Working Paper Series —— 6/2020

A Model of the Euro Area, China and the United States: Trade Links and Trade Wars

Volha Audzei, Jan Brůha

Czech National Bank —— Working Paper Series —— 6/2020

CZECH NATIONAL BANK

www.cnb.cz

Reviewed by: Massimiliano Pisani (Banca d'Italia)
Jakub Matějů (Czech National Bank)

Project Coordinator: Michal Franta

A Model of the Euro Area, China and the United States: Trade Links and Trade Wars

Volha Audzei and Jan Brůha *

Abstract

In this paper we develop a dynamic stochastic general equilibrium model featuring the euro area, the United States and China, with an exogenous rest of the world. The countries in the model are linked through trade and international bond purchases. Having estimated the model, we study several scenarios of trade wars between the countries. Our findings suggest that no country benefits from imposing tariffs in the long run. The degree to which a particular country is hurt depends on the strength of its import and export links.

Abstrakt

V tomto článku vyvíjíme dynamický stochastický model všeobecné rovnováhy, který zahrnuje eurozónu, USA a Čínu, přičemž zbytek světa je pojat jako exogenní sektor. Země zahrnuté do modelu jsou propojeny prostřednictvím obchodu a nákupu mezinárodních dluhopisů. Po odhadu modelu zkoumáme několik scénářů obchodních válek mezi těmito zeměmi. Naše zjištění naznačují, že z uvalení cel nemá v dlouhém období prospěch žádná země. Míra, v níž jsou jednotlivé země poškozeny, závisí na síle jejich dovozních a vývozních vazeb.

JEL Codes: C11, E37, F13, F41.
Keywords: Bayesian estimation, China, multi-country DSGE, trade wars.

*Volha Audzei, Economic Research Division, Monetary Department, Czech National Bank; volha.audzei@cnb.cz
Jan Brůha, Economic Research Division, Monetary Department, Czech National Bank.
The authors are grateful to Gregory de Walque, Thomas Lejeune and Yuliya Rychalovska for comments and for sharing their code and data for the two-country model. The paper benefited from comments by Massimilliano Pisani, Michal Franta, František Brázdik, Jakub Matějů, Ben Schumann, participants of the ECB China Expert Network and participants of various workshops held at the Czech National Bank. We thank Oxana Babecká-Kucharčuková for sharing the data on China. The views expressed in this paper are those of the authors and not necessarily those of the Czech National Bank. All remaining errors and omissions are the authors' responsibility.

1. Introduction

Modelling international trade links and understanding cross-country spillovers have been relevant topics in macroeconomics, especially when it comes to models for policy analysis. Recently, the increasing threat of a trade war has stimulated a debate in the literature on the possible winners and losers in this war.

We contribute to the literature by developing and estimating a structural (DSGE) three-country model of the euro area (EA), the United States (US) and China (CH) featuring an exogenous rest of the world sector (RoW). The countries are linked through bilateral trade and international bond purchases. Foreign goods and oil products enter the consumption basket and are used as intermediate inputs for production. Exchange rates are then endogenously determined by the uncovered interest rate parity condition, with restricted flexibility of the Chinese currency. Total goods imports and exports in each country are modelled as aggregates from the different countries and exogenous RoW demand. Such a model allows us to consider spillovers of foreign shocks into each economy and to study the consequences of possible trade war realization. We consider five trade war scenarios depending on the countries' responses, and discuss their effect on each country modelled.

Our results indicate that no country benefits from a trade war under any scenario we study. The degree to which a country is hurt by the tariffs depends on the trade structure. Our simulations show that imposing a tariff on an important trade partner, such as when the US imposes tariffs on China, hurts the home country through an increase in production costs and consumption inflation. US tariffs hurt China in the medium term under all scenarios. Even when the Eurozone is not subject to tariffs, and US producers and consumers switch towards euro area goods, the decline in US and Chinese production has a negative impact on the Eurozone. Under a global trade war scenario where all three countries impose symmetric tariffs on each other, all economies incur significant loses.

We find that if the ECB and the Fed deviate from Taylor-rule based monetary policy and do not raise interest rates in response to higher inflation, the negative effects of the stimulus can be somewhat offset in the short to medium run. However, our model does not account for potential caveats of such policies with devastating long-term effects, such as loss of central bank credibility and currency wars.

Our paper is related to studies that develop multi-country DSGE models in various central banks and international organizations, for example, EAGLE (Gomes et al., 2010) and NAWM II (Coenen et al., 2018) in the European Central Bank, GIMF (Laxton et al., 2010) in the IMF, and the model by de Walque et al. (2017) in the National Bank of Belgium. Because of the complicated structure of DSGE models, for the sake of tractability such papers usually consider just two or three countries. Both Gomes et al. (2010) and de Walque et al. (2017) feature the euro area and the US economy and incorporate an RoW block to different extents. Razafindrabe (2016) develops a multi-country DSGE model with incomplete pass-through stemming from price rigidities. The model is calibrated for several countries, including the euro area, China and the United States. In our framework, while considering fewer countries, we allow for a richer structure of the economies, with capital in the production function and endogenous shares of imported goods in a consumption basket. We draw extensively from the two-country model by de Walque et al. (2017). Our choice of structure is motivated by relative tractability while delivering reasonable performance. We modify the structure to incorporate the Chinese economy as a third country, accounting for the specifics of Chinese monetary policy. Semi-structural approaches to modelling the euro area and studying the impact of outside shocks include Dieppe et al. (2018), Andrle et al. (2015), Carabenciov et al. (2013) and Blagrave et al. (2013).

Adding China to the model requires knowledge of the specifics of its economy. Among the studies we use are Chang et al. (2018), Ma et al. (2013) and Sun (2013), who document the use of different policy instruments. In particular, they show extensive use of reserve requirements. Kim and Chen (2019) discuss the use of various monetary policy tools in China and show that recent monetary policy there can be viewed as an interest-based framework. Gu et al. (2014), Dai et al. (2015) and Li and Liu (2017) estimate a DSGE model of the Chinese economy. We use the estimates from these papers as inspiration for our parameter priors and for the structure of the Chinese block.

When modelling the Chinese economy, we account for the use of reserve requirements as a policy tool consistent with the aforementioned studies. Similarly to Dieppe et al. (2018) and Blagrave et al. (2013) we model a change in the reserve requirement ratio as a rule that reacts to deviations of inflation from the target and to the output gap. The reserve requirement ratio then affects the lending conditions of households and firms, increasing or decreasing the cost of credit for them. As documented in Kim and Chen (2019), there are various reserve requirement ratios for different types of banks in China. When estimating our model, we use the reserve requirements applying to large banks, as we believe they have the most influence on credit provision on the macro level. Another challenging Chinese variable to model is the nominal exchange rate against the US dollar. Because the exchange rate is not flexible and is used as a policy instrument, we model it as only partially pinned down by the uncovered interest rate parity condition. The rest of the movements in the exchange rate are attributed to policy interventions, which are exogenous in our linear model. In the interval we use for the estimation, 1991–2016, there are several structural breaks in the Chinese variables: reserve requirement ratios started to be used, the exchange rate became more volatile, and average inflation dropped at the end of the 1990s. We address these changes using the modelling device from de Walque et al. (2006), who model the time-variable trend in inflation for the euro area with a non-stationary shock to the inflation target.

Our paper is also related to studies focusing on possible scenarios and outcomes of trade wars. Among them are Bouet and Laborde Debucquet (2017), in which the authors use a multi-country computable general equilibrium (CGE) model to study possible trade war scenarios, the empirical study by Amiti et al. (2019) and the estimates of export and import supply elasticities by Fajgelbaum et al. (2019). Bolt et al. (2019) use an EAGLE general equilibrium model to study the effect of the US-China tariff war on the euro area, though they do not model China explicitly but consider it within the RoW block. Strong empirical evidence against tariffs and trade protectionism can be found in Furceri et al. (2019). All these studies agree that under all possible responses of its trading partners, the US economy does not benefit from imposing tariffs.[1] Lindé and Pescatori (2019) consider the introduction of import tariffs together with export subsidies and show that such a policy is not always neutral in the short run. Specifically, price rigidities, slow exchange rate adjustment and limited exchange rate pass-through generate significant deviations from neutrality. In this paper we consider a range of trade war scenarios, but through the lens of a large-scale DSGE model. In particular, we evaluate the consequences of the US imposing tariffs on both the euro area and China with and without a response, the US imposing tariffs on China only, again with and without a response, and finally, a global war scenario with the US imposing tariffs on both the euro area and China with a symmetric response.

The paper is organized as follows. Section 2 describes the model in detail. In section 3 we present the estimation methodology and the data used, together with the priors and posteriors. In section 4 we study the impulse responses and model properties. In section 5 we consider five trade war

[1] Fajgelbaum et al. (2019) finds that some sectors of the US economy benefit, but in general the economy loses.

scenarios and their effect on each country. The last section concludes and sketches extensions and future work.

2. The Model

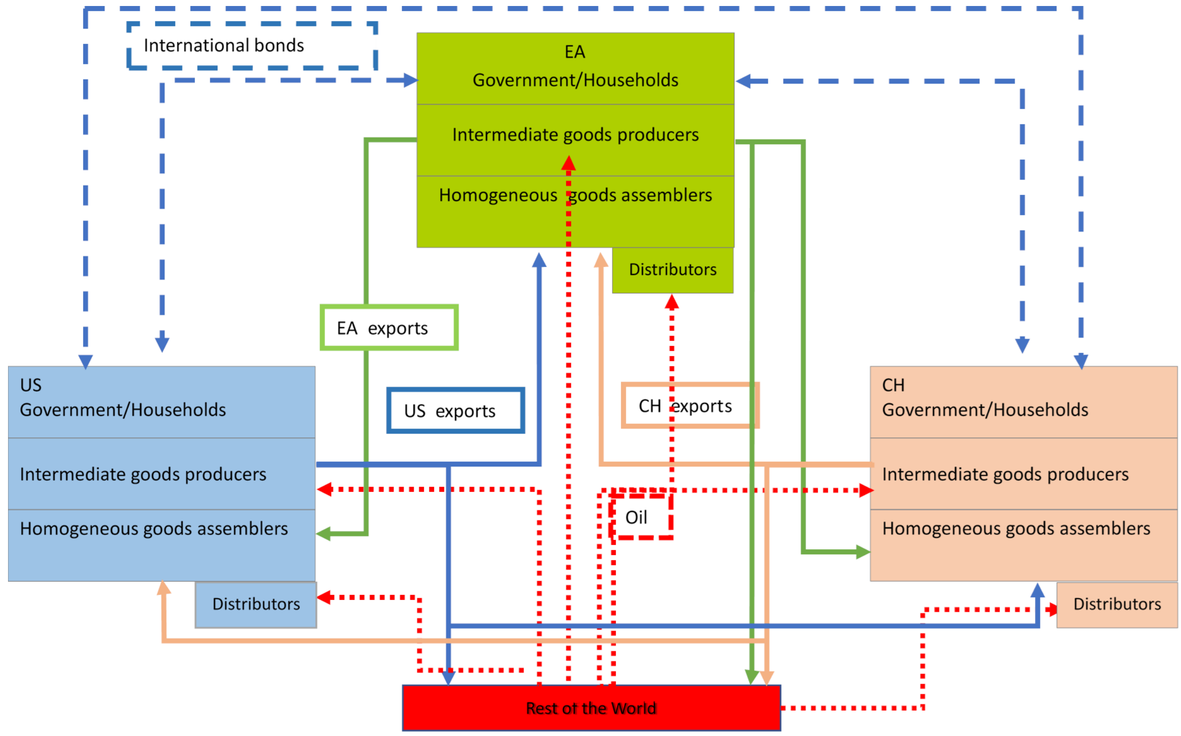
The model we use is based on de Walque et al. (2017). We expand their structure to incorporate China as a third country. The model in de Walque et al. (2017) is an extension of Smets and Wouters (2007), where two economies – the US and the euro area – are interlinked through trade and government bond purchases. The structure of each economy resembles the closed economies in Smets and Wouters (2007) with the standard set of frictions. Foreign goods and oil enter the production functions and consumers' baskets. With households investing in foreign bonds, the euro-US dollar exchange rate is determined by the uncovered interest rate parity condition. The yuan-US dollar exchange rate is affected by uncovered interest parity and policy adjustments, which are exogenous in the model.

The trade links among the countries are illustrated in Figure 1. The three countries we model have symmetric trade links. There is an exogenous rest of the world sector (RoW), which acts as an exogenous demand shifter to match the data on bilateral trade. Households issue international bonds and sell them to foreign households. Producers of differentiated intermediate goods export their goods to foreign goods assembler firms and to the rest of the world and import oil from an exogenous oil production sector, while the oil price is an exogenous process.[2] The price of crude oil is set in US dollars. Distributors of final consumption goods also import oil to make oil products for consumption purposes. The structure of the production and distribution sectors is illustrated in Figure 2. The first block consists of monopolistic intermediate goods producers with the Leontief production function. They combine domestic labour and capital, foreign production goods and crude oil to produce differentiated intermediate domestic goods. They sell these goods to foreign and domestic homogeneous goods assemblers. The assemblers are perfectly competitive. They aggregate their inputs into two types of homogeneous domestic and foreign goods – consumption and production goods. The production goods are sold back to intermediate goods producers. The consumption goods are then sold to final goods assemblers, which represent the distribution channel. We use the modelling device from de Walque et al. (2017) whereby foreign consumption goods and consumption oil products must be combined with domestic goods for final consumption. This allows us not to model the non-tradables sector explicitly and introduces a wedge between prices of imports and prices of products for direct consumption. Thus, prices of crude oil and foreign goods affect consumption inflation, but this effect is mitigated via the distribution channel. Domestic goods are distributed to final consumers without additional costs. Consumers use final consumption goods to consume and invest.

Below we briefly sketch the structure of the model. For a rigorous discussion of the underlying assumptions, the reader is referred to de Walque et al. (2017) and Smets and Wouters (2007). The equations are symmetric for all countries unless explicitly specified otherwise. The economies are described from the point of view of the home country ω, with subscripts H and F denoting home and foreign variables respectively. The star superscript, *, means that the variable is associated with the foreign market. For example, $Y^*_{H,t}$ refers to a good produced in the home country ω but exported abroad.

[2] Even though there is oil production in China and the US, both countries are the largest net oil importers in the world. Therefore, we model oil production as exogenous.

Figure 1: Trade Links in the Model



2.1 Households

There is a continuum of households, indexed by h. Each household consumes a composite good, $\mathbb{C}$, supplies a differentiated labour service, l, invests in domestic physical capital, I, and holds positions in domestic, B_H, and foreign, B_F, bonds. The households own all the firms in the domestic economy. Each household maximizes the following utility:

$$U_t(h) \equiv E_t \sum_{j=0}^{\infty} \beta^j \left(\frac{(\mathbb{C}_{t+j}(h) - H_{t+j})^{1-\sigma_c}}{1-\sigma_c} \right) exp\left(\frac{\sigma_c - 1}{1+\sigma_l} l_{t+j}(h)^{1+\sigma_l} \right), \tag{1}$$

where σ_c is the degree of relative risk aversion, σ_l is the inverse of the Frisch elasticity of labour supply and H_t is the external habit variable, such that $H_t = \lambda_{hab}\mathbb{C}_{t-1}$.

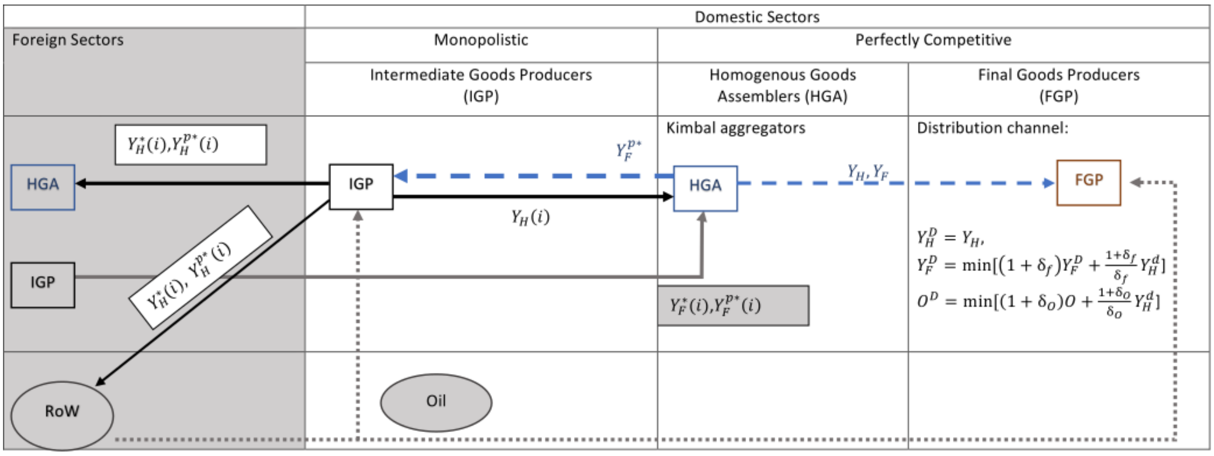
The composite consumption good, $\mathbb{C}$, consists of energy consumption good, which we refer to as oil good, O^D, and non-oil good, C. The consumption index and the corresponding price index are:

$$\mathbb{C}_t(h) = \left[(1-\phi_{oil})^{\frac{1}{\lambda_{oil}}} C_t(h)^{\frac{\lambda_{oil}-1}{\lambda_{oil}}} + \phi_{oil}^{\frac{1}{\lambda_{oil}}} O_t^D(h)^{\frac{\lambda_{oil}-1}{\lambda_{oil}}} \right]^{\frac{\lambda_{oil}}{\lambda_{oil}-1}}, \tag{2}$$

$$P_{\mathbb{C},t} = \left[(1-\phi_{oil}) P_{c,t}^{1-\lambda_{oil}} + \phi_{oil} P_{oil,t}^{D\ \ 1-\lambda_{oil}} \right]^{\frac{1}{1-\lambda_{oil}}} exp(\varepsilon_t^p), \tag{3}$$

where ε_t^p is the price shock, which is an AR(1) process with i.i.d. normal errors. $P_{\mathbb{C}}$, P_c and P_{oil}^D stand for the price of the total consumption aggregate, the price of non-oil consumption and the price of oil products for direct consumption. Superscript D denotes that the good is ready for direct

Figure 2: Production and Distributional Chain in the Model



consumption. λ_{oil} is the price elasticity of demand in total consumption, and ϕ_{oil} is the share of oil in consumption.

Non-oil consumption is a CES aggregator of domestic, C_H, and foreign, C_F, goods with degree of intertemporal substitution λ:

$$C_t(h) = \left[\phi_H^{\frac{1}{\lambda}} C_{H,t}(h)^{\frac{\lambda-1}{\lambda}} + (1-\phi_H)^{\frac{1}{\lambda}} [(1-\Omega_{c,t})C_{F,t}(h)]^{\frac{\lambda-1}{\lambda}}\right]^{\frac{\lambda}{\lambda-1}}, \tag{4}$$

$$P_{c,t} = \left[\phi_H P_{H,t}^{D\ 1-\lambda} + (1-\phi_H) P_{F,t}^{D\ 1-\lambda}\right]^{\frac{1}{1-\lambda}}, \tag{5}$$

where ϕ_H is home bias in consumption. P_c, P_H^D, and P_F^D stand for the consumption price and the prices of distributed domestic and foreign goods respectively. Ω_c is the adjustment cost in the use of foreign good. It captures the limited ability of households to substitute between foreign and domestic goods in the short run, and replicates the slow adjustment of imports to changes in relative prices:[3]

$$\Omega_{c,t} = \frac{\Omega_c}{2}\left(\frac{C_{F,t}/C_t}{C_{F,t-1}/C_{t-1}} - 1\right)^2. \tag{6}$$

Similarly, an investment good, I, is a combination of domestic and foreign goods. It is further assumed that the price of the investment good equals the price of the non-oil consumption bundle, P_c, and that the same elasticity and home bias apply:

$$I_t(h) = \left[\phi_H^{\frac{1}{\lambda}} I_{H,t}(h)^{\frac{\lambda-1}{\lambda}} + (1-\phi_H)^{\frac{1}{\lambda}} (1-\Omega_{I,t}) I_{F,t}(h)^{\frac{\lambda-1}{\lambda}}\right]^{\frac{\lambda}{\lambda-1}}. \tag{7}$$

In our model every country has two foreign trade partners and an exogenous RoW trade partner. To combine bilateral foreign goods into an aggregate foreign good, we use a similar CES aggregator

[3] See the references in de Walque et al. (2017).

with adjustment costs, but allow the adjustment costs and elasticity to differ for different trade partners.

$$C_{F,t}(h) = \left[\beta_m^{\frac{1}{\lambda_m}}[(1-\Omega^j_{F,t})C^j_{F,t}(h)]^{\frac{\lambda_m-1}{\lambda_m}} + (1-\beta_m)^{\frac{1}{\lambda_m}}[(1-\Omega^i_{F,t})C^i_{F,t}(h)]^{\frac{\lambda_m-1}{\lambda_m}}\right]^{\frac{\lambda_m}{\lambda_m-1}}, \quad (8)$$

$$P_{F,t} = \left[\beta_m P_{F,t}^{j,D^{1-\lambda_m}} + (1-\beta_m)P_{F,t}^{i,D^{1-\lambda_m}}\right]^{\frac{1}{1-\lambda_m}}, \quad (9)$$

where β_m is share of goods from country j in home country imports, normalized such that $(1-\beta_m)$ is the share of country i. λ_m is the degree of substitution between goods from different countries, capturing the limited ability of countries to start manufacturing new products. The adjustment costs, Ω_F, reflect the difficulty of switching between suppliers from different countries in the short to medium term:

$$\Omega^i_{F,t} = \frac{\Omega_F}{2}\left(\frac{C^i_{F,t}/C_{F,t}}{C^i_{F,t-1}/C_{F,t-1}} - 1\right)^2. \quad (10)$$

2.2 The International Bond Market and the Nominal Exchange Rate

Following de Walque et al. (2017) and Laxton et al. (2010) we assume that all foreign bonds are denominated in US dollars and pay the US interest rate. Then, the budget constraint for a domestic household in country ω is:

$$\begin{aligned} &P_{\mathbb{C},t}\left(\mathbb{C}_t(h) + I_t(h)\right) + \frac{B_{H,t}(h)}{exp(\varepsilon^b_t)R_t} + \frac{S_t^{\omega/USD}B_{F,t}(h)}{exp(\varepsilon^b_t)\tilde{R}^f_t} \\ &\leq W_t(h)l_t(h) + B_{H,t-1}(h) + S_t^{\omega/USD}B_{F,t-1}(h) \\ &+R^k_t u_t(h)K_{t-1}(h) - \psi(u_t)K_{t-1}(h) + \int Div_i(i,h)di. \end{aligned} \quad (11)$$

On the revenue side, there is labour income, $W_t(h)l_t(h)$, the return on domestic bonds, $B_{H,t-1}(h)$, and the return on foreign bonds, $B_{F,t-1}(h)$. If the household is a borrower on the bond market, the return enters with a negative sign. $S_t^{\omega/USD}$ denotes the nominal exchange rate between the home currency, ω, and the US dollar (USD) in indirect quotation: ω per unit of USD. The household receives a return on the capital stock, $R^k_t u_t(h)K_{t-1}(h)$, minus utilization costs, $\psi(u_t)K_{t-1}(h)$, and dividends from domestic intermediate goods firms, indexed by i: $\int Div_i(i,h)di$.

On the expenditure side, there is total consumption, including consumption of oil good, $\mathbb{C}_t(h)$, investment in physical capital, $I_t(h)$, and the positions on the domestic and foreign bond markets. R_t and R^F_t stand for the domestic and foreign gross interest rate, and ε^b replicates the risk premium shock from Smets and Wouters (2007). It is assumed that households pay a premium over the foreign bond return to participate in the international bond market. Thus, the return on foreign bonds equals $\tilde{R}^F_t = R^{US}_t\Theta_t$. This wedge between the foreign interest rate and households' return on bonds is modelled as the real costs of holding foreign bonds, which are a function of total foreign bond holdings in the economy and changes in the nominal exchange rate:

$$\Theta_t = exp\left(-\theta_a\frac{S_t^{\omega/USD}B_{F,t}(h)}{P_{\mathbb{C},t}\gamma^t} - \theta_s\left(\frac{E(S_{t+1}^{\omega/USD})}{S_t^{\omega/USD}}\frac{S_t^{\omega/USD}}{S_{t-1}^{\omega/USD}} - 1\right) + \varepsilon^{s,\omega/USD}\right), \quad (12)$$

where γ is the deterministic growth rate of the economy and θ_a and θ_s are parameters capturing the persistence in the exchange rate data when the model is estimated. $\varepsilon^{s,\omega/USD}$ is an autoregressive process capturing exogenous variations in the foreign bond market. Individual households take these costs as given in their optimal decisions.

Households optimal bond holdings result in the following conditions:

$$\begin{aligned} \left[\partial B_{H,t}(h)\right] \quad \vartheta_t &= exp(\varepsilon_t^b) R_t \beta E_t \left[\vartheta_{t+1} \frac{P_{\mathbb{C},t}}{P_{\mathbb{C},t+1}}\right], && (13)\\ \left[\partial B_{F,t}(h)\right] \quad \vartheta_t &= exp(\varepsilon_t^b) \tilde{R}_t^F \beta E_t \left[\vartheta_{t+1} \frac{ES_{t+1}^{\omega/USD}}{S_t^{\omega/USD}} \frac{P_{\mathbb{C},t}}{P_{\mathbb{C},t+1}}\right], && (14) \end{aligned}$$

where ϑ is the associated Langrage multiplier. Combining these two equations for the euro area, we get the equation for the corresponding nominal exchange rate – the uncovered interest rate parity condition.

$$E_t\left[\frac{S_{t+1}^{EUR/USD}}{S_t^{EUR/USD}}\right] = \frac{R_t^{EA}}{\tilde{R}_t^F} = \frac{R_t^{EA}}{R_t^{US}\Theta_t}. \tag{15}$$

To reflect the fact that the Chinese economy does not have a flexible exchange rate regime and it is challenging to determine the rule for its exchange rate policy, we introduce a policy component into the equation for the Chinese exchange rate, similarly to Dieppe et al. (2018) and Blagrave et al. (2013). The exchange rate determined by the uncovered interest rate parity condition is then combined with a policy intervention:

$$E_t\left[\frac{S_{t+1}^{CNY/USD}}{S_t^{CNY/USD}}\right] = \left(\frac{R_t^{CH}}{\tilde{R}_t^F}\right)^{\theta_{UIP}} \left(S_t^{pol}\right)^{1-\theta_{UIP}}, \tag{16}$$

where S^{pol} is an exogenous shock accounting for the unmodelled exchange rate policy. If $\theta_{UIP} = 1$ the Chinese condition is identical to the usual market determination of the exchange rate, and if $\theta_{UIP} = 0$ the exchange rate is driven by factors exogenous to our model.

The uncovered interest rate parity condition determines the EUR/USD and CNY/USD exchange rates. The EUR/CNY rate is calculated through the dollar exchange rate.

Households optimal decisions on consumption, investment, capital and utilization rates, as well as the treatment of the labour market, are standard and replicate the corresponding equations in Smets and Wouters (2007). Capital adjustment is costly, and there is an investment-specific technology shock. On the labour market, labour unions represent households with the same type of labour and decide on wages. A complete set of securities and full consumption risk sharing is assumed, so that households' budget constraints are independent of their labour types. Nominal wages demonstrate rigidities à la Calvo, with only a random share $(1-\xi_w)$ of unions being able to re-negotiate their wages each period. The rest of the unions adjust their wages by the deterministic growth rate γ and a weighted average of trend inflation, $\bar{\pi}$, and previous period consumption inflation, $\pi_{\mathbb{C},t-1}$, to be defined below. Those standard mechanisms are described in Appendix A as log-linearized equations.

2.3 Intermediate Goods Producers

Intermediate goods producers are monopolistic producers of differentiated intermediate goods. Producer i uses Leontief technology:

$$Y_t(i) = \min\left[\frac{1}{1-\rho_m-\rho_o}J_t(i); \frac{1}{\rho_m}Y^p_{F,t}(i); \frac{1}{\rho_o}O^p_t(i)\right] - \gamma^t\Phi, \tag{17}$$

$$J_t(i) = \tilde{K}^\alpha_t\left[\gamma^t L_t(i)\right]^{1-\alpha} exp(\varepsilon^\alpha_t). \tag{18}$$

where O^p_t is oil used in production and $Y^p_{F,t}$ denotes foreign production goods; ρ_m and ρ_o are the respective shares in production and Φ is a fixed cost of production. $L_t(i)$ is the aggregate labour input of the different types of labour used by the producer, and $\tilde{K}^\alpha_t$ are the effective capital services. ε^a_t is an AR(1) process with i.i.d. normal errors. We interpret it as a neutral productivity shock. There is also labour-augmenting deterministic growth, γ, which determines long-term growth in the economy.

The Leontief production function implies the following relationships:

$$\frac{J_t(i)}{O^p_t(i)} = \frac{1-\rho_m-\rho_o}{\rho_o}, \tag{19}$$

$$\frac{J_t(i)}{Y^p_{F,t}(i)} = \frac{1-\rho_m-\rho_o}{\rho_m}, \tag{20}$$

$$\frac{W_t L_t(i)}{r^k_t \tilde{K}_t(i)} = \frac{1-\alpha}{\alpha}. \tag{21}$$

Those relationships result in the following marginal costs of one unit of an intermediate good:

$$MC_t = (1-\rho_m-\rho_o)\frac{W_t^{1-\alpha}(r^k_t)^\alpha}{\alpha^\alpha(1-\alpha)^{1-\alpha}\varepsilon^\alpha_t} + \rho_m P^p_{F,t} + \rho_o P_{oil,t}. \tag{22}$$

Foreign production goods from different countries are combined in a similar fashion as consumption goods, with adjustment costs modelled as in (10):

$$Y^p_{F,t}(h) = \left[\beta_m^{\frac{1}{\lambda_m}}\left[(1-\Omega^j_{F,t})Y^{p,j}_{F,t}(h)\right]^{\frac{\lambda_m-1}{\lambda_m}} + (1-\beta_m)^{\frac{1}{\lambda_m}}\left[(1-\Omega^i_{F,t})Y^{p,i}_{F,t}(h)\right]^{\frac{\lambda_m-1}{\lambda_m}}\right]^{\frac{\lambda_m}{\lambda_m-1}}, \tag{23}$$

$$P^p_{F,t}(h) = \left[\beta_m[P^{p,j}_{F,t}(h)]^{\frac{\lambda_m-1}{\lambda_m}} + (1-\beta_m)[P^{p,i}_{F,t}(h)]^{\frac{\lambda_m-1}{\lambda_m}}\right]^{\frac{\lambda_m}{\lambda_m-1}}. \tag{24}$$

The intermediate goods firm sets the prices of the goods produced: domestic intermediate goods, Y_H, exported intermediate goods, Y^*_H, and exported production goods, Y^{*p}_H. When setting the prices, the firm maximizes its profit and faces Calvo price-setting rigidities:

$$\begin{aligned}\max_{\tilde{P}_{H,t}(i)\tilde{P}^*_{H,t}(i)\tilde{P}^{*p}_{H,t}(i)} & E_t\sum_{j=0}^{\infty}(\beta\zeta_p)^j\frac{\vartheta_{t+j}P_{\mathbb{C},t}}{\vartheta_t P_{\mathbb{C},t+j}}\left[\tilde{P}_{H,t}(i)\chi_{t,j}Y_{H,t+j}(i) - MC_{t+j}Y_{H,t+j}(i)\right] \\ & + \sum_{\psi\neq\omega}\Bigg(E_t\sum_{j=0}^{\infty}(\beta\zeta^{*\psi}_{pF})^j\frac{\vartheta_{t+j}P_{\mathbb{C},t}}{\vartheta_t P_{\mathbb{C},t+j}}\Big[S^{\omega/\psi}_{t+j}\tilde{P}^{*\psi}_{H,t}(i)\chi^*_{t,j}Y^{*\psi}_{H,t+j}(i) - MC_{t+j}Y^{*\psi}_{H,t+j}(i) \\ & + S^{\omega/\psi}_{t+j}\tilde{P}^{*\psi}_{H,t}(i)\chi^{p*\psi}_{t,j}Y^{p*\psi}_{H,t+j}(i) - MC_{t+j}Y^{p*\psi}_{H,t+j}(i)\Big]\Bigg),\end{aligned} \tag{25}$$

where χ is the inflation indexation for each type of goods: χ_j for domestic goods, χ_j^* for foreign consumption goods and χ_j^{p*} for foreign production goods. Foreign indices are computed for each destination country, indexed by ψ, and differ by local inflation indexation parameters ι_{pF}^* and $\bar{\pi}_H^*$:

$$\chi_{t,j} = \begin{cases} 1 & \text{if} \quad j=0, \\ \Pi_{k=1}^{j} \pi_{H,t+k-1}^{\iota_p} \bar{\pi}_H^{1-\iota_p} & \text{if} \quad j=1,\dots,\infty \end{cases}, \tag{26}$$

$$\chi_{t,j}^* = \begin{cases} 1 & \text{if} \quad j=0, \\ \Pi_{k=1}^{j} \pi_{H,t+k-1}^{*\iota_{pF}^*} \bar{\pi}_H^{*1-\iota_{pF}^*} & \text{if} \quad j=1,\dots,\infty \end{cases}, \tag{27}$$

$$\chi_{t,j}^{p*} = \begin{cases} 1 & \text{if} \quad j=0, \\ \Pi_{k=1}^{j} \pi_{H,t+k-1}^{p*\iota_{pF}^*} \bar{\pi}_H^{p*1-\iota_{pF}^*} & \text{if} \quad j=1,\dots,\infty \end{cases}. \tag{28}$$

Prices with ˜ denote intermediate goods prices, to distinguish them from final goods prices. Variables with * are exported variables. The price of domestic goods, $\tilde{P}_{H,t}$ is set in the domestic currency and the prices of exported consumption and production goods, $\tilde{P}_{H,t}^*$ and $\tilde{P}_{H,t}^{*p}$, are set in the foreign currency. In our model, producers consider separate export prices for each importing country, which are indexed by ψ, and take the exchange rates, $S_{t+j}^{\omega/\psi}$, into account. Export prices are rigid in the destination currency. Parameters ζ_p, ζ_{pF}^* are the Calvo probabilities of not being able to re-optimize prices for home and foreign prices respectively. Prices that are not optimized are indexed to past inflation with a weight ι_p or ι_{pF}^* for domestic and export prices respectively, and to trend inflation with a weight $1-\iota_p$ or $1-\iota_{pF}^*$. There are three types of trend inflation: domestic inflation, $\bar{\pi}_H$, exported intermediate goods inflation, $\bar{\pi}_H^*$, and exported production goods inflation, $\bar{\pi}_H^{p*}$.

Note that a manufacturer produces all goods with the same marginal costs, but the distribution costs are different: production goods are not processed through the distribution channel, and local markets have different exchange rates and different degrees of price rigidity. Domestic good is then sold to domestic homogeneous goods assemblers, and export goods are sold to foreign homogeneous goods assemblers.

2.4 Homogeneous Goods Assemblers

The assemblers are perfectly competitive and produce homogeneous domestic good, $Y_{H,t}$, and imported goods, $Y_{F,t}$ and $Y_{F,t}^p$, out of $Y_{H,t}(i)$, $Y_{F,t}(i)$ and $Y_{F,t}^p(i)$ respectively. They have Kimball production functions:

$$1 = \int_0^1 G\left(\frac{Y_{H,t}(i)}{Y_{H,t}}\right) di, \tag{29}$$

$$1 = \int_0^1 G\left(\frac{Y_{F,t}(j)}{Y_{F,t}}\right) dj, \tag{30}$$

$$1 = \int_0^1 G\left(\frac{Y_{F,t}^p(l)}{Y_{F,t}^p}\right) dl, \tag{31}$$

where G has the following properties: $G(1)=1$, $G'(x)>0$ and $G''(x)<0$ for $x>0$.

Assemblers select the optimal inputs and output levels, taking prices as given. The first-order conditions for domestic good imply:

$$Y_{H,t}(i) = G^{'-1}\left(\frac{P_{H,t}(i)}{P_{H,t}}\mathbb{I}_t\right)Y_{H,t}, \tag{32}$$

$$\mathbb{I}_t = \int_0^1 G'\left(\frac{Y_{H,t}(i)}{Y_{H,t}}\right)\frac{Y_{H,t}(i)}{Y_{H,t}}di. \tag{33}$$

Similarly for imported goods:

$$Y^j_{F,t}(i) = G^{'-1}\left(\frac{P^j_{F,t}(i)}{P^j_{F,t}}\mathbb{I}^j_{F,t}\right)Y^j_{F,t}, \tag{34}$$

$$Y^{j,p}_{F,t}(i) = G^{'-1}\left(\frac{P^{pj}_{F,t}(i)}{P^{pj}_{F,t}}\mathbb{I}^{pj}_{F,t}\right)Y^{pj}_{F,t}, \tag{35}$$

where the prices are determined by demand from final goods firms. Note that when importing from each country, the assembler faces a different demand schedule, where j is the index for foreign countries.

The homogeneous goods assemblers sell domestic and foreign goods, $Y_{H,t}$ and $Y_{F,t}$, to final goods producers and production good, Y^p_F, to domestic intermediate goods producers.

2.5 Final Goods Firms

There is a continuum of competitive final goods firms, indexed by m, that produce retail goods (with superscript D) using homogeneous domestic and foreign goods, $Y_{H,t}$ and $Y_{F,t}$, and taking all prices as given. They are assumed to have Leontief technology combining homogeneous domestic and foreign goods with the home product as an input. The home product used in the distribution channel is labelled as Y^d:

$$Y^D_{H,t}(m) = min\left[(1+\delta_f)Y_{H,t}(m); \frac{1+\delta_f}{\delta_f}Y^d_{H,t}\right], \tag{36}$$

$$Y^{j,D}_{F,t}(m) = min\left[(1+\delta_f)Y^j_{F,t}(m); \frac{1+\delta_f}{\delta_f}Y^d_{H,t}\right], \tag{37}$$

where j is the index of the foreign country from which the good was imported, and δ_f governs the share of home goods used in the distribution process. Consequently, it also limits the exchange rate and foreign inflation pass-through to domestic inflation. As it is optimal to have no unused inputs at equilibrium, the following conditions arise:

$$(1+\delta_f)Y_{H,t}(m) = \frac{1+\delta_f}{\delta_f}Y^d_{H,t} = Y^D_{H,t}(m), \tag{38}$$

$$(1+\delta_f)Y^j_{F,t}(m) = \frac{1+\delta_f}{\delta_f}Y^d_{H,t} = Y^{j,D}_{F,t}(m). \tag{39}$$

$Y^d_{H,t}$ is pinned down by the demand for consumption goods. The demand for inputs is then a linear function of the distributed goods:

$$Y_{H,t}(m) = \frac{1}{1+\delta_f} Y^D_{H,t}(m), \tag{40}$$

$$Y^j_{F,t}(m) = \frac{1}{1+\delta_f} Y^{j,D}_{F,t}(m). \tag{41}$$

The final goods firms also produce oil product for final consumption using the same technology, but with an oil-specific distribution parameter:

$$O^D_t(m) = min\left[(1+\delta_o)O^c_t(m); \frac{1+\delta_o}{\delta_o} Y^d_{H,t}\right], \tag{42}$$

$$P^D_{oil,t} = \frac{1}{1+\delta_o} P_{oil,t} + \frac{\delta_o}{1+\delta_o} P_{H,t}, \tag{43}$$

where $P_{oil,t}$ is the oil price in the home currency. That is, for countries other than the United States, the oil price is given by:

$$P^{\omega}_{oil,t} = P^{US}_{oil,t} S^{\omega/US}_t. \tag{44}$$

2.6 International Trade

The model contains three countries trading with each other bilaterally, and the “rest of the world” (RoW), which is not modelled explicitly and is captured as an exogenous demand shock. Exports are driven by non-oil demand from foreign countries:

$$X_{H,t} = \Pi_{j\neq\omega}(M^j_{F,t})^{\beta^{j/\omega}_x} exp(\varepsilon^{nt}_t), \tag{45}$$

where ε^{nt} is exogenous RoW demand, modelled as an AR(1) process with i.i.d. errors, and M^j_F are imports to country j.

In each economy j, its imports, M_H, depend on the demand from final goods firms and homogeneous goods assemblers. The model also allows for transit goods, which are imported to be exported.[4] The price of the transit goods is assumed to be equal to the price of foreign consumption goods. Employing the notation from de Walque et al. (2017), we define total imports as an aggregate of foreign goods, Y^T_F, and transit goods, X_F (superscripts ω and j are dropped for convenience):

$$M_{H,t} = \left[\phi^{H\,\frac{1}{\lambda_m}}_m (Y^T_{F,t})^{\frac{\lambda_m-1}{\lambda_m}} + (1-\phi^H_m)^{\frac{1}{\lambda_m}} (X_{F,t})^{\frac{\lambda_m-1}{\lambda_m}}\right]^{\frac{\lambda_m}{\lambda_m-1}}, \tag{46}$$

$$Y^T_{F,t} = \left[\phi_F^{\frac{1}{\lambda_F}} (Y_{F,t})^{\frac{\lambda_F-1}{\lambda_F}} + (1-\phi_F)^{\frac{1}{\lambda_F}} (Y^p_{F,t})^{\frac{\lambda_F-1}{\lambda_F}}\right]^{\frac{\lambda_F}{\lambda_F-1}}, \tag{47}$$

where Y^T_F stands for total demand for foreign goods. This total demand consists of foreign goods for consumption and production, with the elasticity of substitution between them denoted as λ_F.

[4] According to OECD statistics, in 2016 the import content of exports was more than 12.5% for the euro area, more than 9% for the US and more than 16.6% for China, so re-exports account for a significant proportion of exports.

Total foreign good is then aggregated with the transit good with elasticity of substitution λ_m. Parameters ϕ_m^H and ϕ_F govern the relative shares of total foreign good and total consumption good in the corresponding aggregates.

The total exports of a country are then defined in a similar fashion by combining its total exports of goods for production and consumption with the transit good:

$$X_{H,t} = \left[{\phi_x^H}^{\frac{1}{\lambda_x}} (Y_{H,t}^{T*})^{\frac{\lambda_x - 1}{\lambda_x}} + (1 - \phi_x^H)^{\frac{1}{\lambda_x}} (X_{F,t})^{\frac{\lambda_x - 1}{\lambda_x}} \right]^{\frac{\lambda_x}{\lambda_x - 1}}, \tag{48}$$

where λ_x is the corresponding elasticity of substitution and $Y_{H,t}^{T*}$ are total goods exported to country j, which are determined symmetrically to (47): $Y_{H,t}^{T*}$ for a country ω is $Y_{F,t}^{T}$ for the counterpart country j.

Constant elasticity of substitution between transit and non-transit goods implies the following price aggregators:

$$P_{M,t} = \left[\phi_m^H (P_{F,t}^T)^{1-\lambda_m} + (1 - \phi_m^H)(P_{F,t})^{1-\lambda_m} \right]^{\frac{1}{1-\lambda_m}}, \tag{49}$$

$$P_{X,t} = \left[\phi_x^H (P_{H,t}^{T*})^{1-\lambda_x} + (1 - \phi_x^H)(P_{F,t})^{1-\lambda_x} \right]^{\frac{1}{1-\lambda_x}}, \tag{50}$$

$$P_{F,t}^T = \left[\phi_F (P_{F,t})^{1-\lambda_F} + (1 - \phi_F)(P_{F,t}^p)^{1-\lambda_F} \right]^{\frac{1}{1-\lambda_F}}. \tag{51}$$

Again, P_H^{T*} is defined symmetrically to P_F^T.

Combining total non-oil imports with oil imports we get the price of total imports:

$$\mathbb{M}_{H,t} = \left[{\phi_m^{oil}}^{\frac{1}{\lambda_m^{oil}}} (M_{H,t})^{\frac{\lambda_m^{oil} - 1}{\lambda_m^{oil}}} + (1 - \phi_m^{oil})^{\frac{1}{\lambda_m^{oil}}} (OIL_t)^{\frac{\lambda_m^{oil} - 1}{\lambda_m^{oil}}} \right]^{\frac{\lambda_m^{oil}}{\lambda_m^{oil} - 1}}, \tag{52}$$

$$P_{\mathbb{M},t} = \left[\phi_m^{oil} (P_{M,t})^{1-\lambda_m^{oil}} + (1 - \phi_m^{oil})(P_{oil,t})^{1-\lambda_m^{oil}} \right]^{\frac{1}{1-\lambda_m^{oil}}}, \tag{53}$$

with λ_m^{oil} being the elasticity of substitution between oil and non-oil imports and ϕ_m^{oil} the relative share of non-oil imports in total imports. P_{oil} is the price of crude oil in the domestic currency. OIL_t is the total oil imported. Total oil imports consist of oil for consumption and oil for manufacturing purposes:

$$OIL_t = O_t^c + O_t^p. \tag{54}$$

Bilateral imports and exports, together with the corresponding prices, are defined by the same equations, substituting the total import and export components with the bilateral ones (i.e. $Y_{H,t}^{T*}$ with $Y_{H,t}^{j,T*}$).

2.7 Aggregation and Monetary Policy

Final users use distributed goods to invest and consume. It is assumed that government spending and utilization costs are paid only in terms of domestic goods. In other words:

$$Y_{H,t}^{D} = C_{H,t} + I_{H,t} + G_t + \psi(u_t)K_{t-1}, \tag{55}$$

$$\sum_{j \neq \omega} Y_{F,t}^{j,D} = C_{F,t} + I_{F,t}, \tag{56}$$

where j indexes the countries of origin of imported goods. Government spending, G_t, is not modelled explicitly but is assumed to be an exogenous AR(1) process with i.i.d. shock μ_t^g and persistence ρ_g.

Each economy features several New Keynesian Phillips curves capturing the development of prices of specific products: imported consumption goods, imported production goods, exported consumption goods, exported production goods, bilateral exported and imported consumption and production goods, home inflation and consumption inflation. To derive the Phillips curves, we first substitute the demand of final goods producers for final goods (40) and (41) and the demand of foreign producers for production good into the demand of homogeneous goods assemblers for intermediate goods (32), (34) and (35):

$$Y_{H,t}(i) = G^{'-1}\left(\frac{P_{H,t}(i)}{P_{H,t}}\mathbb{I}_t\right)\frac{1}{1+\delta_f}Y_{H,t}^{D}, \tag{57}$$

$$Y_{H,t}^{*j}(i) = G^{'-1}\left(\frac{P_{H,t}^{*j}(i)}{P_{H,t}^{*j}}\mathbb{I}_t^{*j}\right)\frac{1}{1+\delta_f^{*j}}Y_{F,t}^{*jD}, \tag{58}$$

$$Y_{H,t}^{*pj}(i) = G^{'-1}\left(\frac{P_{H,t}^{*pj}(i)}{P_{F,t}^{*pj}}\mathbb{I}_t^{*pj}\right)\frac{1}{\rho_m^{*j}}Y_{F,t}^{j}. \tag{59}$$

Then, from the zero-profit condition of assemblers, the price index for the domestic product is:

$$P_{H,t} = \xi_p \pi_{H,t-1}^{\iota_p}\bar{\pi}_H^{1-\iota_p}P_{H,t-1}G'^{-1}\left(\frac{\pi_{H,t-1}^{\iota_p}\bar{\pi}_{H,}^{1-\iota_p}P_{H,t-1}}{P_{H,t}}\mathbb{I}_t\right) + (1-\xi_p)\tilde{P}_{H,t}G'^{-1}\left(\frac{\tilde{P}_{H,t}}{P_{H,t}}\mathbb{I}_t\right). \tag{60}$$

For exports of consumption and production goods to country j, the price indices are the following:

$$\begin{aligned} P_{H,t}^{*j} &= \xi_p^{*j}(\pi_{H,t-1}^{*j})^{\iota_p^{*j}}(\bar{\pi}_H^{*j})^{1-\iota_p^{*j}}P_{H,t-1}^{*j}G'^{-1}\left(\frac{(\pi_{H,t-1}^{*j})^{\iota_p^{*j}}(\bar{\pi}_H^{*j})^{1-\iota_p^{*j}}P_{H,t-1}^{*j}}{P_{H,t}^{*j}}\mathbb{I}_t^{*j}\right) + \\ &\quad (1-\xi_p^{*j})\tilde{P}_{H,t}^{*j}G'^{-1}\left(\frac{\tilde{P}_{H,t}^{*j}}{P_{H,t}^{*j}}\mathbb{I}_t^{*j}\right), \end{aligned} \tag{61}$$

$$\begin{aligned} P_{H,t}^{*pj} &= \xi_p^{*j}(\pi_{H,t-1}^{*pj})^{\iota_p^{*j}}(\bar{\pi}_H^{*pj})^{1-\iota_p^{*j}}P_{H,t-1}^{*pj}G'^{-1}\left(\frac{(\pi_{H,t-1}^{*pj})^{\iota_p^{*j}}(\bar{\pi}_H^{*pj})^{1-\iota_p^{*j}}P_{H,t-1}^{*pj}}{P_{H,t}^{*pj}}\mathbb{I}_t^{*pj}\right) + \\ &\quad (1-\xi_p^{*j})\tilde{P}_{H,t}^{*pj}G'^{-1}\left(\frac{\tilde{P}_{H,t}^{*pj}}{P_{H,t}^{*pj}}\mathbb{I}_t^{*pj}\right). \end{aligned} \tag{62}$$

If an intermediate firm was last able to optimize its price at time t, then its product will be priced in the distribution channel as:

$$P^D_{H,t+i}(m) = \frac{1}{1+\delta_f}\tilde{P}_{H,t}(m)\chi_{t,i} + \frac{\delta_f}{1+\delta_f}P_{H,t+i}. \tag{63}$$

Analogously, its export consumption good will be priced via the foreign distribution channel as:

$$P^{D*j}_{H,t+i}(m) = \frac{1}{1+\delta^{*j}_f}\tilde{P}^{*j}_{H,t}(m)\chi^{*j}_{t,i} + \frac{\delta^{*j}_f}{1+\delta^{*j}_f}P^{*j}_{H,t+i}, \tag{64}$$

where superscript $*j$ means exported to country j. A similar relationship holds for imported goods for direct consumption:

$$P^{Dj}_{F,t+i}(m) = \frac{1}{1+\delta_f}\tilde{P}^{j}_{F,t}(m)\chi_{t,i} + \frac{\delta_f}{1+\delta_f}P_{H,t+i}, \tag{65}$$

where superscript j now means imported from country j. Note again that the distribution parameters are specific to the country where the product is to be distributed.

The zero-profit condition for final goods producers implies that on aggregation the final prices of foreign goods are influenced by domestic prices:

$$P^D_{H,t} = \frac{1}{1+\delta_f}P_{H,t} + \frac{\delta_f}{1+\delta_f}P_{H,t} = P_{H,t}, \tag{66}$$

$$P^D_{F,t} = \frac{1}{1+\delta_f}P_{F,t} + \frac{\delta_f}{1+\delta_f}P_{H,t}. \tag{67}$$

The New Keynesian Phillips curves are described in Appendix A.

Domestic output in each economy is used for household and government consumption, investment, utilization of capital and net exports and as distribution channel inputs to create distributed domestic and foreign goods and oil products. The resource constraint then takes the form:

$$\begin{aligned} Y_t \quad = \quad & \left(s_{H,t}\frac{1}{1+\delta_f} + s^d_{H,t}\frac{\delta_f}{1+\delta_f}\right)(C_{H,t}+I_{H,t}+G_t+\psi(u_t)K_{t-1}) + s^*_{H,t}Y^*_{H,t} + s^{p*}_{H,t}Y^{*p}_{H,t} \\ & s^d_{H,t}Y_{F,t} + s^d_{H,t}\frac{\delta_o}{1+\delta_o}O^D_t, \end{aligned} \tag{68}$$

where "s" terms reflect price dispersion and are calculated as $s_x = \int G^{'-1}\left(\frac{P_{x,t}(m)}{P_{x,t}}\mathbb{I}_{x,t}\right)$.

In each economy there is a central bank that sets the nominal interest rate using the following rule:

$$\frac{R_t}{\bar{R}} = \left(\frac{R_{t-1}}{\bar{R}}\right)^{\rho_r}\left[\left(\frac{\Pi_t}{\bar{\Pi}}\right)^{\phi_\pi}\left(\frac{Y_t}{Y^f_t}\right)^{\phi_y}\right]^{1-\rho_r}\left(\frac{Y_t/Y_{t-1}}{Y^f_t/Y^f_{t-1}}\right)^{\psi_{\Delta y}}\varepsilon^r_t. \tag{69}$$

In the rule above, the central bank adjusts the policy rate relative to its steady-state value, $\bar{R}$, responding to deviations of inflation from the target, $\bar{\pi}$, and to the output gap, where Y^f_t is output in the flexible economy. The strength of the response is governed by parameters ϕ_π and ϕ_y. The policy maker also reacts to the growth rate of output relative to its flexible counterpart with parameter $\psi_{\Delta y}$. The flexible counterfactual economy is defined as an economy without price and wage rigidities and without mark-up shocks. In the rule, there is a stochastic AR(1) process, ε^r, with i.i.d. shock μ_t^r and persistence ρ_r.

When considering the implementation of tariffs in section 5, in the baseline scenario we assume that central banks react to after-tax inflation according to the rule above. In reality, the tariffs were implemented in a low-inflation environment where a rise in inflation did not necessarily mean an overshooting of the inflation target. In Appendix F we conduct a hypothetical simulation of tariff implementation in the situation where the euro area is at the effective lower bound while US inflation is under the target. Both central banks decide not to raise rates in response to the tariffs, but do stimulate the economy, the Fed by cutting interest rates and the ECB by committing not to raise rates in the medium term.

Reserve requirements have become a frequently used policy instrument in China. Following Blagrave et al. (2013) we model change in Chinese reserve requirement policy as a reaction to the output gap and the deviation of inflation from the target:[5]

$$\Delta RRQ_t = \Delta RRQ_{t-1}^{\rho^{rrq}} \left(\frac{Y_t}{Y_t^f}\right)^{\phi_y^{rrq}} \left(\frac{\Pi_t}{\bar{\Pi}}\right)^{\phi_\pi^{rrq}} exp(\varepsilon_t^{rrq}). \tag{70}$$

Reserve requirements affect the costs of borrowing of households and businesses. In our framework, we model this effect as feedback in the consumption Euler equation and the price of capital in the Chinese block in the corresponding equations in Appendix A.

In our model, we allow all countries to buy and sell foreign bonds. Following de Walque et al. (2017) we keep the assumption that all countries have zero foreign bond positions in the steady state. Then for country ω the net foreign asset position is the difference between acquired foreign bonds in US dollars and issued bonds sold abroad, also in US dollars:

$$NFA_t^\omega = S_t^{\omega/US} B_{F,t}. \tag{71}$$

$B_{F,t}$ stands for total net acquisition of foreign bonds – bonds bought minus bonds issued.

Definition 1. *Equilibrium. A monopolistically competitive equilibrium for an open economy has the following properties:*

(i) Households maximize utility over consumption of domestic and foreign goods, oil consumption, investment, labour, bond holdings and wages; intermediate goods producers optimize profits over foreign inputs, oil, labour demand, domestic capital and prices in each market; and homogeneous goods producers and final goods producers maximize profit over demand for home and foreign differentiated intermediate goods and home and foreign homogeneous goods and oil respectively.

[5] There are semi-structural models – Dieppe et al. (2018) and Blagrave et al. (2013), among others – that modify Chinese monetary policy and reserve requirement policy to include exchange rate feedback. Moreover, in Dieppe et al. (2018) monetary policy innovations enter the reserve requirement rule and vice versa. In our estimation we do not find any significant correlation between policy innovations and the exchange rate. We interpret this as meaning that the two rules react to a similar set of factors and there is no need to introduce an additional correlation between them.

(ii) Nominal exchange rates are determined by (15) and (16).

(iii) The set of domestic, exported and imported prices of final goods for consumption and production and wages clears all markets.

Having described the model, we move to specifying the set-up for the estimation and analysing the model performance.

3. Estimation

3.1 Data and Measurement Equations

For the US and the euro area we closely follow the data choices of de Walque et al. (2017). For China we try to use similar data series, subject to availability and quality. In total, there are 29 observation series, including two exchange rate and oil price series. The data are listed in Table B1 in Appendix B. All the Chinese data except for the reserve requirements are from Datastream. The euro area data are from the euro area-wide model database. The US data are from the Bureau of Economic Analysis and the US Department of Labour. For the Chinese reserve requirements we use information from The People's Bank of China. For US and euro area short-term interest rates we use information from the Fed and the ECB respectively. We use 101 quarterly observations in total, running from 1991Q4 to 2016Q4. The time span is limited by the data availability for China.

All real data are divided by the working age population (except for Chinese real GDP, available per capita) and transformed into quarter-to-quarter growth rates, as in:

$$\Delta GDP = 100\Delta ln\left(\frac{\text{Real GDP}}{\text{Population}}\right).$$

For the labour supply we use employment divided by the working age population and multiplied by hours worked. Following Smets and Wouters (2003), for the euro area we construct an employment variable, e:

$$\hat{e}_t = \hat{e}_{t-1} + \bar{\beta}\gamma(\hat{e}_{t+1} - \hat{e}_t) + (1-\xi_e)\frac{1-\xi_e\bar{\beta}\gamma}{\xi_e}\left(\hat{l}_t - \hat{e}_t\right),$$

where $\hat{e}$ is the number of employed people and $\hat{l}$ is the labour supply, featuring Calvo adjustment of employment with probability ξ_e.

We use the net exports to GDP ratio for the EA series to minimize intra-union trade in the data. The observables are linked to the model equations as shown in Table 1. Note that the observables have trends.

Similarly to de Walque et al. (2006) we allow for a time-varying trend in the Chinese inflation target, $\hat{\bar{\pi}}$. The variable target is modelled as a non-stationary process:

$$\Delta\hat{\bar{\pi}}_t = \rho^{\bar{\pi}}\Delta\hat{\bar{\pi}}_{t-1} + \mu^{\bar{\pi}}.$$

The variable target is useful for modelling Chinese inflation, which demonstrates a change in trend during the selected period. We employ a similar mechanism to capture a change in trend in the

Table 1: Measurement Equations

Name	Trend	Model Variables
Common equations:		
Δ Real GDP	$=\bar{\gamma}$	$+(1-\rho_m-\rho_o)(\hat{y}_t-\hat{y}_{t-1})$
Δ GDP deflator	$=\bar{\pi}+\hat{\bar{\pi}}_t$	$+\hat{\pi}_t$
Δ Consumption deflator	$=\bar{\pi}+\hat{\bar{\pi}}_t$	$+\hat{\pi}_{\mathbf{c},t}$
Δ Real consumption	$=\bar{\gamma}$	$+\hat{\mathbf{c}}_t-\hat{\mathbf{c}}_{t-1}$
Δ Real investment	$=\bar{\gamma}$	$+\hat{i}_t-\hat{i}_{t-1}$
Net exports	$=\overline{nx}$	$+\alpha_m(\hat{x}_{H,t}-\hat{\mathbf{m}}_{H,t})$
Nominal interest rate	$=4\bar{r}$	$+4\hat{r}_t+\hat{\bar{\pi}}_t$
Country-specific equations		
Δ Import deflator (for US and EA)	$=\bar{\pi}^*$	$+\hat{p}_{\mathbf{m},t}$- $\hat{p}_{\mathbf{m},t-1}+\hat{\pi}_{\mathbf{c},t}$
Δ Real wage (for US and EA)	$=\bar{\gamma}$	$+\hat{w}_t-\hat{w}_{t-1}$
Δ US labour	$=\bar{l}$	$+\hat{l}_t-\hat{l}_{t-1}$
Δ EA labour	$=\bar{l}$	$+\hat{e}_t-\hat{e}_{t-1}$
Δ Reserve requirement	$=\widehat{\Delta RRQ}_t$	$+\Delta\widehat{rrq}_t$
Δ EA/US Nominal exchange rate	$=\bar{s}^{EA/US}$	$+\widehat{rs}_t^{EA/US}-\widehat{rs}_{t-1}^{EA/US}-(\hat{\pi}_{\mathbf{c},t}^{US}-\hat{\bar{\pi}}_t^{US})$ $+(\hat{\pi}_{\mathbf{c},t}^{EA}-\hat{\bar{\pi}}_{,t}^{EA})$
Δ CH/US Nominal exchange rate	$=$	$\widehat{rs}_t^{CH/US}-\widehat{rs}_{t-1}^{CH/US}-(\hat{\pi}_{\mathbf{c},t}^{US}-\hat{\bar{\pi}}_t^{US})+(\hat{\pi}_{\mathbf{c},t}^{CH}-\hat{\bar{\pi}}_t^{CH})$ $+(\widehat{\bar{rs}}_t^{CH/US}-\widehat{\bar{rs}}_{t-1}^{CH/US})$
Δ Oil price	$\bar{\pi}_{oil}$	$+\pi_{oil,t}-\pi_{oil,t-1}+\hat{\pi}_{\mathbf{c},t}^{US}-\hat{\bar{\pi}}_t^{US}$

Note: The variable trend in inflation $\hat{\bar{\pi}}_t$ is used only in the equations for China.

Chinese real exchange rate, $\widehat{\bar{rs}}^{CH/US}$,[6] and a change in the reserve requirement ratio, $\widehat{\overline{RRQ}}$.[7] For all of the non-stationary processes mentioned, we estimate the persistence and standard deviations of innovations.

In our estimation there are 31 observables, with 31 structural shocks and three shocks to variable trends and a shock to exogenous exchange rate policy. The shocks are described in Table 2.

During the estimation we allow for cross-country correlation of the shocks to productivity, risk premium, monetary policy and RoW demand. The domestic productivity shock is allowed to affect government spending and RoW demand. Next, we describe the calibration and estimation strategy.

3.2 Calibration, Priors and Posteriors

Some of the parameters of the model are hard to identify using the available data. We thus fix them at the calibrated or implied values. We report those parameters in Tables 3–5. The consumption, investment and imports to GDP ratios are fixed at their historical averages. The capital depreciation rate is set at 0.025 quarterly, corresponding to 0.01 annually. Following de Walque et al. (2017) and Smets and Wouters (2007), we fix the wage mark-up parameter, λ_w, at 0.25 and the Kimball

[6] While the shock in 16 is white noise in the nominal exchange rate equation, the trend is an AR(1) process in the first differences in the real exchange rate equation.
[7] Both series were mostly constant for about half of the sample and demonstrate some volatility around a non-zero constant in other half. Using a time-variable trend helps us to account for the switch in Chinese policy within a linear model.

Table 2: Description of the Shocks

Name	Process	Shock
Common shocks:		
TFP	ε^a, AR(1)	μ^a
Risk premium	ε^b, AR(1)	μ^b
Government spending	ε^g, AR(1)+$\eta_{gy}\mu^a$	μ^g
Investment	ε^i, AR(1)	μ^i
Interest rate	ε^r, AR(1)	μ^r
Home price mark-up	ε^{p_H}, ARMA(1,1)	μ^{pH}
Wage mark-up	ε^w, ARMA(1,1)	μ^w
Consumer prices	ε^p, AR(1)	μ^p
Consumer prices	ε^p, AR(1)	μ^p
RoW demand	ε^{nt}, AR(1)+$\eta_a\mu^a$	μ^{nt}
Country-specific shocks:		
Imported price mark-up (EA and US)	ε^{p_F}, ARMA(1,1)	μ^{p_F}
Reserve requirement	ε^{rrq}, AR(1)	μ^{rrq}
Oil price	$p_{oil,t}$, ARMA(1)	μ^{oil}
Exchange rates	$\varepsilon^{s,EA/US}$ AR(1)	$\mu^{s,EA/US}$
	$\varepsilon^{s,CH/US}$ AR(1)	$\mu^{s,CH/US}$
Exchange rate policy		S^{pol}
Shocks to variable trends:		
Inflation trend (only China)		$\mu^{\hat{\bar{\pi}}}$
Reserve requirement trend		$\mu^{\widehat{r\bar{r}q}}$
CNY/USD exchange rate trend		$\mu^{\hat{\bar{s}}}$

curvature – the curvature of the demand from homogeneous goods assemblers – ε at 10. We also assume that the demand for transit goods moves one-to-one with the demand for exported goods, and therefore set λ_x at 0. The oil demand elasticity and the shares in consumption and exports for the euro area and the US are set in accordance with de Walque et al. (2017). For China the parameters are set to match the corresponding statistics on gasoline and petroleum products.

The trade matrix calibration is of utmost importance for trade war analysis. For this purpose we fix the corresponding trade shares at the historical pre-tariff averages. The share of the rest of the world is then determined as the residual trade share in Table 4.

Some of the parameters of the Chinese monetary policy rule are poorly identified – the parameters on the lagged interest rate and the reaction to inflation. We therefore fix these values at the estimates of Dieppe et al. (2018).

The priors for the Bayesian estimation procedure are set in accordance with the long-standing tradition in the literature and for the euro area and the US closely follow the choices of de Walque et al. (2017). The standard deviations of the shocks are assumed to follow an inverted gamma distribution with mean 0.2 and 2 degrees of freedom. The ARMA parameters follow a beta distribution with

Table 3: Calibrated Parameters: Matched Data and Steady-State Ratios

Name	Symbol	EA	US	China
Common parameters:				
Consumption to GDP	α_c	0.564	0.645	0.5
Investment to GDP	α_i	0.22	0.173	0.4
Imports to GDP	α_m	0.2	0.14	0.2
Oil demand elasticity	λ^{oil}	0.3	0.3	0.3
Oil share in consumption	ϕ^{oil}	0.04	0.06	0.02
Oil share in exports	ϕ_x^{oil}	0.04	0.08	0.02

Table 4: Trade Matrix, Historical Averages

Name	Symbol	EA	US	China
Import shares:				
in US imports	$\beta_m^{j/US}$	0.15	N / A	0.2
in CH imports	$\beta_m^{j/CH}$	0.1	0.07	N/A
in EA imports	$\beta_m^{j/EA}$	N/A	0.1	0.13
Export shares:				
in US exports	$\beta_x^{j/US}$	0.13	N / A	0.08
in CH exports	$\beta_x^{j/CH}$	0.11	0.19	N/A
in EA exports	$\beta_x^{j/EA}$	N/A	0.13	0.07
Oil import shares:				
in US oil imports	$\beta_{oil,m}^{j/US}$	0.12	N / A	0.005
in CH oil imports	$\beta_{oil,m}^{j/CH}$	0.015	0.015	N/A
in EA oil imports	$\beta_{oil,m}^{j/EA}$	N/A	0.02	0.002
Oil export shares:				
in US oil exports	$\beta_{oil,x}^{j/US}$	0.2	N / A	0.015
in CH oil exports	$\beta_{oil,x}^{j/CH}$	0.01	0.01	N/A
in EA oil exports	$\beta_{oil,x}^{j/EA}$	N/A	0.24	0.016

Table 5: Calibrated Parameters

Name	Symbol	EA	US	China
Common parameters:				
Capital depreciation	τ	0.025	0.025	0.025
Wage elasticity	λ_w	0.25	0.25	0.25
Kimball curvature	ε	10	10	10
Substitution transit goods	λ_x	0	0	0
Chinese monetary policy rule parameters:				
Lagged interest rate	ρ^r	N /A	N / A	0.8
Reaction to inflation	ρ^π	N /A	N / A	2.5

mean 0.5 and standard deviation 0.2. For the shock correlations we assume normality around zero with a standard deviation of 0.3.[8]

The complete description of the posterior estimates is presented in Tables D1–D5 in Appendix D.

4. Model Assessment

4.1 Impulse Responses

In this section we describe the impulse responses for the selected shocks. The complete list of impulse responses is presented in Appendix C. We present impulse responses with parameters as estimated at the posterior mode, but for clarity of the model analysis we report the responses for uncorrelated shocks. In the impulse response analysis we do not account for the zero lower bound.

4.1.1 Impulse Responses to a Euro Area Productivity Shock

When the euro area experiences a positive productivity shock, its output, consumption and investment rise, but inflation falls. The rise in productivity spurs European demand for foreign production inputs, stimulating US and Chinese output growth. While the ECB lowers its policy rate, the euro depreciates with respect to both the US dollar and the yuan. As a result, prices of foreign inputs and products rise, and consumption inflation falls slightly short of home inflation. The deterioration of home prices relative to import prices transfers the effect of the positive productivity shock to the foreign economies, although the transmission of the shock is very limited. At the same time, foreign – US and Chinese – consumers and producers benefit from lower import prices, which additionally increases their production. The demand for foreign investment and consumption goods rises. With prices of domestic goods falling short of foreign ones, domestic consumption and investment decline, resulting in a slight decrease of total consumption and investment.

The appreciation of the US dollar and the yuan relative to the euro results in a fall in consumption inflation in the US and China and a consequent decline in their policy rates. European net exports rise, reflecting the higher productivity and currency depreciation. The higher demand for foreign goods in the euro area stimulates net exports in both China and the US.

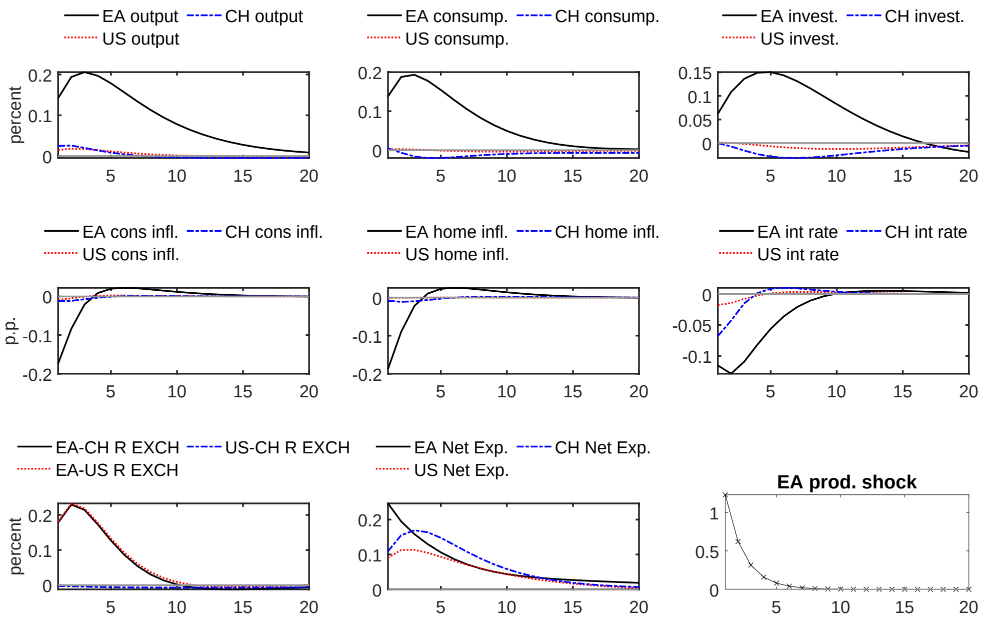
When we do not impose correlation between the shocks, the spillovers from the euro area to its trading partners are small but visible. The transmission goes through the exchange rate channel and prices of domestic relative to foreign products. The lack of flexibility in the yuan-US dollar exchange rate limits the transmission of European shocks to China.

4.1.2 Impulse Responses to a positive US Monetary Policy Shock

After a positive US monetary policy shock, US output and inflation decline, as do consumption and investment. With output falling, US demand for foreign goods falls too. A rise in US interest rates results in the dollar appreciating relative to the euro. US goods become more expensive in the euro area, but Chinese goods also become expensive in the euro area, as the yuan-euro rate is determined through the US dollar. The Chinese nominal exchange rate does not respond to the shock, so the real rate reflects the changes in relative inflation. The response of the Chinese real exchange rate is very persistent, due to the lack of nominal rate adjustment. Cheap European goods stimulate Chinese production and consumption, but the strong yuan depresses exports. As

[8] The model was estimated using Dynare 4.5 (Adjemian et al., 2011). We used 600,000 draws from the posterior distribution. The identification and convergence diagnostics were performed using Dynare tools.

Figure 3: Impulse Responses to a Positive Euro Area Productivity Shock



Note: The posterior mode is used for the simulation. All responses are reported as percentage deviations from the steady state, except for the responses of inflation and interest rates, which are annualized percentage-point deviations from the steady state. An increase in the X-Y exchange rate corresponds to a depreciation of currency X with respect to currency Y.

a result, Chinese consumption rises but output falls, albeit by only a small amount. As the euro depreciates, consumption inflation rises in the euro area, and there is a small decline in output and an increase in home prices due to higher prices of foreign manufacturing inputs. The ECB reacts by raising interest rates to reduce inflation. While US inflation and monetary policy recover, there is depreciation pressure on the US dollar from the yuan and the euro.

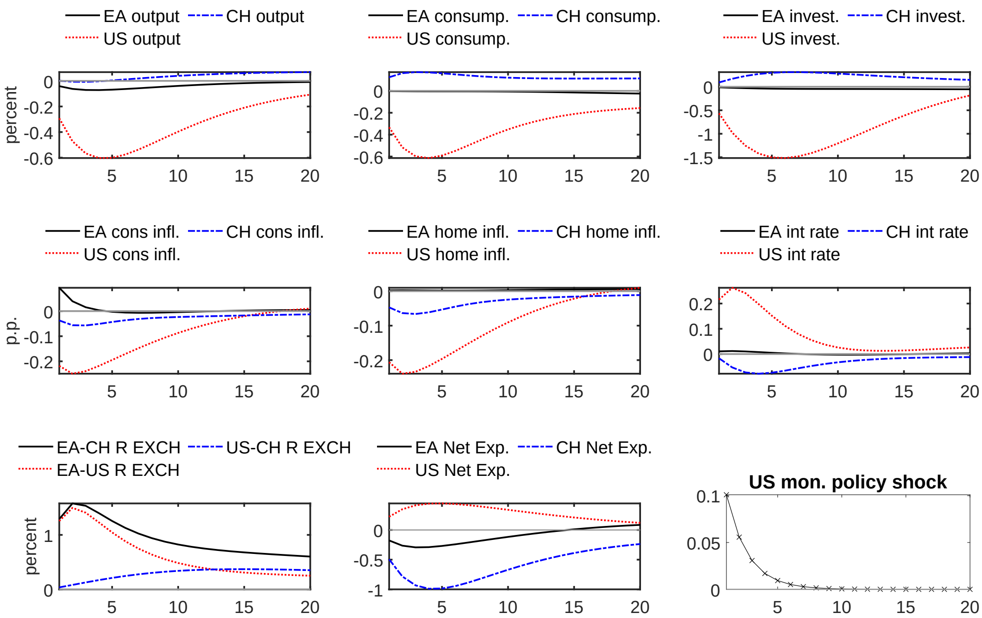
4.1.3 Impulse Responses to UIRP Shocks

When the euro depreciates with respect to the US dollar (see Figure 5), European net exports rise, stimulating production. At the same time, prices of imported consumption goods and manufacturing inputs rise, stimulating an increase in home inflation and, to a larger extent, consumption inflation. The central bank reacts to the rise in inflation with higher interest rates. The higher borrowing costs suppress investment and consumption and put downward pressure on output. As the euro-yuan exchange rate is determined indirectly through the US dollar, the euro depreciates with respect to the yuan. The US and Chinese economies benefit from cheaper imports. At the same time, the demand for their goods in Europe falls, as do net exports in both countries.

When the US dollar depreciates with respect to the yuan (see Figure 6), imported inflation rises in the US, transmitting to higher production and consumption prices.[9] At the same time, the exchange rate against the euro is not affected, so the US does not experience the same boost to net exports as the euro area in Figure 5. The dollar-yuan depreciation spills over to euro-yuan depreciation. European exports rise, as does imported inflation. China benefits from lower prices. A decline in

[9] We use posterior mode estimates of the UIRP shock deviation and persistence, and the shock is small and short-lived, so the responses are also small.

Figure 4: Impulse Responses to a Positive US Monetary Policy Shock

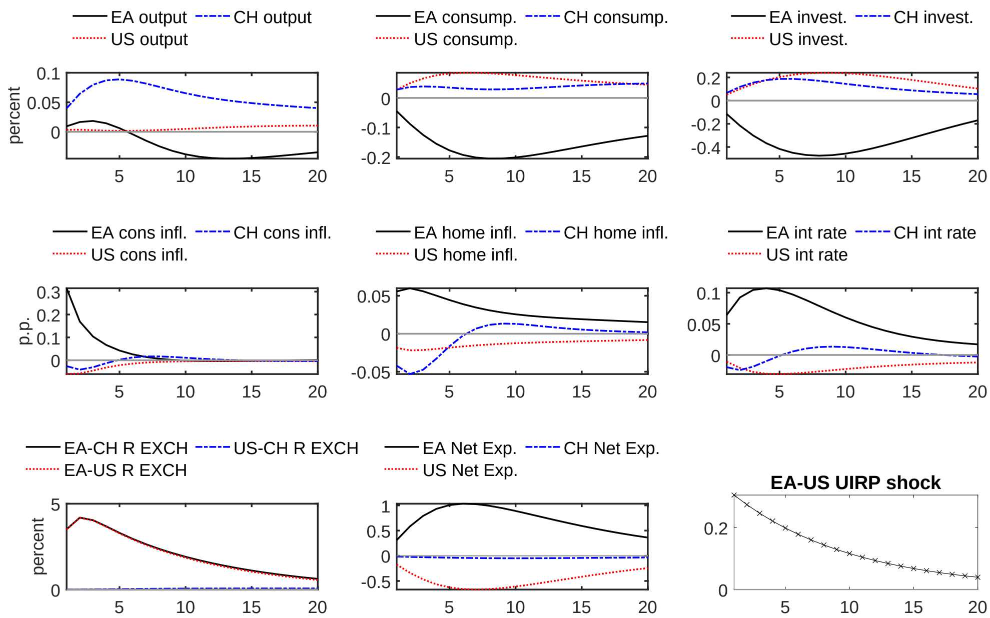


Note: The posterior mode is used for the simulation. All responses are reported as percentage deviations from the steady state, except for the responses of inflation and interest rates, which are annualized percentage-point deviations from the steady state. An increase in the X-Y exchange rate corresponds to a depreciation of currency X with respect to currency Y.

the Chinese policy rate stimulates investment and consumption, adding to the increase in Chinese output growth.

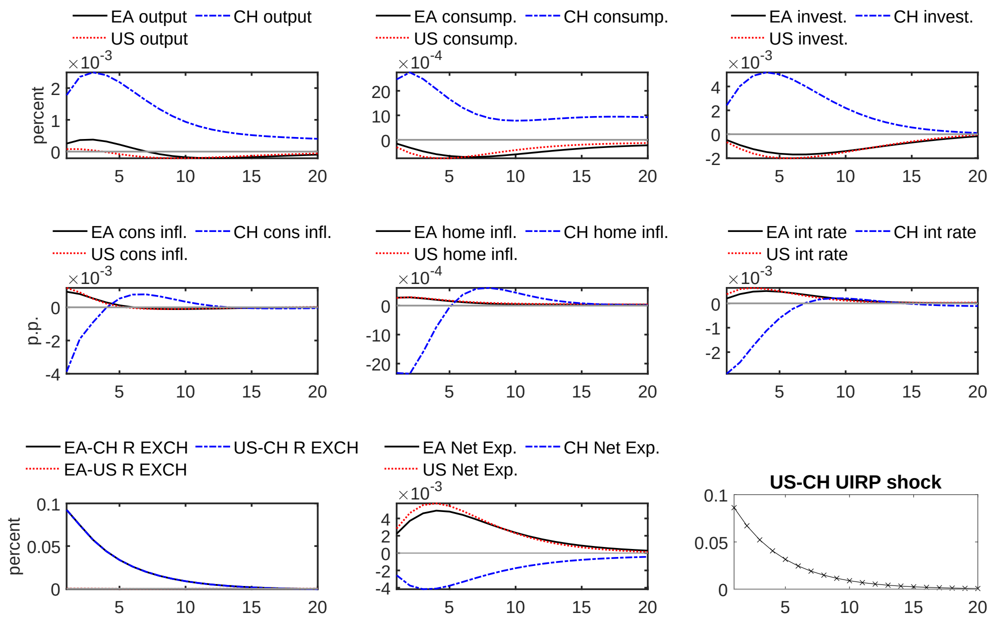
Note that a depreciation is often expected to be expansionary. A real exchange rate depreciation can have an expansionary effect through increased competitiveness of domestic goods abroad, yet it has a contractionary effect through an increase in the cost of production and a deterioration of household balance sheets. As was shown in Lane and Stracca (2018), the contractionary effect dominates for the euro area, at least for exchange rate and monetary policy shocks. In our model, where production depends on oil priced in US dollars and on foreign inputs, a depreciation of the euro results in a slight and short-lived increase in output and net exports, but total consumption falls due to high prices.

Figure 5: Impulse Responses to a Positive EA-US UIRP Shock (Euro Depreciates)



Note: The posterior mode is used for the simulation. All responses are reported as percentage deviations from the steady state, except for the responses of inflation and interest rates, which are annualized percentage-point deviations from the steady state. An increase in the X-Y exchange rate corresponds to a depreciation of currency X with respect to currency Y.

Figure 6: Impulse Responses to a Positive US-CH UIRP Shock (US Dollar Depreciates)



Note: The posterior mode is used for the simulation. All responses are reported as percentage deviations from the steady state, except for the responses of inflation and interest rates, which are annualized percentage-point deviations from the steady state. An increase in the X-Y exchange rate corresponds to a depreciation of currency X with respect to currency Y.

4.2 Historical Shock Decomposition

In this section we present a historical shock decomposition for the variables for the period 2007Q1 to 2016Q4.[10] All parameters are at the posterior mode, where correlation between the shocks is allowed. The estimated correlation is reported in Table D4.[11] For each variable we show the contributions of the three most important shocks[12] and the contributions of shocks aggregated by country of origin. The conditional variance decomposition for countries' output growth, inflation and exchange rates is presented in Appendix E.

Figure 7 shows the variance decomposition of detrended quarterly output growth for the three countries. The solid line depicts the detrended value of output growth. Risk premium and demand shocks are important contributors to the output declines in the US and the euro area, reflecting the tough credit conditions during and after the crisis. In the euro area, this explains much of the output decline during the sovereign debt crisis. Our model does not account for any global factors that might have caused the financial crisis. As we allow for correlation between risk premium shocks and some demand shocks, the model attributes the crisis to domestic shocks. For the euro area and the US, demand shocks are important contributors (government spending shocks and shocks to demand from the rest of the world), as are technology and productivity shocks. Chinese output growth is affected by the domestic demand, monetary policy and home mark-up shocks.[13]

Output is mostly driven by domestic shocks, though over the time period under review there is a visible contribution from shocks to other countries, especially during the recent recession; foreign shocks (oil price shocks and foreign inflation shocks) and exchange rate shocks have a small but non-negligible impact on output in all the countries.

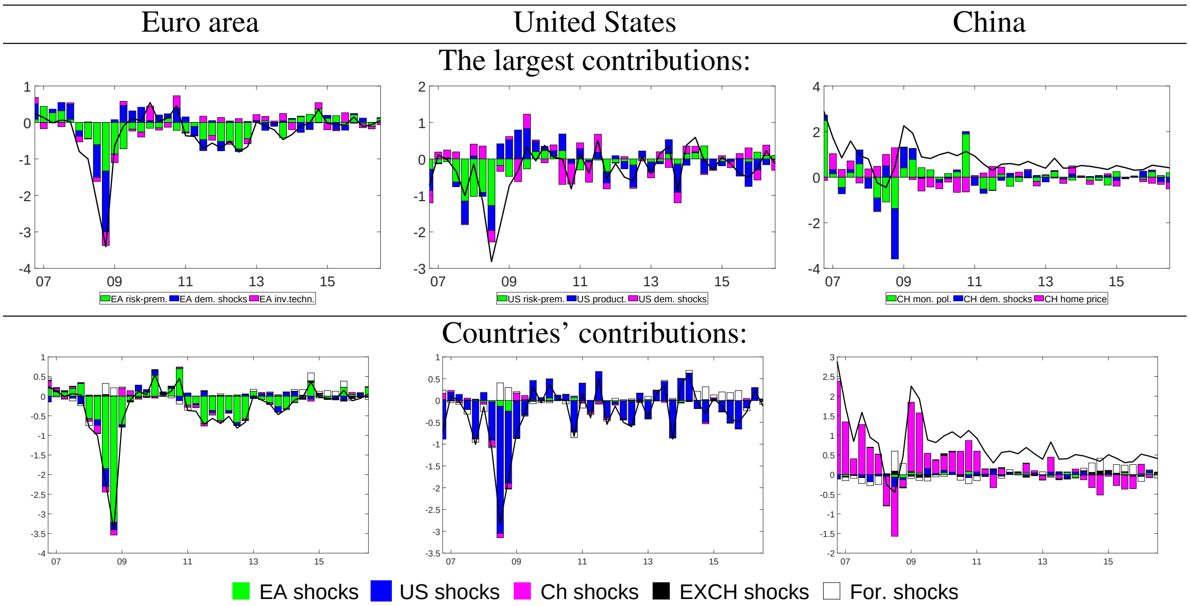
In Figure 8 we report the historical variance decomposition for consumption inflation. The domestic consumption and home price mark-up shocks are the most important drivers of consumption inflation. For the euro area and the US the oil price shock plays an important role, while in the US the risk premium shock makes a significant contribution.

There are spillovers from US shocks to euro area inflation, and Chinese shocks have a significant impact on US and Eurozone consumption prices. Exchange rate shocks play an important role in the euro area, are small in the US, and are negligible in China, which can be explained by its rigid nominal exchange rate. Oil prices are found to be important in the US and the euro area, while movements in Chinese inflation are predominantly explained by domestic shocks. The large contribution of oil price shocks in 2008 is attributed to an extreme, though short-lived, drop in oil prices due to a combination of demand and supply factors.

The historical decomposition of the euro-dollar and dollar-yuan exchange rates is shown in Figure 9. For the euro-dollar rate, its own exchange rate shock is important; the other contributors are US and euro area monetary policy. As for the dollar-yuan rate, which was modelled to be largely determined by exogenous policy, the decomposition is dominated by Chinese shocks – exchange rate policy,

[10] We choose to show only the last ten years of the sample, exclusively for the purposes of visibility in the graphs.
[11] When computing the variance decomposition with correlated shocks, it is assumed that all comovements between EA and US shocks are driven by US shocks, that all comovements between Chinese and EA shocks are driven by EA shocks, and that all comovements between Chinese and US shocks are driven by US shocks.
[12] The shocks were selected according to the sum of the absolute contributions over the whole period.
[13] In our model, however, part of Chinese output growth is not explained by any structural shock and is attributed to the initial conditions. One possible explanation is that Chinese output growth may be overstated, as is repeatedly claimed by economists, for example Chen et al. (2019). There may also be a persistent component of Chinese growth that we do not account for.

Figure 7: Historical Shock Decomposition of Detrended Output Growth



Note: Posterior mode; the solid line is the detrended variable. Foreign shocks include imported price shocks and oil shocks. Demand shocks include government spending shocks and demand shocks from the rest of the world.

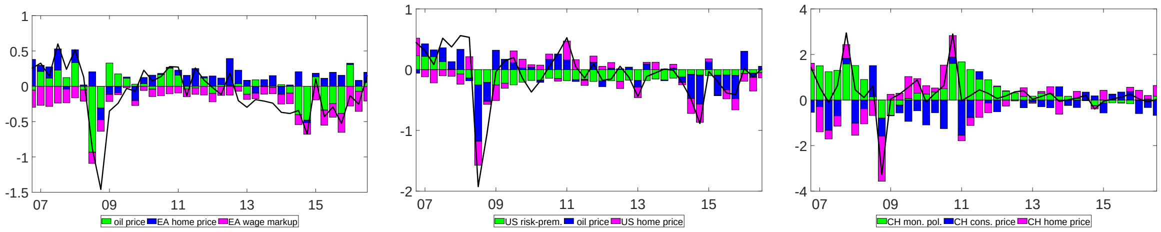
change in exchange rate regime and consumption mark-up. This result is straightforward given the nature of Chinese exchange rate policy and the way we model it.

The conditional variance decomposition of the forecast errors is presented in Appendix E. To conclude, similarly to the analogous multi-country models with rational expectations and with no financial sector, the model does not generate large international spillovers. Possible solutions to this include incorporating financial links or relaxing the rational expectations assumption.

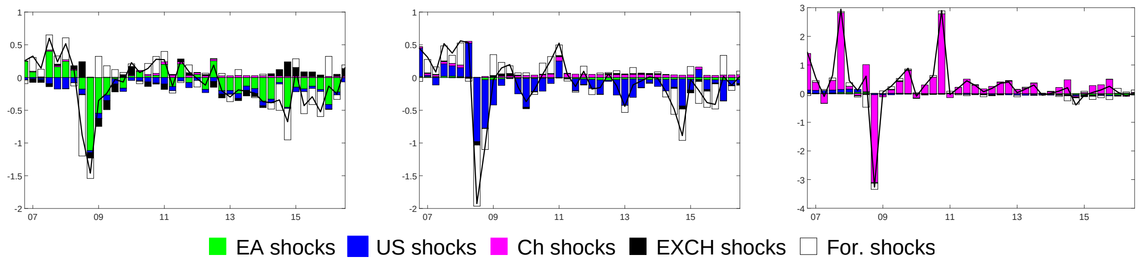
Figure 8: Historical Shock Decomposition of Detrended Consumption Inflation, QoQ Change

Euro area	United States	China

The largest contributions:



Countries' contributions:

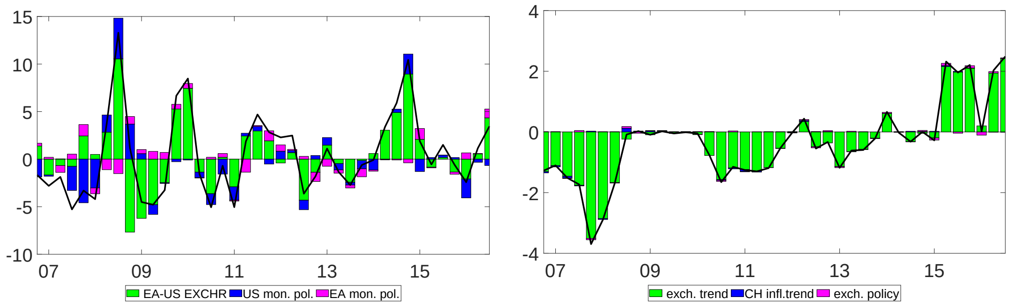


Note: Posterior mode; the solid line is the detrended variable. Foreign shocks include imported price shocks and oil shocks.

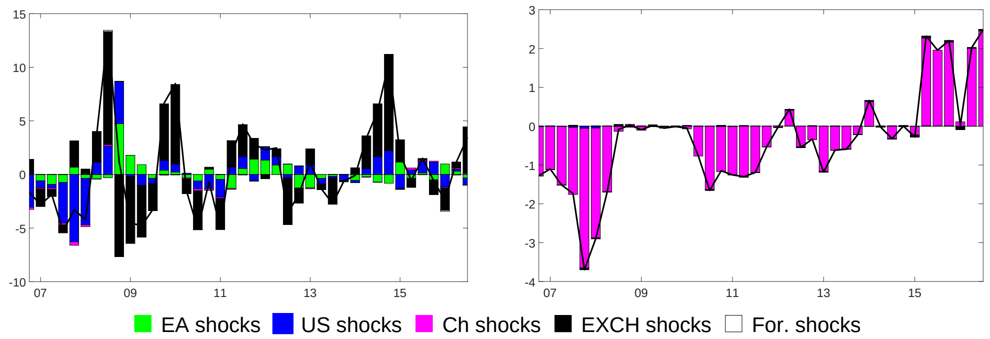
Figure 9: Historical Shock Decomposition of Detrended Nominal Exchange Rate Growth, QoQ Change

euro-dollar	yuan-dollar

The largest contributions:



Countries' contributions:



Note: Posterior mode; the solid line is the detrended variable. Foreign shocks include imported price shocks and oil shocks.

5. Trade Wars

In this section we consider several alternative trade war scenarios. One set of scenarios implies no response from trade partners. We consider the cases where the US administration imposes tariffs on either China only, or both China and the euro area. Another set of scenarios implies a symmetric response from a trade partner, with China and/or the euro area implementing the same tariffs on US goods. The last – hopefully unrealistic – scenario is a global trade war, where all three countries modelled impose tariffs on bilateral imports. That scenario serves to illustrate the individual countries losses and benefits from engaging in a trade war.

In all the scenarios we abstract from the reaction of the rest of the world. The countries in question have different effective RoW trade partners, each responding differently to changes in exchange rates and relative prices. Modelling the effective RoW reaction would thus be equivalent to modelling three other structural blocks. Modelling the RoW reaction would in principle reduce the impact of tariffs both on the countries imposing them and on those exposed to them by diverting part of trade. Yet we believe that substitution between goods and redirection of global value chains is limited in the short and medium term. We therefore choose to keep the rest of the world exogenous, while accounting for its share in the countries' trade. Thus, how much the countries are hurt by the tariffs depends on their bilateral trade shares.

In our model, final goods producers and homogeneous goods assemblers are perfectly competitive. Producers of intermediate goods are monopolistic competitors that face price rigidities à la Calvo. They price their goods using the price-to-market logic. That is, the price is set separately for each country and purpose (consumption and production). When import tariffs are imposed, they take the form of a distortive tax on the intermediate goods producer, who then shares the burden with consumers when setting its prices.[14] More specifically, the price-setting problem of an intermediate goods producer is modified as:

$$
\begin{aligned}
\max_{\tilde{P}_{H,t}(i)\tilde{P}^{*}_{H,t}(i)\tilde{P}^{*p}_{H,t}(i)} & E_t \sum_{j=0}^{\infty} (\beta\zeta_p)^j \frac{\vartheta_{t+j}P_{\mathbb{C},t}}{\vartheta_t P_{\mathbb{C},t+j}} \left[\tilde{P}_{H,t}(i)\chi_{t,j}Y_{H,t+j}(i) - MC_{t+j}Y_{H,t+j}(i)\right] \\
& + \sum_{\psi\neq\omega} \left(E_t \sum_{j=0}^{\infty} (\beta\zeta^{*\psi}_{pF})^j \frac{\vartheta_{t+j}P_{\mathbb{C},t}}{\vartheta_t P_{\mathbb{C},t+j}} \left[S^{\omega/\psi}_{t+j} \frac{\tilde{P}^{*\psi}_{H,t}(i)}{1+\tau^{\psi}_t} \chi^{*}_{t,j} Y^{*\psi}_{H,t+j}(i) - MC_{t+j} Y^{*\psi}_{H,t+j}(i) \right.\right. \\
& \left.\left. + S^{\omega/\psi}_{t+j} \frac{\tilde{P}^{*\psi}_{H,t}(i)}{1+\tau^{\psi}_t} \chi^{p*\psi}_{t,j} Y^{p*\psi}_{H,t+j}(i) - MC_{t+j} Y^{p*\psi}_{H,t+j}(i) \right] \right),
\end{aligned}
\tag{72}
$$

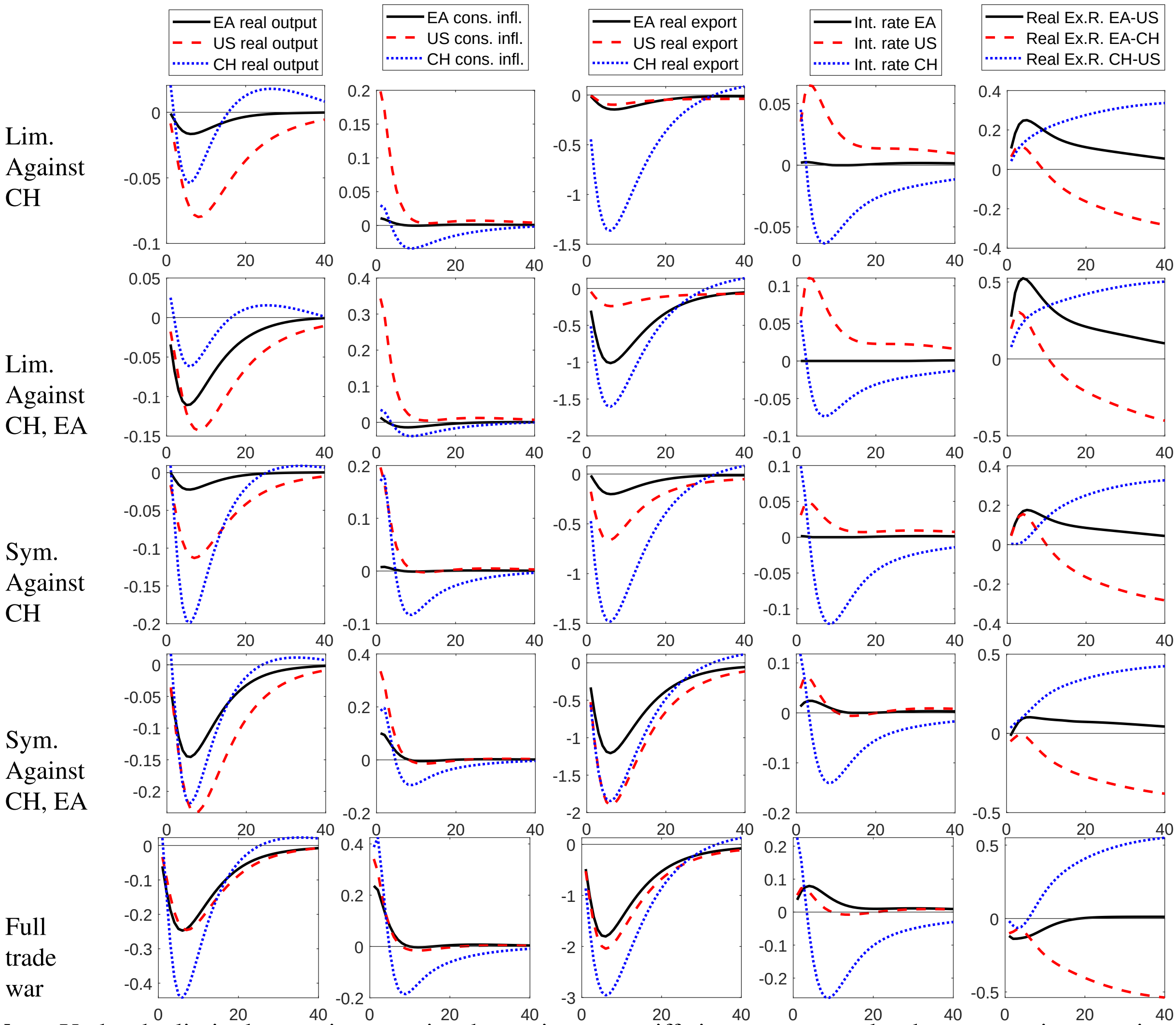
where Y_H and $\tilde{P}_H$ stand for domestic intermediate goods and prices, Y^*_H and $\tilde{P}^*_H$ for exported intermediate goods and prices and Y^{*p}_H and $\tilde{P}*_H$ for exported production goods and prices respectively, and τ^{ψ} is the destination country-specific import tax.[15] In our linear framework we model a tariff as a persistent shock that decreases by half in ten periods. We choose the size of the tariff to be 10% on all imported products from a particular trade partner so as to roughly match the simulations in Dizioli and van Roye (2018) and Bolt et al. (2019).[16]

[14] A similar approach is used in other studies, for example Bolt et al. (2019).

[15] It can be argued that tariffs are not imposed on all imported goods, but only on some categories, for example production goods. In our linear model, imposing tariffs only on production goods has the same effect qualitatively, but scaled down. In this section we consider the effect of a tariff on all imported goods.

[16] Note that, as constantly stated by the US president, tariffs are fiscal revenues. However, even with very optimistic estimates assuming no distortion in imports and no response from trading partners, the revenues constitute

Figure 10: A Persistent 10% Tariff



Note: Under the limited scenario countries do not impose tariffs in response, under the symmetric scenario they impose the same tariffs in response, and the under full scenario all three countries impose bilateral tariffs on each other. Under all the scenarios the tariff is 10% and the persistence parameter 0.9. In all the figures the posterior mode is used for the simulation. All responses are reported as percentage deviations from the steady state, except for inflation and interest rates, which are annualized percentage-point deviations from the steady state. An increase in the X-Y exchange rate corresponds to a depreciation of currency X with respect to currency Y.

The simulation results are presented in Figure 10.[17] We start the discussion with tariffs imposed by the US on Chinese goods without retaliation from China. We call this the "limited against China" scenario. While substitution between imports from different countries is limited in the short run, the more expensive Chinese inputs raise the prices of US producers and distributors of final goods, driving consumption inflation up overall. US real output falls by about 0.08%, leading to a decrease in demand for foreign goods – from the euro area and even more so from China – and to a fall in

a negligible share of US spending. Also, it is challenging to assess what share of these revenues would constitute productive government spending, which is crucial for their effect on the economy.

[17] We do not show the response of the Chinese reserve requirements. The change in the reserve requirements acts in the same direction as the Chinese monetary policy rate and tightens or loosens credit conditions.

US real exports. The drop in China's real exports is more pronounced, resulting in a decline in GDP comparable to that of the US (0.05%).

As the Fed reacts to inflation by raising interest rates, the US dollar appreciates more with respect to the euro, as the reaction of the yuan is limited, leading to appreciation of the yuan against the euro in the medium term. In the very short term, Chinese producers benefit from cheap foreign goods, which results in an increase in output accompanied by a slight rise in inflation. This effect is short-lived, and as the yuan depreciates with respect to the euro, Chinese output growth falls almost as much as in the US (close to 0.05% in the long run). There is a dramatic decline in Chinese exports, as Chinese goods become more expensive in the US due to the tariffs.

While the euro area is not directly affected by the tariffs, it is affected by the fall in demand from US and Chinese producers. Euro area output and exports decline, though the fall is less pronounced than in the other countries. A slight depreciation of the euro against the dollar leads to a small rise in inflation and the monetary policy rate.

When tariffs are imposed on both Chinese and euro area goods (the "limited against China, euro area" scenario), there is an even more dramatic decline in US output, as tariffs are now imposed on 35% of its imports. Given the limited ability of US manufacturers and consumers to switch to imports from the rest of the world in the short run, US output falls more and inflation rises more. Similarly to the previous scenario, the US dollar appreciates with respect to the euro, and the euro depreciates with respect to the yuan. The effect is now stronger due to the stronger initial rise in US inflation and the following policy rate response. The Eurozone suffers from a fall in US demand, while China benefits from cheap European imports in the very short term. As time goes by, China also faces a fall in demand from euro area importers. The euro area experiences a fall in demand from US firms and high inflation. Also, the US market is quantitatively more important for the euro area than for China; this results in a larger output drop in the euro area than in China.

When the tariffs are symmetric, similar mechanisms are in place. A country that imposes tariffs suffers from high inflation and high production costs, which results in a fall in output. The same holds for a country experiencing strong currency depreciation. As the nominal yuan-US dollar exchange rate is rigid, the reaction of the real rate is lagged and very persistent. Under a flexible exchange rate regime, the nominal exchange rate reacts to differences in countries' interest rates. This response contributes to bringing the real exchange rate back to the steady state. This feedback is missing in the yuan-US dollar exchange rate, leading to a pronounced real exchange rate response.

A decline in a country's output further affects its trade partners negatively through a fall in exports. However, a country to which export tariffs are applied suffers more from a fall in exports. If the tariffs are imposed on a very large fraction of exports (i.e. a major trade partner imposes tariffs), the fall in exports becomes the driving force of the output decline.

This intuition can be applied when all three countries impose tariffs on one another. As for the Eurozone, tariffs are imposed on 23% of its imports, which makes the first-order increase in inflation smaller than that in the US. For the US, tariffs are imposed on 35% of its imports, while for China the figure is 17%. However, the nominal response of the yuan is limited, which, together with a more dramatic fall in exports, results in a larger fall in output in China than in the other countries.

It can be argued that there is a non-trivial interaction between tariffs and monetary policy. The impact of tariffs depends on the monetary policy reaction. In the analysis above, we assume that central banks conduct monetary policy in accordance with their policy rules defined earlier in the paper. On the other hand, monetary authorities – for example the Fed have chosen to ease policy in light of the uncertainty surrounding the implementation of tariffs. To address this interaction we consider alternative, hypothetical scenarios in Figure F1 in Appendix F. Specifically, we add the policy easing implemented by the Fed and the continuing forward guidance introduced by the ECB in response to the tariffs. Due to the limitations of our model – the most important being a missing financial sector – the results of the simulations must be taken with caution. Also, central banks may implement a different set of policies, and this decision is difficult to predict ex-ante. However, we believe the results serve to illustrate how policy easing can offset the negative effects of tariffs at least in the short term.

To summarize, trade wars – as recently used by the US administration – result in major economic losses for most of the participants in the short to medium term. Tariffs hurt the imposing country through a rise in prices. The impact on both sides depends heavily on the importance of bilateral trade for both countries. If the US imposes tariffs on a country that accounts for a very low share of its imports, the impact on the US economy is negligible. If, however, a country starts a trade war with its major trade partners, it loses as much as them or even more.

Our results are in line with the literature. Bouet and Laborde Debucquet (2017) find that the US economy loses under each of 18 trade war scenarios they consider. While they also find relatively small losses for China, the estimated loss for Mexico is dramatic. This supports our conclusion that the impact depends heavily on the strength of the trade links. The estimates by Dizioli and van Roye (2018) and Deutsche Bundesbank (2017), among others, show that the US economy may encounter significant losses, while Dizioli and van Roye (2018) find that the Chinese economy may even benefit in the short term. The first-order effect of tariffs with Chinese retaliation on the US economy as calculated by International Monetary Fund (2018) is around -0.2%. Our model features a similar, but somewhat smaller, decline of 0.1%. The difference can be attributed to the fact that we do not model volatility in the financial markets or changes in productivity, which are addressed by International Monetary Fund (2018). Bolt et al. (2019) impose a permanent shock to trade, which, with Chinese retaliation, leads to a much larger drop in US output of 0.8% in the long run.

6. Conclusion

In this paper we develop a multi-country DSGE model that incorporates the euro area, the United States and China. The model is an extension of the two country model by de Walque et al. (2017), in which we modify the Chinese Taylor rule and uncovered interest rate parity condition and model China's reserve requirement policy. In order to estimate the model, we account for changes in the Chinese reserve requirements and for China's exchange rate policy and time-varying inflation target. Having estimated the model, we find, as is typical in the literature, that the model does not fully replicate international spillovers unless we allow for correlation of shocks between countries.

We study the properties of the model by computing impulse responses, historical shock decompositions and conditional variance decompositions for the variables of interest. The model spillovers occur through changes in relative prices and the exchange rate and through the trade channel.

Within the framework developed, we study the consequences of imposing tariffs on goods imported from one or all trade partners. We study several scenarios where the US imposes tariffs on either China only, or both China and the euro area, with and without symmetric responses from those countries. We find that the US economy suffers under each scenario. Its main trading partners incur losses too. The magnitude of the losses depends substantially on how deeply the countries are connected through trade. A country imposing a tariff experiences a rise in prices of both consumption goods and manufacturing imports. The rise in inflation, combined with tougher monetary policy, suppresses output growth and investment. A country that faces a tariff from a trade partner suffers from a decrease in exports. In alternative simulations we allow central banks to deviate from the Taylor rule and to tolerate high inflation. This helps the economies to offset the devastating effects of tariffs on output.

We acknowledge the limitations of our model, as it does not include financial links, which are shown in the literature to be a source of shocks and a shock propagation mechanism. We limit ourselves to considering three countries in the model, leaving the rest of the world as an exogenous component. One could model the reaction of the rest of the world as mimicking that of the US or Chinese economy. However, we are convinced that a combination of the two would be more appropriate, but we leave this for further research. Another set of limitations in our study arises from modelling the Chinese economy. The nominal exchange rate is explained mostly by exogenous shocks, as we do not have a rule for policy interventions. In addition, we are not able to identify all the parameters given the data limitations. We leave all the limitations as issues to be addressed in future work.

References

INTERNATIONAL MONETARY FUND (2018): "World Economic Outlook: Challenges to Steady Growth." Monthly Report, International Monetary Fund,Washington, DC

ADJEMIAN, S., M. BASTANI HOUTAN ANDJUILLARD, J. KARAMÉ FRÉDERIC ANDMAIH, G. MIHOUBI FERHAT ANDPERENDIA, M. PFEIFER JOHANNES ANDRATTO, AND S. VILLEMOT (2011): "Dynare: Reference Manual Version 4." Dynare Working Papers 1, CEPREMAP

AMITI, M., S. J. REDDING, AND D. WEINSTEIN (2019): "The Impact of the 2018 Trade War on U.S. Prices and Welfare." Discussion Papers 1603, Centre for Economic Performance, LSE

ANDRLE, M., P. BLAGRAVE, P. ESPAILLAT, K. HONJO, B. L. HUNT, M. KORTELAINEN, R. LALONDE, D. LAXTON, E. MAVROEIDI, D. V. MUIR, S. MURSULA, AND S. SNU (2015): "The Flexible System of Global Models FSGM." IMF Working Papers 15/64, International Monetary Fund

BLAGRAVE, P., P. ELLIOTT, R. GARCIA-SALTOS, D. HOSTLAND, D. LAXTON, AND F. ZHANG (2013): "Adding China to the Global Projection Model." IMF Working Papers 13/256, International Monetary Fund

BOLT, W., K. MAVROMATIS, AND S. VAN WIJNBERGEN (2019): "The Global Macroeconomics of a Trade War: The EAGLE model on the US-China trade conflict." Discussion Papers 13495, C.E.P.R.

BOUET, A. AND D. LABORDE DEBUCQUET (2017): "US Trade Wars with Emerging Countries in the 21st Century: Make America and Its Partners Lose Again." IFPRI discussion papers 1669, International Food Policy Research Institute (IFPRI)

CARABENCIOV, I., C. FREEDMAN, R. GARCIA-SALTOS, D. LAXTON, O. KAMENIK, AND P. MANCHEV (2013): "GPM6; The Global Projection Model with 6 Regions." IMF Working Papers 13/87, International Monetary Fund

CHANG, C., Z. LIU, M. SPIEGEL, AND J. ZHANG (2018): "Reserve Requirements and Optimal Chinese Stabilization Policy." *Journal of Monetary Economics.*

CHEN, W., X. CHEN, C.-T. HSIEH, AND Z. SONG (2019): "A Forensic Examination of China's National Accounts." NBER Working Papers 25754, National Bureau of Economic Research, Inc

COENEN, G., P. KARADI, S. SCHMIDT, AND A. WARNE (2018): "The New Area-Wide Model II: an extended version of the ECBs micro-founded model for forecasting and policy analysis with a financial sector." Working Paper Series 2200, European Central Bank

DAI, L., P. MINFORD, AND P. ZHOU (2015): "A DSGE Model of China." *Applied Economics,* 47:6438–6460.

DE WALQUE, G., F. SMETS, AND R. WOUTERS (2006): "Firm-Specific Production Factors in a DSGE Model with Taylor Price Setting." *International Journal of Central Banking,* 2(3).

DE WALQUE, G., T. LEJEUNE, Y. RYCHALOVSKA, AND R. WOUTERS (2017): "An Estimated Two-Country EA-US Model with Limited Exchange Rate Pass-Through." Working Paper Research 317, National Bank of Belgium

DEUTSCHE BUNDESBANK (2017): "The Danger Posed to the Global Economy by Protectionist Tendencies." Monthly Report, July, Deutsche Bundesbank

DIEPPE, A., G. GEORGIADIS, M. RICCI, I. VAN ROBAYS, AND B. VAN ROYE (2018): "ECB-Global: Introducing the ECB's Global Macroeconomic Model for Spillover Analysis." *Economic Modelling,* 72(C):78–98.

DIZIOLI, A. G. AND B. VAN ROYE (2018): "Macroeconomic Implications of Increasing Protectionism." ECB Economic Bulletin 6/2018, European Central Bank

FAJGELBAUM, P. D., P. K. GOLDBERG, P. J. KENNEDY, AND A. K. KHANDELWAL (2019): "The Return to Protectionism." Working Papers 25638, National Bureau of Economic Research, Inc

FURCERI, D., S. A. HANNAN, J. D. OSTRY, AND A. K. ROSE (2019): "Macroeconomic Consequences of Tariffs." IMF Working Papers 19/9, International Monetary Fund

GOMES, S., P. JACQUINOT, AND M. PISANI (2010): "The EAGLE. A Model for Policy Analysis of Macroeconomic Interdependence in the Euro Area." Temi di discussione (Economic working papers) 770, Bank of Italy, Economic Research and International Relations Area

GU, B., J. WANG, AND J. WU (2014): "Business Cycles in an Estimated DSGE Model of China." *China Economic Journal,* 7(3):361–381.

KIM, S. AND H. CHEN (2019): "From Quantity - To Interest Rate-Based Framework: Multiple Monetary Policy Instruments And Their Effects In China." Working Paper No.01/2019, Hong Kong Institute For Monetary Research

LANE, P. R. AND L. STRACCA (2018): "Can Appreciation be Expansionary? Evidence from the Euro Area." *Economic Policy,* 33(94):225–264.

LAXTON, D., S. MURSULA, M. KUMHOF, AND D. V. MUIR (2010): "The Global Integrated Monetary and Fiscal Model (GIMF) Theoretical Structure." IMF Working Papers 10/34, International Monetary Fund

LI, B. AND Q. LIU (2017): "On the Choice of Monetary Policy Rules for China: A Bayesian DSGE Approach." *China Economic Review,* 44:166 – 185.

LINDÉ, J. AND A. PESCATORI (2019): "The macroeconomic effects of trade tariffs: Revisiting the Lerner symmetry result." *Journal of International Money and Finance,* 95(C):52–69.

MA, G., Y. XIANDONG, AND L. XI (2013): "Chinas Evolving Reserve Requirements." *Journal of Chinese Economic and Business Studies,* 11(2):117–137.

RAZAFINDRABE, T. M. (2016): "A Multi-Country DSGE Model with Incomplete Exchange Rate Pass-Through: An Application for the Euro-Area." *Economic Modelling,* 52(PA):78–100.

SMETS, F. AND R. WOUTERS (2003): "An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area." *Journal of the European Economic Association,* 1(5):1123–1175.

SMETS, F. AND R. WOUTERS (2007): "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach." *American Economic Review,* 97(3):586–606.

SUN, R. (2013): "Does Monetary Policy Matter in China? A Narrative Approach." *China Economic Review,* 26:56 – 74.

Appendix A: Log-linearized Equations

In this section we describe the log-linearized equations, where small letters with a hat stand for log deviations from the steady state: $\hat{x}_t = log(\frac{X_t}{\bar{X}_t})$. Because the model features deterministic growth, γ, we first detrend the real variables and divide nominal variables by a composite consumer price, $P_{\mathbb{C}}$. Below, small letters, p, stand for relative prices – divided by the composite consumer price. Many of the equations are standard in the DSGE literature and resemble those from de Walque et al. (2017), but they are adjusted to include a third country in the model. The Chinese UIP and policy rules are modified as shown below.

To account for changing trends in the Chinese data, we subtract variable trends from the relevant Chinese variables: the real exchange rate, consumption inflation and the reserve requirements. The inflation trend is also subtracted from the Chinese monetary policy rate.

A.1 Households

Under the assumption of external habit formation, households' total real consumption depends on its past and expected values, expected changes in labour supply, and the expected real interest rate:

$$\begin{aligned}\hat{\mathbf{c}}_t &= \frac{\lambda_{hab}/\gamma}{1+\lambda_{hab}/\gamma}\hat{\mathbf{c}}_{t-1} + \frac{1}{1+\lambda_{hab}}E_t\hat{\mathbf{c}}_{t+1} + \left[(\sigma_c - 1)\frac{\bar{w}}{\bar{l}\bar{\mathbf{c}}}(\sigma_c(1+\lambda_{hab}/\gamma))^{-1}\right](\hat{l}_t - E_t\hat{l}_{t+1}) \\ &- (1-\lambda_{hab}/\gamma)(\sigma_c(1+\lambda_{hab}/\gamma))^{-1}(\hat{r}_t - E_t\hat{\pi}^c_{t+1} + \varepsilon^b_t), \qquad \text{(A1)}\end{aligned}$$

where $\hat{\mathbf{c}}$ is the log deviation of total consumption, $\mathbb{C}$, from its steady state and $\hat{\pi}^c_t = \hat{p}_{\mathbf{c},t} - \hat{p}_{\mathbf{c},t-1}$ is the corresponding deviation of consumption inflation from its steady state. The term $\frac{\bar{w}}{\bar{l}\bar{\mathbf{c}}}$ stands for the steady-state ratio of the detrended real wage to labour and total consumption, $\hat{r}_t$ is the nominal central bank policy rate and ε^b is a risk premium AR(1) process with an i.i.d. shock μ^b_t.

For China, the Euler equation is modified to account for the use of the reserve requirements as a policy instrument, where a rise in the reserve requirements means an increase in borrowing costs.

$$\begin{aligned}\hat{\mathbf{c}}_t &= \frac{\lambda_{hab}/\gamma}{1+\lambda_{hab}/\gamma}\hat{\mathbf{c}}_{t-1} + \frac{1}{1+\lambda_{hab}}E_t\hat{\mathbf{c}}_{t+1} + \left[(\sigma_c - 1)\frac{\bar{w}}{\bar{l}\bar{\mathbf{c}}}(\sigma_c(1+\lambda_{hab}/\gamma))^{-1}\right](\hat{l}_t - E_t\hat{l}_{t+1}) \\ &- (1-\lambda_{hab}/\gamma)(\sigma_c(1+\lambda_{hab}/\gamma))^{-1}(\hat{r}_t + \lambda^c_{rrq}\Delta r\hat{r}g_t - E_t\hat{\pi}^c_{t+1} + \varepsilon^b_t), \qquad \text{(A2)}\end{aligned}$$

The first-order conditions with respect to investment and capital result in the following equations:

$$\begin{aligned}\hat{i}_t &= \frac{1}{1+\bar{\beta}\gamma}\left(\hat{i}_{t-1} + \bar{\beta}\gamma E_t\hat{i}_{t+1} + \frac{1}{\Psi^{we''}\gamma^2}(\hat{q}_t - \hat{p}_{\mathbf{c},t}) + \frac{1}{\Psi^{we''}\gamma^2}\varepsilon^i_t\right), \qquad \text{(A3)} \\ \hat{q}_t &= \bar{\beta}(1-\tau)E_t\hat{q}_{t+1} + (1-\bar{\beta}(1-\tau))E_t\hat{r}^k_{t+1} - \bar{\beta}(\bar{r}^k + (1-\tau))(\hat{r}_t - E_t\hat{\pi}^c_{t+1} + \varepsilon^b_t). \qquad \text{(A4)}\end{aligned}$$

where $\hat{i}$ is the log deviation of investment and $\hat{q}$ is the log deviation of the real price of capital. Parameter $\Psi^{we''}$ is the steady-state second derivative of the investment adjustment cost function, $\bar{\beta} \equiv \beta\gamma^{-1}$ and $\bar{\beta}(\bar{r}^k + (1-\tau)) = 1$, where τ is the depreciation rate. $\hat{p}_{\mathbf{c},t}$ is the deviation of the price of total consumption. As we divide nominal variables by the total consumption price, $\hat{p}_{\mathbf{c},t} = 0$.

The real price of capital for China reflects the change in borrowing costs due to changes in the reserve requirements:

$$\hat{q}_t = \bar{\beta}(1-\tau)E_t\hat{q}_{t+1} + (1-\bar{\beta}(1-\tau))E_t\hat{r}^k_{t+1} - \bar{\beta}(\bar{r}^k + (1-\tau))(\hat{r}_t + \lambda^q_{rrq}\Delta r\hat{r}g_t - E_t\hat{\pi}^c_{t+1} + \varepsilon^b_t). \qquad \text{(A5)}$$

Capital is accumulated according to the rule:

$$\hat{k}_t = \frac{1-\tau}{\gamma}\hat{k}_{t-1} + \left(1 - \frac{1-\tau}{\gamma}\right)(\hat{\imath}_t + \varepsilon_t^i). \tag{A6}$$

With $\bar{r}^k = \psi'(1)$, capital utilization is determined as:

$$\hat{u} = \frac{\psi'(1)}{\psi''(1)}\hat{r}_t^k. \tag{A7}$$

Wages are subject to Calvo stickiness with probability ξ_w and partial indexation with probability ι_w. Real wages then depend on past and future wages, consumption inflation and the wage mark-up:

$$\begin{aligned}
\hat{w}_t &= \frac{1}{1+\bar{\beta}\gamma}\left(\hat{w}_{t-1} + \bar{\beta}\gamma E_t \hat{w}_{t+1} + \iota_w \hat{\pi}_{t-1} + \bar{\beta}\gamma E_t \hat{\pi}_{t+1} - (1+\bar{\beta}\gamma\iota_w)\hat{\pi}_t\right. \\
&+ \left.(1-\iota_w)\hat{\bar{\pi}}_t - \bar{\beta}\gamma(1-\iota_w)\hat{\bar{\pi}}_{t+1}\right) \\
&+ \frac{(1-\bar{\beta}\gamma\xi_w)(1-\xi_w)}{\xi_w\left(1+\frac{1+\lambda_w}{\lambda_w}\sigma_l\right)}\left(\frac{1}{1-\lambda_{hab}/\gamma}(\hat{\mathbf{c}}_t - \lambda_{hab}/\gamma\hat{\mathbf{c}}_{t-1}) + \sigma_l \hat{l}_t - \hat{w}_t\right) \\
&+ \varepsilon_t^w.
\end{aligned} \tag{A8}$$

In the expression above $\hat{\bar{\pi}}$ stands for the deviation of the inflation trend from the steady state.

A.2 Producers and Prices

Intermediate goods producers' optimal conditions for output, demand for capital and the resulting marginal costs are:

$$\hat{y}_t = \Phi_y\left(\alpha\hat{\hat{k}}_t + (1-\alpha)\hat{l}_t + \varepsilon_t^a\right), \tag{A9}$$

$$\hat{k}_t = \hat{w}_t - \hat{r}_t^k + \hat{l}_t, \tag{A10}$$

$$\begin{aligned}
\widehat{mc}_t &= \Phi_y\left(\frac{1}{\Phi_y} - \rho_m - \rho_o\right)\left(\alpha\hat{r}_t^k + (1-\alpha)\hat{w}_t - \varepsilon_t^a\right) \\
&\quad \Phi_y\left(\rho_m \hat{p}_{F,t}^p + \rho_o \hat{p}_{oil,t}\right).
\end{aligned} \tag{A11}$$

In the lines above, $\hat{\hat{k}} = \hat{u}_t\hat{k}_{t-1}$ stands for log-linearized effective capital and $\Phi_y = \frac{\bar{y}+\Phi}{\bar{y}}$ is the inverse of the share of the variables' costs in intermediate goods production. Dividing both sides of (60) by $P_{\mathbb{C},t}$ we obtain that in the steady state, the relative price of individual manufacturers equals the home price: $\bar{\bar{p}}_H(i) = \bar{p}_H$. Using that expression, we derive the relative distribution prices of intermediate products in (63):

$$\bar{p}_H^D(i) = \frac{1}{1+\delta_f}\bar{p}_H + \frac{\delta_f}{1+\delta_f}\bar{p}_H = \bar{p}_H = \bar{p}_H^D. \tag{A12}$$

That is, in the steady state, all home goods have the same relative price, and that price equals the distribution price. We further normalize $\bar{p}_H = \bar{p}_H^D = 1$ and $\bar{p}_F^D = 1$ in each country. From exporters' point of view, the relative distribution prices of their goods in foreign countries are also unity in the steady state:

$$\bar{p}_F^D = \frac{1}{1+\delta_f}\bar{p}_F + \frac{\delta_f}{1+\delta_f}\bar{p}_H = 1, \tag{A13}$$

which results in $\bar{p}_F = 1$. With home and foreign relative prices equal to unity, the steady-state relative price of non-oil consumption composite goods is also unity, $\bar{p}_c = 1$. It must then follow that the oil price relative to the total consumption price is also unity: $\bar{p}_{oil} = 1$, together with relative import and export prices. Therefore, the normalization implies that all relative prices are unity in the steady state.

Linearizing the equation for the price of total consumption aggregate, $P_{\mathbb{C},t}$, with $\hat{p}_{\mathbb{C},t} = 0$, we obtain the dependencies between home, foreign and oil prices as:

$$0 = (1-\phi_{oil})\left[\frac{\phi_c+\delta_f}{1+\delta_f}\hat{p}_{H,t} + \frac{1-\phi_c}{1+\delta_f}\hat{p}_{F,t}\right] + \phi_{oil}\hat{p}^D_{oil} + \varepsilon^p_t, \tag{A14}$$

$$0 = (1-\phi_{oil})\hat{p}_{c,t} + \phi_{oil}\hat{p}^D_{oil} + \varepsilon^p_t. \tag{A15}$$

When linearizing (60) in relative prices, we use the fact that in the steady state $G^{'-1} = 1$ and $\bar{\mathbb{I}} = G'(1)$ to obtain the New Keynesian Philips curve for home inflation:

$$\begin{aligned}\hat{\pi}_{H,t} &= \frac{1}{1+\beta\iota_p}\left(\beta\hat{\pi}_{H,t+1} + \iota_p\hat{\pi}_{H,t-1}\right) \\ &+ \frac{(1-\xi_p)(1-\beta\xi_p)}{\xi_p(1+\beta\iota_p)}\frac{\eta-1-\delta_f}{\eta+\varepsilon-1}(\widehat{mc}_t - \hat{p}_{H,t}) + \varepsilon^{pH}_t - \nu\varepsilon^p_t.\end{aligned} \tag{A16}$$

Parameter η is the steady-state price elasticity of demand, with $\eta_t = -\frac{G'(z_t)}{z_t G''(z_t)}$ and $z_t = G^{'-1}\left(\frac{P^D_{j,t}(i)}{P^D_{j,t}}\mathbb{I}_t\right)$, where $j = H, F$. ε is the curvature of Kimball's aggregator G. Following de Walque et al. (2017) among others, we define the curvature as the steady-state elasticity of the price elasticity of demand with respect to the relative price. For home prices, it is defined as:

$$\varepsilon = \frac{\bar{\tilde{p}}_H/\bar{P}_H}{\eta_H(z_{SS})}\frac{\partial\eta_H(z_{SS})}{\partial\bar{\tilde{p}}_H}|_{z_{SS}=1} = 1+\eta\left(1+\frac{G'''(1)}{G''(1)}\right), \tag{A17}$$

$$\frac{\left(1+(1+\delta_f)\frac{G''(1)}{G'(1)}\right)}{\left(2+\frac{G'''(1)}{G''(1)}\right)} = \frac{\eta-1+\delta_f}{\eta-1+\varepsilon}. \tag{A18}$$

The domestic inflation New Keynesian Philips curve features two stochastic AR(1) processes, each with i.i.d. errors: the domestic price mark-up, ε^{pH}_t, and the feedback from the consumption price mark-up, ε^p_t, with a negative sign. The consumption inflation index data contain some elements that introduce additional volatility into the index, but they are unmodelled here, so we use the feedback from ε^p_t to subtract them from home inflation.

The Philips curves for the bilateral imported inflation indices from country j, where superscript * denotes foreign variables, are derived in a similar fashion:

$$\begin{aligned}\hat{\pi}_{F,t} &= \frac{1}{1+\beta^*\iota^*_{pF}}\left(\beta^*\hat{\pi}_{F,t+1}+\iota^*_{pF}\hat{\pi}_{F,t-1}\right)\\ &+\frac{(1-\xi^*_{pF})(1-\beta\xi^*_{pF})}{\xi^*_{pF}(1+\beta^*\iota^*_{pF})}\frac{1}{\eta+\varepsilon-1}((\widehat{mc}^*_t+\widehat{rs}_t)+\delta_f\hat{p}_H-(\eta-1)\hat{p}_{F,t})\\ &+\varepsilon^{pF}_t, \qquad\qquad (A19)\\ \hat{\pi}^p_{F,t} &= \frac{1}{1+\beta^*\iota^*_{pF}}\left(\beta^*\hat{\pi}^p_{F,t+1}+\iota^*_{pF}\hat{\pi}^p_{F,t-1}\right)\\ &+\frac{(1-\xi^*_{pF})(1-\beta\xi^*_{pF})}{\xi^*_{pF}(1+\beta^*\iota^*_{pF})}\frac{\eta-1}{\eta+\varepsilon-1}(\widehat{mc}^*_t+\widehat{rs}_t-\hat{p}^p_{F,t})\\ &+\varepsilon^{pF}_t, \qquad\qquad (A20)\end{aligned}$$

where $\hat{\pi}_F$ and $\hat{\pi}^p_F$ are imported inflation and imported production goods inflation respectively. Foreign intermediate goods producers set their export prices directly in the currency of the importing (destination) country and take into account the destination distribution costs, δ_f, and price elasticity, η. Calvo pricing parameters ξ^*_{pF}, ι^*_{pF} stand for the probability and degree of price indexation of imported goods in the destination market. Note that these parameters can be different from those for goods produced locally in the destination country, ξ_p, ι_p, even though they are applied on the same destination market. The real marginal costs in the foreign currency, $\widehat{mc}^*$, are converted into the local currency using the real exchange rate, $\widehat{rs}$. Because production goods are not processed through the distribution channel, the distribution costs, δ_f, do not enter the corresponding expression for inflation. Both imported inflation indices are affected by mark-up shocks, which are AR(1) processes with i.i.d. disturbances. These mark-up processes originate in the local market, but only affect foreign goods prices.

A.3 Exchange Rates and International Trade

To derive the equation for the real euro-US dollar exchange rate we make use of UIRP condition (15). We follow de Walque et al. (2017) in assuming that the net foreign asset position is zero in the steady state. In the equation below, the net foreign asset position, nfa, is linearized, but the rest of the terms are log-linearized around the steady state:

$$\begin{aligned}\widehat{rs}^{Euro/USD}_t &= (1-\theta_s)E_t\widehat{rs}^{Euro/USD}_{t+1}+\\ &\theta_s\widehat{rs}^{Euro/USD}_{t-1}+r^{US}_t-r^{EA}_t-E_t\hat{\pi}^{US}_{t+1}+E_t\hat{\pi}^{EA}_{t+1}-\rho_{nfa}nfa^{EA}_t+\varepsilon^{s^{Euro/USD}}_t, \qquad (A21)\end{aligned}$$

where $\widehat{rs}^{Euro/USD}$ is the real exchange rate in indirect quotation (euros per 1 US dollar), θ_s is the parameter on exchange rate persistence obtained from the definition of the risk premium over foreign bonds (Θ_t) and $\rho_{nfa}=\Theta'(0)\bar{y}\gamma^t$ ensures stationarity and is set to be a very small number.

Linearizing the Chinese UIRP condition (16), we pin down the nominal yuan-dollar exchange rate $\hat{s}^{USD/CNY}$:

$$\begin{aligned}\hat{s}^{USD/CNY}_t &= \theta_{uip}\left((1-\theta_s)E_t\widehat{rs}^{USD/CNY}_{t+1}+\theta_s\widehat{rs}^{USD/CNY}_{t-1}+r^{CH}_t-r^{US}_t-\rho_{nfa}nfa^{US}_t\right)\\ &+(1-\theta_{uip})\hat{s}^{pol}_t+\varepsilon^{s^{USD/CNY}}_t. \qquad (A22)\end{aligned}$$

Foreign consumption and investment goods from the point of view of the home country are derived using the expression for the non-oil consumption aggregate (4) and the adjustment costs for foreign goods consumption (6).

$$\begin{aligned}
\hat{c}_{F,t} &= \hat{c}_t - \lambda(\hat{p}^D_{F,t} - \hat{p}_{c,t}) - \Omega_c\lambda(\hat{c}_{F,t} - \hat{c}_t - \hat{c}_{F,t-1} + \hat{c}_{t-1}) \\
&+ \beta\Omega_c\lambda(\hat{c}_{F,t+1} - \hat{c}_{t+1} - \hat{c}_{F,t} + \hat{c}_t), \quad \text{(A23)} \\
\hat{i}_{F,t} &= \hat{i}_t - \lambda(\hat{p}^D_{F,t} - \hat{p}_{c,t}) - \Omega_i\lambda(\hat{i}_{F,t} - \hat{i}_t - \hat{i}_{F,t-1} + \hat{i}_{t-1}) \\
&+ \beta\Omega_c\lambda(\hat{i}_{F,t+1} - \hat{i}_{t+1} - \hat{i}_{F,t} + \hat{i}_t), \quad \text{(A24)} \\
\hat{c}_t &= \hat{\mathbf{c}}_t - \lambda_{oil}\hat{p}_{c,t}, \quad \text{(A25)}
\end{aligned}$$

where $\hat{c}_{F,t}$ and $\hat{i}_{F,t}$ are, respectively, consumption and investment of foreign goods and $\hat{c}_t$ is total non-oil consumption. The bilateral demand for consumption, investment and production goods is determined as follows:

$$\begin{aligned}
\hat{c}_{F,j,t} &= \hat{c}_{F,t} - \lambda_{im}(\hat{p}^{D,j}_{F,t} - \hat{p}_{F,t}) - \Omega_{im}\lambda_{im}(\hat{c}_{F,j,t} - \hat{c}_{F,t} - \hat{c}_{F,j,t-1} + \hat{c}_{F,t-1}) \\
&+ \beta\Omega_{im}\lambda_{im}(\hat{c}_{F,j,t+1} - \hat{c}_{j,t+1} - \hat{c}_{F,j,t} + \hat{c}_{F,t}), \quad \text{(A26)} \\
\hat{i}_{F,j,t} &= \hat{i}_{F,t} - \lambda_{im}(\hat{p}^{D,j}_{F,t} - \hat{p}_{F,t}) - \Omega_{im}\lambda_{im}(\hat{i}_{F,j,t} - \hat{i}_{F,t} - \hat{i}_{F,j,t-1} + \hat{i}_{F,t-1}) \\
&+ \beta\Omega_{im}\lambda_{im}(\hat{i}_{F,j,t+1} - \hat{i}_{F,t+1} - \hat{i}_{F,j,t} + \hat{i}_{F,t}), \quad \text{(A27)} \\
\hat{y}^p_{F,j,t} &= \frac{1}{\rho_m}y_t - \lambda_{im}(\hat{p}^{p,j}_{F,t} - \hat{p}^p_{F,t}) - \Omega_{im}\lambda_{im}(\hat{y}^p_{F,j,t} - \frac{1}{\rho_m}\hat{y}_t - \hat{y}^p_{F,j,t-1} + \frac{1}{\rho_m}\hat{y}_{t-1}) \\
&+ \beta\Omega_{im}\lambda_{im}(\hat{y}^p_{F,j,t+1} - \frac{1}{\rho_m}\hat{y}_{t+1} - \hat{y}^p_{F,j,t} + \frac{1}{\rho_m}\hat{y}_t), \quad \text{(A28)}
\end{aligned}$$

where we use the fact that total demand for foreign production goods is given by $\frac{1}{\rho_m}\hat{y}_t$. The log-linearized demand for transit goods is derived from (48):

$$\hat{x}_{F,t} = \hat{x}_{H,t} - \lambda_x(\hat{p}_{F,t} - \hat{p}_{x,t}). \quad \text{(A29)}$$

Log-linearization of non-oil imports (46) and (47), together with the use of $Y^D_{F,t} = C_{F,t} + I_{F,t}$, results in:

$$\begin{aligned}
\hat{m}_{H,t} &= \phi^H_m\left(\frac{\bar{y}_F}{\bar{y}^T_F}\hat{y}_{F,t} + \frac{\bar{y}^p_F}{\bar{y}^T_F}\hat{y}^p_{F,t}\right) + (1-\phi^H_m)\hat{x}_{F,t} \\
&= \phi^H_m\left(\frac{\bar{y}_F}{\bar{y}^T_F}\left[\frac{\bar{c}_F}{\bar{y}^D_F}\hat{c}_{F,t} + \frac{\bar{i}_F}{\bar{y}^D_F}\hat{c}_{F,t}\right] + \frac{\bar{y}^p_F}{\bar{y}^T_F}\frac{1}{\rho_m}\frac{\bar{y}}{\bar{y}^p_F}\hat{y}_t\right) + (1-\phi^H_m)\hat{x}_{F,t}. \quad \text{(A30)}
\end{aligned}$$

Employing the trick by de Walque et al. (2017) we express the coefficients in the above expression as:

$$\begin{aligned}
\frac{\bar{c}_F}{\bar{y}^D_F} &= \frac{\bar{y}}{\bar{\mathbf{m}}}\frac{\bar{\mathbf{m}}}{\bar{m}_H}\frac{\bar{m}_H}{\bar{y}^T_F}\frac{\bar{y}^T_F}{\bar{y}_F}\frac{\bar{y}_F}{\bar{y}^D_F}\frac{\bar{c}_F}{\bar{c}}\frac{\bar{c}}{\bar{\mathbf{c}}}\frac{\bar{\mathbf{c}}}{\bar{y}}\frac{\bar{y}_F}{\bar{y}^T_F} \\
&= \alpha_m^{-1}(1-\phi^{oil}_m)^{-1}(\phi^H_m)^{-1}(1+\delta_f)^{-1}(1-\phi^H_c)(1-\phi^{oil}_c)\alpha_c, \quad \text{(A31)} \\
\frac{\bar{i}_F}{\bar{y}^D_F} &= \alpha_m^{-1}(1-\phi^{oil}_m)^{-1}(\phi^H_m)^{-1}(1+\delta_f)^{-1}(1-\phi^H_c)\alpha_i, \quad \text{(A32)}
\end{aligned}$$

where α_c and α_i are the steady-state ratios of total consumption to GDP and total investment to GDP respectively. Then, the expression for imports becomes:

$$\begin{aligned} \hat{m}_{H,t} &= \phi_m^H \left(\alpha_m^{-1}(1-\phi_m^{oil})^{-1}(\phi_m^H)^{-1}(1+\delta_f)^{-1}(1-\phi_c^H)\left[(1-\phi_{oil})\alpha_c\hat{c}_{F,t}+\alpha_i\hat{i}_{F,t}\right]+(1-\phi_F)\hat{y}_t\right) \\ &+ (1-\phi_m^H)\hat{x}_{F,t}, \qquad \text{(A33)} \\ \phi_F &= \left(\frac{1-\phi_H}{1+\delta_f}((1-\phi_{oil})\alpha_c+\alpha_i)\right) / \left(\frac{1-\phi_H}{1+\delta_f}((1-\phi_{oil})\alpha_c+\alpha_i)+\rho_m\right). \qquad \text{(A34)} \end{aligned}$$

Bilateral exports are driven by foreign demand and are then aggregated using the corresponding export shares:

$$\hat{x}_{H,t} = \sum_j \beta_x^j \hat{m}_{F,t} + \varepsilon_t^{nt}. \qquad \text{(A35)}$$

Total imports, including imports of oil products, are log-linearized as:

$$\hat{\mathbf{m}}_t = (1-\phi_m^{oil})\hat{m}_{h,t} + \phi_m^{oil}\widehat{oil}_t. \qquad \text{(A36)}$$

There are bilateral and total equations for $\hat{\mathbf{m}}$ depending on whether bilateral or total imports are used.

A.4 Resource Constraints and Monetary Policy

Log-linearized around the steady state, the resource constraint (68) looks like:

$$\hat{y}_t = \frac{\bar{\mathbf{c}}}{\bar{y}}\hat{\mathbf{c}}_t + \frac{\bar{i}}{\bar{y}}\hat{i}_t + \frac{\bar{g}}{\bar{y}}\hat{g}_t + \frac{\bar{r}^k\bar{k}}{\gamma\bar{y}}\hat{u}_t + \frac{\bar{\mathbf{m}}}{\bar{y}}(\hat{x}_{H,t} - \mathbf{m}_t) + (\rho_o+\rho_m)\hat{y}_t. \qquad \text{(A37)}$$

Note that as $\bar{S}\bar{B}_F = 0$ in the steady state, the trade balance is also zero in the steady state and $\frac{\bar{x}}{\bar{y}} = \frac{\bar{\mathbf{m}}}{\bar{y}}$. When log-linearizing (71), we linearize the terms in nfa and log-linearize the rest:

$$\beta^* nfa_t = \gamma^{-1} nfa_{t-1} + \frac{\bar{\mathbf{m}}}{\bar{y}}(\hat{p}_{x,t} + \hat{x}_F - \hat{p}_{\mathbf{m},t} - \mathbf{m}). \qquad \text{(A38)}$$

The trade balance is then defined as:

$$\widehat{tb}_t = \hat{p}_{x,t} + \hat{x}_F - \hat{p}_{\mathbf{m},t} - \mathbf{m}. \qquad \text{(A39)}$$

Monetary policy is set as the following rule:

$$\hat{r}_t = \rho^r\hat{r}_{t-1} + (1-\rho^r)(\rho^\pi\hat{\pi}_t + \rho^y(\hat{y}_t - \hat{y}_t^f)) + \rho^\Delta(\hat{y}_t - \hat{y}_{t-1} - \hat{y}_t^f + \hat{y}_{t-1}^f) + \varepsilon_t^r. \qquad \text{(A40)}$$

Appendix B: List of Data

Table B1: List of Data

Data Series	Euro area	US	China
Real GDP	+	+	
Real GDP per capita			+
Real individual consumption	+		
Private consumption, current prices		+	+
Gross fixed capital formation	+		+
Private investment, current prices		+	
Real wage per head	+		
Hourly compensation		+	
Hours worked or employment	+	+	
Short-term interest rate, annualized	+	+	+
Consumption deflator	+	+	+
Import deflator	+	+	
Reserve requirements			+
GDP deflator	+	+	+
Net exports	+	+	+
Working age population	+	+	
Exchange rate	+		+
Oil price		+	

Appendix C: Impulse Responses

In all the figures the posterior mode is used for the simulation. All responses are reported as percentage deviations from the steady state, except for inflation and interest rates, which are annualized percentage-point deviations from the steady state. An increase in the X-Y exchange rate corresponds to a depreciation of currency X with respect to currency Y.

Figure C1: Impulse Responses to a Positive US TFP Shock

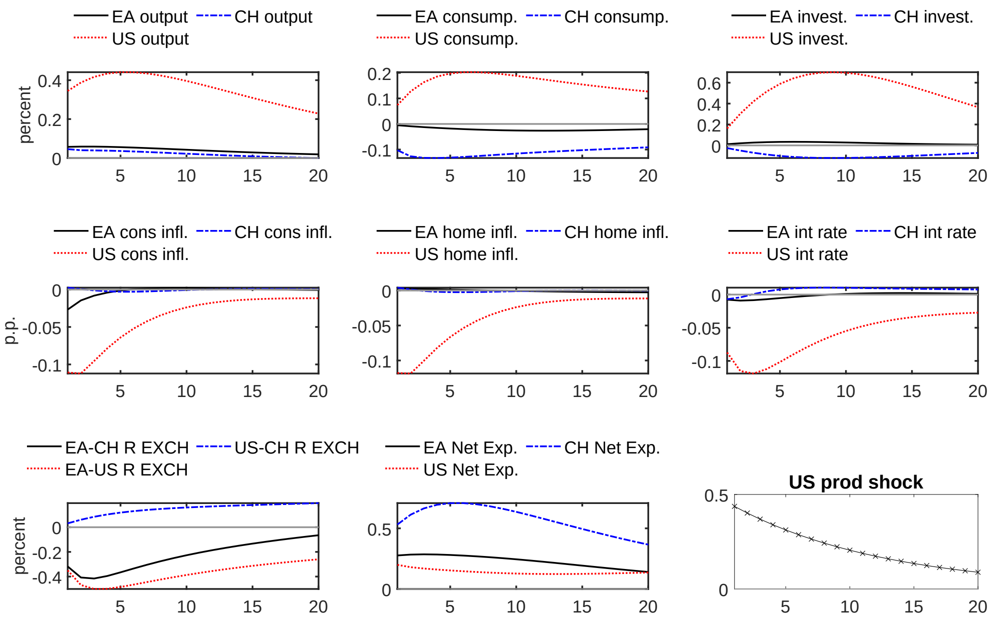


Figure C2: Impulse Responses to a Positive Chinese TFP Shock

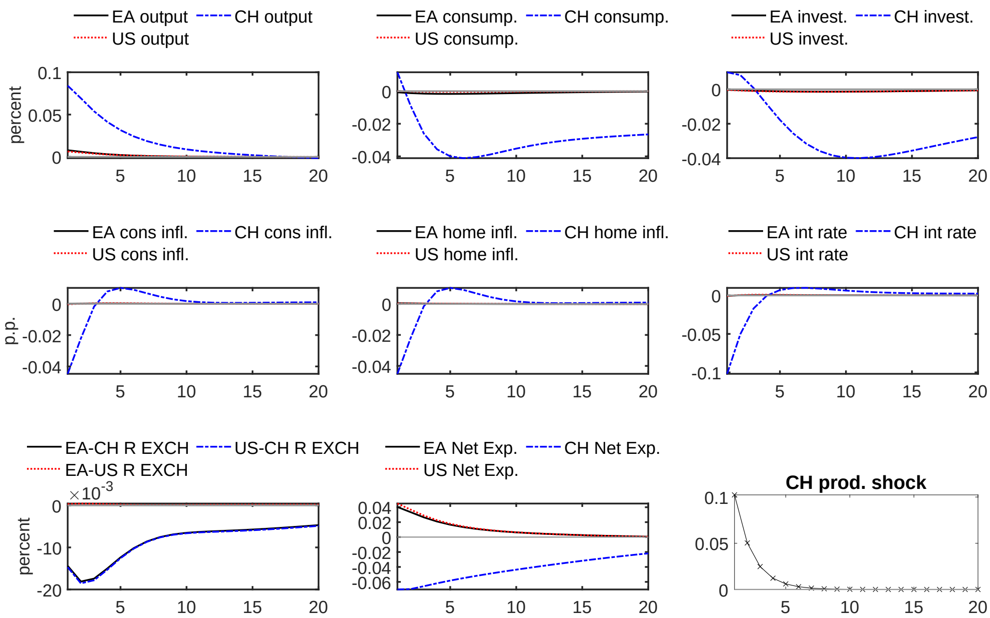


Figure C3: Impulse Responses to a Positive Euro Area Risk Premium Shock

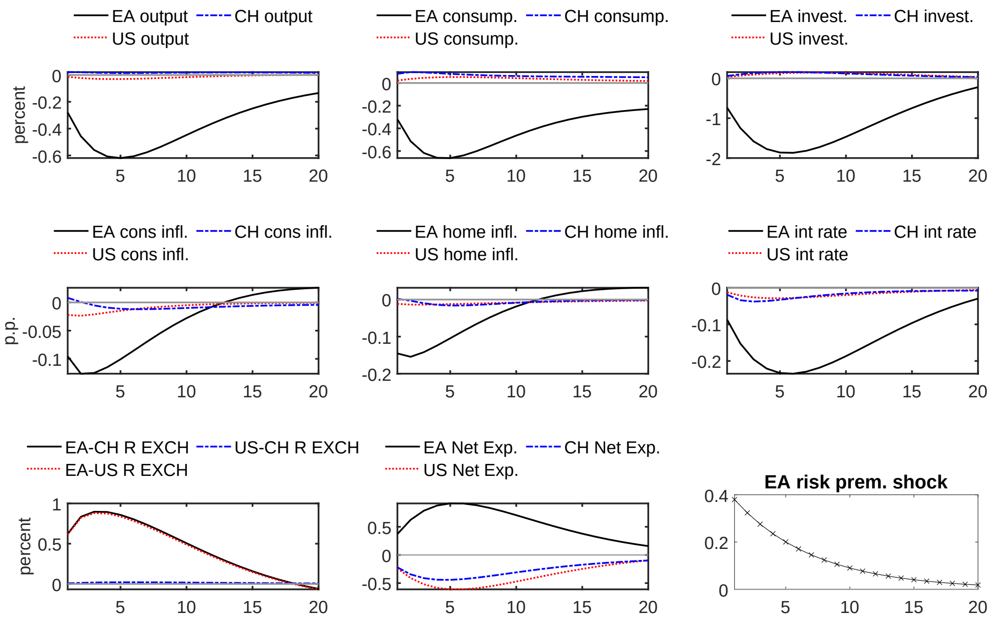


Figure C4: Impulse Responses to a Positive US Risk Premium Shock

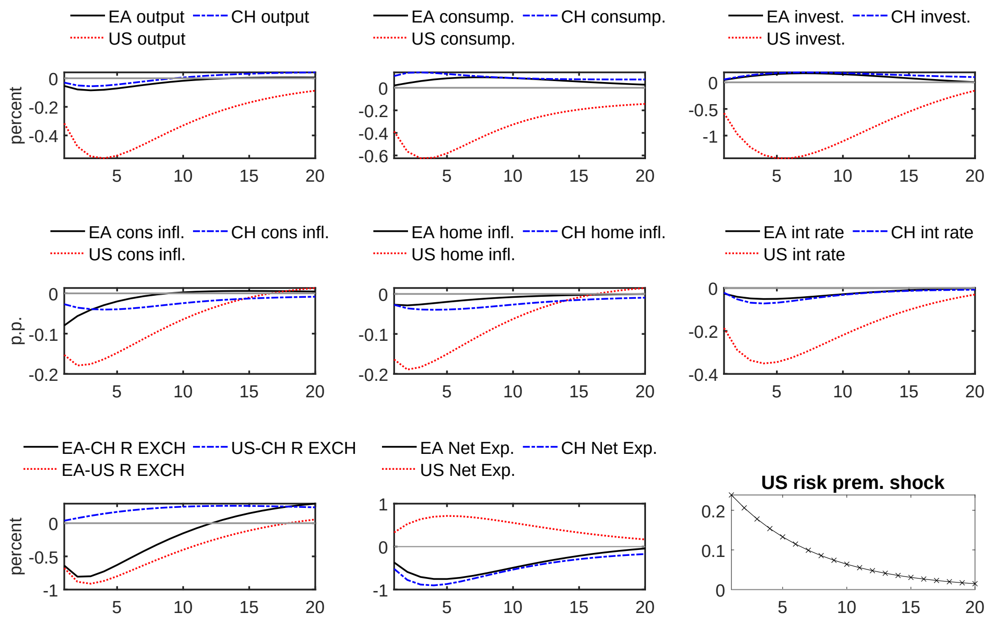


Figure C5: Impulse Responses to a Positive Chinese Risk Premium Shock

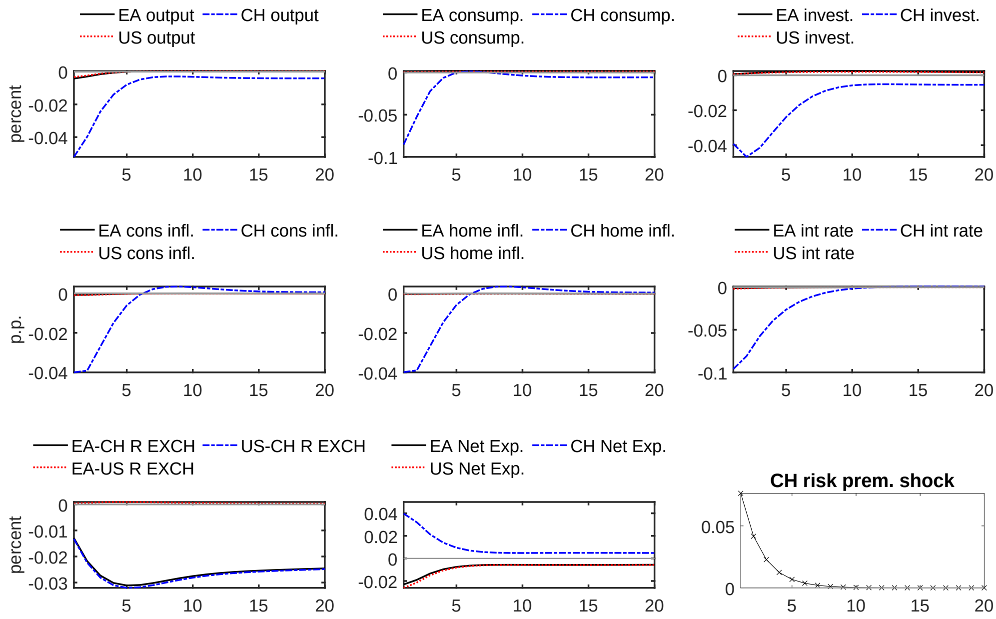


Figure C6: Impulse Responses to a Positive Euro Area Monetary Policy Shock

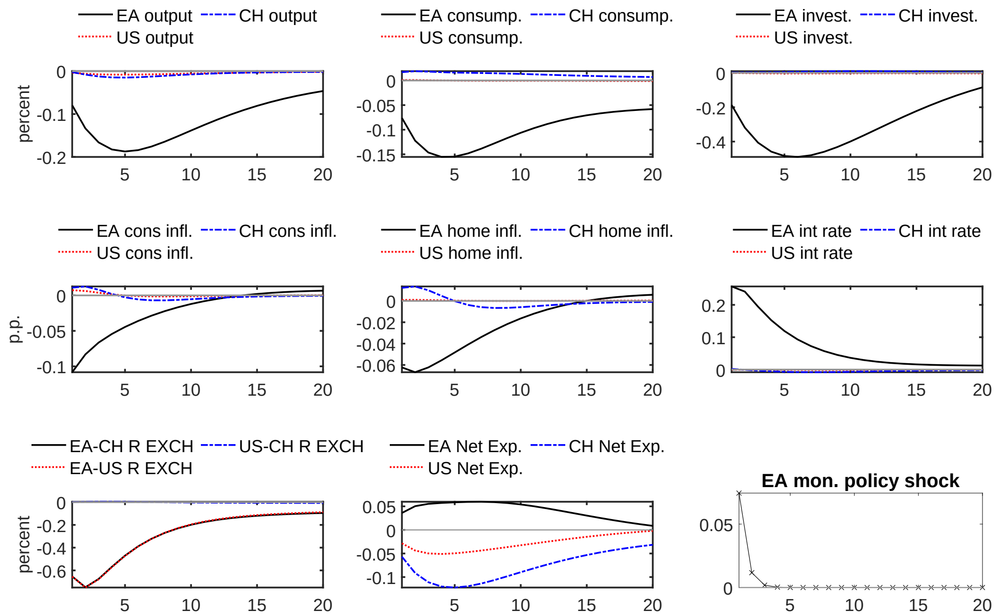


Figure C7: Impulse Responses to a Positive Chinese Monetary Policy Shock

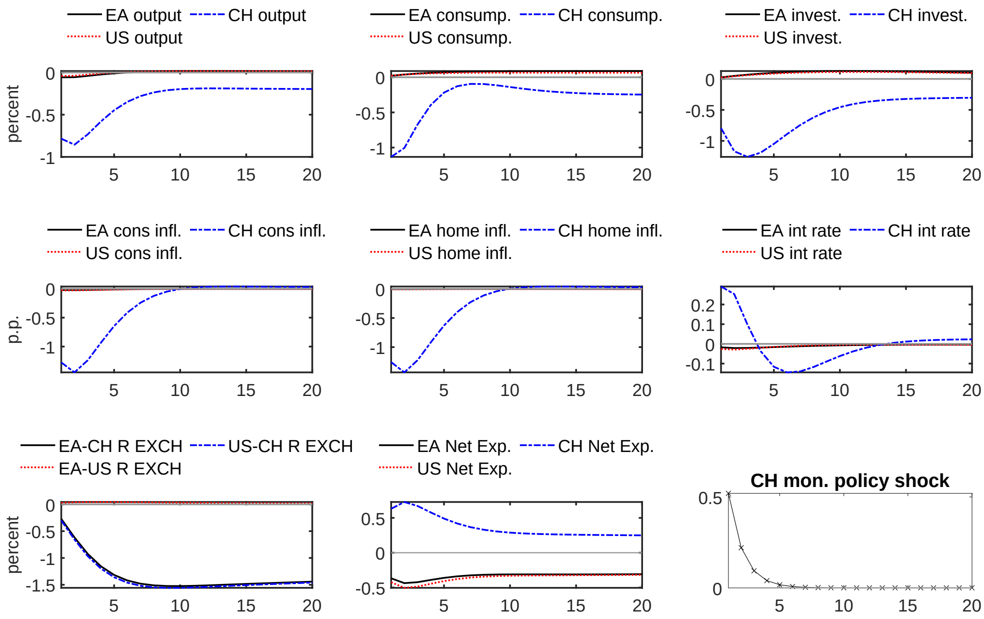


Figure C8: Impulse Responses to a Positive Chinese Reserve Requirements Shock

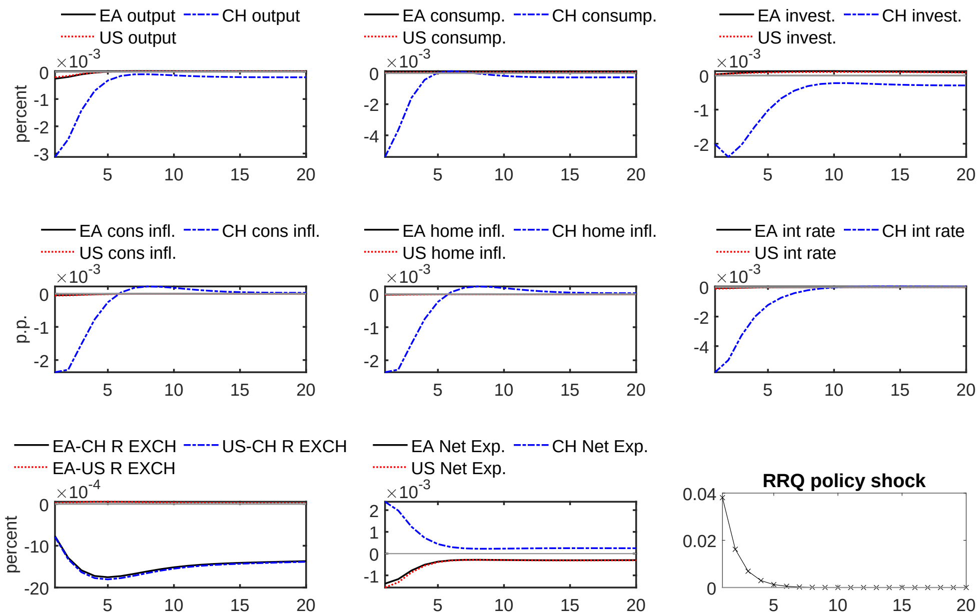


Figure C9: Impulse Responses to a Positive Euro Area Consumption Price Mark-up Shock

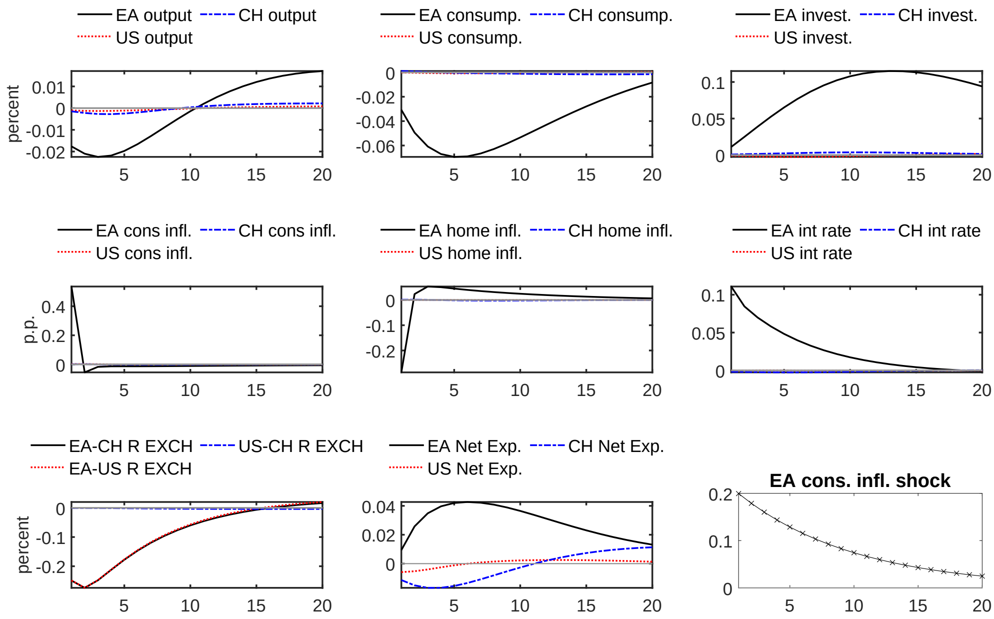


Figure C10: Impulse Responses to a Positive US Consumption Price Mark-up Shock

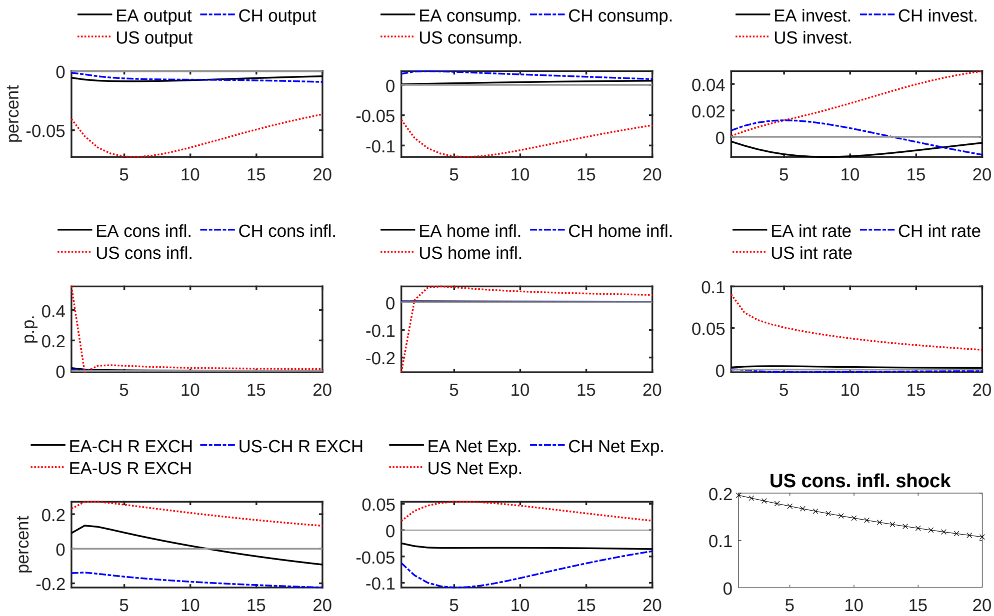


Figure C11: Impulse Responses to a Positive Chinese Consumption Price Mark-up Shock

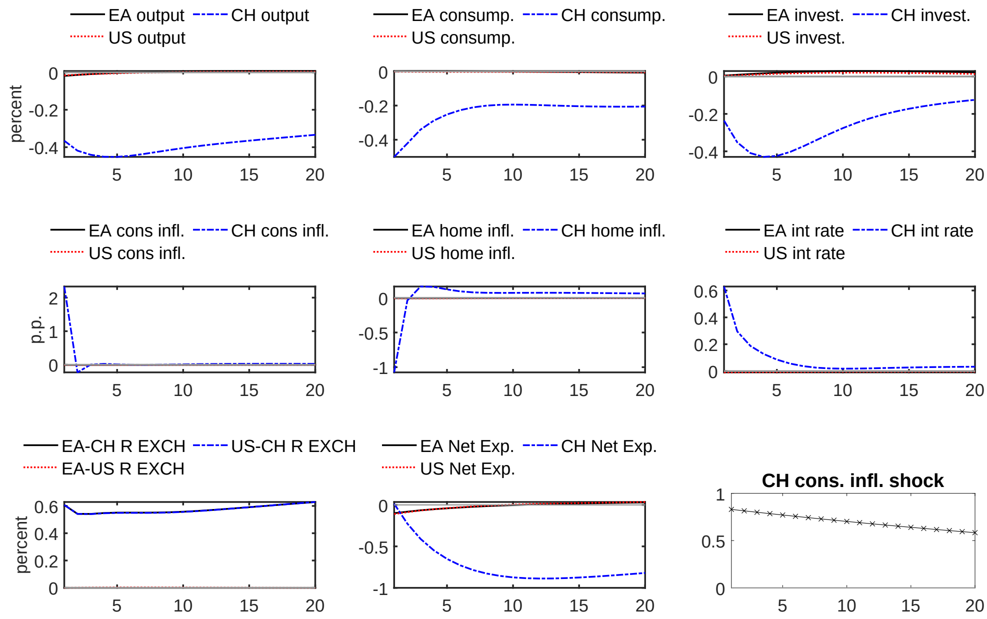


Figure C12: Impulse Responses to a Positive Euro Area Home Price Mark-up Shock

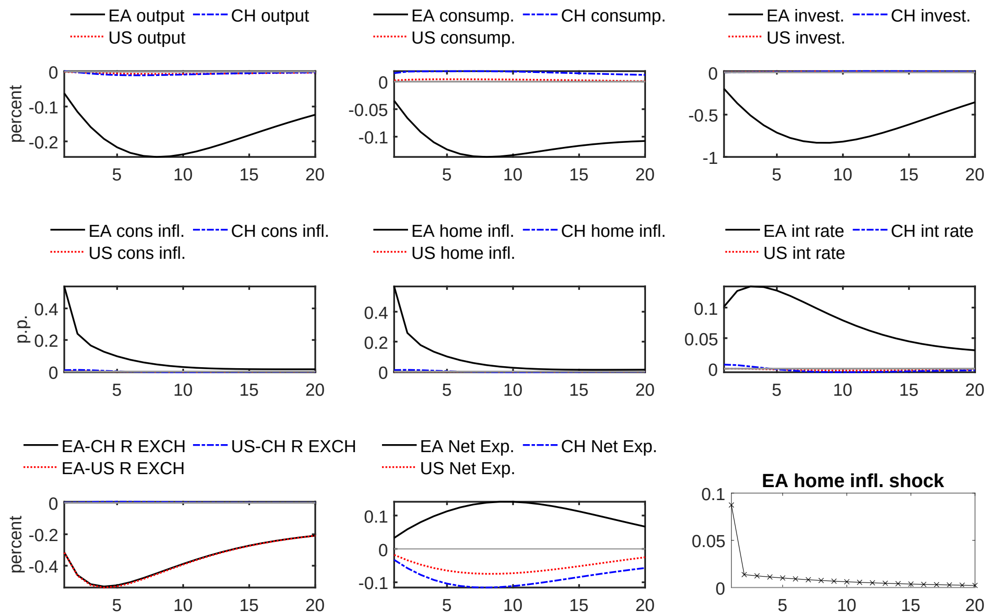


Figure C13: Impulse Responses to a Positive US Home Price Mark-up Shock

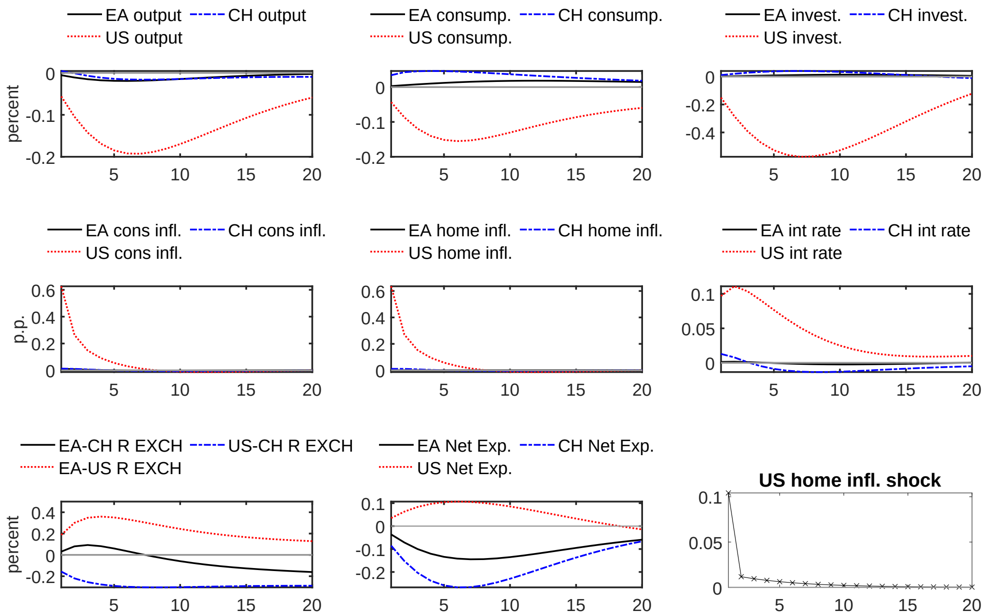


Figure C14: Impulse Responses to a Positive Chinese Home Price Mark-up Shock

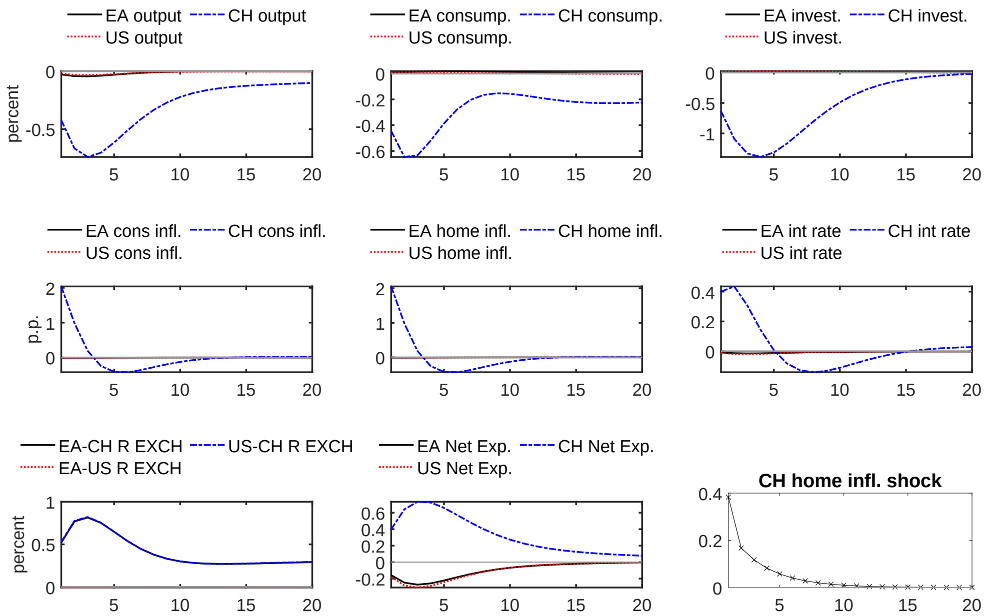
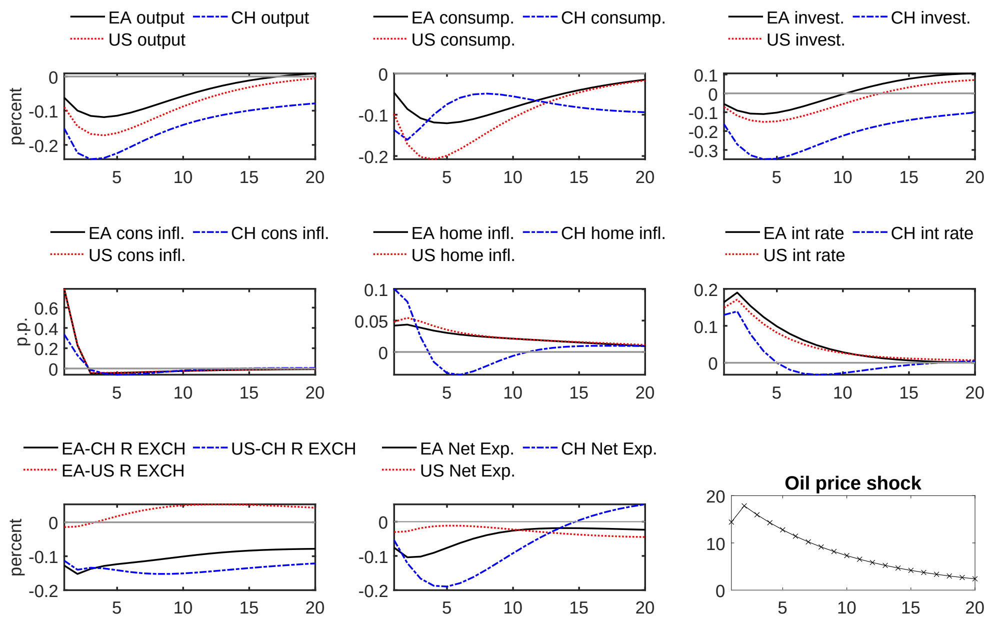


Figure C15: Impulse Responses to a Positive Oil Price Shock



Appendix D: Priors and Posteriors

Here we present the priors and the estimation results. For the correlation of shocks, we assume a beta distribution with the parameters $(0, 0.3)$. Most of the choices for the priors are in line with de Walque et al. (2017).

Table D1: Posteriors for Standard Errors of Shocks

Name	EA Posteriors		US Posteriors		CH Posteriors	
	mode	std.error	mode	std.error	mode	std.error
Productivity	1.230	0.180	0.437	0.038	0.102	0.051
Risk premium	0.380	0.136	0.239	0.052	0.076	0.024
Gov. spending	0.323	0.025	0.311	0.024	1.181	0.090
Inv. technology	0.438	0.047	0.329	0.061	0.920	0.116
Monetary policy	0.074	0.006	0.101	0.010	0.520	0.068
Home price	0.087	0.014	0.104	0.012	0.383	0.052
Wage mark-up	0.104	0.012	0.491	0.045		
Consumer price	0.200	0.015	0.195	0.015	0.830	0.063
Imp. price	0.638	0.049	1.070	0.082		
RoW demand	2.084	0.162	1.790	0.144	6.035	0.504
Res. req.					0.038	0.005
Infl. trend dev.					0.215	0.019
Res. req. trend					0.027	0.003
US-CH EXCR trend					0.298	0.026
US-CH EXCR policy					0.084	0.028
Oil price shock	0.144	0.011				
US-CH EXCR	0.086	0.031				
EA-US EXCR	0.305	0.089				

Note: All standard errors are assumed to have a prior inverse gamma distribution with mean 0.2 and two degrees of freedom. The moments of the posterior distribution are available from the authors on request.

Table D2: Posteriors for Constant Trends

Name	EA Posteriors		US Posteriors		CH Posteriors	
	mode	std. error	mode	std. error	mode	std. error
	mode	std.error	mode	std.error	mode	std.error
Imp. price	0.330	0.123	0.435	0.127		
Labour	0.066	0.013	-0.087	0.015		
Net trade	1.987	0.430	-2.017	0.101	1.937	0.473
Inflation	0.408	0.099	0.481	0.069	0.4040	0.096
Disc. factor	0.219	0.095	0.189	0.083		
Real GDP growth					1.2532	0.4974
Exchange rate EUR/USD	-0.016	0.080				

Note: All trends are assumed to have a normal beta distribution. The moments of the posterior distribution and detailed priors are available from the authors on request.

Table D3: Posteriors for the ARMA Parameters of the Stochastic Processes

Name		EA Posteriors		US Posteriors		CH Posteriors	
		mode	std. error	mode	std. error	mode	std. error
TFP	AR	0.506	0.123	0.919	0.040	0.492	0.110
Risk premium	AR	0.852	0.041	0.864	0.025	0.546	0.171
Gov. spending	AR	0.911	0.030	0.934	0.025		
Investment	AR	0.179	0.092	0.659	0.106	0.679	0.145
Monetary policy	AR	0.157	0.078	0.552	0.055	0.425	0.089
Home price mark-up	AR	0.904	0.049	0.811	0.112	0.701	0.074
Cons price mark-up	AR	0.896	0.043	0.969	0.015	0.982	0.005
Wage mark-up	AR	0.959	0.021	0.357	0.207		
Home price mark-up	MA	0.156	0.074	0.113	0.062	0.437	0.131
Wage mark-up	MA	0.046	0.030	0.056	0.041		
Imp. price mark-up	AR	0.482	0.136	0.253	0.194		
RoW demand	AR	0.876	0.054	0.980	0.012	0.789	0.044
Imp. price mark-up	MA	0.391	0.082	0.223	0.093		
Reaction of home inflation to consumption inflation		0.393	0.083	0.336	0.078	0.340	0.080
Reaction of exports to TFP		0.290	0.141	0.700	0.196	0.644	0.280
Reaction of gov. spending to TFP		0.037	0.022	0.541	0.075	0.618	0.106
Reserve requirement trend, first difference	AR					0.153	0.063
Exchange rate trend in USD/CNY, first difference	AR					0.650	0.061
Inflation target trend, first difference	AR					0.268	0.079
Persistence of res. req.						0.252	0.100
Oil price	AR	0.895	0.04				
Oil price	MA	0.343	0.091				
Exchange rate EUR/USD	AR	0.898	0.032				
Exchange rate USD/CNY	AR	0.778	0.149				

Note: All ARMA parameters are assumed to have a prior beta distribution with mean 0.5 and standard deviation 0.2. The moments of the posterior distribution are available from the authors on request.

Table D4: Correlation of Shocks: Posteriors

	United States		**China**	
Euro Area	mode	std. error	mode	std. error
TFP	0.13	0.10	0.62	0.25
Risk premium	0.20	0.11	0.35	0.24
Monetary policy	0.51	0.08	0.32	0.06
RoW demand	-0.07	0.11	0.14	0.08
Im. Price	0.61	0.07		
United States				
TFP			0.33	0.24
Risk premium			0.36	0.25
Monetary policy			0.48	0.07
RoW demand			0.26	0.06

Note: All correlations are assumed to have a prior beta distribution with mean 0 and 0.3 degrees of freedom. The moments of the posterior distribution are available from the authors on request.

Table D5: Posteriors for the Domestic and Open Economy Parameters

Name	EA Posteriors		US Posteriors		CH Posteriors	
	mode	std.error	mode	std.error	mode	std.error
inv. adj. costs	7.522	1.030	5.116	1.076	3.248	0.506
rel. risk aversion	0.912	0.023	1.079	0.151	0.907	0.083
inv. Frisch elast.	1.858	0.207	1.094	0.829	1.642	0.459
habit	0.851	0.025	0.649	0.061	0.222	0.058
fixed costs	1.313	0.086	1.420	0.085	1.447	0.096
Calvo wage	0.783	0.036	0.704	0.051	0.379	0.111
wage index.	0.122	0.057	0.481	0.157	0.469	0.174
Calvo price	0.780	0.034	0.818	0.033	0.571	0.073
price index.	0.120	0.060	0.193	0.073	0.310	0.107
cap. util. adj. costs	0.138	0.056	0.181	0.075	0.043	0.033
capital share	0.300	0.028	0.272	0.025	0.484	0.066
imp. goods in prod.	0.062	0.016	0.045	0.019	0.287	0.021
oil in production	0.002	0.001	0.004	0.001	0.011	0.007
distrib. in cons.	0.482	0.097	1.059	0.653	0.651	0.094
distrib. in oil	2.259	0.376	3.871	0.485	4.063	0.499
Calvo im. price	0.459	0.097	0.308	0.099	0.479	0.191
im. price index.	0.480	0.167	0.387	0.162	0.377	0.159
elast. of substitution	2.504	0.746	2.047	0.832	4.559	0.966
adj. costs	4.054	0.979	3.946	1.011	3.814	1.021
im elast. of substitution	3.290	1.041	2.211	0.800	1.004	0.336
im. adj. costs	4.172	0.968	4.324	0.973	4.116	0.978
Taylor rule parameters						
lagged int. rate	0.880	0.015	0.872	0.015		
inflation	1.792	0.197	1.553	0.136		
output gap	0.055	0.017	0.065	0.026		
diff. in output gap	0.049	0.014	0.116	0.021	0.356	0.057
Reserve requirements parameters						
parameter in Euler equation					0.114	0.100
parameter in price of capital equation					0.100	0.010
reaction to output gap					0.001	0.001
reaction to inflation					0.004	0.007
Exchange rate parameters						
UIRP EUR/USD smooth. Param	0.244	0.047				
UIRP USD/CNY smooth. Param	0.280	0.106				
UIRP adj. param.	0.135	0.098				

Appendix E: Conditional Variance Decomposition of the Forecast Errors

In Tables E1–E3 we report the conditional variance decomposition of the forecast errors for countries' output, consumption inflation and real exchange rates. We show the decomposition for periods of 1 quarter, 4 quarters and 40 quarters. All parameters are at the posterior mode, with no correlation between shocks. Foreign shocks in the table stand for foreign demand from the rest of the world and the foreign inflation mark-up shocks. We only report shocks with a contribution larger than 0.00%.

Table E1: Conditional Variance Decomposition of Real Output Growth, %

	EA output			US output			CH output		
Shocks	1Q	4Q	40Q	1Q	4Q	40Q	1Q	4Q	40Q
EA contribution	**64.01**	**67.23**	**68.38**	**0.27**	**0.27**	**0.27**	**0.08**	**0.09**	**0.09**
productivity	5.37	5.03	5.22	0.04	0.04	0.04	0.03	0.02	0.03
risk premium	20.86	26.76	28.2	0.04	0.05	0.06	0.02	0.02	0.02
gov. spending	26.63	23.14	21.86	0.14	0.13	0.12	0.02	0.03	0.03
inv. technology	8.13	6.75	6.35	0.05	0.04	0.04	0.01	0.01	0.01
monetary policy	1.69	2.31	2.43	0	0	0	0	0	0
home price	1.02	2.12	2.53	0	0	0	0	0	0
wage mark-up	0.24	1.04	1.7	0	0	0	0	0.01	0.01
consumer price	0.08	0.07	0.09	0	0	0	0	0	0
infl. trend dev.	0	0	0	0	0	0	0	0	0
growth trend dev.	0	0	0	0	0	0	0	0	0
US contribution	**3.21**	**3.05**	**3.1**	**88.72**	**89.62**	**90**	**0.27**	**0.28**	**0.32**
productivity	0.87	0.71	0.68	23.62	19.89	18.98	0.08	0.07	0.07
risk premium	0.77	0.77	0.86	19.81	21.37	22.06	0.04	0.05	0.07
gov. spending	0.72	0.65	0.62	18.36	15.74	14.8	0.13	0.13	0.13
inv. technology	0.37	0.38	0.39	8.96	9.76	9.87	0.01	0.01	0.02
monetary policy	0.45	0.49	0.51	16.99	20.89	21.94	0	0	0.02
home price	0.01	0.02	0.02	0.62	1.25	1.44	0	0	0
wage mark-up	0.01	0.01	0.02	0.02	0.4	0.59	0	0.01	0.01
consumer price	0.01	0.01	0.01	0.33	0.32	0.32	0	0	0
infl. trend dev.	0	0	0	0	0	0	0	0	0
growth trend dev.	0	0	0	0	0	0	0	0	0
CH contribution	**3.45**	**3.28**	**3.23**	**1.48**	**1.42**	**1.39**	**77.5**	**76.14**	**76.7**
productivity	0.02	0.02	0.01	0.01	0.01	0.01	0.29	0.27	0.27
risk premium	0	0	0	0	0	0	0.11	0.11	0.11
gov. spending	1.71	1.61	1.5	0.81	0.75	0.71	23.01	22.11	21.58
inv. technology	0.52	0.49	0.51	0.19	0.18	0.19	15.97	17.06	17.04
monetary policy	0.89	0.84	0.84	0.34	0.33	0.34	25.27	23.13	23.32
home price	0.22	0.23	0.26	0.09	0.09	0.1	7.32	8.58	9.67
wage mark-up	0	0	0	0	0	0	0	0	0
consumer price	0.1	0.09	0.09	0.05	0.05	0.04	5.49	4.81	4.66
infl. trend dev.	0	0	0	0	0	0	0.05	0.05	0.05
growth trend dev.	0	0	0	0	0	0	0	0	0
US-CH EXCR policy	0	0	0	0	0	0	0	0	0
res. req.	0	0	0	0	0	0	0	0	0
rrq trend	0	0	0	0	0	0	0	0	0
US-CH EXCR trend	0	0	0	0	0	0	0	0	0
EXCHR contribution	**0.02**	**0.03**	**0.14**	**0**	**0**	**0**	**0.07**	**0.09**	**0.09**
For. shocks contribution	**28.28**	**25.2**	**23.79**	**7.93**	**6.78**	**6.29**	**21.14**	**22.4**	**21.77**
Oil price shock	**1.02**	**1.21**	**1.35**	**1.6**	**1.91**	**2.06**	**0.95**	**1**	**1.03**

Table E2: Conditional Variance Decomposition of Quarterly Consumption Inflation, %

	EA cons. inflation			US cons. inflation			CH cons. inflation		
Shocks	1Q	4Q	40Q	1Q	4Q	40Q	1Q	4Q	40Q
EA contribution	**47.01**	**51.58**	**59.07**	**0.06**	**0.15**	**0.19**	**0.01**	**0.03**	**0.04**
productivity	2.18	2.16	1.89	0.01	0.01	0.01	0	0	0
risk premium	0.66	3.08	4.37	0.03	0.09	0.11	0	0	0.01
gov. spending	0.04	0.1	0.12	0	0	0	0	0	0
inv. technology	0.02	0.15	0.48	0	0	0	0	0	0
monetary policy	0.85	1.49	1.51	0	0.01	0.01	0	0	0
home price	20.96	22.33	19.82	0	0	0	0	0	0
wage mark-up	1.62	5.7	17.07	0.01	0.04	0.07	0.01	0.02	0.02
consumer price	20.69	16.58	13.82	0	0	0	0	0	0
infl. trend dev.	0	0	0	0	0	0	0	0	0
growth trend dev.	0	0	0	0	0	0	0	0	0
US contribution	**1.21**	**1.46**	**1.35**	**57.03**	**65.16**	**69.23**	**0.03**	**0.11**	**0.21**
productivity	0.05	0.06	0.05	0.85	2.02	2.41	0	0	0
risk premium	0.46	0.69	0.62	1.62	5.68	8.47	0.01	0.03	0.07
gov. spending	0.03	0.04	0.04	0.07	0.2	0.38	0	0.01	0.01
inv. technology	0	0	0.05	0	0.01	1.2	0	0	0.01
monetary policy	0.62	0.6	0.52	3.29	10.79	15.38	0.01	0.06	0.11
home price	0.01	0.01	0.01	27.13	24.72	21.51	0	0	0
wage mark-up	0.01	0.03	0.03	2.69	6.06	6.08	0.01	0.01	0.01
consumer price	0.02	0.02	0.02	21.38	15.67	13.8	0	0	0
infl. trend dev.	0	0	0	0	0	0	0	0	0
growth trend dev.	0	0	0	0	0	0	0	0	0
CH contribution	**0.07**	**0.2**	**0.26**	**0.1**	**0.24**	**0.35**	**98.37**	**98.27**	**98.2**
productivity	0	0	0	0	0	0	0.02	0.01	0.01
risk premium	0	0	0	0	0	0	0.01	0.02	0.02
gov. spending	0	0.01	0.01	0.01	0.01	0.01	0.55	0.8	0.79
inv. technology	0.03	0.08	0.11	0.03	0.08	0.12	2.98	6.54	6.84
monetary policy	0.03	0.08	0.09	0.06	0.13	0.18	13.69	32.98	33.88
home price	0.01	0.01	0.01	0	0.01	0.01	35.01	28.12	29.03
wage mark-up	0	0	0	0	0	0	0	0	0
consumer price	0	0.01	0.03	0	0.01	0.03	45.83	29.59	27.4
infl. trend dev.	0	0	0	0	0	0	0.28	0.21	0.21
growth trend dev.	0	0	0	0	0	0	0	0	0
US-CH EXCR policy	0	0	0	0	0	0	0	0	0
res. req.	0	0	0	0	0	0	0	0	0
rrq trend	0	0	0	0	0	0	0	0	0
US-CH EXCR trend	0	0	0	0	0	0	0	0	0.01
EXCHR contribution	**7.15**	**8.16**	**6.89**	**0.25**	**0.51**	**0.49**	**0.01**	**0.02**	**0.02**
For. shocks contribution	**0.06**	**0.11**	**0.12**	**0.03**	**0.09**	**0.24**	**0.64**	**0.86**	**0.81**
Oil price shock	**44.5**	**38.5**	**32.31**	**42.52**	**33.86**	**29.49**	**0.95**	**0.71**	**0.72**

Table E3: Conditional Variance Decomposition of the Quarterly Difference in the Nominal Exchange Rate, %

	dollar-yuan			euro-dollar		
Shocks	1Q	4Q	40Q	1Q	4Q	40Q
EA contribution	**0**	**0**	**0**	**6.09**	**6.3**	**6.71**
productivity	0	0	0	0.12	0.13	0.15
risk premium	0	0	0	2.18	2.26	2.5
gov. spending	0	0	0	0.06	0.07	0.07
inv. technology	0	0	0	0.07	0.07	0.08
monetary policy	0	0	0	2.86	2.86	2.82
home price	0	0	0	0.2	0.24	0.32
wage mark-up	0	0	0	0.52	0.58	0.67
consumer price	0	0	0	0.08	0.09	0.11
infl. trend dev.	0	0	0	0	0	0
growth trend dev.	0	0	0	0	0	0
US contribution	**0.04**	**0.03**	**0.03**	**14.44**	**14.64**	**14.81**
productivity	0	0	0	0.66	0.68	0.69
risk premium	0.01	0.01	0.01	2.66	2.73	3.08
gov. spending	0	0	0	0.13	0.13	0.13
inv. technology	0	0	0	0.03	0.04	0.1
monetary policy	0.02	0.02	0.02	10.89	10.97	10.66
home price	0	0	0	0.01	0.02	0.05
wage mark-up	0	0	0	0	0	0.02
consumer price	0	0	0	0.06	0.07	0.08
infl. trend dev.	0	0	0	0	0	0
growth trend dev.	0	0	0	0	0	0
CH contribution	**97.5**	**98.37**	**98.37**	**0.02**	**0.03**	**0.02**
productivity	0	0	0	0	0	0
risk premium	0	0	0	0	0	0
gov. spending	0.06	0.04	0.04	0	0	0
inv. technology	0.15	0.13	0.16	0	0	0
monetary policy	0.04	0.03	0.03	0.01	0.01	0.01
home price	0.07	0.05	0.06	0	0	0
wage mark-up	0	0	0	0	0	0
consumer price	0.14	0.11	0.1	0	0	0
infl. trend dev.	0.27	0.18	0.17	0	0	0
growth trend dev.	0	0	0	0	0	0
US-CH EXCR policy	1.41	1.64	1.59	0	0	0
res. req.	0	0	0	0	0	0
rrq trend	0	0	0	0	0	0
US-CH EXCR trend	95.36	96.19	96.22	0.02	0.02	0.02
EXCHR contribution	**2.35**	**1.54**	**1.53**	**79.31**	**78.89**	**78.31**
For. shocks contribution	**0.1**	**0.07**	**0.07**	**0.14**	**0.15**	**0.14**
Oil price shock	**0**	**0**	**0**	**0**	**0**	**0**

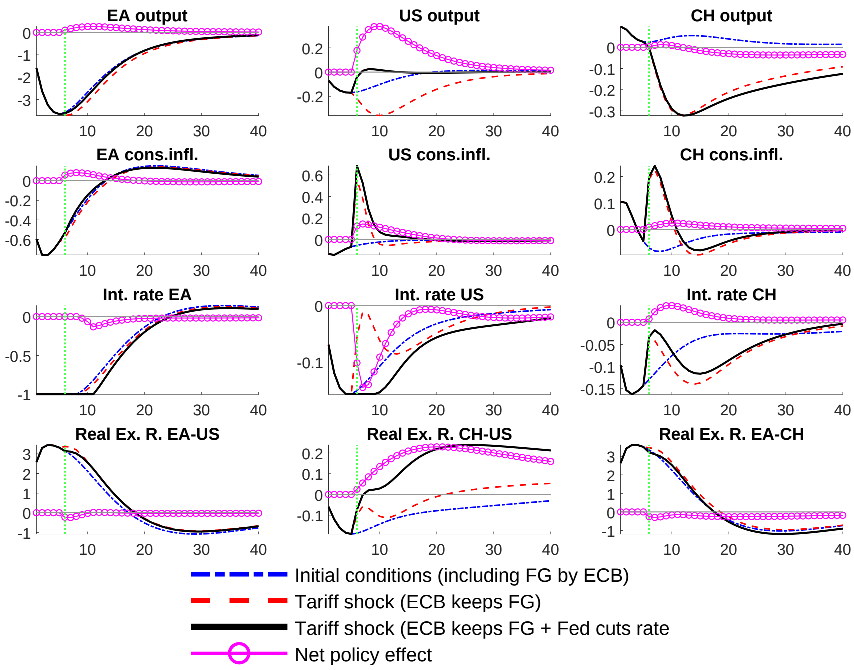
Appendix F: Alternative Monetary Policy and Initial Conditions

The reactions of economies to tariffs are influenced by the reactions of monetary authorities. In normal times, as tariffs raise inflation, the expected monetary policy response is to raise rates. In reality, the actual reactions may be different. First, the ECB is currently keeping its rates below zero for now and giving the market guidance that they will stay negative in the future. The ECB is unlikely to raise its rates in response to tariffs. In fact, since tariffs negatively affect output, it would be easier to communicate continued low interest rate policy after an increase in inflation induced by trade wars. As such, this represents a monetary policy stimulus that can alter the effects of tariffs. Moreover, other monetary authorities may also be tempted not to raise rates in order to accommodate the effects of tariffs on their economies. For these reasons, we analyse the effects of the introduction of tariffs when the euro area economy is in distress and the ECB commits to forward guidance about the future path of interest rates. We further consider the scenario of the Fed not raising its rates in addition to the ECB's low interest rate policy.

In Figure F1 we consider an exercise with initial conditions deviating from the steady state and an alternative monetary policy. We model the Eurozone subject to an initial positive risk premium shock of standard deviation equal to unity, which reduces output and inflation. The ECB follows its policy rule and reduces the interest rate. However, it commits to deviating from the policy rule by keeping rates low for a finite period of 8 quarters (solid line "Initial conditions (including FG by ECB)"). The "full trade war scenario" is implemented over this period, at $t = 6$. We then model two sets of policy responses to the tariff shock: (1) the ECB honours its initial commitment (dashed line "Tariff shock, ECB keeps FG") and the Fed follows its standard reaction function, and (2) the Fed lowers its policy rate and commits to keeping it low until $t = 8$, while the ECB extends its forward guidance to $t = 12$ (dashed and dotted line "Tariff shock, ECB keeps FG + Fed cuts rate").

From the simulations, it is clear that under this scenario, monetary policy accommodation can *temporarily* alleviate the negative effects of tariffs on output at the cost of higher inflation. The stimulative effects are clearly limited when the economy is at the effective lower bound, as can be seen from the euro area responses. The partial effects of the ECB's extension of its FG and/or the Fed's rate cuts on output are positive and are boosted by trade links. In the longer run, the negative effects of tariffs on output dominate and inflation rates in all countries remain higher than in the baseline scenario.

Figure F1: A 10% Tariff with Alternative Initial Conditions and Monetary Policy



Note: The alternative initial conditions are simulated as a positive risk premium shock in the euro area in period $t = 1$ accompanied by forward guidance by the ECB (initial conditions). A tariff of 10% is imposed bilaterally by all countries at time $t = 6$ (green dotted line). The alternative policies are: the ECB commits to forward guidance for 8 periods (tariff shock, ECB keeps FG) and the Fed lowers the policy rate at $t = 6$ and does not increase the policy rate for 8 periods and the ECB extends its commitment to 12 periods (tariff shock, ECB keeps FG + Fed cuts rate). The net policy effect is the difference between the solid black line and the dashed red line. A positive net effect means a smaller decline or larger increase as a result of the policy response.

CNB Working Paper Series (since 2019)

WP 6/2020	Volha Audzei Jan Brůha	*A model of the Euro Area, China and the United States: Trade links and trade wars*
WP 5/2020	Dominika Ehrenbergerová Martin Hodula Zuzana Rakovská	*Does capital-based regulation affect bank pricing policy?*
WP 4/2020	Alexis Derviz	*Sovereign capital, external balance, and the investment-based Balassa-Samuelson effect in a global dynamic equilibrium*
WP 3/2020	Milan Szabo	*Growth-at-risk: Bayesian approach*
WP 2/2020	Martin Hodula Ngoc Anh Ngo	*Finance, growth and (macro)prudential policy: European evidence*
WP 1/2020	Michal Franta Ivan Sutóris	*Dynamics of Czech inflation: The role of the trend and the cycle*
WP 12/2019	Josef Bajzík Tomáš Havránek Zuzana Iršová Jiří Schwarz	*The elasticity of substitution between domestic and foreign goods: A quantitative survey*
WP 11/2019	Martin Hodula Simona Malovaná Jan Frait	*Too much of a good thing? Households' macroeconomic conditions and credit dynamics*
WP 10/2019	Martin Hodula Simona Malovaná Jan Frait	*Introducing a new index of households' macroeconomic conditions*
WP 9/2019	Jiří Panoš Petr Polák	*How to improve the model selection procedure within a stress testing framework?*
WP 8/2019	Sebastian Gechert Tomáš Havránek Zuzana Iršová Dominika Kolcunová	*Death to the Cobb-Douglas production function? A quantitative survey of the capital-labor substitution elasticity*
WP 7/2019	Alexis Derviz	*Coexistence of physical and crypto assets in a stochastic endogenous growth model*
WP 6/2019	Dominika Ehrenbergerová Simona Malovaná	*Introducing macro-financial variables into semi-structural model*
WP 5/2019	Martin Hodula	*Monetary policy and shadow banking: Trapped between a rock and a hard place*
WP 4/2019	Simona Malovaná Žaneta Tesařová	*Banks' credit losses and provisioning over the business cycle: Implications for IFRS 9*
WP 3/2019	Aleš Bulíř	*Monetary policy is not always systematic and data-driven: Evidence*

	Jan Vlček	*from the yield curve*
WP 2/2019	Dominika Kolcunová Simona Malovaná	*The effect of higher capital requirements on bank lending: The capital surplus matters*
WP 1/2019	Jaromír Baxa Tomáš Šestořád	*The Czech exchange rate floor: Depreciation without inflation?*

CNB Research and Policy Notes (since 2019)

RPN 1/2020	Simona Malovaná	*How to organize research in central banks: The Czech National Bank's experience*
RPN 4/2019	Tomáš Konečný Lukáš Pfeifer	*Macroprudential ring-fencing*
RPN 3/2019	Petr Polák Jiří Panoš	*Impact of expectations on IFRS 9 loan loss provisions*
RPN 2/2019	Jan Filáček Ivan Sutóris	*Inflation targeting flexibility: The CNB's reaction function under scrutiny*
RPN 1/2019	Iveta Polášková Luboš Komárek Michal Škoda	*The contemporary role of gold in central banks' balance sheets*

CZECH NATIONAL BANK
Na Příkopě 28
115 03 Praha 1
Czech Republic

ECONOMIC RESEARCH DIVISION
Tel.: +420 224 412 321
Fax: +420 224 412 329
http://www.cnb.cz
e-mail: research@cnb.cz

ISSN 1803-7070