

$$\mathfrak{C}_{it}(f_i) = \sum_{j=1}^{N} \mathfrak{C}_{jit}(f_i)\mathcal{P}_j \tag{38}$$

where $\mathfrak{C}_{jit}(f_i)$ is the quantity of goods imported by country j's retailers that is produced by country i's firm f_i, and is defined as:

$$\mathfrak{C}_{jit}(f_i) = \left(\frac{P^d_{it}(f_i)}{P^d_{it}}\right)^{-\frac{1+\lambda^p_{it}}{\lambda^p_{it}}} \mathfrak{C}_{jit} \tag{39}$$

where $P^d_{it}(f_i)$ is the producer price of firm f_i, P^d_{it} is the aggregate producer price index of country i, and $\mathfrak{C}_{jit}$ is the quantity of goods imported by country j's retailers from country i.

Like wage setting optimization, it is assumed that **prices are sticky** and firms set prices in a staggered fashion à la Calvo (1983). A fraction $1 - \theta_{iH}$ of randomly selected firms set new prices $\tilde{P}_{it}^{d,o}(f_i)$ each period, whereas a fraction θ_{iH} of firms keep their prices unchanged and simply adopt the following indexation rule:

$$P_{it}^d(f_i) = \left(\frac{P_{it-1}^d}{P_{it-2}^d}\right)^{\gamma_{id}} P_{it-1}^d(f_i) = \left(\Pi_{it-1}^d\right)^{\gamma_{id}} P_{it-1}^d(f_i)$$

Note that, the probability of re-optimizing in any given period is independent of the time elapsed since firms last reset price. Therefore, prices are sticky in average duration of $(1-\theta_{iH})^{-1}$ and θ_{iH} is interpreted as the index of **price stickiness**. Formally, individual firm f_i solves the following problem:

$$\max_{\tilde{P}_{it}^{d,o}(f_i)} \sum_{k=0}^{\infty} \theta_{iH}^k E_t \left\{ Q_{it,t+k} \left[\tilde{P}_{it}^{d,o}(f_i) X_{itk}^d \mathfrak{C}_{it+k}(f_i) - \Psi_{it+k}\left(\mathfrak{C}_{it+k}(f_i)\right) \right] \right\}$$

subject to the sequence of demand constraints (38). $Q_{it,t+k}$ is the stochastic discount factor for nominal payoffs, $\Psi_{it+k}(\cdot)$ is the cost function and X_{itk}^d is defined as:

$$X_{itk}^d = \begin{cases} \left(\Pi_{it}^d\right)^{\gamma_{id}} \cdot \left(\Pi_{it+1}^d\right)^{\gamma_{id}} \cdot \dots \cdot \left(\Pi_{it+k-1}^d\right)^{\gamma_{id}} \text{ for } k \geq 1 \\ 1 \text{ for } k = 0 \end{cases}$$

Log-linear deviation from steady state of the first order condition of this optimization problem is typically standard. It is straightforward to derive an expression determining domestic inflation as a function of the deviation of marginal cost from its steady state value. That is,

$$\hat{\pi}_{it}^d = \frac{\gamma_{id}}{1+\gamma_{id}\beta} \hat{\pi}_{it-1}^d + \frac{\beta}{1+\gamma_{id}\beta} E_t \left\{ \hat{\pi}_{it+1}^d \right\} + \lambda_i^d \left(\widehat{mc}_{it} + \varepsilon_{it}^p \right) \tag{40}$$

where $\lambda_i^d = \frac{(1-\beta\theta_{iH})(1-\theta_{iH})}{(1+\gamma_{id}\beta)\theta_{iH}}$ and $\widehat{mc}_{it}$ denotes log-deviation of real marginal cost, deflated by producer price index $P_{i,t}^d$, from its steady-state value.

A.3 Importing firms

There exist a continuum of local retailer firms in country i indexed by $l_i \in [0,1]$ that import goods in international trade market where the law of one price holds "*at the dock*". Nevertheless, retailers behave as a monopolistic firm when setting their home currency price of imported goods. Hence, deviations from the law of one price occur due to the optimal markup problem that the importing firms have to solve when setting prices. We assume that prices are sluggish and are set in a staggered fashion à la Calvo (1983). Denote θ_{iF} the fraction of local retailers that keep their local currency prices unchanged in period t even if nominal exchange rate fluctuates and simply follow the following indexation rule:

$$P_{ijt}(f_j) = \left(\frac{P_{ijt-1}}{P_{ijt-2}}\right)^{\gamma_{if}} P_{ijt-1}(f_j) = \left(\Pi_{it-1}^{jf}\right)^{\gamma_{if}} P_{ijt-1}(f_j)$$

where Π_{it-1}^{jf} is the import inflation that comes from country j. This behavior generates a deviation from the law of one price in the short run until price will be adjusted. In average, prices remain fixed during $(1-\theta_{iF})^{-1}$ periods.[18] This is in line with a large strand of recent empirical studies concerning exchange rate pass-through.[19] Essentially, it is shown that pass-through estimates are incomplete in the short run but become, gradually, complete in the long run.

Formally, country i's local retailer $l_i(f_j)$ that import a single good f_j from country j faces a downward slopping demand (22) from domestic households. Therefore, individual import firm solves the following maximization problem:

$$\max_{\tilde{P}_{ijt}^{o}(f_j)} \sum_{k=0}^{\infty} \theta_{iF}^{k} E_t \left\{ Q_{it,t+k} \left[\tilde{P}_{ijt}^{o}(f_j) X_{itk}^{jf} - E_{ijt+k} P_{jt+k}^{d}(f_j) \right] \mathfrak{C}_{ijt+k}(l_i(f_j)) \right\}$$

subject to the sequence of demand constraints given by:

$$\mathfrak{C}_{ijt+k}(l_i(f_j)) = \ddot{C}_{i,t+k}(f_j) = \left(\frac{\tilde{P}_{ijt}^{o}(f_j) X_{itk}^{jf}}{P_{ijt+k}} \right)^{-\frac{1+\lambda_{jt}^{p}}{\lambda_{jt}^{p}}} C_{ijt+k}$$

where $\ddot{C}_{i,t}(f_j) = \mathfrak{C}_{ijt}(l_i(f_j))$ is the country i's individual consumption of good produced by an individual firm f_j and imported by local retailer $l_i(f_j)$ from country j and

$$X_{itk}^{jf} = \begin{cases} \left(\Pi_{it}^{jf}\right)^{\gamma_{if}} \cdot \left(\Pi_{it+1}^{jf}\right)^{\gamma_{if}} \cdot \ldots \cdot \left(\Pi_{it+k-1}^{jf}\right)^{\gamma_{if}} & \text{for } k \geq 1 \\ 1 \text{ for } k = 0 \end{cases}$$

Log-linear deviation from steady state of the first order condition of this optimization problem yields:

$$\begin{aligned} & \hat{p}_{ijt}^{o} - \gamma_{if} \hat{p}_{ijt-1} \\ = \quad & (1-\beta\theta_{iF}) E_t \left\{ \sum_{k=0}^{\infty} (\theta_{iF}\beta)^k \left[\psi_{ij,t+k} + \hat{p}_{ijt+k} - \gamma_{if} \hat{p}_{ijt+k-1} + \varepsilon_{jt+k}^{p} \right] \right\} \end{aligned} \tag{41}$$

where ψ_{ijt}, defined in (6), is the **bilateral** l.o.p gap between country i and j. By definition, it is the difference between the price paid by importing firms in the world market and the home currency price of the imported goods. Therefore, it stands clear from the last equation that the l.o.p gap acts as marginal cost. Moreover, country i's aggregate (log-deviation) import price index evolves according to:

$$\hat{p}_{ijt} = \theta_{iF} \gamma_{if} \hat{\pi}_{it-1}^{jf} + \theta_{iF} \hat{p}_{ijt-1} + (1-\theta_{iF}) \hat{p}_{ijt}^{o} \tag{42}$$

[18] As pointed out by Obsteld and Rogoff (2000)[32], import price stickiness last in average 90 days.

[19] Among others, one can cite Campa and Goldberg (2002)[11], Anderton (2003) and Bailliu and Fujii (2004).

Using optimal condition (41), calvo import pricing law of motion (42), and the definition of import inflation $\hat{\pi}_{it}^{jf} = \hat{p}_{ijt} - \hat{p}_{ijt-1}$, we have an expression determining import inflation as a function of **bilateral** l.o.p gap:

$$\hat{\pi}_{it}^{jf} = \frac{\gamma_{if}}{1 + \gamma_{if}\beta} \hat{\pi}_{it-1}^{jf} + \frac{\beta}{1 + \gamma_{if}\beta} E_t \left\{ \hat{\pi}_{it+1}^{jf} \right\} + \lambda_i^f \left(\psi_{ijt} + \varepsilon_{jt}^p \right)$$

where $\lambda_i^f = \frac{(1-\beta\theta_{iF})(1-\theta_{iF})}{(1+\gamma_{if}\beta)\theta_{iF}}$.

A.4 Market clearing conditions

A.4.1 Goods market clearing

Import goods market clear when the quantity imported by retailer firms match exactly that consumed by households. That is, $\mathfrak{C}_{ijt}(f_j) = \ddot{C}_{i,t}(f_j)$ and $\mathfrak{C}_{ijt} = C_{ijt}$ $\forall i, j \in \{1, \ldots, N\}$.

Country i's goods market clear when aggregate demand of good f_i by domestic and foreign retailers equals its production by domestic firm. That is,

$$Y_{it}(f_i) = \sum_{j=1}^{N} \mathfrak{C}_{jit}(f_i) \mathcal{P}_j$$

Aggregating through domestic firm f_i by using a Dixit-Stiglitz aggregator analogous to that of consumption index (18), using the expression of individual demand (39) and domestic producer price index (34), one can derive the following aggregate good market clearing condition:

$$Y_{it} = \sum_{j=1}^{N} \mathcal{P}_j C_{jit} \tag{43}$$

Denote the share of country i's domestic product that is exported to country j as:

$$\varkappa_{ijt} = \frac{\mathcal{P}_j C_{jit}}{Y_{it}} \tag{44}$$

where $\sum_{j=1}^{N} \varkappa_{ijt} = 1$. Therefore, log-linearization of the aggregate good market clearing condition around steady state yields:

$$\hat{y}_{it} = \sum_{j=1}^{N} \varkappa_{ij} \hat{c}_{jit}$$

Using the optimal allocation of expenditures between goods produced in different countries j (23), the risk sharing condition (11), and the definition of effective terms of trade (3), domestic output and consumption are linked according to:

$$\hat{y}_{it} - h\hat{y}_{it-1} = (\hat{c}_{it} - h\hat{c}_{it-1}) + (1-h)\hat{s}_{it} + h\Phi_{it} \tag{45}$$

where Φ_{it} denotes country i's effective real interest rate differential defined as:

$$\Phi_{it} = \sum_{j=1}^{N} \varkappa_{ij} \left[\left(\hat{r}^{n}_{it-1} - \hat{\pi}^{d}_{it} \right) - \left(\hat{r}^{n}_{jt-1} - \hat{\pi}_{jt} \right) \right] \tag{46}$$

As can be seen here, the existence of the habit formation increases the volatility of the output via the real interest rate differential. This permits the model to generate volatility in the real exchange rate which is an important characteristics of the data.

A.4.2 Labor market clearing

Labor market clears when the aggregate firms' labor demand equals the aggregate households' labor supply:

$$\int_0^1 L_{it}(f_i) df_i = \int_0^{\mathcal{P}_i} L_{it}(h) dh$$

That is,

$$L_{it} = L_{it}(h) \mathcal{P}_i \tag{47}$$

A.4.3 Real marginal cost

Up to a first order approximation, the relationship between aggregate output and employment is obtained using the labor market clearing condition, the production technology (31) and the Dixit-Stiglitz aggregator index for domestic output, analogous to the one for consumption index (18). That is,

$$\hat{y}_{it} = \hat{a}_{it} + \hat{l}_{it} \tag{48}$$

Substituting the labor market friction (28) and the effective terms of trade (3) into the expression of the real marginal cost (35), and using the aggregate domestic output (48) and the good market clearing condition (45) yield:

$$\begin{aligned} \widehat{mc}_{it} &= \frac{1}{1-h} \left[(1 + \psi (1-h)) \hat{y}_{it} - h \hat{y}_{it-1} - h \Phi_{it} \right] \\ &\quad + \hat{\mu}^{w}_{it} - (1+\psi) \hat{a}_{it} \end{aligned} \tag{49}$$

Moreover, it is worth noting that under flexible price natural equilibrium, the real marginal cost is constant, there is no friction in the labor market and the exchange rate pass-through is complete. Therefore, the natural level of output evolves according to:

$$\hat{y}^{n}_{it} = \hat{a}_{it} + \frac{h}{1 + \psi (1-h)} \left(\hat{y}^{n}_{it-1} - \hat{a}_{it} \right) \tag{50}$$

A.4.4 Output and consumption

Using the link between CPI and PPI index (8) and good market clearing condition (45), one obtains in matrix notation an aggregate equation for the output. That is,

$$\hat{\mathbf{y}}_t - h\hat{\mathbf{y}}_{t-1} = \hat{\mathbf{c}}_t - h\hat{\mathbf{c}}_{t-1} + (1-h)(\mathbf{I}_N - \mathbf{M})\left(\hat{\mathbf{e}}_t - \hat{\mathbf{p}}_t^d\right) - (1-h)\mathbf{\Psi}_t + h\mathbf{\Phi}_t \tag{51}$$

where $\hat{\mathbf{y}}_t = (\hat{y}_{1t}, \ldots, \hat{y}_{Nt})'$ and $\hat{\mathbf{c}}_t = (\hat{c}_{1t}, \ldots, \hat{c}_{Nt})'$.

Moreover, using the international risk sharing condition (11), relative consumption and effective real exchange rate are linked according to:

$$(\mathbf{I}_N - \mathbf{M})(\hat{\mathbf{c}}_t - h\hat{\mathbf{c}}_{t-1}) = (1-h)\,\mathbf{q}_t$$

which combined with the aggregate output equation above and using the expression of the effective real exchange rate (9) yield a simple relationship between relative output and domestic prices. That is,

$$(\mathbf{I}_N - \mathbf{M})(\hat{\mathbf{y}}_t - h\hat{\mathbf{y}}_{t-1}) = (1-h)(\mathbf{I}_N - \mathbf{M})\left(\hat{\mathbf{e}}_t - \hat{\mathbf{p}}_t^d\right) + h\,(\mathbf{I}_N - \mathbf{M})\,\mathbf{\Phi}_t \tag{52}$$

Finally, substituting the last equation into (51) yields a link between consumption and output given by:

$$\hat{\mathbf{c}}_t - h\hat{\mathbf{c}}_{t-1} = \mathbf{M}(\hat{\mathbf{y}}_t - h\hat{\mathbf{y}}_{t-1}) + (1-h)\mathbf{\Psi}_t - h\mathbf{M}\mathbf{\Phi}_t \tag{53}$$

B GVAR estimates of the steady states

Estimating the steady state using Global VAR in this paper steems from two important limits in the empirical and theoretical macro-modelling literature. One the one hand, macro-econometric models such as the Global VAR suffer from the problem of identification procedure of the stuctural shocks. On the other hand, macro-economic models, namely the estimated DSGE model, suffer from the lack of economic interpretation of the statistical filtering procedure, qualified by Garratt et al. (2006) as a "black box", that is used to compute deviations of variables from steady states. The use of GVAR to estimate the steady state is introduced by Dees et al. (2009) and used by Dees et al. (2010) to estimate structural parameters of multi-country new Keynesian model. We follow this approach and use the long-horizon forecasts from a reduced-form cointegrating Global VAR to measure steady state of variables. Estimating structural parameters of the multi-country DSGE model, using variables expressed in deviation from their respective GVAR estimates of the steady states, permits to take into account the direct and indirect link between domestic and foreign variables, but also possible cointegration within domestic variables and between domestic and foreign variables. Moreover, structural analysis using the estimated multi-country DSGE model permits to circumvent the identification problem procedure.

Formally, deviation of a given variable from its steady state, $\hat{x}_t = x_t - \bar{x}_t$, could be acheived using GVAR model by decomposing variables into their permanent $x_t^P = \bar{x}_t$ and transitory component $x_t^T = \hat{x}_t$. In the case of stationary or trend-stationary variables, the steady state value $\bar{x}_t$ is respectively approximated by a constant term and a linear trend. However, there are cases where variables under consideration are likely to contain stochastic trends. Therefore, a given variable can be decomposed into transitory and permanent components as $x_t = x_t^T + x_t^P$ where x_t^P can be further decomposed into deterministic and stochastic components, that is, $x_t^P = x_{d,t}^P + x_{s,t}^P$.

The permanent deterministic component $x_{d,t}^P$ is defined as:

$$x_{d,t}^P = c + \theta t$$

where c is a constant and t a linear trend. The permanent stochastic component $x_{s,t}^P$ is defined as long horizon forecast of x_t. That is,

$$x_{s,t}^P = \lim_{h \longrightarrow \infty} E_t \left[x_{t+h} - x_{d,t+h}^P \right] = \lim_{h \longrightarrow \infty} E_t \left[x_{t+h} - c - \theta \left(t+h \right) \right]$$

where $E_t [\cdot]$ is the expectational operator conditional on all information available at the period t and $\lim_{h \longrightarrow \infty} E_t \left[x_{t+h}^T \right] = 0$.

As shown in Dees et al. (2009), the global error correction representation of the GVAR is given by the following equation:

$$\mathbf{G}\Delta\mathbf{x}_t = \mathbf{a} - \boldsymbol{\alpha}\boldsymbol{\beta}' \left[\mathbf{x}_{t-1} - \boldsymbol{\gamma}(t-1) \right] + \sum_{i=1}^{p-1} \Gamma_i \Delta\mathbf{x}_{t-i} + \mathbf{u}_t \tag{54}$$

The (kxk) link matrix $\mathbf{G}$ is the contemporaneous coefficients that contain trade weights ω_{ij} that verify $\sum_{j=1}^{N} \omega_{ij} = 1$ and $\omega_{ii} = 0$.[20] It reflects inter-country linkages by the means of bilateral trade. $\mathbf{x}_t = (x'_{1t}, x'_{2t}, ..., x'_{it})'$ is a global vector that contains individual country-specific vector of variables x_{it}. In this study, $x_{it} = (y_{it}, r_{it}^n, \pi_{it}^d, \pi_{it}^f, e_{it}, wr_{it}, p_t^{oil})'$ where y_{it} is the logarithm of real output, r_{it}^n the nominal interest rate, π_{it}^d the domestic price inflation, π_{it}^f the import price inflation, e_{it} the logarithm of the bilateral nominal exchange rate between country i and numeraire country, wr_{it} the logarithm of the real wage and p_t^{oil} the logarithm of the oil price. It is worth noting that the link matrix $\mathbf{G}$ is constructed such that:

- for the United Kingdom, China, Japan and Switzerland, individual country VARX model is composed of vector of domestic endogeneous variables $x_{it}^d = (y_{it}, r_{it}^n, \pi_{it}^d, \pi_{it}^f, e_{it}, wr_{it})'$ and foreign weakly exogeneous variables $x_{it}^* = (y_{it}^*, r_{it}^{n,*}, wr_{it}^*, p_t^{oil})'$,

[20] In this study, the trade weight is given by:

$$\omega_{ij} = \frac{IM_{ij} + EX_{ij}}{\sum_{j=1}^{N} \left(IM_{ij} + EX_{ij} \right)}$$

where IM_{ij} and EX_{ij} represent respectively the value of country i's import and export from country j.

- for the Euro-area, $x_{it}^d = (y_{it}, r_{it}^n, \pi_{it}^d, \pi_{it}^f, wr_{it})'$ and $x_{it}^* = (y_{it}^*, r_{it}^{n,*}, e_{it}^*, wr_{it}^*, p_t^{oil})'$,
- for the United States, $x_{it}^d = (y_{it}, r_{it}^n, \pi_{it}^d, \pi_{it}^f, e_{it}, wr_{it}, p_t^{oil})'$ and $x_{it}^* = (y_{it}^*, e_{it}^*, wr_{it}^*)'$

Within the context of international interdependencies and variables co-movements, the role of observed and unobserved common factors is crucial. In this study, the oil price is chosen as observed common factor and is considered as an endogeneous variable for the United States. For the rest of countries, it is considered as "long run forcing".[21] Moreover, $r_{it}^{n,*}$ is not included as part of the United States specific foreign variables. Given the major role of the United States financial variables, $r_{it}^{n,*}$ is unlikely to be long run forcing.

The global error correction representation of the GVAR in (54) can be re-arranged to become a VAR(p) specification given by:[22]

$$\mathbf{x}_t = \mathbf{b}_0 + \mathbf{b}_1 t + \sum_{i=1}^{p} \Phi_i \mathbf{x}_{t-i} + \epsilon_t$$

from which the permanent stochastic component $x_{s,t}^P$ is derived as:

$$\mathbf{x}_{s,t}^P = \mathbf{C}(1) \sum_{j=1}^{t} \epsilon_j \tag{55}$$

where $\mathbf{C}_i = \mathbf{C}_{i-1}\Phi_1 + \mathbf{C}_{i-2}\Phi_2 + \cdots + \mathbf{C}_{i-P}\Phi_P$, $\mathbf{C}_0 = I_k$, $\mathbf{C}_1 = -(I_k - \Phi_1)$, $\mathbf{C}_i = 0$ for $i < 0$, and $\mathbf{C}(1) = \sum_{i=0}^{\infty} \mathbf{C}_i$. It is worth noting that the expression (55) is the multivariate version of Beveridge-Nelson stochastic trend component. Therefore, if we denote $\mathbf{z}_t = \mathbf{x}_t - \mathbf{x}_{s,t}^P$, the transitory component or the deviation from the steady state $\mathbf{x}_t^T$ can be estimated as:

$$\mathbf{z}_t = \hat{\boldsymbol{\alpha}} + \hat{\boldsymbol{\theta}} t + \hat{\mathbf{x}}_t^T$$

where $\hat{\mathbf{x}}_t^T$ is the OLS residuals from the regression of $\mathbf{z}_t$ on a constant $\boldsymbol{\alpha}$ and a linear trend t.

[21] One variable is qualified to be "long run forcing" when it is weakly exogenous. In the context of cointegrating models, it implies that there is no long-run feedback from domestic or endogeneous variables to the exogeneous variable.

[22] See Dees et al. (2009) for derivation.

C Prior and Posterior distribution

Parameters	Prior distribution			Posterior mode			
	type	mean	std	model1	10%	90%	model2
Behavioral parameters							
Habit formation (h)							
- Euro-area	beta	0.60	0.05	0.4575	0.4276	0.4956	0.5093
- United-Kingdom	beta	0.60	0.05	0.3746	0.3519	0.4098	0.4739
- China	beta	0.60	0.05	0.5202	0.4852	0.5754	0.3458
- United-states	beta	0.60	0.05	0.4863	0.4543	0.5335	0.5151
- Japan	beta	0.60	0.05	0.4147	0.3796	0.5287	0.4451
- Switzerland	beta	0.60	0.05	0.5120	0.4879	0.5504	0.4843
Frisch elasticity (ψ)							
- Euro-area	normal	2.00	0.75	0.6551	0.5000	1.4159	1.8936
- United-Kingdom	normal	2.00	0.75	1.8925	0.8596	2.9805	1.0484
- China	normal	2.00	0.75	1.5862	0.9010	2.9200	0.6222
- United-states	normal	2.00	0.75	2.1938	1.2223	3.3953	2.1653
- Japan	normal	2.00	0.75	0.5000	0.5002	2.2827	2.0317
- Switzerland	normal	2.00	0.75	2.3387	1.8572	3.5137	2.5035
Autoregressive parameters							
Technology (ρ_a)							
- Euro-area	beta	0.80	0.10	0.9387	0.7378	0.9735	0.8301
- United-Kingdom	beta	0.80	0.10	0.7566	0.5698	0.8656	0.9224
- China	beta	0.80	0.10	0.9050	0.8135	0.9659	0.9224
- United-states	beta	0.80	0.10	0.7169	0.6250	0.8121	0.8396
- Japan	beta	0.80	0.10	0.8264	0.7605	0.9265	0.8833
- Switzerland	beta	0.80	0.10	0.9448	0.9046	0.9732	0.6712
Preference law of motion (ρ_g)							
- Euro-area	beta	0.85	0.05	0.8397	0.7375	0.8687	0.7512
- United-Kingdom	beta	0.85	0.05	0.9007	0.7974	0.9424	0.8994
- China	beta	0.85	0.05	0.8583	0.7283	0.9015	0.8677
- United-states	beta	0.85	0.05	0.8616	0.7394	0.9076	0.8669
- Japan	beta	0.85	0.05	0.8445	0.7039	0.9030	0.7836
- Switzerland	beta	0.85	0.05	0.8713	0.8044	0.9313	0.8629
Exchange rate (ρ_e)							
- Euro-area	beta	0.85	0.05	–	–	–	–
- United-Kingdom	beta	0.85	0.05	0.7538	0.6685	0.8505	0.8661
- China	beta	0.85	0.05	0.8348	0.7746	0.9081	0.8939
- United-states	beta	0.85	0.05	0.8412	0.7218	0.8823	0.8817
- Japan	beta	0.85	0.05	0.7880	0.7106	0.8794	0.8839
- Switzerland	beta	0.85	0.05	0.7828	0.6773	0.8625	0.9039

Parameters	Prior distribution			Posterior mode			
	type	mean	std	model1	10%	90%	model2
Interest rate (ρ_r)							
- Euro-area	beta	0.85	0.05	0.9899	0.9884	0.9899	0.9827
- United-Kingdom	beta	0.85	0.05	0.9640	0.9495	0.9735	0.9741
- China	beta	0.85	0.05	0.9743	0.9676	0.9794	0.9799
- United-states	beta	0.85	0.05	0.9583	0.9354	0.9650	0.9786
- Japan	beta	0.85	0.05	0.9899	0.9870	0.9899	0.9899
- Switzerland	beta	0.85	0.05	0.9075	0.9046	0.9338	0.9776
Inflation objective ($\rho_{\bar{\pi}}$)							
- Euro-area	beta	0.85	0.10	0.8941	0.8630	0.9403	0.9035
- United-Kingdom	beta	0.85	0.10	0.8962	0.8501	0.9265	0.5581
- China	beta	0.85	0.10	0.8201	0.7415	0.8764	0.5899
- United-states	beta	0.85	0.10	0.8604	0.7941	0.9145	0.9074
- Japan	beta	0.85	0.10	0.7043	0.6534	0.8023	0.7943
- Switzerland	beta	0.85	0.10	0.6377	0.5545	0.7207	0.7652
Price and wage setting parameters							
Calvo domestic prices (θ_H)							
- Euro-area	beta	0.75	0.05	0.9499	0.9483	0.9499	0.7996
- United-Kingdom	beta	0.75	0.05	0.8989	0.8711	0.9225	0.8464
- China	beta	0.75	0.05	0.8573	0.8175	0.9185	0.6305
- United-states	beta	0.75	0.05	0.6922	0.6253	0.7231	0.7964
- Japan	beta	0.75	0.05	0.8001	0.7531	0.8360	0.8055
- Switzerland	beta	0.75	0.05	0.8489	0.8230	0.8748	0.8732
Calvo import prices (θ_F)							
- Euro-area	beta	0.60	0.05	0.8573	0.8365	0.8649	0.6211
- United-Kingdom	beta	0.60	0.05	0.6998	0.6582	0.7587	0.6741
- China	beta	0.60	0.05	0.6793	0.6095	0.7138	0.6207
- United-states	beta	0.60	0.05	0.6504	0.5774	0.7073	0.6817
- Japan	beta	0.60	0.05	0.6256	0.5787	0.6534	0.6676
- Switzerland	beta	0.60	0.05	0.7929	0.7304	0.8258	0.6325
Calvo wages (θ_W)							
- Euro-area	beta	0.75	0.05	0.8299	0.8075	0.8625	0.7684
- United-Kingdom	beta	0.75	0.05	0.6388	0.5548	0.6602	0.7613
- China	beta	0.75	0.05	0.8155	0.7604	0.8560	0.6816
- United-states	beta	0.75	0.05	0.7219	0.6320	0.7641	0.7620
- Japan	beta	0.75	0.05	0.7823	0.6951	0.8139	0.7583
- Switzerland	beta	0.75	0.05	0.8428	0.8028	0.8802	0.7711

Parameters	Prior distribution			Posterior mode			
	type	mean	std	model1	10%	90%	model2
Domestic prices inflation indexation (γ_d)							
- Euro-area	beta	0.50	0.10	0.4585	0.3440	0.5208	0.3230
- United-Kingdom	beta	0.50	0.10	0.4991	0.3851	0.6010	0.3822
- China	beta	0.50	0.10	0.4304	0.3040	0.4967	0.3418
- United-states	beta	0.50	0.10	0.3773	0.2772	0.4615	0.3368
- Japan	beta	0.50	0.10	0.2352	0.1313	0.2831	0.2006
- Switzerland	beta	0.50	0.10	0.3133	0.1889	0.4322	0.3169
Import prices inflation indexation (γ_f)							
- Euro-area	beta	0.50	0.10	0.7525	0.6839	0.8604	0.5163
- United-Kingdom	beta	0.50	0.10	0.5195	0.4270	0.6115	0.5936
- China	beta	0.50	0.10	0.6404	0.4918	0.7184	0.6427
- United-states	beta	0.50	0.10	0.5892	0.4984	0.7087	0.6193
- Japan	beta	0.50	0.10	0.4465	0.3261	0.5411	0.6039
- Switzerland	beta	0.50	0.10	0.6023	0.5145	0.6825	0.5900
Wages inflation indexation (γ_w)							
- Euro-area	beta	0.50	0.15	0.7004	0.5205	0.7658	0.3394
- United-Kingdom	beta	0.50	0.15	0.3355	0.1844	0.5240	0.4742
- China	beta	0.50	0.15	0.5785	0.3836	0.6689	0.5204
- United-states	beta	0.50	0.15	0.5241	0.3407	0.7101	0.5740
- Japan	beta	0.50	0.15	0.5034	0.3732	0.7127	0.6176
- Switzerland	beta	0.50	0.15	0.61792	0.4728	0.7499	0.4391
Steady state wage mark-up (λ^w)							
- Euro-area	normal	0.50	0.15	0.5297	0.4371	0.7328	0.4828
- United-Kingdom	normal	0.50	0.15	0.6287	0.4996	0.8707	0.5022
- China	normal	0.50	0.15	0.5436	0.4030	0.6892	0.5488
- United-states	normal	0.50	0.15	0.4106	0.4000	0.5545	0.5131
- Japan	normal	0.50	0.15	0.6312	0.5361	0.7923	0.5148
- Switzerland	normal	0.50	0.15	0.4000	0.4000	0.5576	0.4843
Monetary policy parameters							
Interest rate response to inflation (r_π)							
- Euro-area	normal	1.70	0.10	1.8049	1.7588	1.8380	1.6280
- United-Kingdom	normal	1.70	0.10	1.8965	1.8361	1.9327	1.8672
- China	normal	1.70	0.10	1.7320	1.6954	1.7927	1.7828
- United-states	normal	1.70	0.10	1.6934	1.6586	1.7859	1.6265
- Japan	normal	1.70	0.10	1.6217	1.5728	1.6552	1.6443
- Switzerland	normal	1.70	0.10	1.5968	1.5777	1.6353	1.6779

Parameters	Prior distribution			Posterior mode			
	type	mean	std	model1	10%	90%	model2
Interest rate response to output gap (r_y)							
- Euro-area	normal	0.125	0.05	0.1353	0.1191	0.1541	0.0906
- United-Kingdom	normal	0.125	0.05	0.0981	0.0742	0.1179	0.1187
- China	normal	0.125	0.05	0.0269	0.0100	0.0435	0.0887
- United-states	normal	0.125	0.05	0.0576	0.0548	0.0836	0.0819
- Japan	normal	0.125	0.05	0.1174	0.0995	0.1340	0.1533
- Switzerland	normal	0.125	0.05	0.1700	0.1375	0.1695	0.1552
Interest rate response to l.o.p gap (r_ψ)							
- Euro-area	normal	0.05	0.05	0.0556	0.0339	0.0645	0.0354
- United-Kingdom	normal	0.05	0.05	0.1028	0.0720	0.1257	0.0884
- China	normal	0.05	0.05	0.0040	0.0000	0.0284	0.0043
- United-states	normal	0.05	0.05	0.0515	0.0234	0.0590	0.0038
- Japan	normal	0.05	0.05	0.0120	0.0000	0.0226	0.0901
- Switzerland	normal	0.05	0.05	0.0290	0.0049	0.0731	0.0545
Interest rate response to change in inflation ($r_{\Delta\pi}$)							
- Euro-area	normal	0.30	0.10	0.0100	0.0100	0.0126	0.0100
- United-Kingdom	normal	0.30	0.10	0.0238	0.0100	0.0295	0.0100
- China	normal	0.30	0.10	0.0100	0.0100	0.0165	0.0100
- United-states	normal	0.30	0.10	0.0100	0.0100	0.0144	0.0100
- Japan	normal	0.30	0.10	0.0100	0.0100	0.0113	0.0100
- Switzerland	normal	0.30	0.10	0.0529	0.0164	0.0623	0.0194
Interest rate response to change in output gap ($r_{\Delta y}$)							
- Euro-area	normal	0.125	0.05	0.2934	0.2752	0.3058	0.0667
- United-Kingdom	normal	0.125	0.05	0.1813	0.1740	0.1980	0.1156
- China	normal	0.125	0.05	0.1115	0.0919	0.1273	0.0617
- United-states	normal	0.125	0.05	0.1013	0.0944	0.1247	0.0757
- Japan	normal	0.125	0.05	0.0500	0.0500	0.05480	0.0696
- Switzerland	normal	0.125	0.05	0.1918	0.1733	0.1998	0.1166
Standard deviations of shocks							
Idiosyncratic technology shocks (σ_{ε_a})							
- Euro-area	Inv. gam.	0.70	2	1.8918	0.2050	2.1933	1.0510
- United-Kingdom	Inv. gam.	0.70	2	1.2717	0.9789	1.6249	1.2448
- China	Inv. gam.	0.70	2	3.7334	2.9439	4.9275	3.7574
- United-states	Inv. gam.	0.70	2	4.2720	3.2088	5.4352	0.3377
- Japan	Inv. gam.	0.70	2	2.2951	1.7501	2.7368	1.8148
- Switzerland	Inv. gam.	0.70	2	1.4703	1.1531	1.8865	0.8948

Parameters	Prior distribution			Posterior mode			
	type	mean	std	model1	10%	90%	model2
Preference shocks (σ_g)							
- Euro-area	Inv. gam.	0.20	2	6.7195	5.5190	10.1022	1.6386
- United-Kingdom	Inv. gam.	0.20	2	0.1623	0.0582	0.37193	0.2825
- China	Inv. gam.	0.20	2	0.0917	0.0506	0.29311	0.0928
- United-states	Inv. gam.	0.20	2	0.0947	0.0525	0.38445	0.0916
- Japan	Inv. gam.	0.20	2	1.1420	0.7263	2.7936	1.7004
- Switzerland	Inv. gam.	0.20	2	0.0902	0.0472	0.2320	0.0866
Exchange rate shocks (σ_e)							
- Euro-area	Inv. gam.	–	–	–	–	–	–
- United-Kingdom	Inv. gam.	2.50	2	9.0875	7.8376	10.6148	2.7678
- China	Inv. gam.	2.50	2	6.7975	5.9192	8.3449	4.1530
- United-states	Inv. gam.	2.50	2	2.7054	2.2998	3.1652	4.2323
- Japan	Inv. gam.	2.50	2	5.0098	4.2206	5.8833	5.0516
- Switzerland	Inv. gam.	2.50	2	1.5544	1.3322	1.8186	1.8986
Domestic price mark-up shocks (σ_{ε^p})							
- Euro-area	Inv. gam.	2.00	2	2.4142	2.0216	2.9955	0.6805
- United-Kingdom	Inv. gam.	2.00	2	0.4559	0.3983	0.5677	0.4824
- China	Inv. gam.	2.00	2	1.5563	1.3559	1.9023	0.8780
- United-states	Inv. gam.	2.00	2	1.4994	1.2582	1.8912	1.6442
- Japan	Inv. gam.	2.00	2	0.5712	0.4678	0.7033	0.5378
- Switzerland	Inv. gam.	2.00	2	0.3855	0.3336	0.4628	0.4009
Import price mark-up shocks (σ_{ε^f})							
- Euro-area	Inv. gam.	2.50	2	11.1442	9.3925	12.4874	4.0187
- United-Kingdom	Inv. gam.	2.50	2	1.3906	1.1153	1.6688	1.3077
- China	Inv. gam.	2.50	2	4.2043	3.6180	5.2544	4.1071
- United-states	Inv. gam.	2.50	2	2.5290	2.1019	3.2342	2.4997
- Japan	Inv. gam.	2.50	2	4.5901	4.0441	5.7329	4.9456
- Switzerland	Inv. gam.	2.50	2	1.2265	1.0173	1.6920	1.1021
Wage mark-up shocks (σ_{ε^w})							
- Euro-area	Inv. gam.	0.25	2	10.5981	8.7066	11.8695	2.3589
- United-Kingdom	Inv. gam.	0.25	2	2.0569	1.6444	2.3217	1.0543
- China	Inv. gam.	0.25	2	3.3418	2.8671	4.1175	3.3540
- United-states	Inv. gam.	0.25	2	2.7771	2.4307	3.4218	2.7215
- Japan	Inv. gam.	0.25	2	3.0837	2.6995	3.8421	3.4512
- Switzerland	Inv. gam.	0.25	2	0.8285	0.7089	1.0344	0.6293

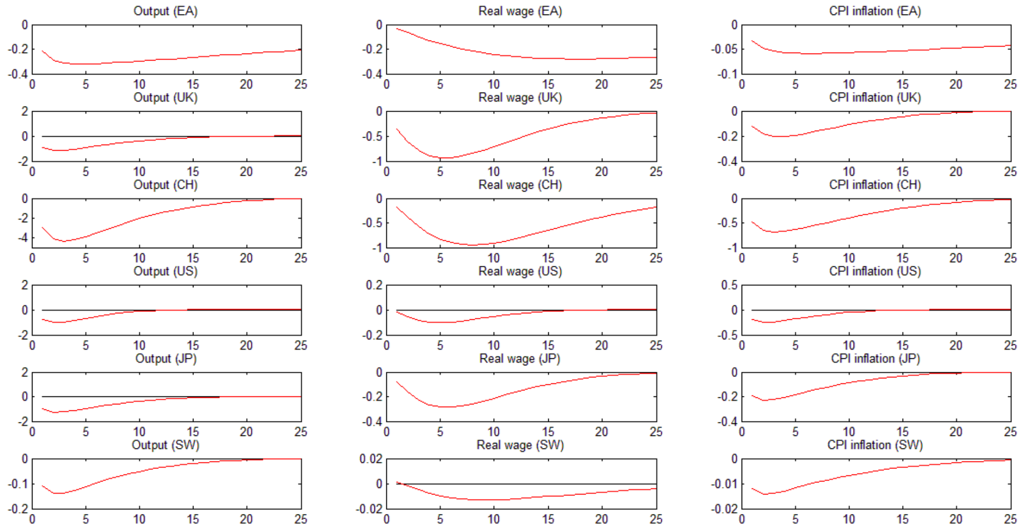
Parameters	Prior distribution			Posterior mode			
	type	mean	std	model1	10%	90%	model2
Inflation objective shocks (σ_{η^π})							
- Euro-area	Inv. gam.	2.00	2	4.3174	2.7985	4.9419	0.9779
- United-Kingdom	Inv. gam.	2.00	2	1.0157	0.7547	1.4099	1.1279
- China	Inv. gam.	2.00	2	0.9951	0.6866	1.5685	1.0702
- United-states	Inv. gam.	2.00	2	1.0342	0.6405	1.3662	1.2465
- Japan	Inv. gam.	2.00	2	1.6114	0.9625	2.0682	1.5655
- Switzerland	Inv. gam.	2.00	2	2.9131	1.8501	3.1541	0.8552
Monetary policy shocks (σ_{ε_r})							
- Euro-area	Inv. gam.	0.10	2	0.0451	0.0249	0.1038	0.0415
- United-Kingdom	Inv. gam.	0.10	2	0.1494	0.0619	0.2145	0.0345
- China	Inv. gam.	0.10	2	0.3134	0.2444	0.4061	0.0766
- United-states	Inv. gam.	0.10	2	0.1298	0.0406	0.2575	0.1946
- Japan	Inv. gam.	0.10	2	0.0408	0.0311	0.0656	0.0429
- Switzerland	Inv. gam.	0.10	2	0.0426	0.0242	0.0738	0.0455
Modified Harmonic Mean estimator				-3792			-3115

D Variance decomposition

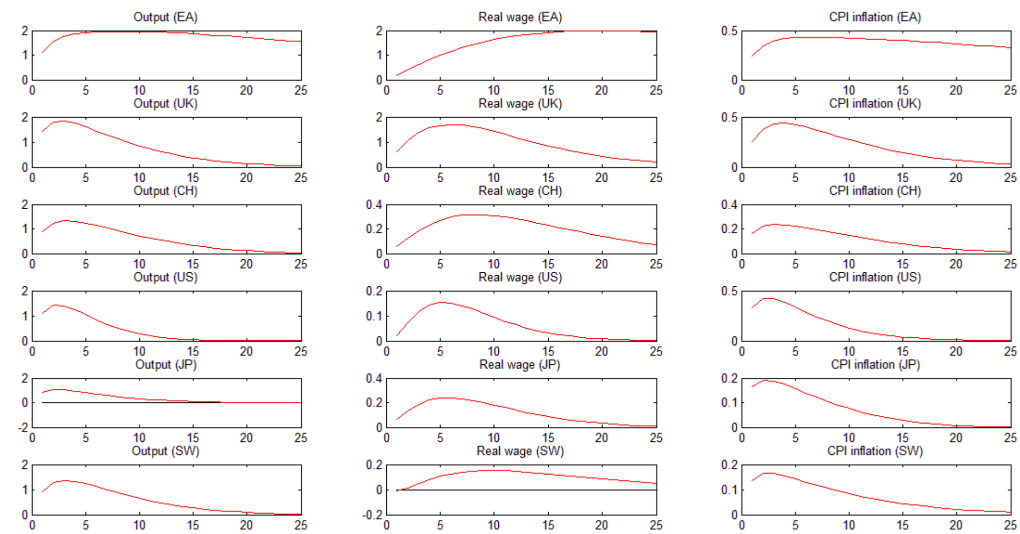
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Exchange rate shock (ε_{e_it})								
$i = UK$	45.16	38.91	32.70	26.98	22.19	18.54	15.99	14.37
$i = CH$	20.27	18.66	16.64	14.43	12.29	10.46	9.05	8.05
$i = US$	3.72	3.43	3.05	2.62	2.22	1.87	1.62	1.44
$i = JP$	1.43	1.19	0.97	0.77	0.62	0.51	0.45	0.41
$i = SW$	0.25	0.22	0.19	0.16	0.13	0.11	0.10	0.09
Foreign mark-up shock (ε_{it}^{p})								
$i = UK$	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
$i = CH$	0.14	0.06	0.04	0.03	0.02	0.02	0.02	0.01
$i = US$	0.20	0.10	0.06	0.04	0.03	0.03	0.02	0.02
$i = JP$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$i = SW$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Inflation objective shock ($\eta_t^{\pi_i}$)								
$i = ZE$	2.61	3.41	4.25	5.09	5.86	6.51	7.03	7.45
$i = UK$	6.28	8.24	10.34	12.42	14.32	15.88	17.07	17.91
$i = CH$	0.98	1.28	1.61	1.93	2.22	2.47	2.65	2.79
$i = US$	2.37	3.05	3.74	4.36	4.85	5.17	5.33	5.37
$i = JP$	0.03	0.04	0.05	0.06	0.07	0.08	0.08	0.09
$i = SW$	0.20	0.26	0.32	0.38	0.43	0.46	0.49	0.50
Preference shock (ε_{it}^{g})								
$i = ZE$	2.05	2.81	3.73	4.74	5.76	6.67	7.40	7.91
$i = UK$	0.10	0.12	0.15	0.18	0.21	0.22	0.23	0.24
$i = CH$	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
$i = US$	0.03	0.03	0.04	0.04	0.05	0.05	0.05	0.05
$i = JP$	0.10	0.13	0.16	0.19	0.21	0.23	0.23	0.23
$i = SW$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

E Impulse response

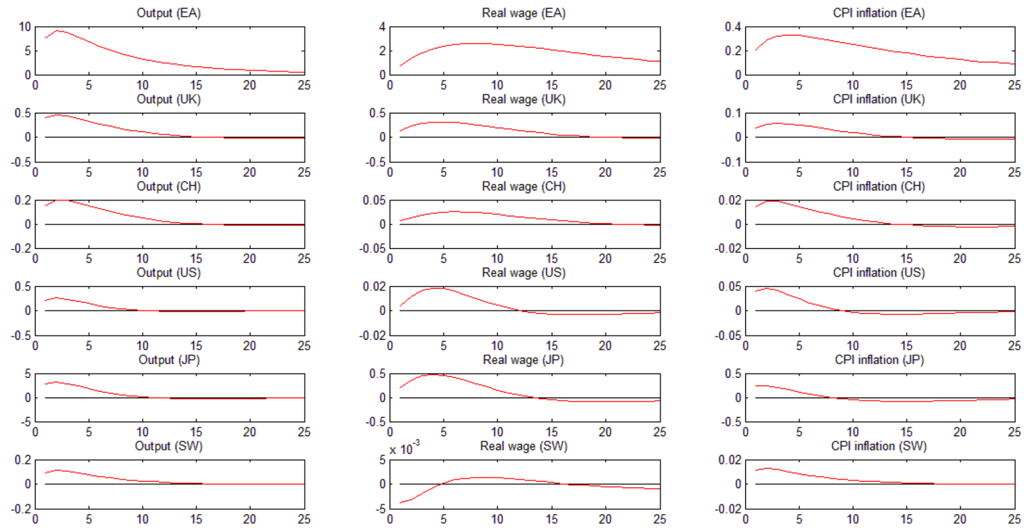
E.1 Monetary policy shock



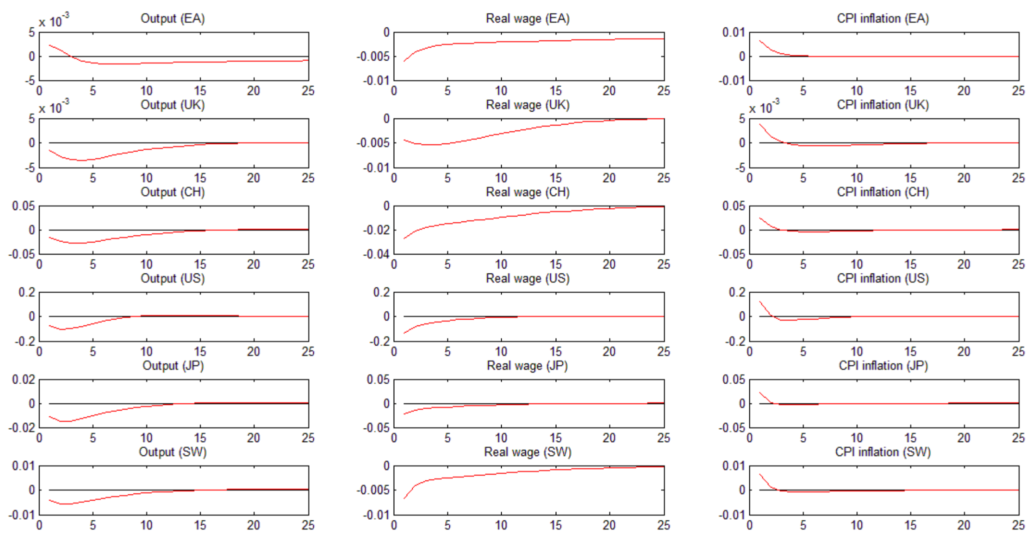
E.2 Inflation objective shock



E.3 Preference shock

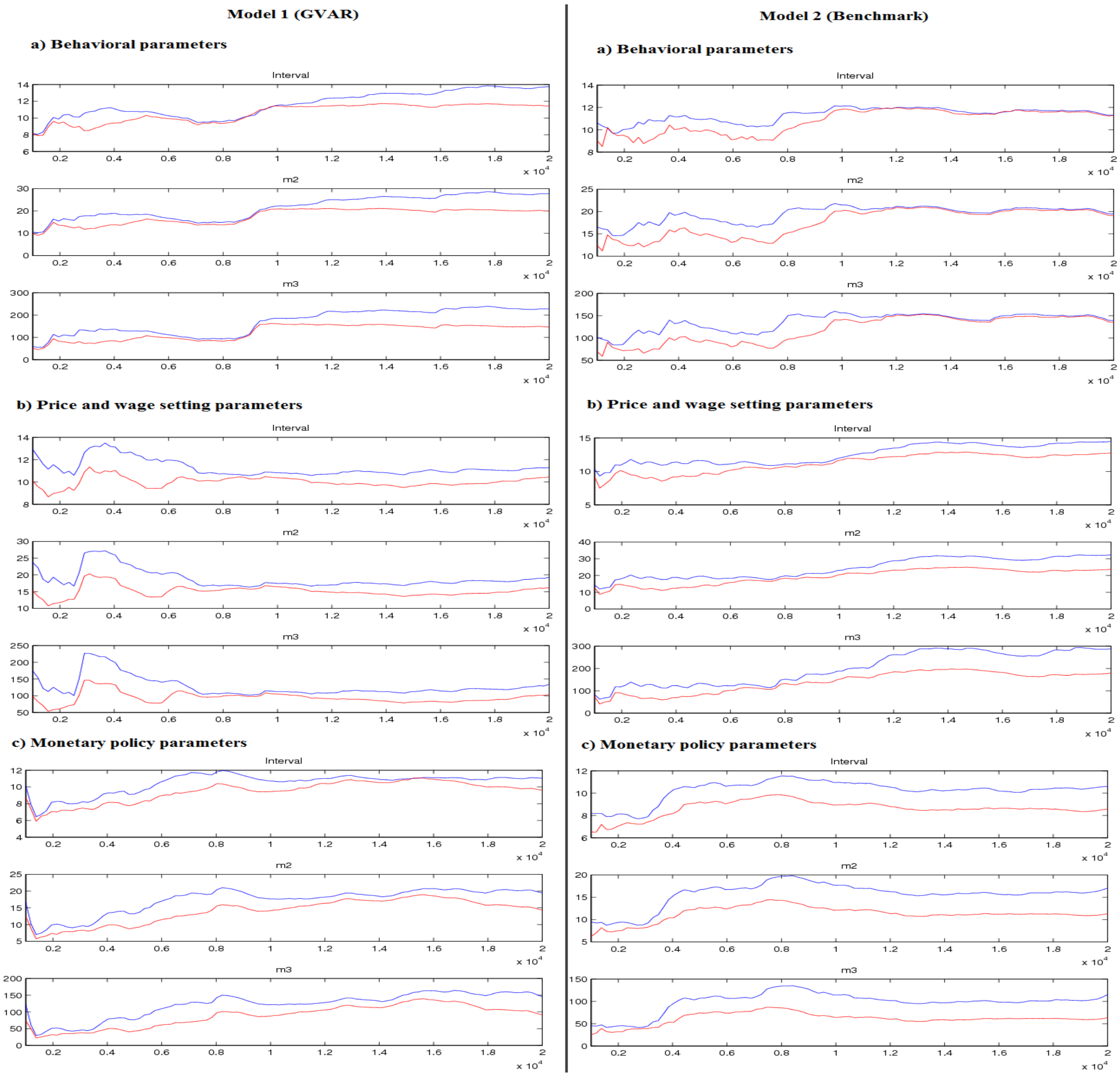


E.4 Mark-up shock

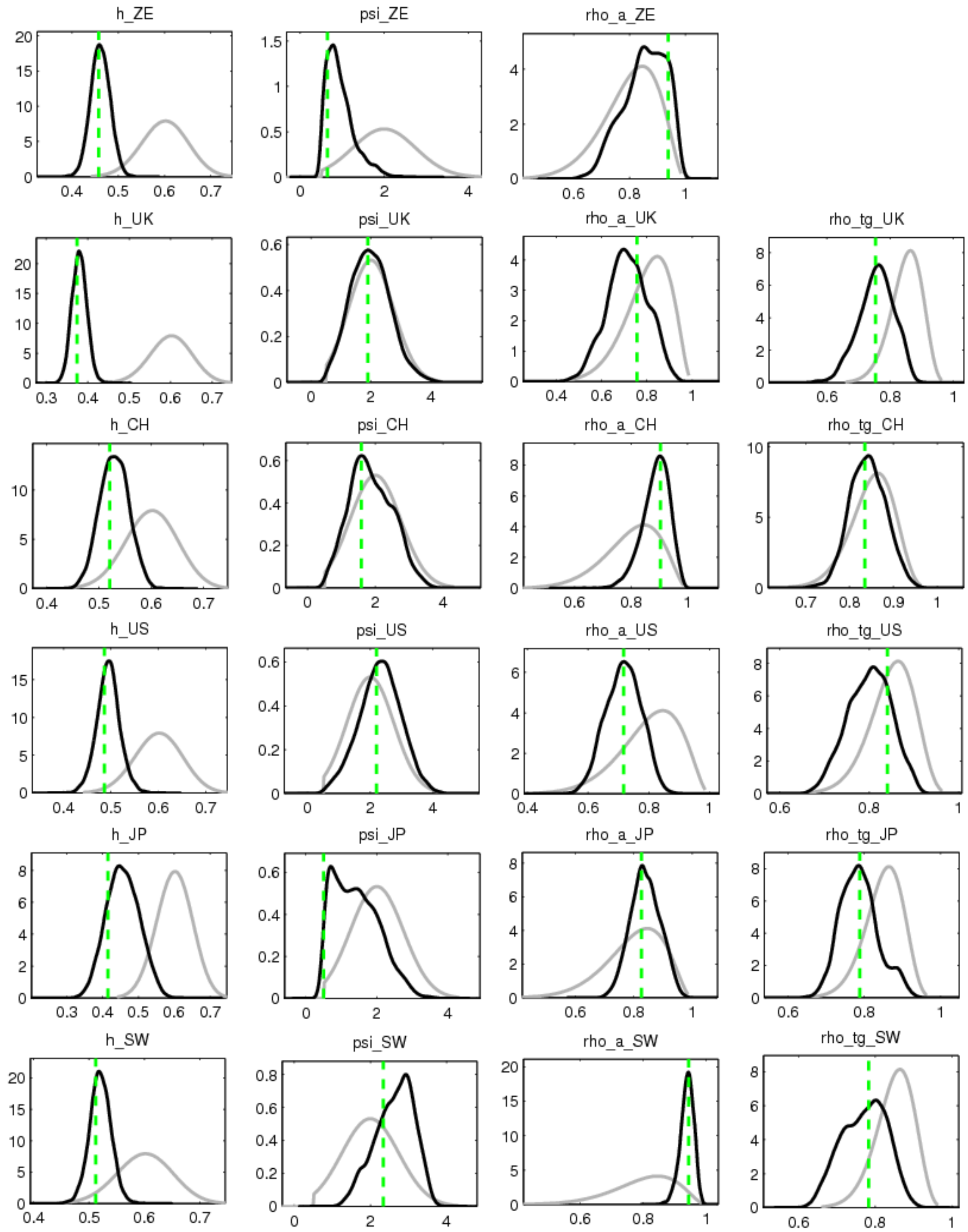


F Convergence diagnostics

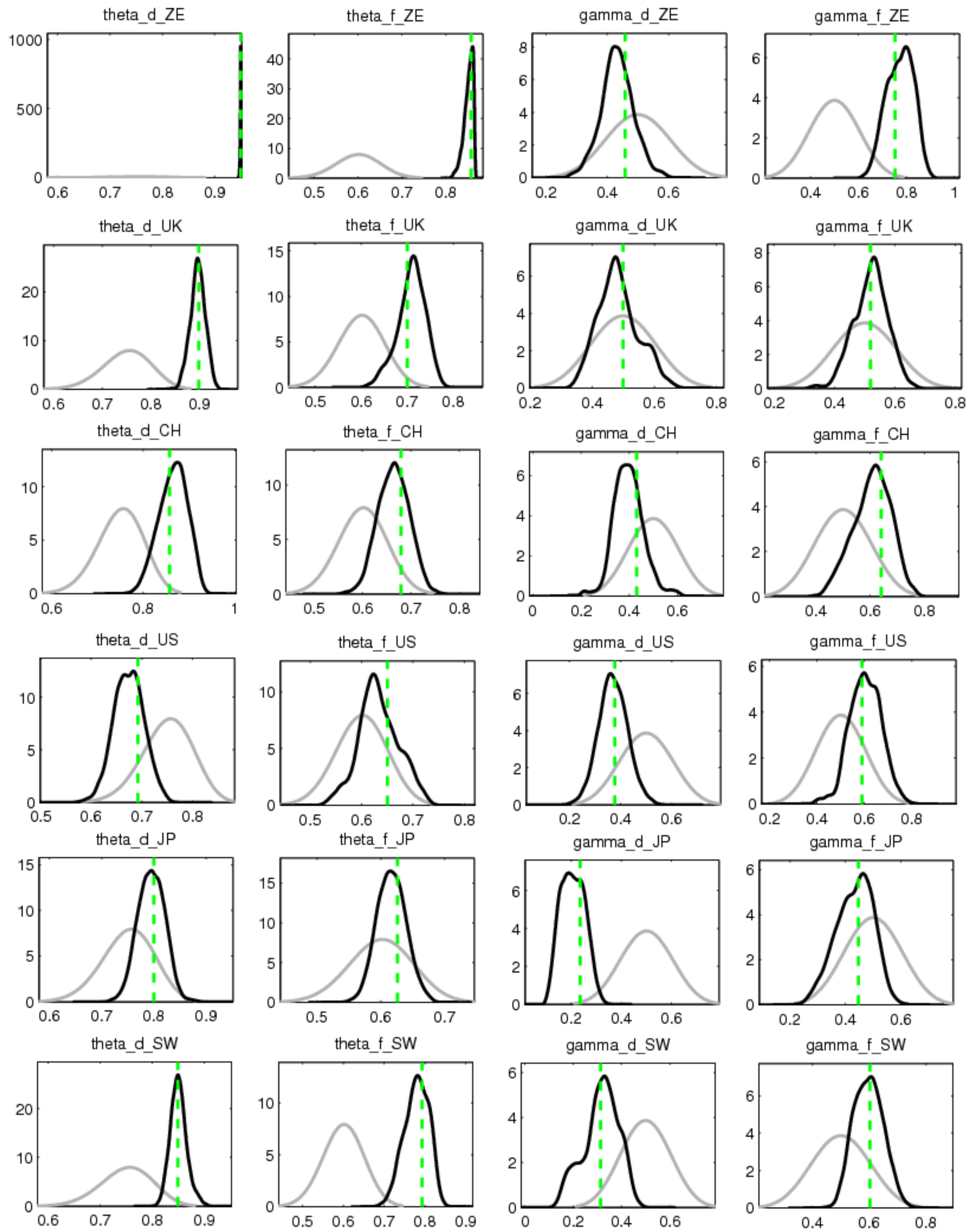
F.1 Multivariate diagnostic



F.2 Prior and posterior of behavioral parameters



F.3 Prior and posterior of price and wage setting parameters



F.4 Prior and posterior of monetary policy parameters