Financially Constrained Intermediaries and the International Pass-Through of Monetary Policy*

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Abstract

This paper highlights the prominent role of financially constrained intermediaries, especially currency dealers, for the international transmission of US (un)conventional monetary policy quantitatively. We examine the transmission mechanism through the lens of global investors' portfolio rebalancing in imperfect financial markets. We develop a two-country New Keynesian dynamic stochastic general equilibrium (DSGE) model with financially constrained investors and currency dealers. The main insight is: following a tightening domestic (un)conventional monetary shock, currency dealers subject to financial constraints intermediate the liquidity imbalances resulting from global investors' substitution towards domestic assets, which further leads to home currency's appreciation. We discipline our quantitative model by targeting estimates from a structural vector autoregression (SVAR). Our quantitative analysis indicates that currency dealers' limited risk bearing capacity plays a key role for the effectiveness of QE in an open economy, and also accounts for the puzzling downward term structure of currency carry trade risk premia.

Keywords: Currency dealers, Exchange rates, Financial constraints, Global investors, Global portfolio flows, Home bias, Risk premia, (Un)conventional monetary policy, ZLB

JEL codes: E12, E52, F31, F32, G11, G21

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1 Introduction

A large empirical literature has documented the strong impact of US monetary policy on international financial markets, especially with regard to exchange rates and global capital flows. One recent remarkable event is: since July 15, 2002, the euro fell below parity with the dollar again on August 22, 2022, following after that the Federal Reserve aggressively raised its baseline interest rate by 75 bps to combat inflation. Many analysts imputed this striking phenomenon to global investors shifting money from euros- to dollar-denominated assets. This portfolio rebalancing process is associated with currency dealers' short position of dollars and long position of euros to cater investors' rising demand for US dollars, which turns to push euro down and dollar up. In this paper, we systematically study the transmission mechanism of US (un)conventional monetary policy in an open economy. Importantly, we first examine the implication of currency (FX) dealers' limited risk bearing capacity for the international pass-through of (un)conventional monetary policy.

In many international macroeconomic models, monetary policy's international spillover is through the uncovered interest rate parity (UIP); for instance, a tightening domestic monetary policy shock appreciates home currency by raising domestic short-term rate. But, the failure of UIP due to the presence of risk premium, as highlighted in Fama (1984), is well known since then. Over the past decades, a vast literature has attempted to rationalize the UIP failure through different arguments. Among these, Gabaix and Maggiori (2015) and Itskhoki and Mukhin (2021) emphasize the important role of currency dealers for the explanations of UIP failure and other related empirical puzzles by connecting exchange rate fluctuations to global capital flows; Maggiori (2022) provides a comprehensive review. However, the role of currency dealers for the pass-through of US monetary policy in an open economy is still not clear, especially given the observation of US monetary policy's large impact on exchange rates and global capital flows.

In this paper, we analyze the role of currency dealers in the international transmission of US (un)conventional monetary policy quantitatively. We first conduct an event study around two special FOMC announcement windows during "Taper Tantrum" period to demonstrate the strong impact of the Fed's asset-purchase tapering on global portfolio flows and exchange rates for both advanced economies (AE) and emerging markets (EM). In particular, the strong fluctuations of exchange rates around these FOMC announcement windows can be explained by currency dealers' liquidity intermediation. To quantitatively investigate this mechanism, we then develop a two-country New Keynesian DSGE model wherein both conventional and unconventional monetary policies are effective. Our framework builds on Gertler and Karadi (2011, 2013), Gabaix and Maggiori (2015), and Itskhoki and Mukhin (2021), and features financially constrained banks (investors) and FX dealers as well as international intermediate goods trading.[1] Importantly, the binding constraints of banking sectors in each country make QE effective, and the binding constraints of FX dealers break the UIP relationship and relate the determination of exchange rates to global portfolio flows. Furthermore, we identify the dynamic effects of (un)conventional monetary shocks on the related financial variables based on a Bayesian proxy structural vector autoregression (BP-SVAR) estimation. We discipline the model by matching the impulse responses to US conventional monetary policy shocks from model simulations and estimation from BP-SVAR. Our quantitative analysis shows that the financial constraint of currency dealers is crucial for impulse response matching between model and estimation, and explain the puzzling facts on downward-sloping term structure of carry trade risk premia in Lustig, Stathopoulos, and Verdelhan (2019). More importantly, without currency dealers' financial constraints, our quantitative results shows that the stimulation of QE on domestic economy would be much less effective, which indicates that currency dealers' limited risk bearing capacity is important for the effectiveness of domestic QE.

We begin with an event study during the "Taper Tantrum" period based on high-frequency exchange rates and currency order flows datasets from CLS and portfolio flow datasets from JP Morgan Chase. Around the narrow windows of two special FOMC announcements in this period, we find that exchange rates of US dollar react to the announcements instantaneously and strongly. Within one hour after a tightening (easing) announcement, the US dollar appreciates (depreciates) by around 1% and 2% against AE and EM currencies, respectively. Importantly, we also find that dollar's appreciation (depreciation) is associated with significant increase of currency dealer banks' net dollar buying from non-dealer banks and net dollar selling to funds or other investors, which can also reflect the increase of demand for US dollars. With the portfolio data from JP Morgan, we also document the continual increase of the portfolio inflows from several emerging markets to the US within this period. The constantly growing portfolio inflows to the US are associated with the continuing appreciation of the dollar against EM currencies. Based on these confidential datasets, we first provide direct empirical evidence for the important role of FX dealers in the global transmission of US unconventional monetary policy: intermediating the currency liquidity imbalance resulting from global investors' portfolio rebalancing. More generally, our SVAR

[1] We follow Gertler and Karadi (2011, 2013), where banking sectors can also be interpreted as levered investors. From now on, "banks" and "investors" are used interchangeably.

estimation on monthly data further confirms the inspired channel from this event study.

We analyze the motivated mechanism quantitatively by developing a two-country New Keynesian DSGE model with banks in each country and an imperfect currency market in the international financial market. Our model extends the framework in Gertler and Karadi (2011, 2013) into the international context with an imperfect currency market as in Gabaix and Maggiori (2015) and Itskhoki and Mukhin (2021). Compared to the existing international macroeconomic models, ours has distinct features on two types of financially constrained intermediaries: banks or investors in each country and currency dealers in the international financial market. More specific, we introduce the bank sector in the classical New Keynesian DSGE model as in Gertler and Karadi (2011, 2013), wherein banks subject to binding financial constraints are levered in equilibrium. In the model, an easing conventional monetary surprise decreases the real deposit rates, that is, domestic investors' funding costs, and then lowers the respective compensated expected returns and raises the prices of domestic risky assets and banks' net worth. Banks's leverage further amplifies this positive shock to bank's net worth and generates an additional positive feedback loop between asset prices and bank's net worth. Hence, the pass-through of easing target surprise is amplified through the traditional financial accelerator mechanism as in Bernanke and Gertler (1989). More importantly, as in Gertler and Karadi (2011, 2013), the banks' binding constraints also make the central bank's QE effective in the model, while QE is ineffective in the traditional macroeconomic models since long-term bonds and short-term bonds are perfectly substitutes. Second, as in Gabaix and Maggiori (2015) and Itskhoki and Mukhin (2021), the currency market is imperfect, and the global imbalances resulting from assets or goods trading is intermediated by a group of FX dealers in the international financial market. FX dealers are also subject to the binding financial constraints and have limited ability to intermediate the global imbalances. Due to the FX dealers' limited liquidity-intermediation ability, the UIP condition fails and capital flows can affect exchange rates in equilibrium. Lastly, there is cross-border trading of intermediate goods for final good production in each country, which is similar to Itskhoki and Mukhin (2021).

However, highlighted by Devereux and Sutherland (2011), the optimal portfolio choices in a two-country DSGE model with first-order approximation display indeterminacy due to indistinguishable risk characteristics of domestic and foreign assets. We tackle this issue by introducing a quadratic holding cost for domestic investors' adjustment of foreign assets around the steady-state amounts, which is then covered by domestic household instantaneously. With this modeling way, we are able to avoid the higher-order approximated solution with the presence of intermediaries' binding financial constraints in our model, which is a much harder problem compared to the model in Devereux and Sutherland (2011). The introduction of holding costs for foreign assets in the model is also consistent with the well-documented home bias of asset holding in the literature. More importantly, the home bias of asset holding and investors' binding financial constraints in our model strengthen each other such that US monetary policy generates largely asymmetric impact on domestic and foreign economy, which is also consistent with empirical findings from SVAR.

We conduct quantitative experiments to assess the effects of (un)conventional monetary policy shocks under different scenarios with estimated parameters by matching the impulse responses from model simulation and BP-SVAR estimation. Our quantitative results of the baseline case are consistent with the empirical findings and also demonstrate the effectiveness of domestic (un)conventional monetary policy in the international context with an imperfect currency market. In addition, we also consider two polar cases: UIP-based and financial autarky, under which FX dealers are willing to absorb any amount of imbalance and unwilling to absorb any imbalances, respectively. Importantly, from the quantitative analysis results, we highlight the crucial role of FX dealers for the effectiveness of QE. Under the UIP case, due to FX dealers' infinite ability of liquidity intermediation, the domestic central bank's liquidity injection quickly spills over into the foreign country. Therefore, the stimulation effects of QE on the financial market and real economic activity are much less effective compared to the baseline case. Overall, the baseline calibration is much closer to the financial autarky case than the UIP-based case, which implies that the effectiveness of QE in an open economy is attributed to FX dealers' financial financial frictions. Finally, our quantitative results show that excess return of carry trade with long-term bonds is much smaller than that of carry trade with short-term bonds, which indicates our model successfully explains the puzzling downward term structure of currency carry trade risk premia uncovered by Lustig, Stathopoulos, and Verdelhan (2019).

Related Literature. Our paper is related to several strands of literature in international finance. First of all, closely related papers are Greenwood, Hanson, Stein, and Sunderam (2021) and Gourinchas, Ray, and Vayanos (2022), which separately extend the preferred-habit model of term structure in Vayanos and Vila (2021) into international setting. In their models, the domestic and foreign bond term premia and currency premia are jointly determined from risk-averse global arbitrager's optimal portfolio choice and hedging relationship among the associated risky assets. Different from this hedging channel based on global arbitrageurs, currency dealers in our model only intermediate liquidity imbalance instead of trading risky assets, which is consistent with Gabaix and Maggiori (2015) and Itskhoki and Mukhin (2021) and also empirical observations. This is the key difference between our and their frameworks. We particularly focus on the implication of currency dealers' binding financial constraints for monetary policy's spillover and asset risk premia. In addition, there are production sectors and international intermediate goods trading in our model, which are absent in their partial equilibrium models. The general equilibrium setting allows us to examine the impact of monetary policy on real economy and the effectiveness of monetary policy in the international context, which is also absent in their analysis.

Our paper also relates to the international DSGE model with portfolio choices. To handle the portfolio indeterminacy issue, Devereux and Sutherland (2010, 2011) propose the local perturbation method, while Tille and Van Wincoop (2010) and Rabitsch, Stepanchuk, and Tsyrennikov (2015) solve the model with global approximation. Bacchetta and Van Wincoop (2021) and Bacchetta, Davenport, and Van Wincoop (2022) introduce a quadratic cost for households' portfolio adjustment. We contribute to this strand of literature by introducing investors' quadratic costs of foreign asset holding covered by households. Compared to other modeling ways, it yields a simple and tractable solution for optimal portfolio choices.

Lastly, our empirical analysis also contributes the vast empirical studies of the impact of US monetary policy on exchange rates. Among the studies of conventional monetary policy, the studies of Eichenbaum and Evans (1995), Faust and Rogers (2003), and Scholl and Uhlig (2008) are based on identified VAR estimation; Andersen, Bollerslev, Diebold, and Vega (2003, 2007), Faust, Rogers, Wang, and Wright (2007), Wright (2012), and Rogers, Scotti, and Wright (2014) focus on FOMC announcement windows. Among the studies of forward guidance and QE, Rogers, Scotti, and Wright (2018), Stavrakeva and Tang (2019), and Miranda-Agrippino and Rey (2020) employ SVAR with external monetary instruments; the examinations of Swanson (2021), Bauer and Neely (2014), Neely (2015), Chari, Dilts Stedman, and Lundblad (2021), and Roussanov and Wang (2022) are based on the event-study approach around FOMC announcements. With confidential datasets, we first the provide direct empirical evidence for prominent roles of currency dealers and global investors in the global spillover of US monetary policy, which is absent among existing empirical studies.

Layout. This paper will proceed as follows. Section 2 shows the empirical evidence during the "Taper Tantrum" period and the estimated results based on BP-SVAR. Section 3 develops a two-country New Keynesian DSGE model in the international context with an imperfect currency market. Section 4 calibrates the model to match important empirical findings and reports the associated quantitative results. Section 5 concludes.

2 Motivation: Taper Tantrum

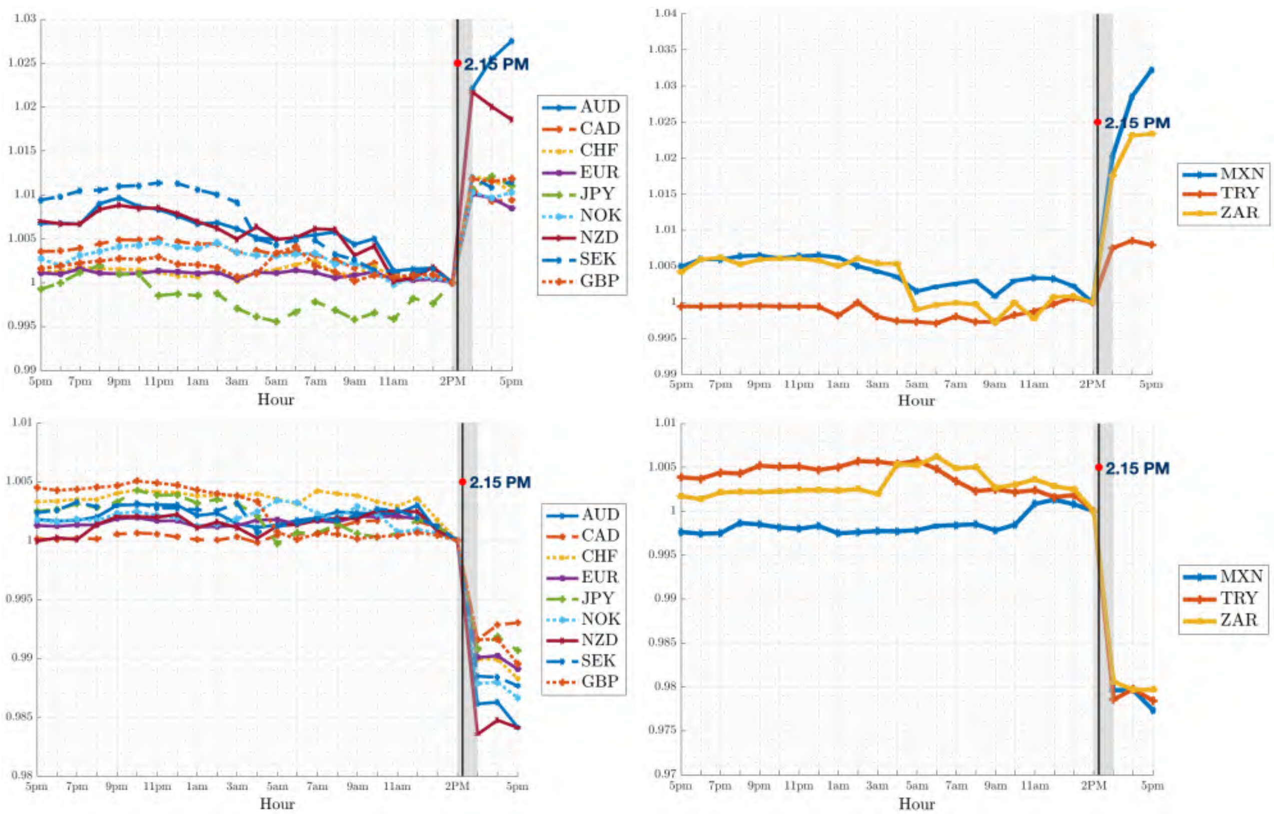
We begin with the event studies around two special FOMC announcements on June 19th, 2013 and September 18th, 2013 during the "Taper Tantrum" period. With high-frequency data, we find the strong reactions of exchange rates to the announcements, which can be explained by FX dealers' currency intermediation around the narrow announcement windows. We also document that dollar's gradual appreciation against EM currencies is associated with investors' constant portfolio inflows from EM to the US during this period.

Since the middle of 2013, the Fed decided to slow down its long-term bond purchases at some future date after several rounds of QE, which started the "Taper Tantrum" period. In particular, on June 19th, 2013, the Fed Committee announced to "anticipate to moderate the monthly pace of purchases later this year", which suddenly surprised financial market since the continuation of QE was sill widely expected. Since then, markets expected that Fed would begin to exist QE and taper its asset purchases soon. However, for the announcement occurred around three months later on September 18, 2013, the Committee decided to "await more evidence" and "sustain the process before adjusting the pace of its purchases", although the Fed was widely expected to announce to begin tapering its asset purchases.[2] Hence, both of these two FOMC announcements surprised the financial market strongly but in the opposite directions. Specifically, on June 19th, 2013, the US 10-year yield had increased by 13 basis points, S&P 500 index had decreased by -1.39%, and USD had appreciated sharply around 1% and 2% against AE and EM currencies, separately. In contrast, on September 18, 2013, the US 10-year yield fell 15 basis points, S&P 500 index rose by 1.23%, and US dollar depreciated around 1% and 2% against AE and EM currencies, separately.

With the hourly frequency exchange rates and currency order flows data from CLS, we show the strong and immediate reactions of currency market to these two FOMC announcements. In Figure 1, we plot the hourly exchange rates of USD against currencies of nine advanced economies and three emerging markets on the corresponding trading days with the normalization of exchange rate levels at 2pm as unity. We document that USD rises (falls) significantly and immediately against both AE and EM currencies after a tightening (easing) announcement on US monetary policy, both of which happened at 2.15pm. The daily standard deviation (std) of average of exchange rates changes for G10 currency pairs since 2000 is around 41bps. Hence, the appreciation and depreciation within one hour (135bps and -111bps) on these days are around 3.30 and -2.78 times of daily std. Among

[2] According to the New York Fed's Survey of Primary Dealers, 75 percent of primary dealers expected tapering to be announced at the September 18, 2013 FOMC meeting.

Figure 1: Exchange rates of G10 and several EMs currency pairs against UD around FOMC announcements on June 19th, 2013 and Sep 18th, 2013

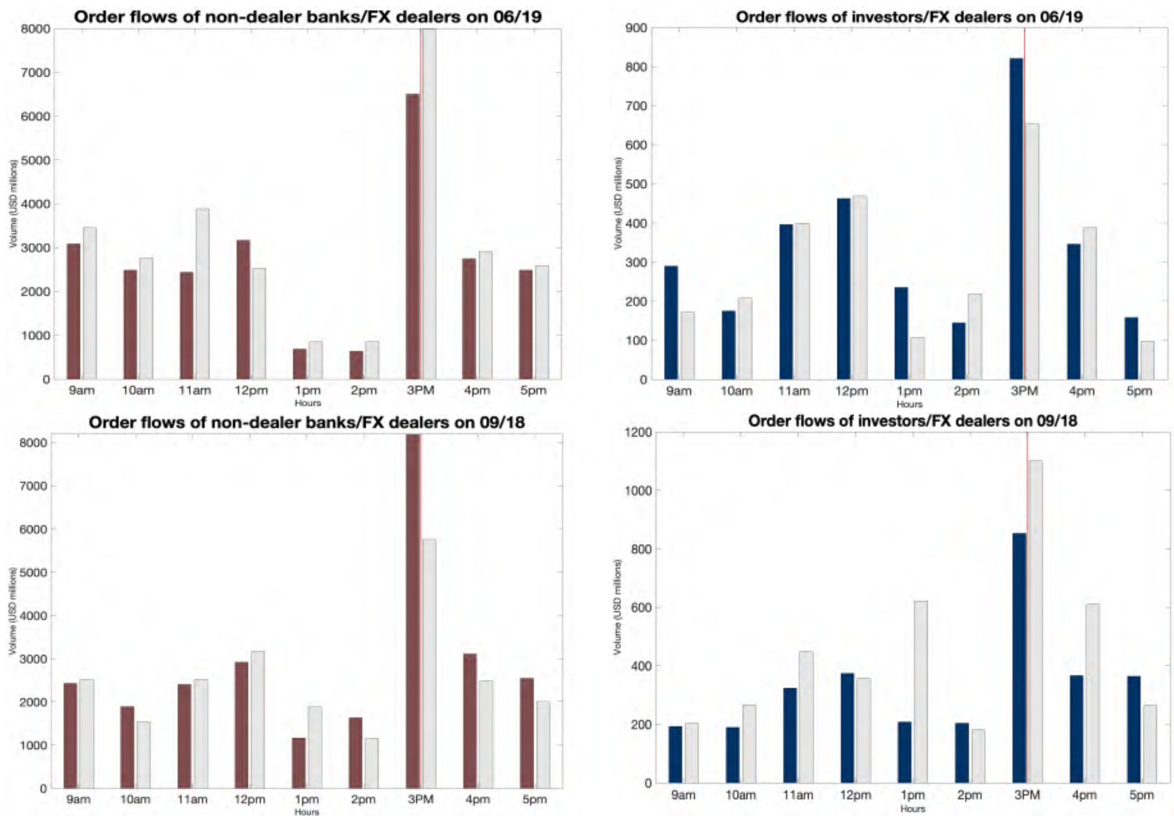


Note: Exchange rate is expressed in units of foreign currency per US dollar; the value at 2 pm is normalized to be 1. The top and bottom panels are for the announcements on June 19th, 2013 and Sep 18th, 2013, separately.

all currency pairs, commodity and EM currencies (AUD and NZD) have much stronger responses to the announcements, which is consistent with the traditional wisdom. To further account for the hourly fixed effect, we also provide the weekly path of exchange rates in the Online Appendix, which indicates that the strong reactions of exchange rates on these FOMC days are independent of specific hours.

To figure out the driving force behind the strong reactions of exchange rates, we have a close look at the trading behaviors of currency market makers around these FOMC announcement windows. In the top panel of Figure 2, from 2pm to 3pm on June 19th, 2013, we find that there is a sharp rise of FX dealers' net dollar buying from non-dealer banks and net dollar selling to investors including hedge funds, pension fund and insurance companies. This observation reflects that, following a tightening unconventional monetary surprise, currency dealers intermediate the sudden increment of USD demands from global investors with funding liquidity from non-dealer banks. On the contrary, for the same time period

Figure 2: The currency order flows between non-dealer banks/investors and FX dealers for G10 currency pairs around FOMC announcements on June 19th, 2013 and Sep 18th, 2013



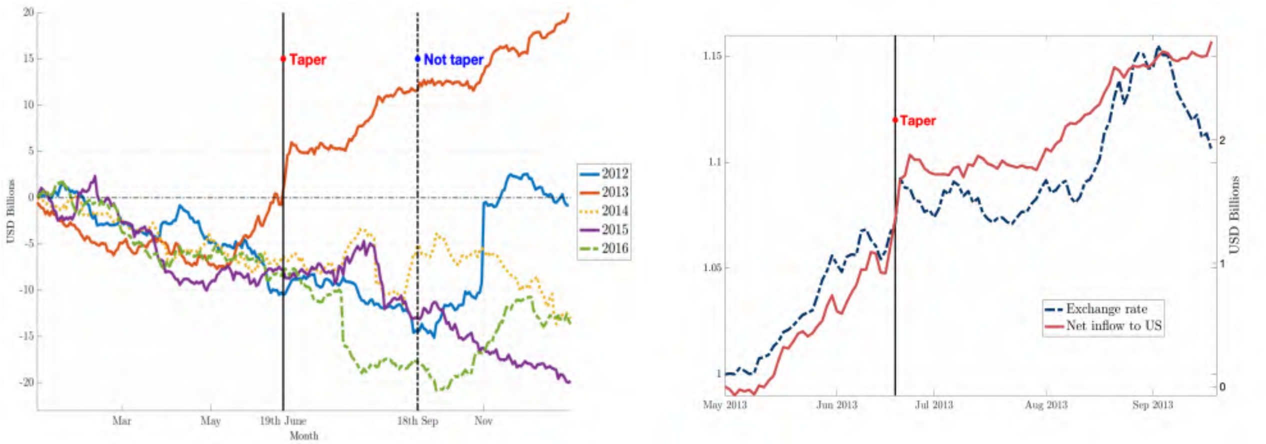
Note: Dark red/blue bar is the side of non-dealer banks and investors' "buying dollars from and selling foreign currencies to" FX dealers, white bar vise versa. The order flows are in units of USD millions.

on September 18, 2013, we observe the opposite pattern in the bottom panel of Figure 2, which indicates the increasing FX dealers' supply and global investors' demand for foreign currencies after an easing monetary surprise. Hence, based on the theoretical framework in Gabaix and Maggiori (2015) and Itskhoki and Mukhin (2021), the strong fluctuations of exchange rates in Figure 1 can be explained by the findings in Figure 2, i.e. the net positive (negative) dollar demand intermediated by currency dealers will put appreciation (depreciation) pressure on the dollar after a tightening (easing) unconventional monetary policy shock. And, this causal relationship is built based on high-frequency data.

Moreover, we examine the US monetary policy's impact on global investors' portfolio flows between EMs and US with the data from JP Morgan Chase& Co. Institute. In left panel of Figure 3, we plot the investors' cumulative net inflows to US from seven EMs with associated currencies: BRL, MXN, IDR, INR, THB, TRY and ZAR.[3] Importantly, we observe

[3] Farrell, Eckerd, Zhao, and O'Brien (2020) show the similar graph, their copyright should be noticed.

Figure 3: Investors' cumulative portfolio inflows from EMs to US



Note: The solid and dashed vertical lines are corresponding to June 19th, 2013 to Sep 18th, 2013. The cumulative flows are in units of USD billions. Exchange rate is expressed in units of foreign currency per US dollar with initial value normalized to be one.

the striking reversal of global investors' portfolio inflows to the US since May 2013, which is exactly corresponding to the beginning of "Taper Tantrum". Specifically, there is a growing portfolio outflow from US to EMs up to 7.68 billions USD until May 2013, but it quickly reverts to the trend in middle of June. In particular, on June 19th, 2013, the cumulative portfolio flows flip sign from -0.74 to 0.81 billions USD. Since then, the portfolio inflows to US from EMs grow rapidly to 20.03 billion USD until the end of 2013. But, in sharp contrast to 2013, there is a constant investors' portfolio outflow from US to EM in other years.

We further zoom in the analysis by just focusing on "Taper Tanrum" period from May 2013 to Sep 2013. The right panel of Figure 3 graphs investors' aggregate portfolio inflows to US from EMs and average of exchange rates of dollar vis-à-vis the related EM currencies within this period. It shows that the growing portfolio inflows to US is associated with the constant appreciation of dollar. Notably, the slopes of both portfolio inflows and appreciation of USD are the steepest on June 19th, 2013, which further justifies the strong impact of the Fed's tapering on exchange rates by inducing global investors' portfolio rebalancing.

Overall, the event study highlights the crucial roles of financial intermediaries in the international transmission of US "LSAP" shock: dollar's appreciation after the Fed's asset tapering is due to that FX dealers intermediate the portfolio inflow resulting from global investors' rebalancing to US long-term bonds. Moreover, the estimation results based on BP-SVAR reported in the Appendix further justify the findings from this event study. However, there is still a lack of study emphasizing the role of intermediaries, especially FX dealers, for the international transmission of US monetary policy until now.

3 The Model

In this paper, we develop a two-country New Keynesian DSGE model to study the international transmission of monetary policy through global investors' portfolio rebalancing channel in an imperfect international financial market. The model extends Gertler and Karadi (2011, 2013) into the international context with cross-border risky assets and intermediate goods trading, and also incorporate the segmented currency market with FX dealers as in Gabaix and Maggiori (2015) and Itskhoki and Mukhin (2021).

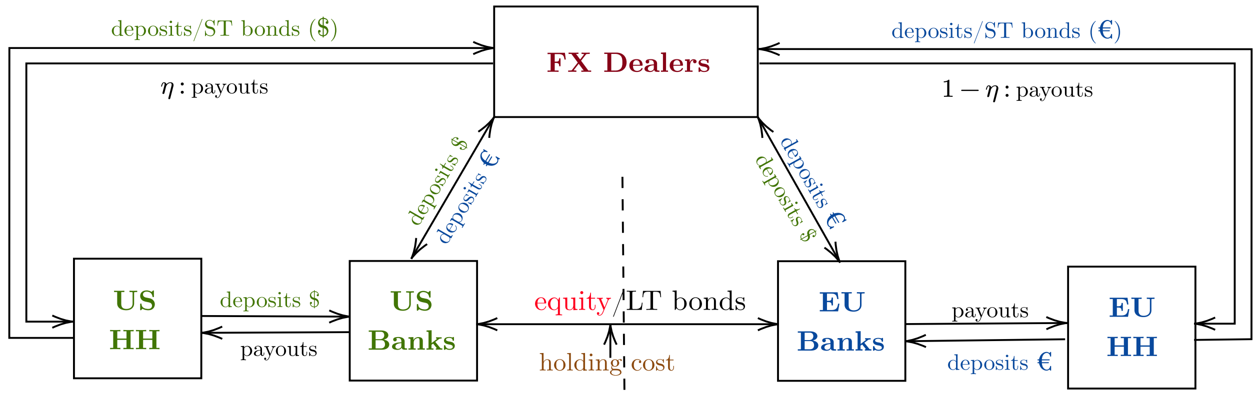
The two countries are symmetric, denoted as home (the United States) and foreign (like the European Union, denoted with an asterisk in the superscript). Each country has its own nominal account in which local prices are quoted. The nominal exchange rate $\mathcal{E}_t$ represents the price of home currency in terms of foreign currency. An increase in $\mathcal{E}_t$ means a nominal appreciation of home currency. We denote $e_t \equiv \mathcal{E}_t \frac{P_t}{P_t^*}$ as the spot real exchange rate in the units of foreign currency per home currency, where P_t and P_t^* are the aggregate price levels of home and foreign countries, respectively.

Each country consists of seven types of agents: households, bankers or investors, intermediate goods producers, capital producers, retailers, final goods producers and FX dealers. The government and central bank in each country conduct monetary and fiscal policy. Figure 4 presents the key sectors in the model, and the whole economy structure is shown in Figure B.1 in Appendix. The following subsections describe the agent setups for the home country, while the setup for the foreign country is analogous and presented in Appendix B.

3.1 Households

In each country, there is a unit continuum of identical households. They consume local final goods and save by depositing funds in local banks or holding domestic short-term bonds. Each household comprises workers and bankers or investors. Workers supply labor to local firms and return wages to the respective households. Each banker runs a certain local bank owned by the related households, make portfolio decision, and rebate retained earnings. We consider two scenarios: imperfect domestic market in which only banks are allowed to hold or trade domestic and foreign risky assets, and partially imperfect market in which households are allowed to hold domestic risky assets but experience a holding cost. Following Gertler and Karadi (2011, 2013), the fraction of each occupation is fixed over time. In each period bankers stochastically exit and become workers with probability $1 - \sigma$ and are replaced with an equal number of workers. Exiting bankers disburse retained

Figure 4: The key ingredients of model structure



earnings to their households, while new bankers receive a fixed startup fund from their households. Importantly, international financial market is segmented such that domestic (foreign) agents are not allowed to make deposits in foreign (domestic) banks. As shown in Figure 4, domestic agents are not able to borrow from or lend to foreign agents directly.

The home household maximizes lifetime utility over consumption and labor:

$$\mathbb{E}_t \sum_{i=0}^{\infty} \beta^i \left\{ \frac{\left(C_{t+i} - hC_{t+i-1}\right)^{1-\sigma_c} - 1}{1-\sigma_c} - \frac{\chi}{1+\eta} L_{t+i}^{1+\eta} \right\},$$

where β is a discount factor, h captures habit formation, σ_c represents the relative risk aversion, $1/\eta$ is Frisch elasticity of labor supply, and χ governs the importance of labor in utility.

Bank deposits and short-term bonds are perfectly substitutable one-period riskless real bonds that pay a gross real return R_t from period t to $t+1$. Let D_{ht} be the household's total quantity of real short-term debt, w_t be the real wage, DIV_t be the net payouts from ownership of domestic nonfinancial and financial firms, and currency dealers, X be the total startup funds paid out to new bankers, and T_t be the lump-sum transfers. For the brief case that households are not allowed to hold risky assets, their real budget constraint is:

$$C_t + D_{ht} = w_t L_t + DIV_t - X + T_t + R_{t-1} D_{h,t-1}. \tag{1}$$

More details and extensions of the household's problem are given in Appendix B.

3.2 Banks

Within each country, a unit continuum of competitive banks intermediate funds from households to non-financial firms and government. The domestic (foreign) banks raise deposits from domestic (foreign) households and invest in both domestic and foreign equities of non-financial firms and long-term government bonds.

Firms' equities are state-contingent claims issued by intermediate goods firms to finance their working capital. The claims have market value Q_t (Q_t^*) and per-period gross payout Z_t (Z_t^*). Their capital depreciates at a constant rate δ with the replacement price Q_{t+1} (Q_{t+1}^*).[4] Thus, the real returns on domestic and foreign equity, $R_{k,t+1}$ and $R_{k,t+1}^*$, are given by

$$R_{k,t+1} = \frac{Z_{t+1} + (1-\delta)Q_{t+1}}{Q_t} \quad \text{and} \quad R_{k,t+1}^* = \frac{Z_{t+1}^* + (1-\delta)Q_{t+1}^*}{Q_t^*}.$$

Banks also hold long-term government bonds. The government bonds are perpetuities with real income flows of 1, κ, κ^2, etc., as in Carlstrom, Fuerst, and Paustian (2017). Let q_t (q_t^*) be the price of the bond issued by the home (foreign) government, the real returns on the long-term government bonds, $R_{b,t+1}$ and $R_{b,t+1}^*$, are given by

$$R_{b,t+1} = \frac{1 + \kappa q_{t+1}}{q_t} \quad \text{and} \quad R_{b,t+1}^* = \frac{1 + \kappa q_{t+1}^*}{q_t^*}. \tag{2}$$

And, the real long-term bond yields are:

$$R_{yt} = q_t^{-1} + \kappa \quad \text{and} \quad R_{y^*t} = q_t^{*-1} + \kappa. \tag{3}$$

Bank's optimization problem. In each period, a domestic bank acquires s_{ht} (s_{ft}) shares of domestic (foreign) non-financial firm equity and b_{ht} (b_{ft}) shares of domestic (foreign) long-term bonds, and funds asset purchases with deposits d_t from domestic households and accumulated net worth n_t through retained earnings. As a consequence, bank's balance sheet in real home currency is:

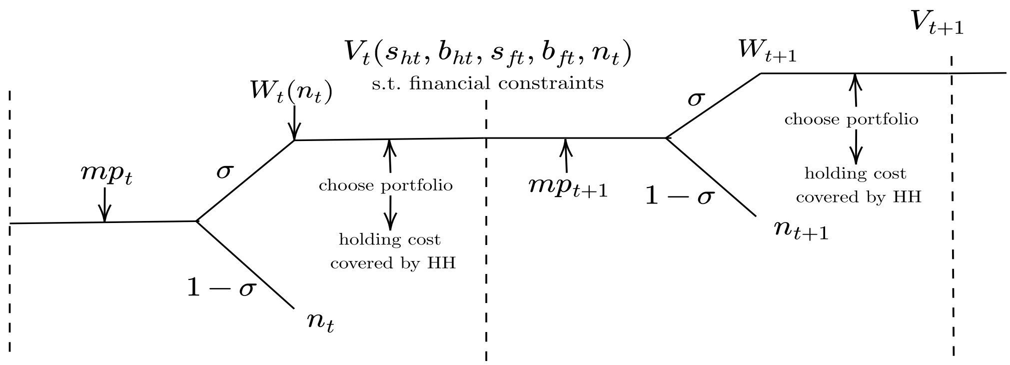
$$Q_t s_{ht} + q_t b_{ht} + \frac{Q_t^* s_{ft} + q_t^* b_{ft}}{e_t} = n_t + d_t, \tag{4}$$

where net worth is accumulated as gross returns of risky assets free of funding cost:

$$n_t = R_{kt} Q_{t-1} s_{h,t-1} + R_{bt} q_{t-1} b_{h,t-1} + \frac{R_{kt}^* Q_{t-1}^* s_{f,t-1} + R_{bt}^* q_{t-1}^* b_{f,t-1}}{e_t} - R_{t-1} d_{t-1}. \tag{5}$$

[4]As in Jarociński and Karadi (2020), the claims can be treated as either equity or corporate bonds.

Figure 5: Timeline of events for each period



Importantly, we assume that domestic banks need to pay a cost for foreign assets holding,

$$\left[\frac{\kappa_1}{2}\left(\frac{Q_t^* s_{ft} - Q_{ss}^* \bar{s}_f}{e_t n_t}\right)^2 + \frac{\kappa_2}{2}\left(\frac{q_t^* b_{ft} - q_{ss}^* \bar{b}_f}{e_t n_t}\right)^2\right] n_t, \tag{6}$$

where Q_{ss}^* and q_{ss}^* are the steady-state real prices of foreign assets in units of foreign currency, and $\bar{s}_f$ and $\bar{b}_f$ are the steady-state shares of foreign assets held by domestic banks. We set the values of $\bar{s}_f$ and $\bar{b}_f$ to match data directly, which is featured with home bias of asset holding. The quadratic holding cost captures home bias of asset holding deviated from steady-state holding volumes with sensitivity parameters κ_1 and κ_2. Therefore, we introduce home bias of asset holdings both at and away from the steady state. This is not only consistent with the large empirical literature on home bias of asset holding, but also crucial for the resolution of well-known portfolio indeterminacy issue highlighted in Devereux and Sutherland (2011). We further assume that the holding cost is covered by bankers as a lump-sum transfer to the respective households. Consequently, this cost does not appear in bank's balance sheet in (4) or evolution of net worth in (5), which yields a simple and tractable solution for the portfolio selection.

Bankers maximize the expected terminal net worth with the following Bellman equations:

$$V_t(s_{ht}, b_{ht}, s_{ft}, b_{ft}, n_t) = \mathbb{E}_t \Lambda_{t,t+1}\left[(1-\sigma)n_{t+1} + \sigma W_{t+1}(n_{t+1})\right],$$

and

$$W_t(n_t) = \max_{s_{ht}, b_{ht}, s_{ft}, b_{ft}} V_t(s_{ht}, b_{ht}, s_{ft}, b_{ft}, n_t) - \left[\frac{\kappa_1}{2}\left(\frac{Q_t^* s_{ft} - Q_{ss}^* \bar{s}_f}{e_t n_t}\right)^2 + \frac{\kappa_2}{2}\left(\frac{q_t^* b_{ft} - q_{ss}^* \bar{b}_f}{e_t n_t}\right)^2\right] n_t,$$

where $\Lambda_{t,t+1}$ is the domestic household's stochastic discount factor between periods t and

$t+1$, $V_t(s_{ht}, b_{ht}, s_{ft}, b_{ft}, n_t)$ is the end-of-period value function (after portfolio decisions), and $W_t(n_t)$ is the beginning-of-period value function (before portfolio decisions, but after occupation shocks). The holding cost of foreign assets is paid during the portfolio decision process, and is covered by the associated bankers as a lump-sum transfer to their households. Figure 5 presents the detailed timeline of bankers' decision making.

As in Gertler and Karadi (2011, 2013), bankers face a moral hazard problem that limits their ability to raise deposits. Towards the end of each period, bankers may divert funds from their assets to the corresponding households after portfolio decisions made. Upon diverting, depositors can force the banks into bankruptcy and recover the remaining portion of assets. As in Gertler and Karadi (2013), we assume it is easier for bankers to divert funds from equity than government bonds. That is, bankers are able to divert θ fraction of equity and $\Delta\theta$ with $\Delta \in [0,1)$ fraction of government bonds under management at the end of each period. For brevity, we further assume the divertible fraction is the same for domestic and foreign assets of the same type. In sum, bankers face the following incentive constraint:

$$V_t(s_{ht}, b_{ht}, s_{ft}, b_{ft}, n_t) \geq \theta \left(Q_t s_{ht} + \Delta q_t b_{ht} + \frac{Q_t^* s_{ft} + \Delta q_t^* b_{ft}}{e_t} \right), \tag{7}$$

where the left-hand side is bankers' loss by diverting funds, while the right-hand side is the gain from doing so.

Solution with aggregation. Since individual banks are identical, we solve the model with solution in aggregate level. We define $\{S_{Ht}, B_{Ht}, S_{Ft}, B_{Ft}\}$ as the domestic banks' aggregate holdings of domestic and foreign assets, and N_t as their aggregate net worth. Given the evolution of individual bank's net worth in (5), the aggregate net worth dynamics is

$$\begin{aligned} N_t = \sigma \Bigg[& (R_{kt} - R_{t-1})\, Q_{t-1} S_{H,t-1} + (R_{bt} - R_{t-1})\, q_{t-1} B_{H,t-1} + \left(\frac{R_{kt}^*}{e_t} - \frac{R_{t-1}}{e_{t-1}} \right) Q_{t-1}^* S_{F,t-1} \\ & + \left(\frac{R_{bt}^*}{e_t} - \frac{R_{t-1}}{e_{t-1}} \right) q_{t-1}^* B_{F,t-1} + R_{t-1} N_{t-1} \Bigg] + X, \end{aligned}$$

where σ is the fraction of surviving banks, and X is the startup funds to the new bankers.

From the optimal conditions for domestic asset holdings, the expected excess returns on the domestic assets relative to the deposit rate are given by

$$\mathbb{E}_t \left[\tilde{\Lambda}_{t,t+1} \left(R_{k,t+1} - R_t \right) \right] = \frac{\lambda_t}{1+\lambda_t} \theta \ \text{ and } \ \mathbb{E}_t \left[\tilde{\Lambda}_{t,t+1} \left(R_{b,t+1} - R_t \right) \right] = \Delta \cdot \frac{\lambda_t}{1+\lambda_t} \theta, \tag{8}$$

where λ_t is the Lagrange multiplier associated with incentive constraint in (7), and $\widetilde{\Lambda}_{t,t+1}$ is banker's "augmented" stochastic discount factor, which is given by

$$\widetilde{\Lambda}_{t,t+1} \equiv \Lambda_{t,t+1} \cdot \left[1 - \sigma + \sigma \frac{\partial W_{t+1}(n_{t+1})}{\partial n_{t+1}}\right].$$

In accordance with Gertler and Karadi (2013), the expected excess returns on the domestic assets depend on the tightness of incentive constraint in (7), which is measured by the multiplier λ_t. If the constraint is non-binding, the expected excess returns on both assets are zero. If the constraint binds, the expected excess returns on both assets become positive due to limits to arbitrage, and increase with the tightness of financial constraint. Since $\Delta < 1$, expected excess return on long-term government bonds is lower than equity, as limits to arbitrage are weaker for long-term bonds compared to equity.

Furthermore, domestic bank's optimal foreign asset holdings are

$$Q_t^* S_{Ft} = Q_{ss}^* \bar{S}_F + (1+\lambda_t)\, \mathbb{E}_t \left[\tilde{\Lambda}_{t,t+1} \left(\frac{R_{k,t+1}^* e_t}{e_{t+1}} - R_{k,t+1}\right)\right] \frac{N_t}{\kappa_1} e_t, \tag{9}$$

$$q_t^* B_{Ft} = q_{ss}^* \bar{B}_F + (1+\lambda_t)\, \mathbb{E}_t \left[\tilde{\Lambda}_{t,t+1} \left(\frac{R_{b,t+1}^* e_t}{e_{t+1}} - R_{b,t+1}\right)\right] \frac{N_t}{\kappa_2} e_t. \tag{10}$$

With quadratic holding cost, bank's first-order conditions for foreign assets holdings pin down optimal holding volumes directly, which is our key idea to tackle portfolio indeterminacy issue in our model. From (9) and (10), deviations of optimal foreign asset holdings away from steady-state values increase with expected excess returns on foreign assets relative to domestic assets of the same type in units of home currency. Deviations are also larger when the incentive constraint is more binding. Intuitively, if the incentive constraint is more binding or shadow value of net worth ($\lambda_t > 0$) is larger, bankers are more willing to "search for yields" and substitute towards the same type assets between two countries with relatively higher returns. Additionally, deviations of optimal foreign asset holdings from steady-state values decrease in parameters κ_1 and κ_2 of holding cost and increase in net worth n_t, as banks are less restricted to adjust foreign asset positions when holding cost is lower or net worth is higher.

Given the optimal foreign asset positions, incentive constraint in (7) places an endogenous capital requirement on banks' domestic assets holding in aggregate level:

$$Q_t S_{Ht} + \Delta q_t B_{Ht} \leq \phi_t N_t + \psi_t \text{ with equality if } \lambda_t > 0, \tag{11}$$

where ϕ_t and ψ_t are independent of bank-specific characteristics and given by (B.8) and (B.9) in Appendix B.2, respectively. This capital requirement constraint stems from the incentive constraint in (7) and imposes an endogenous leverage constraint on domestic banks' aggregate holdings of risk-adjusted domestic assets. Importantly, when the leverage constraint binds, the endogenous leverage ratio ϕ_t amplifies positive shocks to domestic banks' net worth, and then pushes up domestic asset prices and increases bank net worth furthermore through a feedback loop, which is the traditional financial accelerator mechanism as in Bernanke and Gertler (1989).

3.3 Currency Dealers

The international financial market is imperfect and segmented is the sense that domestic and foreign agents cannot directly borrow from or lend to each other in terms of short-term bonds or deposits when there is any trade imbalance between two countries. FX dealers with limited risk-bearing capacity intermediate the currency imbalances arising from goods and/or assets trading. As in Gabaix and Maggiori (2015) and Itskhoki and Mukhin (2021), FX dealers trade short-term bonds denominated in both currencies to finance the intermediation of global imbalances. In our model, there is no distinction for FX dealers borrowing from households or banks, so we do not differentiate between these funding sources. Similar to Gabaix and Maggiori (2015) and Itskhoki and Mukhin (2021), FX dealers are not able to retain capital, and they distribute η fraction of net profits to US households and $1-\eta$ fraction to foreign households based on the ownership share at the end of each period.

FX dealers maximize the real expected return from a long (short) position of foreign short-term debt ($d_{st}e_t$) and a short (long) position of US short-term debt ($-d_{st}$) at period t:

$$V_t^d = \max_{d_{st}} \mathbb{E}_t \left[\left(\eta \Lambda_{t,t+1} + (1-\eta)\Lambda^*_{t,t+1} \frac{e_{t+1}}{e_t} \right) \left(\frac{R_t^* e_t}{e_{t+1}} - R_t \right) \right] d_{st},$$

subject to the financial constraint:[5]

$$V_t^d \geq \Gamma_t d_{st}^2 e_t,$$

where Γ_t measures FX dealers' risk-bearing capacity. FX dealers are willing to absorb any imbalance if $\Gamma_t = 0$, but unable to intermediate any imbalance if $\Gamma_t \to \infty$. Our quantitative analysis specifies: Γ_t is constant over time; $\Gamma_t = \gamma \mathrm{var}_t(\Delta \ln e_{t+1})$ as an endogenous function of exchange rates; and Γ_t with exogenous paths in response to target monetary surprises.

From individual FX dealer's optimization condition, the aggregate FX dealers' position

[5] We follow Gabaix and Maggiori (2015) directly and assume that FX dealers' risk-bearing capacity is limited by $\Gamma_t d_{st}^2 e_t$, which is consistent with Itskhoki and Mukhin (2021) if $\Gamma_t = \gamma \mathrm{var}_{ss}(\Delta \ln e_{t+1})$, with $\mathrm{var}_{ss}(\Delta \ln e_{t+1})$ being the steady-state variance of logarithmic change in real exchange rate.

of US short-term debt D_{st} is given by

$$D_{st} = \frac{1}{\Gamma_t}\mathbb{E}_t\left[\left(\eta\Lambda_{t,t+1} + (1-\eta)\Lambda^*_{t,t+1}\frac{e_{t+1}}{e_t}\right)\left(\frac{R^*_t}{e_{t+1}} - \frac{R_t}{e_t}\right)\right]. \tag{12}$$

If $\Gamma_t = 0$, FX dealers earn zero net profit due to the infinite liquidity intermediation capacity, the risk-adjusted uncovered interest parity (UIP) holds, and capital flows have no impact on exchange rates. In contrast, if $\Gamma_t > 0$, UIP fails and the binding financial constraint makes FX dealers effectively risk averse and generates an upward-sloping supply curve for dollars against foreign currency. In equilibrium, the real exchange rate e_t adjusts so that net dollar demand (D_{dt}) from global capital flows equates FX dealers' dollar supply: $D_{dt} = D_{st}$, i.e. currency market is clearing. The net dollar demand D_{dt} in units of dollars is resulting from assets and goods trading, which comprises US net exports, foreign investors' net buying volume of US risky assets, US dollar debt repaid by FX dealers, and FX dealers' net profits rebated to US households:[6]

$$\begin{aligned}
D_{dt} = &\underbrace{(Q_t S^*_{Ht} - Q_{t-1}S^*_{H,t-1}R_{kt}) - (Q^*_t S_{Ft} - Q^*_{t-1}S_{F,t-1}R^*_{kt})/e_t}_{\text{net equity inflows to US}} \\
&+ \underbrace{(q_t B^*_{Ht} - q_{t-1}B^*_{H,t-1}R_{bt}) - (q^*_t B_{Ft} - q^*_{t-1}B_{F,t-1}R^*_{bt})/e_t}_{\text{net bond inflows to US}} \\
&+ \underbrace{\left[\gamma_y \frac{(p^*_{Ht}e_t)^{1-\eta_y}}{e_t}Y^*_t - \gamma_y\left(\frac{p_{Ft}}{e_t}\right)^{1-\eta_y}Y_t\right]}_{\text{net exports of US}} \\
&+ \underbrace{R_{t-1}D_{s,t-1}}_{\text{dollar debt payoff}} + \underbrace{\eta\left(\frac{R^*_{t-1}e_{t-1}}{e_t} - R_{t-1}\right)D_{s,t-1}}_{\text{profits rebated to US households}}.
\end{aligned} \tag{13}$$

As in Gabaix and Maggiori (2015), the currency market clearing condition and (12) imply that an increase in net dollar demand or net capital inflows to the US appreciates dollar. Intuitively, to intermediate the positive dollar demand ($D_{dt} > 0$), FX dealers exchange dollars to foreign investors with dollar liquidity borrowing from US agents, and also hold foreign currency. In this case, their balance sheets comprise a long position ($D_{dt} \cdot e_t > 0$) in foreign currency and a short position ($-D_{dt} < 0$) in dollars. To incentive FX dealers to absorb positive net dollar demand, dollar appreciates at current period and is expected to depreciate subsequently.

[6]The definition of net portfolio flows aligns with the corresponding empirical measurements in Bertaut and Tryon (2007) and Bertaut and Judson (2014), which is used in our SVAR estimation.

Importantly, FX dealers' limited risk-bearing capacity in our model accounts for the puzzling downward term structure of currency carry trade risk premia documented in Lustig, Stathopoulos, and Verdelhan (2019). Different from the hedging channel of Greenwood et al. (2021) and Gourinchas, Ray, and Vayanos (2022) in partial equilibrium setting, our model rationalizes this puzzle in general equilibrium setting based on the joint effects of banks' portfolio rebalancing and FX dealers' currency intermediation. We first provide some heuristic qualitative analysis here, and then conduct serious quantitative analysis in the following section. If we assume that US long-term bond expected gross return is higher than foreign long-term bonds and also $R_t = R_t^*$, then,

$$\mathbb{E}_t \left[\log \left(\frac{R_{b,t+1}}{R_t} \right) \right] > \mathbb{E}_t \left[\log \left(\frac{R^*_{b,t+1}}{R^*_t} \right) \right]. \tag{14}$$

According to the optimal asset holdings in (10) and (B.2) and the analysis in Section 3.2, global investors substitute towards US long-term bonds with higher return, which induces portfolio inflows to the US, i.e. $D_{dt} > 0$. The currency market clearing condition and (12) further imply:

$$\mathbb{E}_t \left[\log \left(\frac{R^*_t e_t}{R_t e_{t+1}} \right) \right] \approx \mathbb{E}_t \left[\frac{R^*_t e_t}{R_t e_{t+1}} - 1 \right] > 0. \tag{15}$$

Consequently, our model reveals a positive correlation between FX risk premia and US and foreign bond term premia differential, driven by banks' portfolio rebalancing and FX dealers' currency liquidity intermediation.

We compare the expected excess return of currency carry trade with long-term bonds and short-term bond with the following decomposition:

$$\mathbb{E}_t \left[\log \left(\frac{R^*_t e_t}{R_t e_{t+1}} \right) + \log \left(\frac{R^*_{b,t+1}}{R^*_t} \right) - \log \left(\frac{R_{b,t+1}}{R_t} \right) \right] < \mathbb{E}_t \left[\log \left(\frac{R^*_t e_t}{R_t e_{t+1}} \right) \right], \tag{16}$$

where the inequality is derived from (14) and (15). Due to the positive correlation of FX risk premia and US and foreign bond term premia differential, the expected excess return on currency carry trade declines with bond maturities. Intuitively, the compensation to FX dealers' liquidity intermediation offsets investors' extra benefit from higher bond term premia. As such, our model provides a clear and concise explanation for the puzzling fact highlighted in Lustig, Stathopoulos, and Verdelhan (2019). Lastly, the above analysis applies to any type of shock inducing bond portfolio flows, and is not limited to a monetary shock.

3.4 Producers

There are three types of non-financial firms in production sector within each country, which are intermediate goods producers, capital producers, and retail firms. As in Gertler and Karadi (2011), we introduce nominal price rigidities to differentiated retail firms to model the relationship between output and inflation, and to obtain time-varying real exchange rates without violating the law of one price.

3.4.1 Intermediate Goods Producers

Intermediate goods producers are competitive and sell homogeneous intermediate goods to domestic and foreign retail firms, which means there is intermediate good trading. They use labor and capital as inputs and produce output according to a Cobb-Douglas technology:

$$Y_{mt} = A_t \left(u_t K_t\right)^{\alpha} L_{pt}^{1-\alpha},$$

where Y_{mt} is intermediate goods output, A_t is total factor productivity, u_t is capital utilization rate, K_t is capital input, and L_{pt} is labor input. Capital stock depreciates at rate $\delta(u_t)$, and intermediate goods producers buy I_t units of new capital from capital producers at the end of each period. Hence, intermediate goods producers' aggregate capital evolves as:

$$K_{t+1} = I_t + (1 - \delta(u_t))K_t.$$

The intermediate goods firms finance new capital by raising funds from domestic banks. Following Gertler and Karadi (2011, 2013), these firms issue a unit of state-contingent claim for each unit of capital at price Q_t to banks, and pay a dividend of Z_t per claim each period. Then, the total number of claims S_t is equal to the units of capital acquired K_{t+1}, therefore, the prices of each claim and a unit capital are also equal, i.e. Q_t. In addition, since intermediate goods firms are competitive, they earn zero profits in equilibrium.

Let p_{mt} be the real price of home intermediate goods. Then intermediate goods firms' optimal capital utilization rate u_t, labor demand L_{pt} and dividend Z_t are given by

$$\delta'(u_t) Q_t K_t = p_{mt} \alpha \frac{Y_{mt}}{u_t}, \quad w_t = p_{mt}(1-\alpha)\frac{Y_{mt}}{L_{pt}} \quad \text{and} \quad Z_t = p_{mt}\alpha \frac{Y_{mt}}{K_t}.$$

3.4.2 Capital Producers

Within each country, a unit continuum of competitive capital producers make new capital using final goods of their own country as input, subject to adjustment costs. They sell new capital to local intermediate goods producers at real price of Q_t (Q_t^*). We assume that households in the same country own capital producers and receive their profits as lump-sum transfers. Capital producers' objection is to choose the amount of investment goods I_t to maximize discounted real profits:

$$\max_{I_t} \mathbb{E}_t \sum_{k=0}^{\infty} \Lambda_{t,t+k} \left\{ Q_{t+k} I_{t+k} - \left[1 + f\left(\frac{I_{t+k}}{I_{t+k-1}} \right) \right] I_{t+k} \right\},$$

where $f\left(I_t/I_{t-1}\right)$ is the adjustment cost per unit of new capital produced. We assume that adjustment cost is quadratic in net growth rate of new capital goods, i.e. $f\left(I_t/I_{t-1}\right) = \frac{\kappa_i}{2}\left(I_t/I_{t-1} - 1\right)^2$. The price of capital Q_t is determined by the optimal condition for investment goods I_t, which is given in Appendix B.

3.4.3 Retail Firms

Retail firms of each country costlessly repackage a unit of local intermediate goods into a unit of differentiated retail good $i \in [0,1]$. Local and imported retail goods are then aggregated to a final good via a two-layer CES aggregator by competitive final goods producers:

$$Y_{jt} = \left[\int_0^1 Y_{jt}(i)^{\frac{\theta_y - 1}{\theta_y}} di \right]^{\frac{\theta_y}{\theta_y - 1}}, \text{ for } j \in \{H, F\}, \tag{17}$$

and the domestic final consumption goods are produced by:

$$Y_t = \left[(1-\gamma_y)^{\frac{1}{\eta_y}} Y_{Ht}^{\frac{\eta_y - 1}{\eta_y}} + \gamma_y^{\frac{1}{\eta_y}} Y_{Ft}^{\frac{\eta_y - 1}{\eta_y}} \right]^{\frac{\eta_y}{\eta_y - 1}}, \tag{18}$$

where $Y_{jt}(i)$ is retail good i in country $j \in \{H, F\}$, Y_{Ht} (Y_{Ft}) represents the domestic (foreign) goods basket, and Y_t denotes the domestic final goods. The parameter $\theta_y > 1$ measures the elasticity of substitution among retail goods within a basket, $\eta_y > 1$ is the elasticity of substitution between goods baskets, and $\gamma_y \in \left[0, \frac{1}{2}\right)$ captures the degree of home bias. Again, it is worthy noting the international goods trade is introduced here.

The pricing of retail goods is subject to nominal rigidities as in Calvo (1983). In each period a retail firm is able to freely adjust its prices with probability $1 - \phi_p$. Upon the shock, the firm resets prices $\hat{P}_{Ht}(i)$ and $\hat{P}^*_{Ht}(i)$ to maximize expected discounted real profits subject to the restriction on price adjustment frequency. Further details on retail firms sector are given in Appendix B.

3.5 Government Policy

There is a government in each country conducting both fiscal and monetary policies. The consolidated government's expenditures consist of a fixed consumption G, net repayments for long-term bonds $R_{bt}q_{t-1}B_{t-1} - q_tB_t$, net repayments for short-term debt $R_{t-1}D_{g,t-1} - D_{gt}$, and lump-sum transfers to households T_t. The associated revenues are composed of net repayments received from the government's own holdings of long-term bonds $R_{bt}q_{t-1}B_{g,t-1} - q_tB_{gt}$. Thus the consolidated government budget constraint is given by

$$G + R_{bt}q_{t-1}B_{t-1} - q_tB_t + R_{t-1}D_{g,t-1} - D_{gt} + T_t = R_{bt}q_{t-1}B_{g,t-1} - q_tB_{gt}, \tag{19}$$

where total long-term government bond demand $B_t \equiv B_{gt} + B_{Ht} + B^*_{Ht}$, which is the sum of holdings of domestic government, domestic banks and/or households and foreign banks.

Conventional monetary policy. Let i_t be the net nominal interest rate with a steady-state value i_{ss}. We assume the conventional monetary policy is characterized by a Taylor rule:

$$i_t = (1-\rho_r)\left[i_{ss} + \phi_\pi\left(\ln \Pi_t - \ln \Pi_{ss}\right) + \phi_y\left(\ln Y_t - \ln Y_{ss}\right)\right] + \rho_r i_{t-1} + \varepsilon_{it}, \tag{20}$$

where $\rho_r \in (0,1)$ is the smoothing parameter, Π_{ss} and Y_{ss} are the steady-state gross inflation target and gross output, and ε_{it} is an interest rate shock with standard deviation σ_r. We restrict attention to parameter values giving rise to a determinate equilibrium, i.e. $\phi_\pi > 1$.

QE or "LSAP". We model the Fed's QE or "LSAP" policy based on its actual bond purchase during financial crisis, which is different from Carlstrom, Fuerst, and Paustian (2017) and Karadi and Nakov (2021) with modeling QE shock as an AR(2) process. We calibrate QE shocks by matching the Fed's actual holding proportion of US long-term government bonds for two rounds of QE: “QE1" and “QE2". The associated shock sizes are plotted in Figure 6.

Central bank issues domestic short-term debts to fund long-term bond purchases. Then its balance sheet is: $q_tB_{gt} = D_{gt}$, where D_{gt} is the amount of short-term debt issued. Central bank's net profits from open market operation are transferred to the respective fiscal authority.

3.6 Equilibrium

The final output of each country is divided among consumption, investment, government consumption and foreign assets holding cost. Hence, home country' resource constraint is:

$$Y_t = C_t + \left[1 + f\left(\frac{I_t}{I_{t-1}}\right)\right] I_t + G + \left\{\frac{\kappa_1}{2}\left[\frac{Q_t^*\left(S_{Ft} - \bar{S}_F\right)}{e_t N_t}\right]^2 + \frac{\kappa_2}{2}\left[\frac{q_t^*\left(B_{Ft} - \bar{B}_F\right)}{e_t N_t}\right]^2\right\} N_t. \quad (21)$$

For the market of international good trade, the total home intermediate goods production is equal to the aggregation of retail goods used for domestic and foreign final goods production, i.e. $Y_{mt} = \int_0^1 \left[Y_{Ht}(i) + Y_{Ht}^*(i)\right] di$ with $Y_{Ht}(i)$ and $Y_{Ht}^*(i)$ defined in (B.18).

To close the model section, we also need clearing conditions in the markets for equity, long-term government bonds, labor, currency and short-term debt in each country. Equity market clearing requires that $K_{t+1} = S_{Ht} + S_{Ht}^*$, i.e. capital stock is equal to total equity holdings of domestic banks and/or households and foreign banks. The supply of long-term government bonds is fixed at $\bar{B}$, and the market clearing condition is $\bar{B} = B_t$. Labor market clearing requires that the labor demand L_{pt} equals the labor supply L_t, and also real wage w_t adjusts to clear the market. Currency market clearing condition is given by $D_{dt} = D_{st}$. In Appendix B.7, we derive the resource constraints of two countries and demonstrate that the constraints align with the currency market clearing condition. By Walras's Law, the short-term debt market clears automatically. The formal definition of equilibrium is given in Appendix B.8.

4 Quantitative Analysis

In this section, we design several sets of experiments to quantitatively study the impact of (un)conventional monetary shocks on international financial markets, particularly asset returns, global capital flows, and exchange rates. We focus on the equilibrium in which the banks' financial constraints are binding, and study the transmissions of conventional monetary policy in (20) and QE in the baseline model with $\Gamma_t > 0$, UIP model with $\Gamma_t \to 0$, and financial autarky (FA) with $\Gamma_t \to \infty$. The models are solved by a linear approximation around the non-stochastic steady state via Dynare. To further assess the impact of QE in a ZLB environment, we solve a piecewise linear version of the model by employing OccBin developed in Guerrieri and Iacoviello (2015). We solve the model with time-varying Γ_t by a quadratic approximation around the non-stochastic steady state via Dynare.

4.1 Calibration

We calibrate the model and conduct the quantitative experiments in monthly frequency. We calibrate part of parameters in the model based on the standard literature, where the respective values and sources are listed in Table 1. Conditional on these calibrated parameters, we estimate the remaining parameters to match the IRFs from model simulations and BP-SVAR estimation, where the estimates are reported in Table 2.

Specifically, the parameters related to households, producers, and monetary and fiscal policies are drawn from the standard literature. We set the bond coupon decay rate κ in (2) to be $1 - 120^{-1}$, such that the duration of long-term bond is ten years. We choose the monthly survival probability of banks (σ) as 0.98, implying an expected horizon of 50 months, which is close to Gertler and Kiyotaki (2015) and Sims and Wu (2021). We target the steady-state excess returns on equity and long-term bond over the deposit rate, $R_{k,ss} - R_{ss}$ of 500 bps and $R_{b,ss} - R_{ss}$ of 135 bps, respectively.[7] This implies that $\Delta = 1.35/5$ by recalling (8). Following Gertler and Karadi (2011) and Sims and Wu (2021), we target a value of steady-state leverage of four, which implies the internal calibration parameter $\theta = 0.909$ and $X = 0.017$. Importantly, we set the share of domestic banks' and households' total holding of domestic equity $(\bar{S}_H^h + \bar{S}_H)/\bar{K}_H = 0.70$ in the steady state, and symmetrically, $(\bar{S}_F^{h*} + \bar{S}_F^*)/\bar{K}_F = 0.70$. And, the home bias of equity holding at steady state is from Atkeson, Heathcote, and Perri (2022). We further set the share of domestic households' equity holding $\bar{S}_H^h/(\bar{S}_H^h + \bar{S}_H) = 0.37$, which is calculated from the Federal Reserve's US financial accounts. For the holding share of long-term bonds, we choose the value of $(\bar{B}_H^h + \bar{B}_H)/\bar{B} = 0.55$, and symmetrically, $(\bar{B}_F^{h*} + \bar{B}_F^*)/\bar{B}^* = 0.55$, which is consistent with the observation in Tabova and Warnock (2021). The share of domestic households' long-term bond holding is: $\bar{B}_H^h/(\bar{B}_H^h + \bar{B}_H) = 0.20$, which is also obtained based on the Federal Reserve's US financial accounts. Lastly, we let $e_{ss} = 1$ in steady state and consider a symmetric the ownership of FX dealers with $\eta = 1/2$. The choice of other parameters can be found in Table D.1.

4.2 Parameter Estimation

We adopt the approach in Christiano, Eichenbaum, and Evans (2005) to estimate the remaining parameters by matching the model's impulse responses to a conventional mone-

[7] We match the equity excess return with the average of US equity and Baa corporate bond excess returns, which are 700 bps and 300 bps, separately. Similarly, we calibrate the long-term bond excess return with 135 bps as the average of US and G10 10-year bond excess returns over 1995-2019, which are 148bps and 120pbs, separately.

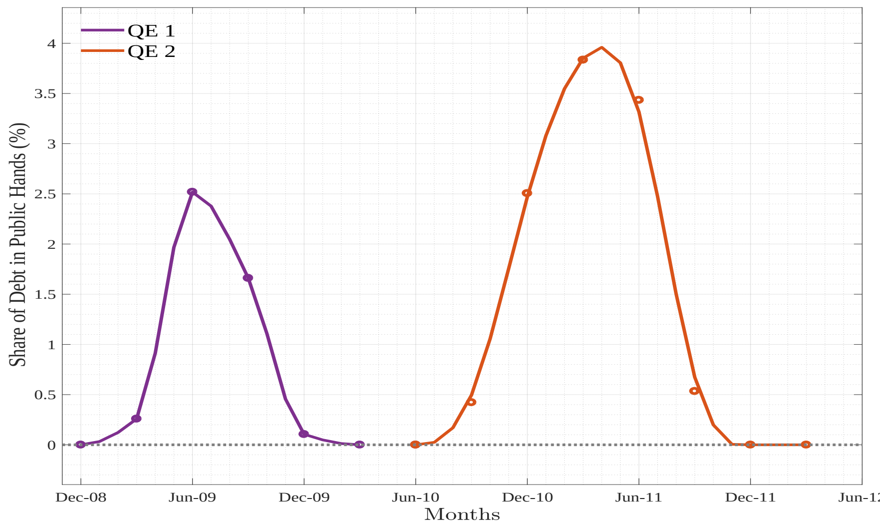
Table 1: Calibrated parameter values

Parameter	Value	Description	Target or source
θ	0.909	Fraction of divertible equity	Leverage 4
Δ	0.270	Scale factor of divertible bond	Targeted excess returns
σ	0.980	Survival Probability of Banks	Gertler and Kiyotaki (2015)
X	0.017	Transfer to the entering banks	Leverage 4
κ	0.992	Bond income flow rate	Sims and Wu (2021)
$(\bar{S}^h_H + \bar{S}_H)/\bar{K}_H$	0.700	Domestic equity holding share	Atkeson, Heathcote, and Perri (2022)
$(\bar{B}^h_H + \bar{B}_H)/\bar{B}$	0.550	Domestic bonds holding share	Tabova and Warnock (2021)
$\bar{S}^h_H/(\bar{S}^h_H + \bar{S}_H)$	0.370	HH equity holding share	Targeted US value
$\bar{B}^h_H/(\bar{B}^h_H + \bar{B}_H)$	0.200	HH bonds holding share	Targeted US value
η	0.500	US share of FX dealers	Gabaix and Maggiori (2015)

Table 2: Estimated parameter values

Parameter	Description	Constant Γ_t	Endogenous Γ_t	Exogenous Γ_t
κ_1	Bank foreign equity holding cost	12.57	16.64	9.834
κ_2	Bank foreign bond holding cost	7.519	7.183	15.87
κ_{h1}	HH domestic equity holding cost	3.965	9.994	3.965
κ_{h2}	HH domestic bond holding cost	0.389	10.00	0.389
δ_2	Capital utilization	21.00	21.65	21.00
κ_I	Investment adjustment cost	2.500	2.500	2.500
ϕ_p	Price rigidity	0.969	0.960	0.969
h	Habit persistence	0.700	0.700	0.700
Γ_{ss}	SS risk-bearing capacity	0.337	0.570	0.001
ρ_r	Taylor rule smoothing	0.922	0.960	0.922
σ_r	Target surprise volatility (bps)	16.14	7.062	19.64

Figure 6: QE1 and QE2 shock sizes in the data



Note: The QE shocks are generated to match the data directly.

tary policy shock with those from BP-SVAR estimates with real data. We estimate eleven parameters, including the banks' and households' portfolio holding costs (κ_1, κ_2, κ_{h1}, κ_{h2}), FX dealers' risk-bearing capacity (Γ_t), habit persistence (h), price rigidity (ϕ_p), investment adjustment cost (κ_i), capital utilization (δ_2), and the persistence and volatility of target surprise (ρ_r, σ_r). For the estimation of Γ_t, we estimate Γ directly under the constant specification and γ under the endogenous specification: $\Gamma_t \equiv \gamma \text{var}_t(\Delta \ln e_{t+1})$. In particular, for the scenario when Γ_t follows an exogenous path following a target surprise, we assume Γ_t deviates from steady-state value, and estimate the steady-state value and entire path of Γ_t for the first 24 months.

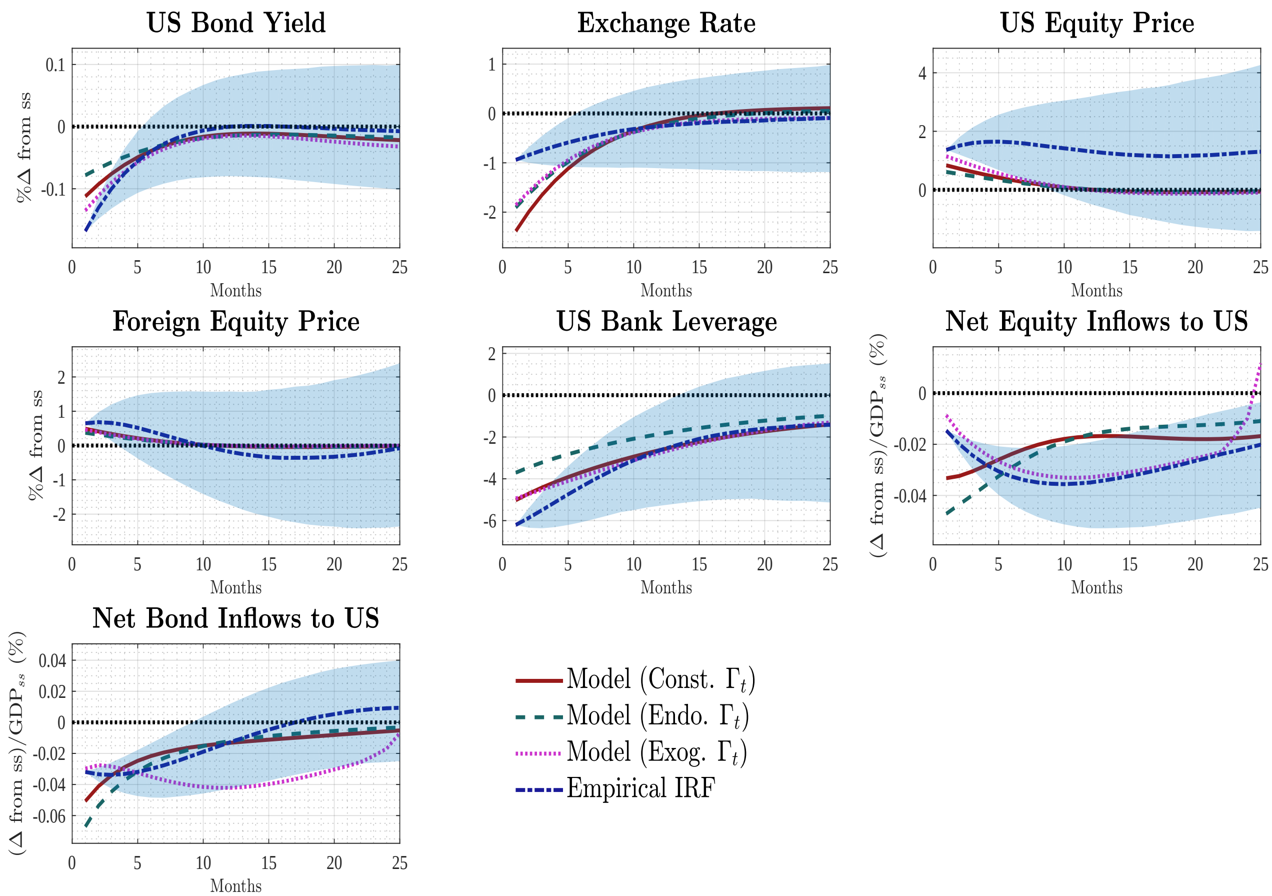
Let Θ be the vector of estimated parameters, $\mathbf{\Psi}(\Theta)$ denote the mapping from Θ to the model's impulse response functions, and $\hat{\mathbf{\Psi}}$ denote the corresponding empirical estimates. Our estimator of Θ is the local minimizer of the following objective function around an initial value Θ_0:

$$J = \min_{\Theta} [\hat{\mathbf{\Psi}} - \mathbf{\Psi}(\Theta)]' \mathbf{V}^{-1} [\hat{\mathbf{\Psi}} - \mathbf{\Psi}(\Theta)].$$

where $\mathbf{V}$ is the inverse of weighting matrix and Θ is estimated with adaptive weighting matrix. More details on the choice of initial values Θ_0 and construction of adaptive weighted matrix $\mathbf{V}$ are presented in Appendix.

We estimate Θ around the initial value by matching the model's impulse responses to a conventional monetary policy shock with IRFs from BP-SVAR. We match the first 24 months of impulse responses for the variables shown in Figure 7. Table 2 reports the estimated pa-

Figure 7: Impulse Responses to Target Surprise: BP-SVAR and Model Simulation

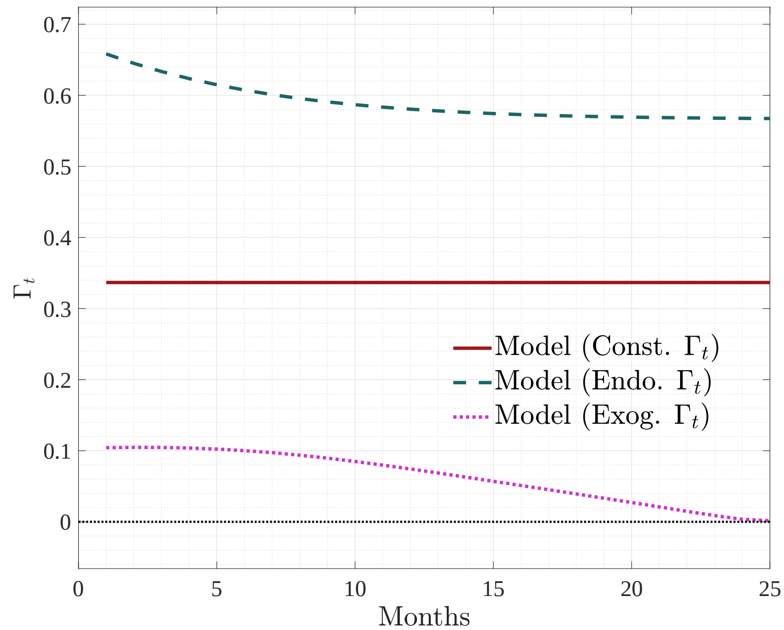


Notes: The simulated impulse responses are based on the estimated parameters in Table 2 and Figure 8. The constant Γ_t case assumes Γ to be fixed over time; the endogenous Γ_t case assumes $\Gamma_t \equiv \gamma \text{var}_t(\Delta \ln e_{t+1})$; the exogenous Γ_t case assumes Γ_t to be an exogenous path upon the target surprise.

rameter values under three scenarios of under three scenarios of FX dealers' risk-bearing capacity, and Figure 7 plots the associated model fitting results for target surprise. Overall the model's simulation results fit data well: the model-generated impulse responses generally fall within the empirical confidence intervals. Although the model's exchange rate responses slightly exceed data estimates in the initial 5 months, the responses of equity and bond inflows, along with the other variables, are on target. Introducing a time-varying Γ_t enhances the model's fit. In the endogenous Γ_t case, the exchange rate responses are closer to data estimates than the constant Γ_t case. The exogenous Γ_t case further improves the model's fit to the data for exchange rate, equity inflows, US bond yield and US equity price.

Figure 8 displays the estimated paths of Γ_t under three scenarios. Our estimated Γ_t are

Figure 8: Estimated Responses of Γ_t to Target Surprise



Notes: The paths of Γ_t are estimated by matching the model's impulse responses to a target surprise with the empirical IRFs from BP-SVAR estimates. The constant Γ_t case assumes Γ to be fixed over time; the endogenous Γ_t case assumes $\Gamma_t \equiv \gamma \text{var}_t(\Delta \ln e_{t+1})$; the exogenous Γ_t case assumes Γ_t to be an exogenous path upon the target surprise.

at the same order of magnitude of 0.1, which is in line with the back-of-the-envelope calculation in Gabaix and Maggiori (2015). For the estimation for time-varying Γ_t, we observe an increase in Γ_t following a conventional monetary policy shock, implying that FX dealers are more financially constrained. This could be attributed to the increased exchange rate volatility upon the monetary shock, which in turn reduces the FX dealers' risk-bearing capacity. This finding also sheds light on the increase of currency dealers' risk aversion around the FOMC announcement windows.

4.3 Quantitative Results

In this section, we quantitatively examine the international transmission of both conventional and unconventional monetary policies on financial markets and real economy. We compare the model simulation results based on baseline ($\Gamma_t > 0$), UIP ($\Gamma_t \to 0$) and financial autarky ($\Gamma_t \to \infty$) cases. For the analysis of QE, we conduct the simulations in the environment with ZLB constraints.

Conventional monetary policy. Figure 7 and 9 plot the impulse responses of related variables to an easing domestic target surprise under baseline case, and Figure D.1 compares the impulse responses under baseline with endogenous Γ_t, UIP and financial autarky cases.

Figure 9 shows that an easing domestic target surprise raises the prices and lowers the returns of domestic equity and long-term bonds for these three cases. This is due to that an easing target shock lowers domestic banks' funding costs due to nominal rigidities such that banks are more willing to hold risky assets regardless of domestic or foreign ones, which pushes up asset prices and raises banks' net worth. Banks' leverage resulting from binding financial constraints amplifies this positive shock to banks' net worth through the traditional financial accelerator mechanism, which is verified by the significant increase of domestic banks' net worth and decline of leverage in Figure 9. Here, the responses of net worth and leverage are consistent with the equity constraint framework as in Bernanke and Gertler (1989), He and Krishnamurthy (2013) and Brunnermeier and Sannikov (2014). Domestic banks' higher net worth promotes investment and pushes up asset prices furthermore, creating a reinforcing positive feedback loop.

Due to domestic banks' larger demand for foreign risky asset, an easing domestic target surprise also increases foreign risky asset prices and lowers the associated expected returns, as plotted in Figure 7 and 9. Notably, the increase of foreign asset prices and bank net worth is significantly smaller than that of domestic ones, which is consistent with the empirical findings. Importantly, this asymmetric impact arises from the joint effect of home bias of risky asset holdings and banks' binding financial constraints. In details, the holding cost of foreign assets impedes domestic banks' incentive to increase positions of foreign assets, therefore, an easing domestic target surprise produces a more pronounced price effect on domestic assets. Given that domestic banks hold more domestic equity in the steady state, the resulting higher domestic assets prices raise domestic banks' net worth much more than foreign banks. This asymmetric impact on bank net worth is further amplified by banks' leverage, then consequentially generates even larger asymmetric impact on asset prices in two countries. Overall, the home bias effect and leverage effect reinforce each other and account for the asymmetric impact on financial markets of two countries.

Figure 7 and 9 also show that an easing domestic target surprise triggers net portfolio outflows from home to foreign country, which is resulting from global investors' substitution towards foreign assets. These outflows, intermediated by FX dealers with limited capacity of liquidity intermediation, results in home currency depreciation. Domestic currency's depreciation promotes domestic net exports, inducing capital inflows to home country. For all cases in Figure 9, the portfolio outflows from assets trading outweigh the capital inflows from goods trading, leading to net capital outflows from home country to foreign country.

Figure 9 further presents the asymmetric stimulation effects on domestic and foreign real economy. In the home country, the easing shock stimulates real economic growth by lowering the domestic real rate, which raises equity price and then promotes domestic capital investment, final output, and consumption. In the foreign country, the domestic monetary shock expands the real foreign economy by raising foreign equity price and lowering the foreign real rate endogenously through portfolio rebalancing. Specifically, domestic banks' risky assets depresses foreign banks' holding of assets, which in turn reduces their demand for deposits from foreign households in equilibrium. Again, we note that the responses of domestic real economic variables in the figure are significantly larger than those of foreign ones. The substantial discrepancy of capital investment and consumption between two countries is also resulting from domestic monetary policy shock's large asymmetric impact on domestic and foreign equity prices.

Quantitative easing. Figure 10 and 11 plot the effects of a "QE2" shock under the baseline with endogenous Γ_t, financial autarky and UIP cases with ZLB constraints, represented by the solid, dash-dotted and dotted red lines, respectively. To drive the economy to achieve ZLB, we simulate a sequence of negative nominal interest rate shocks in Taylor rule. These shocks are designed to ensure that ZLB constraints bind until the end of the QE shock.

First of all, Figure 10 shows that a domestic QE shock raises the prices of domestic equity and long-term bonds, and decreases equity returns and bond yields. Intuitively, central bank's implementation of QE injects liquidity to domestic banks, relaxes their financial constraints, and expands the aggregate demand for risky assets and pushes up the associated prices, including domestic and foreign ones. Higher asset prices raise domestic banks' net worth, which is also amplified by banks' leverage. As a results, banks' leverage decreases due to that increase of banks' net worth dominates the increase of their debt, which is also consistent with equity constraint framework.

As depicted in Figure 10, a domestic QE shock also raises the prices of foreign equity and long-term bonds but with much smaller magnitude compared to domestic assets. This difference stems from foreign banks' holding cost for domestic long-term bonds, leading the domestic central bank to purchase more bonds from domestic banks and inject more liquidity into these banks. Again, due to the holding cost for foreign assets, domestic banks then allocate more injected funds to domestic risky assets. Consequently, domestic QE shock generates a larger price effect on domestic risky assets. This asymmetric price impact is then amplified by the joint effects of home bias and leverage, which shares the similar logic as conventional monetary shock.

Figure 10 further demonstrates that a domestic QE shock triggers net portfolio outflows from home to foreign country due to global investors' substitution towards foreign assets. The resulting portfolio outflows push down home currency due to the imperfect currency market. Weaker home currency encourages domestic exports and induces capital inflows to home country, but is outweighed by the portfolio outflows from assets trading. Hence, there is net capital outflows from home to foreign country in Figure 10. Another important result in this figure is the positive bond inflows to the US, consistent with the empirical results in Section 2. This occurs as central bank's QE implementation not only reduce foreign banks' holding of domestic bonds, but also raises domestic long-term bond price significantly. Recalling the definition of bond flows in(13), the price effect quantitatively dominates quantity effect, which leads to substantial bond inflows to home country in Figure 10.

Figure 11 shows that a domestic QE shock stimulates both domestic and foreign real economy by increasing domestic and foreign equity prices, which in turn expands capital investment and goods production in both countries. The responses of domestic capital investment and final output significantly outweigh those of their foreign counterparts in both baseline and financial autarky cases, which is primarily due to the asymmetric responses of domestic and foreign equity prices. However, the foreign labor supply and inflation decrease in response to the domestic QE shock, as observed in the figure. This is because home currency depreciation lowers the export price of home retail goods, encouraging foreign final good producers to substitute home retail goods for foreign retail goods. The decreased demand for foreign retail goods lowers foreign labor demand and the price index of foreign retail goods basket, leading to deflation in the foreign country.

Next, we examine the effects of "QE2" shock under UIP ($\Gamma_t \to 0$) and FA ($\Gamma_t \to \infty$) with ZLB constraints.[8] In Figure 10, we observe that domestic QE generates significantly larger portfolio flows under UIP than in the baseline case, while the exchange rate remains unaffected. This is because FX dealers can absorb any imbalances under UIP, and the real exchange rate is determined by the real risk-free rate differentials between the two countries. It is important to note that QE has a moderate impact on the risk-free rates in both countries, as it reduces banks' deposits demand by lowering returns on risky assets and also decreases households' deposits supply by boosting consumption. The domestic QE's

[8] Since FX dealers' optimal debt position is undetermined under UIP, the allocation of short-term debt across countries is indeterminate. Therefore, we approximate UIP by setting Γ to 10^{-5}.

impact on portfolio flows and exchange rate under UIP sharply contradicts with the empirical findings in Section 2, providing quantitative evidence of the failure of UIP condition. Figure 10 also shows that the responses of domestic asset prices and associated returns are rather close under baseline and financial autarky cases, suggesting that FX dealers' limited liquidity intermediation does not weaken the stimulation of QE on domestic financial market. In contrast, the net capital flows to the home country are zero under FA, as the portfolio outflows are offset by the increase in domestic exports.

Figure 11 highlights the crucial role of FX dealer's limited liquidity intermediation for the effectiveness of domestic QE, which is one of the key results in our paper. In Figure 11, the responses of domestic real economic variables under UIP are significantly weaker than those in the baseline case, while the responses of foreign real economic variables are nearly identical to domestic ones. Intuitively, capital moves freely without currency market friction, then nearly half of the injected liquidity by domestic central bank quickly spillovers to foreign country through portfolio rebalancing channel, which dilutes domestic stimulation and boosts stimulation on foreign economy compared to the baseline case. Another difference is that the foreign labor supply and inflation increase under UIP, as the foreign final good producers do not substitute towards home retail goods under the fixed exchange rate. Figure 11 also shows that FX dealers' limited liquidity intermediation does not affect the effectiveness of QE on domestic real economy since the related responses of domestic are rather close under baseline and FA cases.

Finally, we analyze the responses of long-term bond term premia and currency risk premia to a negative "QE2" (or "QT") shock such that the expected excess return on US long-term bonds is higher than foreign ones, which is consistent with the analysis in Section 3.3. Figure 12 demonstrates that in the baseline and FA cases, "QT" shock raises the foreign currency expected excess return by prompting portfolio inflows to the US. This results in a positive correlation between foreign currency expected excess return and the difference of US and foreign long-term bond term premia. As a result, we observe a significantly lower expected excess return on currency carry trade with long-term bonds compared to that with short-term bonds, consistent with the qualitative analysis in Section 3.3. In addition to Greenwood et al. (2021) and Gourinchas, Ray, and Vayanos (2022) in partial equilibrium setting, our general equilibrium model is able to explain the puzzling downward term structure of currency carry trade uncovered by Lustig, Stathopoulos, and Verdelhan (2019). However, in the UIP case, there is no significant response of currency risk premia and a significantly weaker response of the difference in US and foreign bond term premia to the

"QT" shock, as the shock has a negligible impact on the exchange rate, and the responses of two countries' real rates and long-term bond returns are closer under the UIP than the baseline case. This provides further quantitative evidence of the failure of UIP condition and importance of currency dealers' financial constraint. This is another important contribution to the literature.

In summary, both conventional and unconventional monetary policies are effective tools for central banks in our model. Banks' binding financial constraints make QE effective, while FX dealers' binding financial constraints are crucial for the effectiveness of QE in an open economy. Further quantitative results are reported in Appendix D, and our conclusions remain robust.

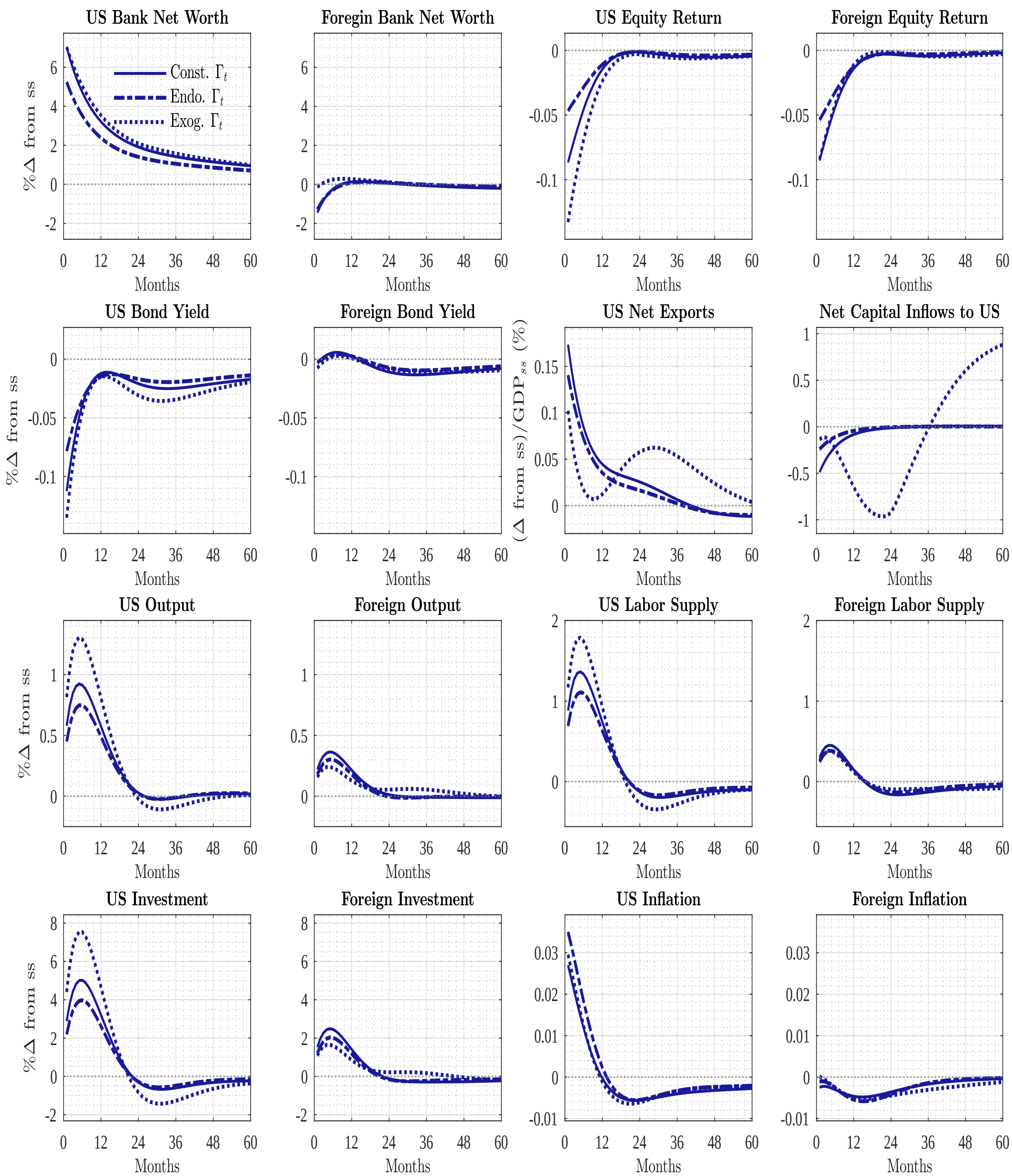
5 Conclusion

This paper develops a two-country quantitative model to study the transmission mechanism of US (un)conventional monetary policy to exchange rates via global investors' portfolio rebalancing. The key ingredients of our model are banks and FX dealers with binding financial constraints. In the model, banks' binding financial constraints amplify the impact of conventional monetary policy on their balance sheets, leading to large global portfolio flows and significant impact on exchange rate under an imperfect currency market. Meanwhile, when banks' financial constraints are binding, QE is effective in the model, which also triggers international portfolio flows. With the segmented international financial market, FX dealers are responsible for absorbing global imbalances. Due to FX dealers' limited liquidity intermediation, the associated capital flows can affect exchange rates.

This paper also examines the effectiveness of US monetary policy under different scenarios in an international context. The quantitative analysis indicates FX dealers play a crucial role for the effectiveness of QE by preventing the spillover of liquidity to foreign countries. In the UIP case, QE is much less effective on financial markets and real economic activities.

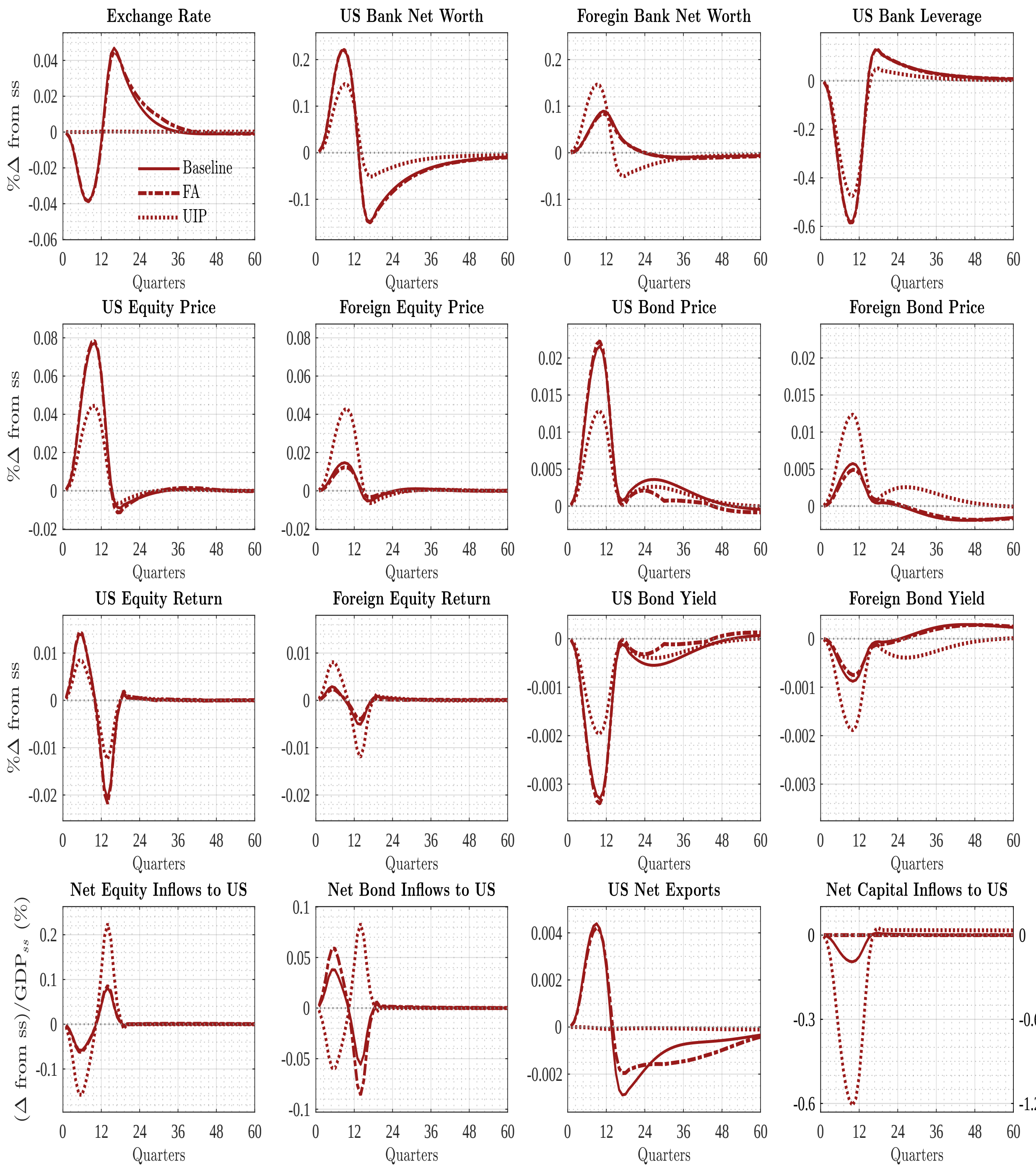
However, the current quantitative analysis does not address the impact of foreign central banks' policy reactions or the coordination between the central banks. In addition, for some EM countries, FX intervention policy is widely adopted, yet there is a lack of corresponding analysis. Both of these are interesting directions for future work.

Figure 9: Conventional monetary policy shocks under alternative Γ_t cases



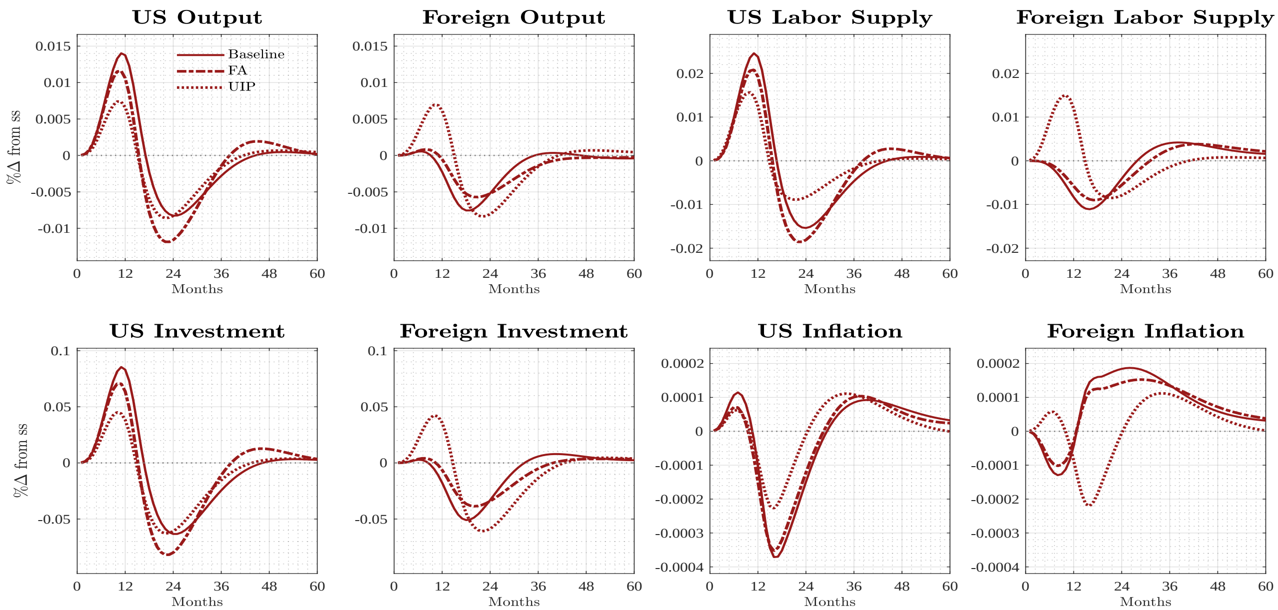
Notes: The simulation results are based on the estimated parameters in Table 2 and Figure 8. For the third and fourth panels in the second row, IRFs are reported as % of the deviation of capital flows from steady-state values relative to GDP values in steady state. In the other panels, the IRFs are reported as % deviation from steady-state values.

Figure 10: "QE2" shocks under baseline, financial autarky and UIP cases with ZLB constraints



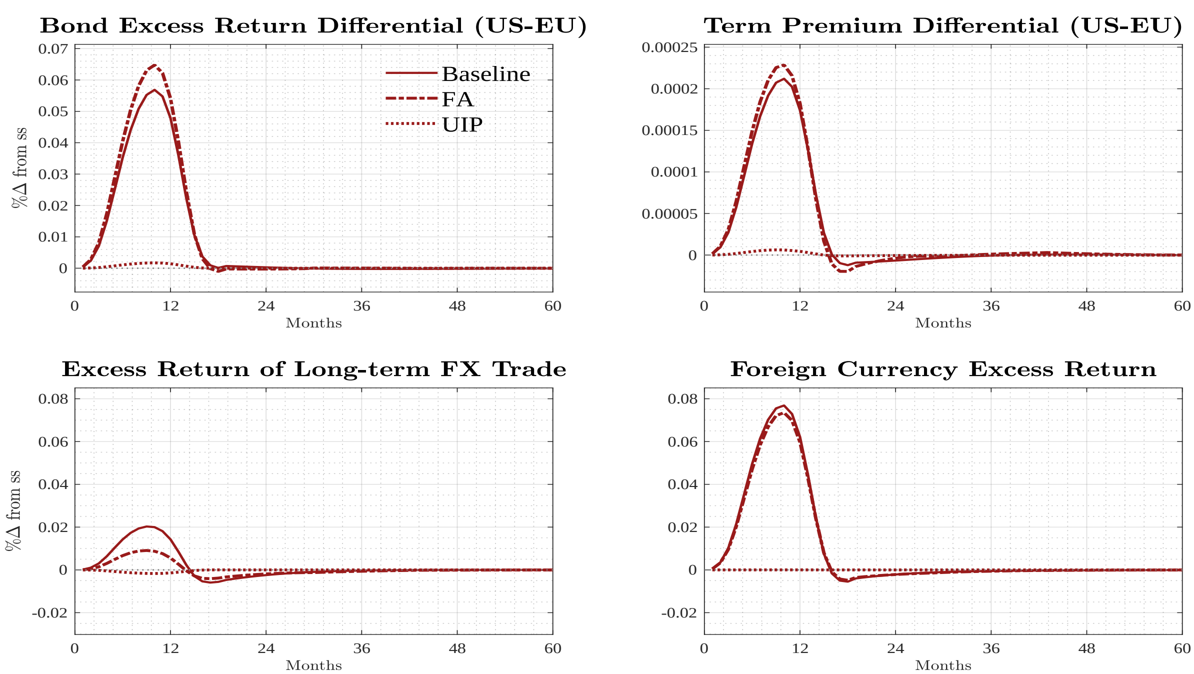
Notes: The simulation results are based on the estimated parameters of endogenous Γ_t (baseline), financial autarky and UIP cases in Table 2, Figure 8 and Table D.3. For the first three rows, the IRFs are reported as % deviation from steady-state values. For the last row, IRFs are reported as % of the deviation of capital flows from steady-state values relative to GDP values in steady state. In the panel with dual-scaled axes, the scale on the left axis is associated with the solid line (baseline case) and dash-dotted line (financial autarky case), and the scale on the right axis is associated with the dotted line (UIP case).

Figure 11: "QE2" shocks under baseline, financial autarky and UIP cases with ZLB constraints



Notes: The simulation results are based on the estimated parameters of endogenous Γ_t (baseline), financial autarky and UIP cases in Table 2, Figure 8 and Table D.3. The IRFs are reported as % deviation from steady-state values.

Figure 12: The response of risk premia to "-QE2" shocks under baseline, financial autarky and UIP cases with ZLB constraints



Notes: The simulation results are based on the estimated parameters of endogenous Γ_t (baseline), financial autarky and UIP cases in Table 2, Figure 8 and Table D.3. The IRFs are reported as % deviation from steady-state values.

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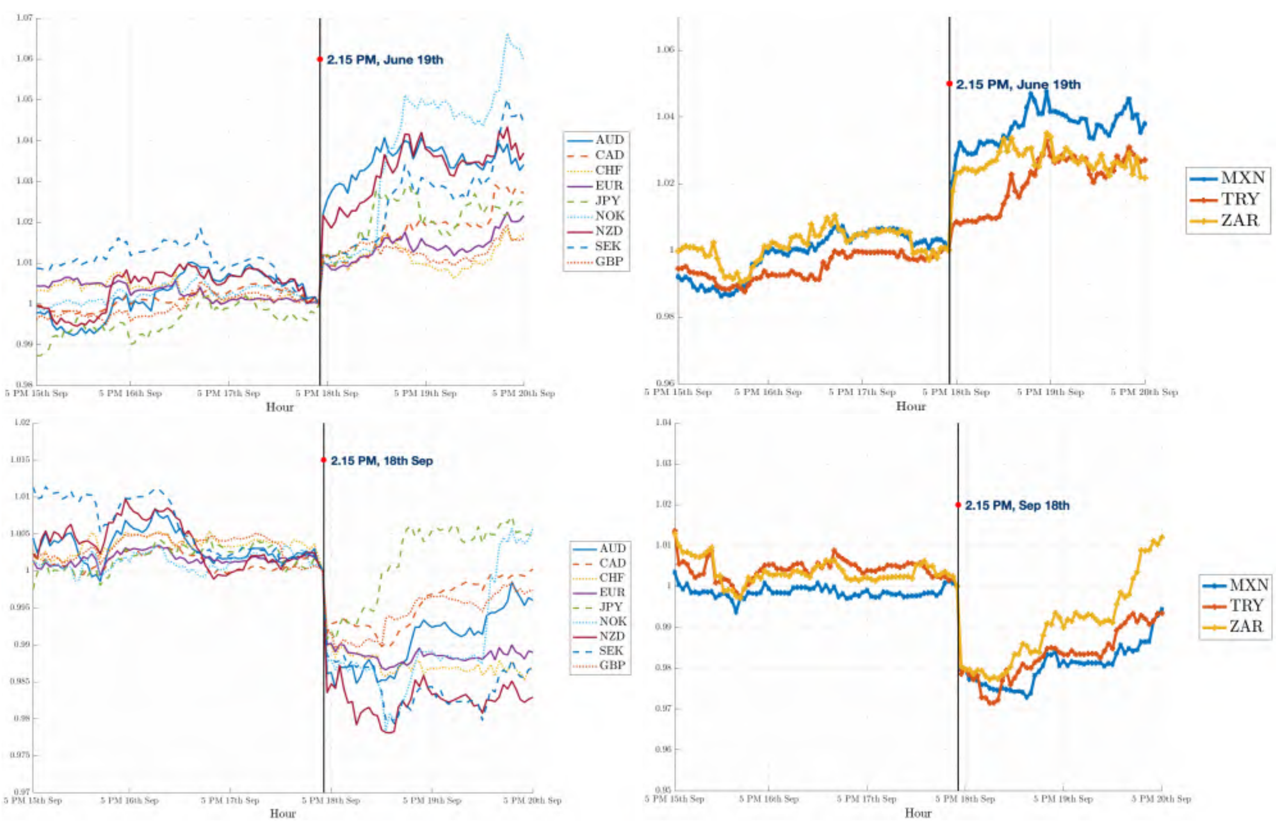
Appendix A Data, Method and Additional Empirical Results

A.1 Additional Results in Event Studies

In Figure A.1, we plot the variations of exchange rates for the whole week to account for the hourly fixed effect. We find that there are no significant reactions of exchange rates from 2pm-3pm on other non-announcement days within the announcement weeks, which indicates that the strong reactions of exchange rates are independent to specific hours. We also report the currency order flow between FX dealers and non-dealer banks or global investor for individual G10 currencies in Figure A.2-A.5 around these two special announcements. Overall, the finding for individual currencies are consistent with the aggregate evidence. However, the finding from order flows for some individual currencies between investors and FX dealers is not consistent with the aggregate findings. This is due to the fact that CLS only covers smaller proportions of global investors' order flows compared to non-dealer banks' order flows. Hence, the results are sensitive to idiosyncratic noisy trading.

Figure A.1: Exchange rates of G10 and several EMs currency pairs against US dollar around FOMC announcement weeks on June 19th, 2013 and September 18th, 2013



Note: Exchange rate is expressed in units of foreign currency per US dollar, and the value at 2 pm on June 19th, 2013 and September 18th, 2013 is normalized to be 1.

Figure A.2: The currency order flows (USD millions) for G10 currency pairs between non-dealer banks and FX dealers around FOMC announcement on June 19th, 2013

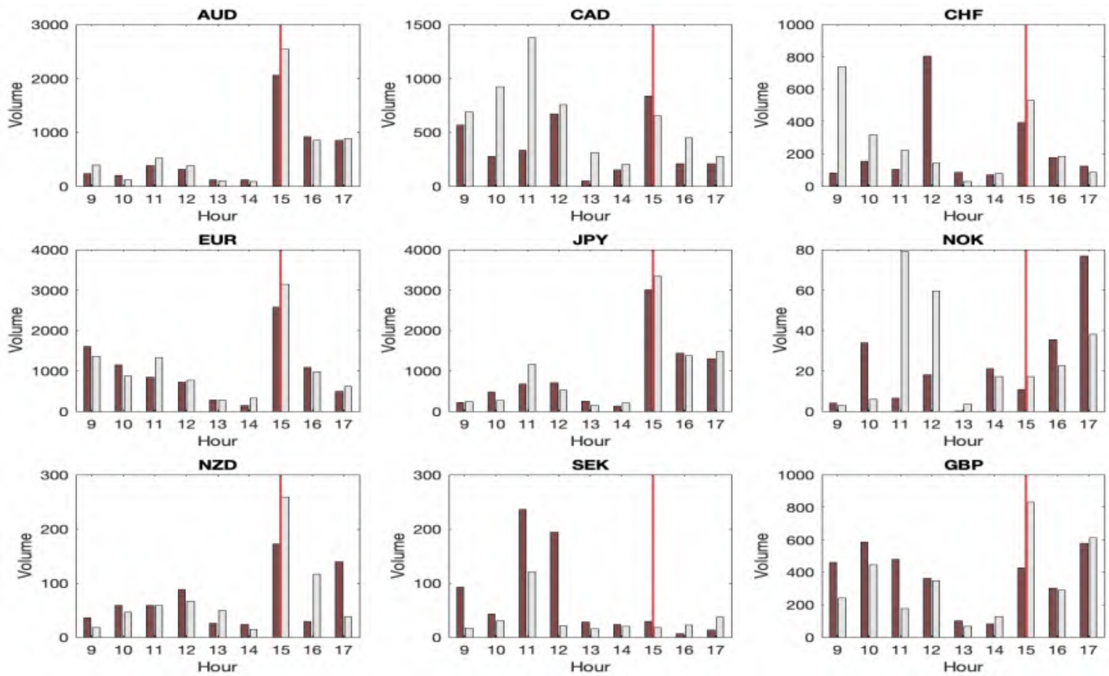
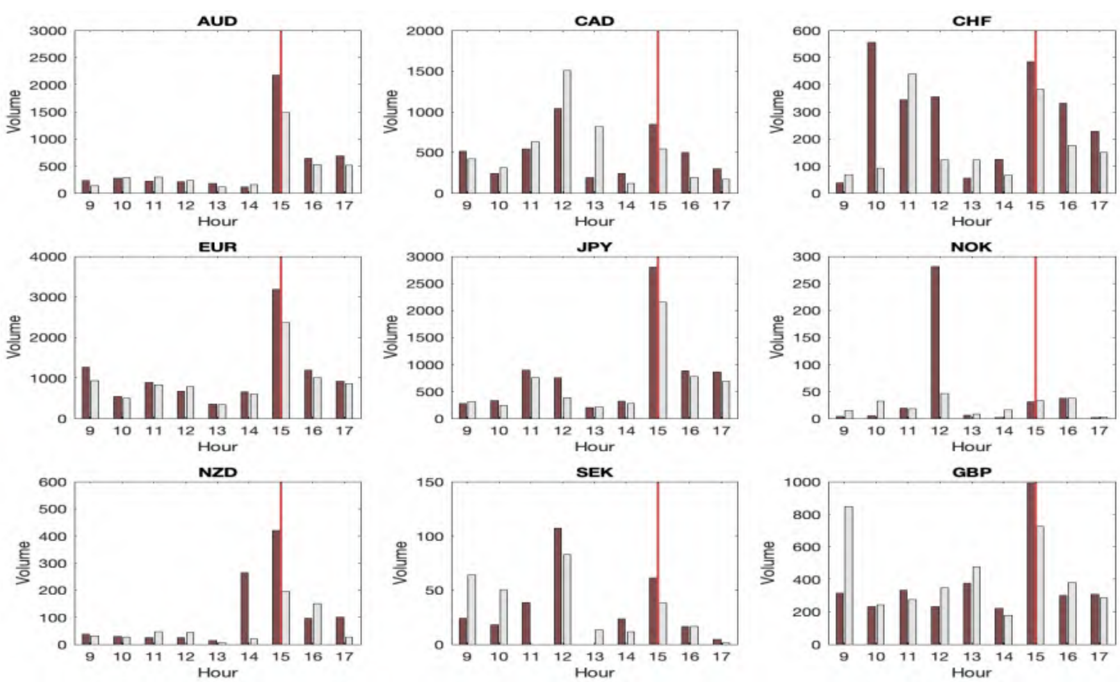


Figure A.3: The currency order flows (USD millions) for G10 currency pairs between non-dealer banks and FX dealers around FOMC announcement on Sep 18th, 2013



Note: Dark red bar is the side of non-dealer banks' " buying dollars from and selling foreign currencies to" FX dealers, the white bar vise versa.

Figure A.4: The currency order flows (USD millions) for G10 currency pairs between global investors and FX dealers around FOMC announcement on June 19th, 2013

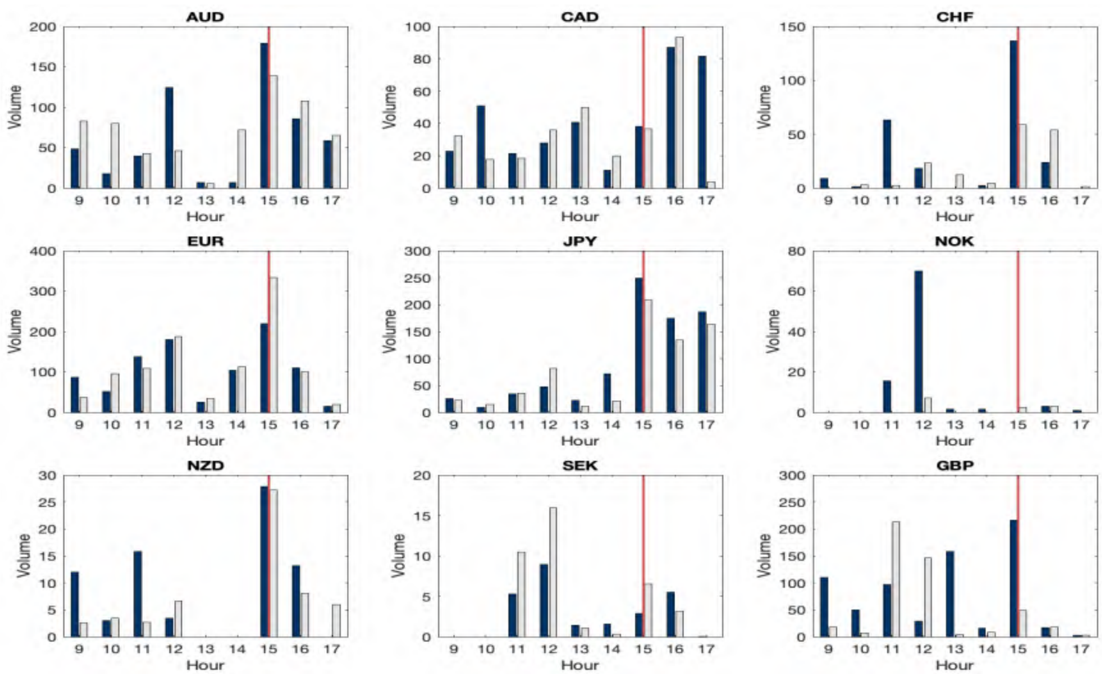
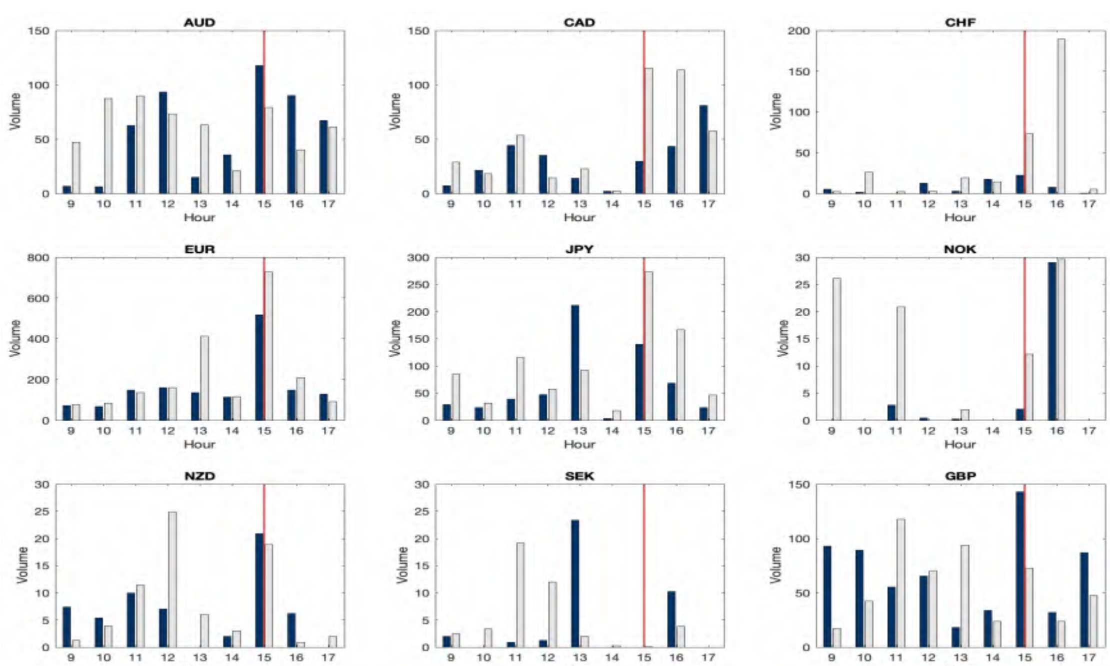


Figure A.5: The currency order flows (USD millions) for G10 currency pairs between global investors and FX dealers around FOMC announcement on Sep 18th, 2013



Note: Dark blue bar is the side of investors' " buying dollars from and selling foreign currencies to" FX dealers, the white bar vise versa.

A.2 BP-SVAR Estimation

A.2.1 Data Descriptions and Variable Constructions

We obtain the daily frequency US treasury yields data, Thomson Reuters exchange rates data (collected at 5pm EST of the US) and MSCI equity index for different countries from Datastream since 01/03/1994 until 06/28/2019. We choose the data of last business day in every month to get the monthly data. For the developed countries group, we focus on the G10 currency pairs (AUD, CAD, CHF, EUR, JPY, NOK, NZD, SEK, GBP) quoted against the U.S. dollar (USD). For the emerging markets group, we select Indian, Indonesia, Mexico, South African, Thailand and Turkey based on the situations of data availability.

The monthly CPI data is from Fred of St. Louis Fed with index level = 100 at 2015. For the countries with only quarterly data available, like Australia and New Zealand, we interpolate the quarterly data into monthly data smoothly. Moreover, the time series of unemployment rate and industrial production of the US are also from Fred.

We get the monetary policy shocks instruments ("target", "forward guidance" and "LASP" factors) and associated FOMC announcement dates from Swanson (2021), where each factor has unit sample variance and positive effects on yields change. We totally include 213 FOMC announcements since 01/03/1994 until 06/28/2019. For the month with more than one FOMC announcements, we aggregate the monetary policy shocks within that month as the monthly instruments.

The US cross-border monthly portfolio flows data is from Bertaut and Tryon (2007) and Bertaut and Judson (2014). Here, we just provide the essential information of the dataset, and more details can be found in the original papers. The monthly cross-border portfolio positions and net flows are summarized by the following accounting identity:

$$S_{i,j,t} = S_{i,j,t-1}\left(1 + R_{i,j,t}\right) + F_{i,j,t} + A_{i,j,t}. \tag{A.1}$$

From the claim side, $S_{i,j,t}$ is U.S. holdings of asset-type j from country i at time t, $R_{i,j,t}$ is the total return on country i's return index for asset type j, $F_{i,j,t}$ is the associated net flow, $A_{i,j,t}$ is the adjustment term; and the other way around for the liability side.

We analyze the portfolio inflow data of foreign holdings of U.S. equity, long-term bond and outflow data of US holdings of foreign equity and long-term bond. Further, as Brennan and Cao (1997) and Hau and Rey (2006), we smooth the net portfolio flows by averaging flows over the previous 12 months. Finally,the value of flows is in billions of U.S. dollars.

A.2.2 Method

To identify the dynamic effects of monetary surprises on exchange rates and global portfolio flows, we consider the following structure VAR model:

$$\mathbf{A}_0\mathbf{y}_t = \sum_{\ell=1}^{p}\mathbf{A}_\ell\mathbf{y}_{t-\ell} + \mathbf{c} + \mathbf{e}_t, \quad \text{for} \quad 1 \le t \le T, \tag{A.2}$$

where the structure matrix $\mathbf{A}_0$ is invertible, $\mathbf{y}_t$ is an $n \times 1$ vector of endogenous variables and $\mathbf{e}_t$ is an $n \times 1$ vector of structural shocks with unit variance. We further assume that the policy indicator y_t^p is the first element of $\mathbf{y}_t$ and $e_t^p \in \mathbf{e}_t$ is the associated policy shock.

By following the literature, we choose 3-month, 1-year and 10-year US TIPS yields as the policy indicators for "target rate" surprise, "forward guidance" surprise and "QE" surprise, separately.[9] The associated external instruments or monetary proxies are from Swanson (2021). For the choice of other endogenous variables in VAR estimation, we include the average real exchange rates of dollar against AE or EM currencies, leverage ratio from He, Kelly, and Manela (2017), and moreover, the net equity and long-term bonds inflows to US. The monthly US claim and liability portfolio flows data are from Bertaut and Tryon (2007) and Bertaut and Judson (2014), where the details of data construction can be found in the related papers. Since the monthly net portfolio flow data is rather volatile, we smooth it by averaging flows over the previous 12 months as in Brennan and Cao (1997) and Hau and Rey (2006). Since the long-term bond portfolio flow data is available after 1995, we analyze the effect of "target rate" surprises since then until June 2019, which is corresponding to the available sample period of monetary proxies in Swanson (2021). For "QE" shocks, we focus on the ZLB period from June 2008 to end of 2015, when Fed's announcements have much larger effect on long-term yields. Importantly, we normalize all nominal variables with CPI and translate them into the respective real ones. As a robust check, we further include the log CPI, the log industrial production (IP) and unemployment rate of US in VAR estimation as Gertler and Karadi (2015) and Ramey (2016), which are potentially useful for forecasting of other variables. More details about data construction can be found in the section above.

Tuning to the SVAR in (A.2), it is equivalent to consider the following reduced form VAR:

$$\mathbf{y}_t - \boldsymbol{B}'\mathbf{x}_t = \varepsilon_t,$$

where $\mathbf{x}_t = \left[\mathbf{y}'_{t-1}, \ldots, \mathbf{y}'_{t-p}, 1\right]'$, $\boldsymbol{B} = \left[\mathbf{A}_0^{-1}\mathbf{A}_1, \ldots, \mathbf{A}_0^{-1}\mathbf{A}_p, \mathbf{c}\right]'$ and $\varepsilon_t|\mathcal{F}_t = \mathbf{A}_0^{-1}\mathbf{e}_t|\mathcal{F}_t \sim$

[9] As discussed later on, since forward guidance is not the focus in this paper, we report the empirical result for path surprise in Section C in the Online Appendix.

$N(\mathbf{0}, \Omega_{\varepsilon,\varepsilon})$ with $\Omega_{\varepsilon,\varepsilon} = (\mathbf{A}_0'\mathbf{A}_0)^{-1}$.

The key identification condition of monetary shocks is

$$\mathbf{z}_t e_t^p \neq 0, \quad \text{and} \quad \mathbf{z}_t \mathbf{e}_{(-p),t} = \mathbf{0},$$

where $\mathbf{z}_t$ denotes the associated proxy for monetary surprises and $\mathbf{e}_{(-p),t}$ denotes the structure shocks except policy indicator shock e_t^p at time t, so as for the reduced form shocks $\varepsilon_{(-p),t}$ and $\varepsilon_{p,t}$. The coefficients are estimated by

$$\varepsilon_{(-p),t} = \frac{\mathbf{A}^{-1}_{0,[(-p),1]}}{A^{-1}_{0,[p,1]}} \widehat{\varepsilon}_t^p + \epsilon_{(-p),t},$$

where $\widehat{\varepsilon}_t^p = \widehat{A}^{-1}_{0,[p,1]} \mathbf{z}_t$ is the fitted value by regressing ε_t^p on $\mathbf{z}_t$, $A^{-1}_{0,[p,1]}$ is the p-th element of the first column of $\mathbf{A}_0^{-1}$, and $\mathbf{A}^{-1}_{0,[(-p),1]}$ includes the left elements in the first column of $\mathbf{A}_0^{-1}$ except $A^{-1}_{0,[p,1]}$.

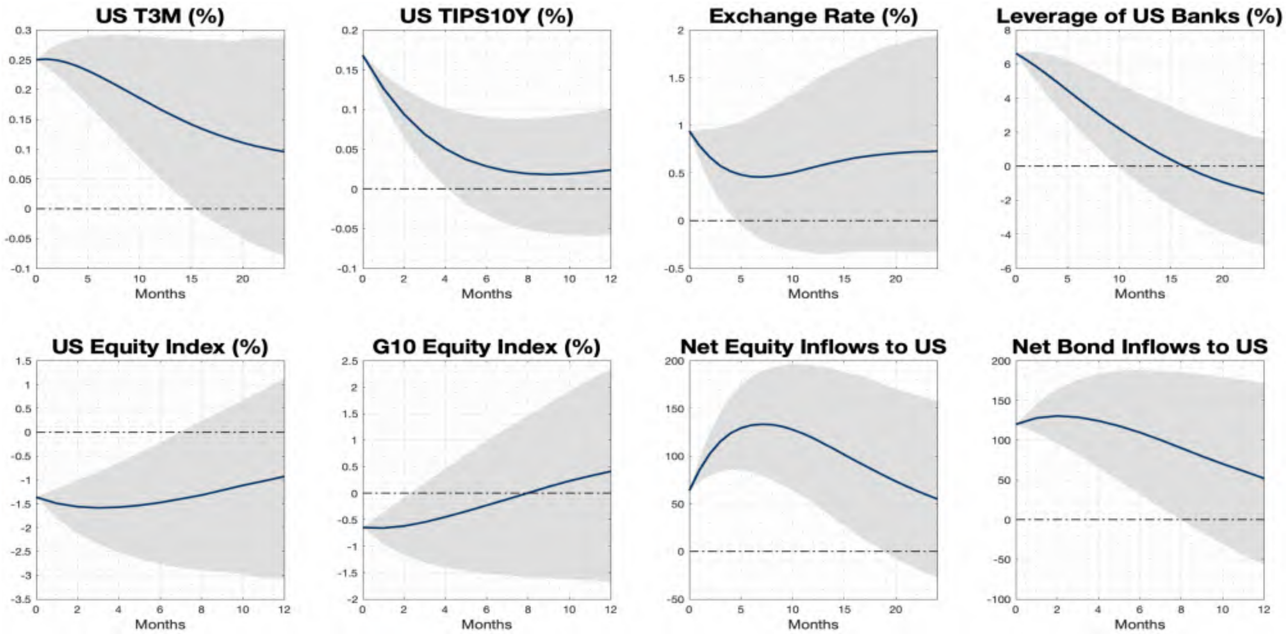
To generate the credible sets, we adopt the Bayes estimation procedure developed in Caldara and Herbst (2019), which is also used in Miranda-Agrippino and Rey (2020) and Rogers, Scotti, and Wright (2018). Bayes methods enjoy the advantages to handle the estimation with short sample period and avoid the potential misleading inference based on bootstrap procedure. We choose the diffuse priors as in Rogers, Scotti, and Wright (2018).[10] The detailed MCMC algorithm is shown in the following section.

A.2.3 Empirical Results

We first report the impulse responses of endogenous variables to conventional monetary policy shocks in Figure A.6. The magnitudes of all coefficients are normalized such that one unit of conventional monetary policy shock increases the US three-month bond yields by 25 basis points. Under this normalization, the US ten-year TIPS yields is increased roughly by 17 basis points and declines quickly then. Further, one unit of "target" surprise raises the average exchange rates of USD against G10 currencies by around 1% instantaneously. The leverage ratio increases on impact 6.62%, and remains significantly positive for the following one year. The increase of leverage following a monetary tightening is consistent with the equity constraint framework such as in Bernanke and Gertler (1989), He and Krishnamurthy (2013) and Brunnermeier and Sannikov (2014), which imply that an adverse

[10] Unlike Caldara and Herbst (2019) and Miranda-Agrippino and Rey (2020) with 12 month lags and Minnesota Priors, we pin down one period lag based on BIC.

Figure A.6: IRFs (with 90% CI) of the variables for average of AE to US conventional monetary policy shocks since 1995

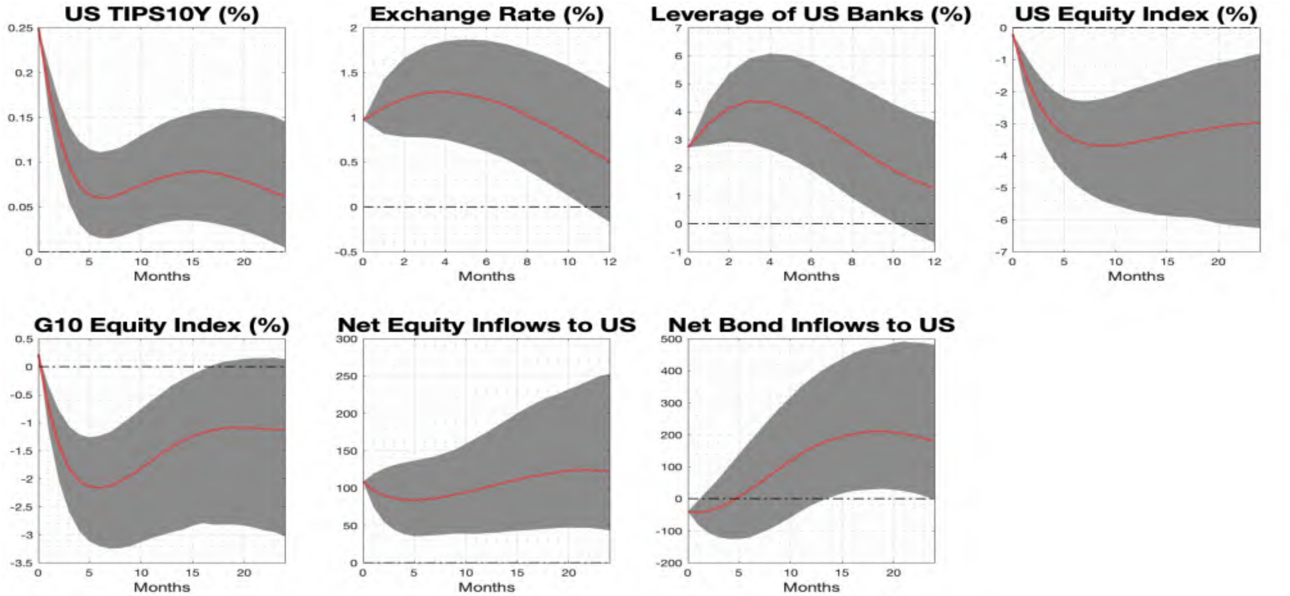


Note: IRFs are reported as % deviation from the sample means. Portfolio flows are in units of USD millions.

shock leading to a fall in net worth increases the bank's leverage. Moreover, consistent with the findings like in Bernanke and Kuttner (2005), a tightening US conventional monetary surprise lowers domestic MSCI equity index by 1.36% with the significant negative effect lasting four months. The average of MSCI equity index for nine developed countries is also decreased by 0.65% with the effects lasting two months, where both the magnitude and duration of response are approximately half of those of US equity index. Importantly, we find that a unit of tightening target surprise induces 63.72 millions USD of net equity inflows from the other advanced economies to the US on average. The respective response achieves the trough six months later to 103.73 millions USD, and then falls to zero around 15 months later. Meanwhile, the initial response of average net bond inflows to US rises sharply by 119.92 millions USD, and then declines to zero gradually. Taken together, the responses of equity and bond inflows provide direct evidence of the transmission of US conventional monetary policy through the investors' portfolio rebalancing.

The IRFs of endogenous variables to negative QE ("QT") surprises are reported in Figure A.7. Here, the sample period is from 08/2008 to 12/2015, which is corresponding to the ZLB period. Since the sample period is relatively short, we report the 68% confidence sets in the figure. We use ten-year TIPS rate as policy indicator for "QT" policy shock and normalize its coefficient of response to be 0.25% at the initial period. It is not surprised that a unit

Figure A.7: IRFs (with 68% CI) of variables for average of AE to negative QE monetary surprises during the ZLB (2008-2015)

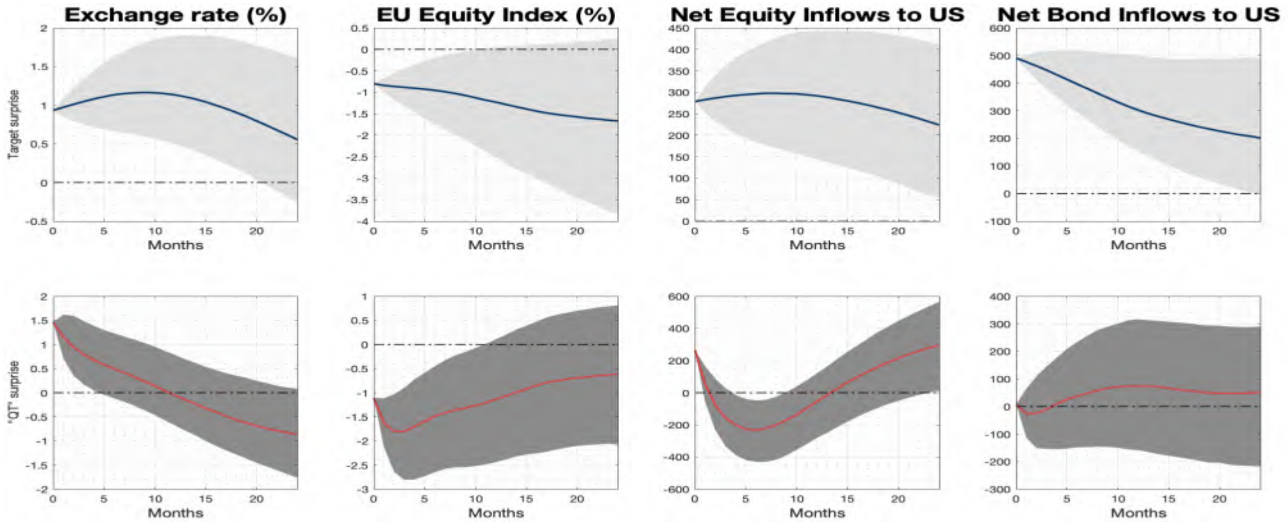


Note: IRFs are reported as % deviation from the sample means. Portfolio flows are in units of USD millions.

of QT surprise causes a long-lasting increase of ten-year rate. USD appreciates 0.87% and then keep increasing for the subsequent four months. The leverage of US banks arises from 2.12% to 3.62% and then return to the trend. "QT" shocks also lower the average MSCI equity index of advanced economy significantly, but both magnitude and horizon on impact are modest compared to US equity index. More importantly, there is an associated constant equity inflows to US (around 100 millions USD), which lasts longer than two years. The puzzling finding for net bond inflows also displays in Figure A.7: there is an initial decline of net bond inflows. In addition to the slow adjustment of foreign investors' bond positions, there are several other potential explanations for this puzzling observation during ZLB period. First, since our analysis includes the financial crisis period, another possible explanation can be the "flight to safety" effect as in Stavrakeva and Tang (2019): foreign investors still prefer to hold US long-term bonds as safe assets even the yields is lower. Second, by noticing the data construction way for portfolio flows in (A.1), since the Fed's QE raises the price of long-term bonds significantly, there might be a positive net bond inflows to US associated with Fed's purchase of long-term bonds due to this large price effect. Our quantitative analysis results in Section 4 further verify this point.

In particular, we report the BP-SVAR estimation results for EU against US in Figure A.8, where we only focus on the IRFs of several important variables. A unit of tightening target

Figure A.8: IRFs (with 90% or 68% CI) of EU variables to US monetary shocks



Note: The sample period is since 1999. Sample period for responses (68% CI) to QE shocks is same as before.

surprise normalized as before is initially associated with 0.94% appreciation of dollar vis-à-vis euro, around 0.80% decline of EU equity index, 328.06 millions USD net equity inflows and 635.76 millions USD net bond inflows from EU to US. We also find that a normalized QT shock induces a 1.38% appreciation of dollar against euro, 1.08% decrease of EU equity index, 345.90 millions USD equity and 27 millions bond inflows from EU to US at the initial period. Similarly, the impact on bond flows in the following months is also ambiguous due to the price effect induced by the Fed's long-term bond purchases. Overall the financial variables of EU have much larger responses to US monetary policy than the average of all nine developed countries.

A.2.4 Bayesian Implementation

In the empirical analysis part, we employ the Bayes Proxy-SVAR developed in Caldara and Herbst (2019) and Rogers, Scotti, and Wright (2018) to identify the effect of monetary policy shocks with the following SVAR(p) model:

$$A(\boldsymbol{L})\mathbf{y}_t = \mathbf{c} + \mathbf{e}_t,$$

with $A(\boldsymbol{L}) = A_0 - A_1\boldsymbol{L} - A_2\boldsymbol{L}^2 - \cdots A_p\boldsymbol{L}^p$. We can rewrite the VAR(p) into the following equation form:

$$\mathbf{A}_0\mathbf{y}_t = \sum_{\ell=1}^{p} \mathbf{A}_\ell \mathbf{y}_{t-\ell} + \mathbf{c} + \mathbf{e}_t, \quad \text{for} \quad 1 \leq t \leq T, \tag{A.3}$$

where $\mathbf{y}_t$ is an $n \times 1$ vector of endogenous variables, $\mathbf{e}_t$ is an $n \times 1$ vector of structural shocks, $\mathbf{A}_\ell$ is an $n \times n$ matrix of structural parameters for $0 \leq \ell \leq p$ where $\mathbf{A}_0$ is invertible, $\mathbf{c}$ is an $n \times 1$ vector of intercepts, p is the lag length, and T is the sample size. $\mathbf{e}_t$ is normally distributed with a mean of zero and covariance matrix $\mathbf{I}_n$ identity matrix, conditional on the information set of past information and the initial conditions $\mathbf{y}_0, \ldots, \mathbf{y}_{1-p}$, which is labeled as $\mathcal{F}_t$.

Equivalently, we can translate the structural VAR model in (A.3) into the following reduced-form VAR:

$$\mathbf{y}_t - \boldsymbol{B}'\mathbf{x}_t = \varepsilon_t, \tag{A.4}$$

where $\mathbf{x}_t = \left[\mathbf{y}'_{t-1}, \ldots, \mathbf{y}'_{t-p}, 1\right]'$, $\boldsymbol{B} = \left[\mathbf{A}_0^{-1}\mathbf{A}_1, \ldots, \mathbf{A}_0^{-1}\mathbf{A}_p, \mathbf{c}\right]'$ and $\varepsilon_t|\mathcal{F}_t = \mathbf{A}_0^{-1}\mathbf{e}_t|\mathcal{F}_t \sim N(\mathbf{0}, \Omega_{\varepsilon,\varepsilon})$ with $\Omega_{\varepsilon,\varepsilon} = (\mathbf{A}'_0\mathbf{A}_0)^{-1}$.

We further denote the instruments of monetary policy shocks in Swanson (2021) as $\mathbf{M}_{1:T} = (m_1, ..., m_T)'$ and the associated structural monetary policy shocks in (A.3) as e_t^{MP}. First, we assume that $m_t|\mathcal{F}_t \sim N(0, \sigma_m^2)$ and $\Delta\mathbf{z}_t|\mathcal{F}_t \sim N(\mathbf{0}, \Omega_{\Delta\mathbf{z},\Delta\mathbf{z}})$. Second, to identify the monetary policy shocks, we impose the standard identification condition that m_t is correlated with e_t^{MP} with covariance $\sigma_{m,MP}$, but is orthogonal to all other structural shocks e_t^{NMP}, i.e., $Cov[m_t, e_t^{MP}|\mathcal{F}_t] = \sigma_{m,MP}$ and $Cov[m_t, e_t^{NMP}|\mathcal{F}_t] = \mathbf{0}$. Finally, to achieve the shaper identification, we assume that monetary policy shocks on FOMC days cannot predict change of any endogenous variables for the following days after the corresponding FOMC announcements. We denote the endogenous variables with daily frequency data available in $\mathbf{y}_t$ as $\mathbf{z}_t$, the last assumption implies that $Cov[\Delta\mathbf{z}_t, m_t|\mathcal{F}_t] = Cov[S\varepsilon_t, m_t|\mathcal{F}_t] \neq \mathbf{0}$ and $Cov[m_t, \Delta\mathbf{z}_{t-j}|\mathcal{F}_t] = \mathbf{0}$ for any $j \neq 0$, where S is the selection matrix such that $\mathbf{z}_t = S\mathbf{y}_t$. Here, as Rogers, Scotti, and Wright (2018), we assume that market is efficient which implies that the information conveyed by monetary policy shocks can be quickly absorbed by the market participates within the corresponding FOMC announcement days.

Given the facts that $[\varepsilon'_t, \ \Delta\mathbf{z}'_t, \ m_t]'$ is conditional Gaussian, we can derive the joint conditional likelihood function of the observed monthly data and daily change of endogenous variables $\mathbf{z}_t$ on FOMC announcement days, and also the instruments of monetary policy shocks as follows:

$$\begin{bmatrix} \mathbf{y}_t - \boldsymbol{B}'\mathbf{x}_t \\ \Delta\mathbf{z}_t \\ m_t \end{bmatrix} \Bigg| \mathcal{F}_t = \begin{bmatrix} \varepsilon_t \\ \Delta\mathbf{z}_t \\ m_t \end{bmatrix} \Bigg| \mathcal{F}_t \sim N\left(\begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ 0 \end{bmatrix}, \begin{bmatrix} \Omega_{\varepsilon,\varepsilon} & \Omega_{\varepsilon,\Delta\mathbf{z}} & \gamma \\ \Omega_{\Delta\mathbf{z},\varepsilon} & \Omega_{\Delta\mathbf{z},\Delta\mathbf{z}} & S\gamma \\ \gamma' & \gamma' S' & \sigma_m^2 \end{bmatrix} \right),$$

where $\boldsymbol{\gamma} = Cov[\varepsilon_t, m_t|\mathcal{F}_t] = \sigma_{m,MP}\mathbf{A}^{-1}_{0,(:,1)}$ and $\mathbf{A}^{-1}_{0,(:,1)}$ is the first column of $\mathbf{A}_0^{-1}$, and S is the selection matrix such that $\mathbf{z}_t = S\mathbf{y}_t$.

By recalling the property of conditional multivariate normal distribution, it follows

$$m_t|\mathbf{y}_t, \Delta\mathbf{z}_t, \boldsymbol{B}, \boldsymbol{\Omega}, \gamma, \sigma_m \sim N(\mu_{m_t|\mathbf{y}_t,\Delta\mathbf{z}_t}, V_{m_t|\mathbf{y}_t,\Delta\mathbf{z}_t}) \tag{A.5}$$

with conditional mean

$$\mu_{m_t|\mathbf{y}_t,\Delta\mathbf{z}_t} = \begin{bmatrix} \gamma' & \gamma' S' \end{bmatrix} \boldsymbol{\Omega}^{-1} \begin{bmatrix} \varepsilon_t \\ \Delta\mathbf{z}_t \end{bmatrix},$$

and conditional variance matrix

$$V_{m_t|\mathbf{y}_t,\Delta\mathbf{z}_t} = \sigma_m^2 - \begin{bmatrix} \gamma' & \gamma' S' \end{bmatrix} \boldsymbol{\Omega}^{-1} \begin{bmatrix} \gamma \\ S\gamma \end{bmatrix},$$

where $\boldsymbol{\Omega} = \begin{bmatrix} \Omega_{\varepsilon,\varepsilon} & \Omega_{\varepsilon,\Delta\mathbf{z}} \\ \Omega_{\Delta\mathbf{z},\varepsilon} & \Omega_{\Delta\mathbf{z},\Delta\mathbf{z}} \end{bmatrix}$.

Based on Bayes Theorem, we can decompose the likelihood function of all the observed data into the likelihood function of endogenous variables which only depends on $\boldsymbol{B}$ and $\boldsymbol{\Omega}$, and the conditional likelihood function of $\mathbf{M_{1:T}}$:

$$p(\mathbf{Y_{1:T}}, \mathbf{\Delta Z_{1:T}}, \mathbf{M_{1:T}}|\boldsymbol{B}, \boldsymbol{\Omega}, \gamma, \sigma_m) = p(\mathbf{Y_{1:T}}, \mathbf{\Delta Z_{1:T}}|\boldsymbol{B}, \boldsymbol{\Omega})p(\mathbf{M_{1:T}}|\mathbf{Y_{1:T}}, \mathbf{\Delta Z_{1:T}}, \boldsymbol{B}, \boldsymbol{\Omega}, \gamma, \sigma_m).$$

With the the conditional normal distribution in (A.5), we can derive the conditional likelihood function of $\mathbf{M_{1:T}}$ as

$$\mathbf{M_{1:T}}|\mathbf{Y_{1:T}}, \mathbf{\Delta Z_{1:T}}, \boldsymbol{B}, \boldsymbol{\Omega}, \gamma, \sigma_m \sim N\left(\mu_{M|Y,\Delta Z}, V_{M|Y,\Delta Z}\right)$$

Finally, we can obtain the posterior distribution of the parameters of interest $(\boldsymbol{B}, \boldsymbol{\Omega}, \gamma, \sigma_m)$ via Bayes rule with a diffuse prior $|\Omega|^{-(l+1)}$ as follows.[11]

[11] For simplicity, we choose the diffuse prior for parameters as Rogers, Scotti, and Wright (2018), instead of Minnesota priors in Caldara and Herbst (2019). We leave the choice of priors as the robust check of the empirical results.

$$
\begin{aligned}
p(B,\Omega,\gamma,\tilde{\psi} \mid Y,W,Z) &\propto p(\mathbf{Y_{1:T}},\boldsymbol{\Delta}\mathbf{Z_{1:T}},\mathbf{M_{1:T}}|\boldsymbol{B},\boldsymbol{\Omega},\gamma,\sigma_m)|\boldsymbol{\Omega}|^{-(l+1)/2} \\
&= p(\mathbf{Y_{1:T}},\boldsymbol{\Delta}\mathbf{Z_{1:T}}|\boldsymbol{B},\boldsymbol{\Omega})p(\mathbf{M_{1:T}}|\mathbf{Y_{1:T}},\boldsymbol{\Delta}\mathbf{Z_{1:T}},\boldsymbol{B},\boldsymbol{\Omega},\gamma,\sigma_m)|\boldsymbol{\Omega}|^{-(l+1)/2} \\
&\propto |\boldsymbol{\Omega}|^{-(l+1)/2}\exp\left(-\frac{1}{2}\operatorname{tr}\left(\boldsymbol{\Omega}^{-1}\boldsymbol{\Lambda}(\boldsymbol{B})'\boldsymbol{\Lambda}(\boldsymbol{B})\right)\right) \\
&\times \frac{1}{V_{M|Y,\Delta Z}}\exp\left(-\frac{1}{2V^2_{M|Y,\Delta Z}}\left(\mathbf{M_{1:T}}-\mu_{M|Y,\Delta Z}\right)'\left(\mathbf{M_{1:T}}-\mu_{M|Y,\Delta Z}\right)\right)
\end{aligned}
$$

where $\boldsymbol{\Lambda}(\boldsymbol{B}) = [\mathbf{Y_{1:T}} - \mathbf{X_{1:T}}\boldsymbol{B} \;\; \boldsymbol{\Delta}\mathbf{Z_{1:T}}]$.

Algorithm : (Metropolis-within-Gibbs Algorithm).-For $i = 1, \dots, N$, at i-th iteration step,

(0): Obtain the OLS estimator of $\boldsymbol{B}$ and associated covariance matrix denoted as $\hat{\boldsymbol{B}}$ and $\hat{\boldsymbol{\Sigma}}$. Pin down the lag of VAR based on BIC.

(1): For parameter block $(\boldsymbol{B},\boldsymbol{\Omega})$, we get the posterior draws from independence chain Metropolis-Hastings. Let $q(\boldsymbol{B},\boldsymbol{\Omega})$ denote the proposal density (normal-Wishart distribution) and $(\boldsymbol{B}^i,\boldsymbol{\Omega}^i)$ denote the realizations of the draws. The algorithm of independence chain Metropolis-Hastings is given by

- Draw $\boldsymbol{\Omega}^i$ from $\mathcal{IW}(\cdot;\boldsymbol{\Lambda}'(\hat{\boldsymbol{B}})\boldsymbol{\Lambda}(\hat{\boldsymbol{B}}),T-l-1)$.
- Draw $vec(\boldsymbol{B}^i)$ from $N(vec(\hat{\boldsymbol{B}}),\hat{\boldsymbol{\Sigma}}\otimes[\mathbf{X}'_{\mathbf{1:T}}\mathbf{X_{1:T}}]^{-1})$.
- Accept the new proposal $(\boldsymbol{B}^i,\boldsymbol{\Omega}^i)$ with probability:

$$
\alpha = \min\left(\frac{p\left(\boldsymbol{B}^i,\boldsymbol{\Omega}^i,\gamma,\tilde{\psi} \mid \mathbf{Y_{1:T}},\boldsymbol{\Delta}\mathbf{Z_{1:T}},\mathbf{M_{1:T}}\right)}{p\left(\boldsymbol{B},\boldsymbol{\Omega},\gamma,\tilde{\psi} \mid \mathbf{Y_{1:T}},\boldsymbol{\Delta}\mathbf{Z_{1:T}},\mathbf{M_{1:T}}\right)}\frac{q(\boldsymbol{B},\boldsymbol{\Omega})}{q(\boldsymbol{B}^i,\boldsymbol{\Omega}^i)},1\right).
$$

(2): For parameter block $(\gamma,\tilde{\psi})$, we get the posterior draws from a random walk Metropolis-Hasting. $\left(\gamma^i,\tilde{\psi}^i\right)$, that is, let the proposed value for each of these parameters be the existing value plus a Gaussian shock. Acceptance probability α is:

- Draw γ^i from $N(\gamma^{i-1},c^2)$.
- Draw $\tilde{\psi}^i$ from $N(\tilde{\psi}^{i-1},c^2)$.
- Accept the new proposal $\left(\gamma^i,\tilde{\psi}^i\right)$ with probability:

$$
\alpha = \min\left(\frac{p\left(\mathbf{M_{1:T}}|\mathbf{Y_{1:T}},\boldsymbol{\Delta}\mathbf{Z_{1:T}},\boldsymbol{B}^i,\boldsymbol{\Omega}^i,\gamma^i,\tilde{\psi}^i\right)}{p\left(\mathbf{M_{1:T}}|\mathbf{Y_{1:T}},\boldsymbol{\Delta}\mathbf{Z_{1:T}},\boldsymbol{B}^i,\boldsymbol{\Omega}^i\gamma,\tilde{\psi}\right)},1\right)
$$

The variance of increment random variable (c^2) is chosen to to target an acceptance rate of around 20%.

(3): Repeat steps (1)–(2) to get the posterior distribution with 5000 times, discarding an initial burning sample (1000 times).

(4): Normalize magnitude of a positive monetary policy shock to increase monthly yield by 25 basis points. “target", “path" and “LSAP" factors are used as the instruments of US 3-month bond, 1-year bond and 10-year bond yields, separately. Based on the posterior draws, calculate the impulse responses and credible sets of the parameters of interest.

Appendix B Full Model Setup and Derivations

In this appendix we provide additional details of setup and derivations of the model in Section 3.

B.1 Households

The representative household in the home country maximizes the following lifetime utility:

$$\mathbb{E}_t \sum_{i=0}^{\infty} \beta_{t+i} \left\{ \frac{(C_{t+i} - hC_{t+i-1})^{1-\sigma_c} - 1}{1-\sigma_c} - \frac{\chi}{1+\eta} L_{t+i}^{1+\eta} \right\},$$

with $h \in (0, 1)$ and $\sigma_c, \chi, \eta > 0$. The parameter h measures the degree of habit formation, σ_c represents the relative risk aversion, $1/\eta$ is the Frisch elasticity of labor supply and χ governs the importance of labor in the utility function. The home household's individual consumption C_t is the home final good as described below, and L_t denots the labor supply of home workers. Moreover, the discount factor β_t is endogenous and is given by

$$\beta_{t+1} = \beta_t \cdot \bar{\beta} \left[\frac{C_t - hC_{t-1}}{(1-h)C_{ss}} \right]^{-\epsilon_c}, \quad \beta_0 = 1,$$

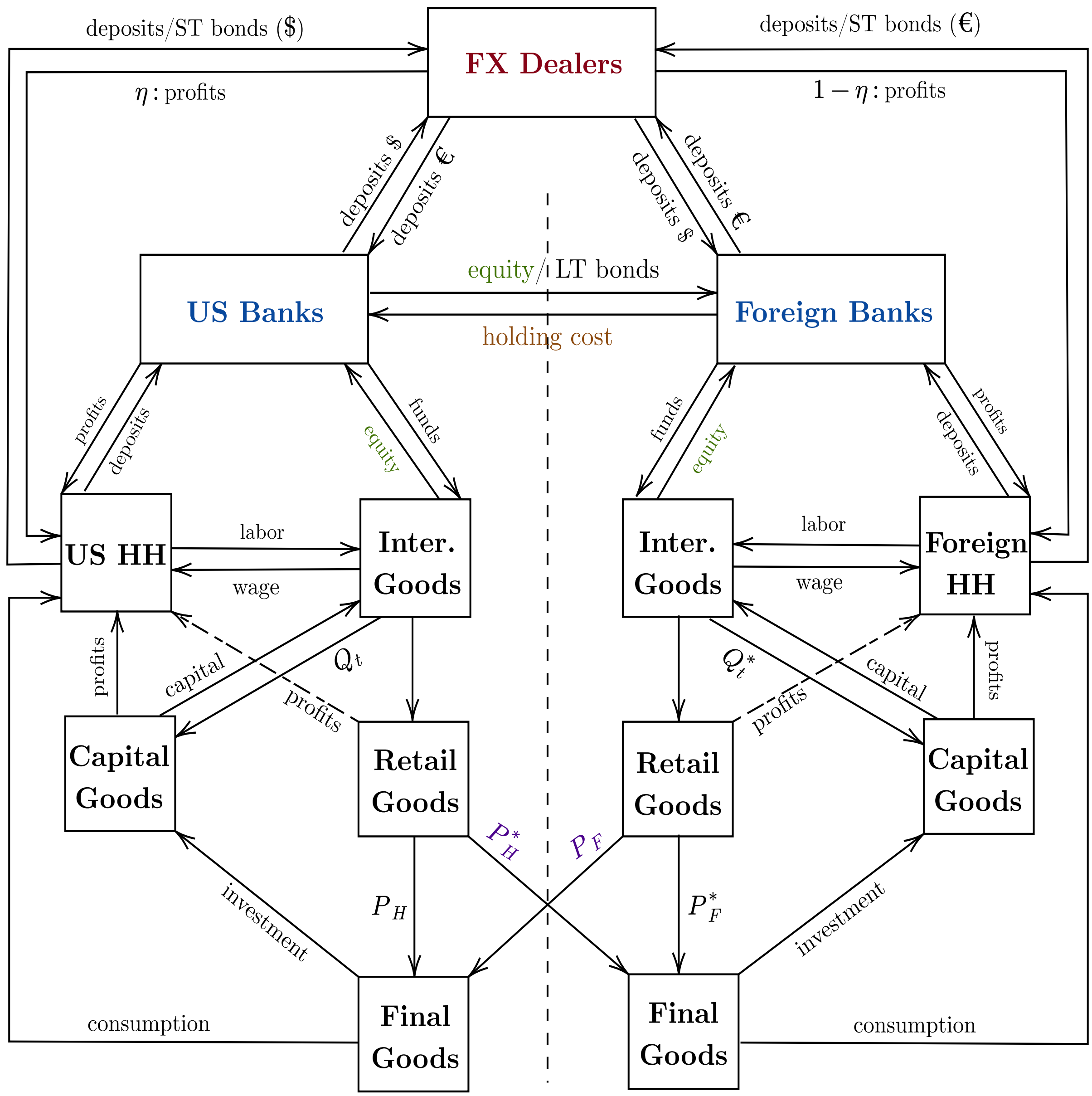
where $\epsilon_c \in (0, \sigma_c)$, $\bar{\beta} \in (0, 1)$, and C_{ss} is the individual home household consumption in steady state.

With all variables in real terms, the household's budget constraint is

$$\begin{aligned} & C_t + D_{ht} + Q_t S_{ht}^h + \frac{1}{2}\kappa_{h1} \left(Q_t S_{ht}^h - Q_{ss}\bar{S}_h^h \right)^2 + q_t B_{ht}^h + \frac{1}{2}\kappa_{h2} \left(q_t B_{ht}^h - q_{ss}\bar{B}_h^h \right)^2 \\ = {} & w_t L_t + DIV_t - X + T_t + R_{t-1} D_{h,t-1} + R_{kt} Q_{t-1} S_{h,t-1}^h + R_{bt} q_{t-1} B_{h,t-1}^h, \end{aligned}$$

where D_{ht} is the household's holdings of real short-term bonds, S_{ht}^h denotes the household's

Figure B.1: The model structure



holdings of domestic firm equity, B_{ht}^h represents the household's holdings of domestic long-term bond, w_t denotes the real wage, DIV_t represents the payouts from the ownership of domestic non-financial and financial firms, X is the total transfer of the household to its members who become new bankers at period t, and T_t denotes the lump-sum transfer. Note that to invest in the risky assets, the household pays holding costs $\frac{\kappa_{h1}}{2}\left(Q_t S_{ht}^h - Q_{ss}\bar{S}_h^h\right)^2$ and $\frac{\kappa_{h2}}{2}\left(q_t B_{ht}^h - q_{ss}\bar{B}_h^h\right)^2$.

Denote $\tilde{\beta}_t \equiv \bar{\beta}\left[\frac{C_t - hC_{t-1}}{(1-h)C_{ss}}\right]^{-\epsilon_c}$ as the per period discount factor and $\tilde{\beta}_{c,t} \equiv -\epsilon_c \bar{\beta}\frac{(C_t - hC_{t-1})^{-\epsilon_c - 1}}{[(1-h)C_{ss}]^{-\epsilon_c}}$

as the derivative of $\tilde{\beta}_t$ with respect to C_t. Then the first-order conditions for a representative home household are

$$\begin{aligned}
\chi L_t^{\eta} &= \mu_t w_t, \\
1 &= \mathbb{E}_t \left[\Lambda_{t,t+1} R_t\right], \\
Q_t S_{ht}^{h} &= Q_{ss} \bar{S}_h^{h} + \frac{1}{\kappa_{h1}} \mathbb{E}_t \left[\Lambda_{t,t+1} \left(R_{k,t+1} - R_t\right)\right], \\
q_t B_{ht}^{h} &= q_{ss} \bar{B}_h^{h} + \frac{1}{\kappa_{h2}} \mathbb{E}_t \left[\Lambda_{t,t+1} \left(R_{b,t+1} - R_t\right)\right],
\end{aligned}$$

with the associated variables defined as

$$\begin{aligned}
\Lambda_{t,t+1} &= \frac{\tilde{\beta}_t \mu_{t+1}}{\mu_t}, \\
\mu_t &= \left(C_t - hC_{t-1}\right)^{-\sigma_c} - h\tilde{\beta}_t \mathbb{E}_t (C_{t+1} - hC_t)^{-\sigma_c} - \tilde{\beta}_{ct} \psi_{ct} + h\tilde{\beta}_t \mathbb{E}_t \left[\tilde{\beta}_{c,t+1} \psi_{c,t+1}\right], \\
\psi_{ct} &= -\mathbb{E}_t \left[\frac{\left(C_t - hC_{t-1}\right)^{1-\sigma_c} - 1}{1-\sigma_c} - \frac{\chi}{1+\eta} L_t^{1+\eta}\right] + \mathbb{E}_t \left[\psi_{c,t+1} \tilde{\beta}_{t+1}\right],
\end{aligned}$$

where $\Lambda_{t,t+1}$ is the stochastic discount factor between period t and $t+1$ and μ_t is the marginal utility of consumption C_t.

We use the asterisks on superscript to denote the variables related to the foreign households' utility maximization problem. Symmetrically, their first-order conditions of utility maximization are given by

$$\begin{aligned}
\chi \left(L_t^*\right)^{\eta} &= \mu_t^* w_t^*, \\
1 &= \mathbb{E}_t \left[\Lambda_{t,t+1}^* R_t^*\right], \\
Q_t^* S_{ht}^{h*} &= Q_{ss}^* \bar{S}_h^{h*} + \frac{1}{\kappa_{h1}} \mathbb{E}_t \left[\Lambda_{t,t+1} \left(R_{k,t+1}^* - R_t^*\right)\right], \\
q_t^* B_{ht}^{h*} &= q_{ss}^* \bar{B}_h^{h*} + \frac{1}{\kappa_{h2}} \mathbb{E}_t \left[\Lambda_{t,t+1} \left(R_{b,t+1}^* - R_t^*\right)\right],
\end{aligned}$$

with the associated variables defined as

$$\begin{aligned}
\Lambda_{t,t+1}^* &= \frac{\tilde{\beta}_t^* \mu_{t+1}^*}{\mu_t^*}, \\
\mu_t^* &= \left(C_t^* - hC_{t-1}^*\right)^{-\sigma_c} - h\tilde{\beta}_t^* \mathbb{E}_t (C_{t+1}^* - hC_t^*)^{-\sigma_c} - \tilde{\beta}_{ct}^* \psi_{ct}^* + h\tilde{\beta}_t^* \mathbb{E}_t \left[\tilde{\beta}_{c,t+1}^* \psi_{c,t+1}^*\right], \\
\psi_{ct}^* &= -\mathbb{E}_t \left[\frac{\left(C_t^* - hC_{t-1}^*\right)^{1-\sigma_c} - 1}{1-\sigma_c} - \frac{\chi}{1+\eta} \left(L_t^*\right)^{1+\eta}\right] + \mathbb{E}_t \left[\psi_{c,t+1}^* \tilde{\beta}_{t+1}^*\right],
\end{aligned}$$

where $\tilde{\beta}^*_t \equiv \bar{\beta}\left[\frac{C^*_t - hC^*_{t-1}}{(1-h)C^*_{ss}}\right]^{-\epsilon_c}$ and $\tilde{\beta}^*_{c,t} \equiv -\epsilon_c \bar{\beta}\frac{\left(C^*_t - hC^*_{t-1}\right)^{-\epsilon_c - 1}}{[(1-h)C^*_{ss}]^{-\epsilon_c}}$.

B.2 Banks

In this part, we solve the value functions for $W_t(n_t)$ (before the portfolio decision, but after occupation shocks) and $V_t(s_{ht}, b_{ht}, s_{ft}, b_{ft}, n_t)$ (after the portfolio decision) for each period. The domestic banker's value function at the beginning of each period is defined as

$$W_t(n_t) = \max_{s_{ht}, b_{ht}, s_{ft}, b_{ft}} V_t(s_{ht}, b_{ht}, s_{ft}, b_{ft}, n_t) - \left[\frac{\kappa_1}{2}\left(\frac{Q^*_t s_{ft} - Q^*_{ss}\bar{s}_f}{e_t n_t}\right)^2 + \frac{\kappa_2}{2}\left(\frac{q^*_t b_{ft} - q^*_{ss}\bar{b}_f}{e_t n_t}\right)^2\right] n_t, \quad \text{(B.1)}$$

subject to the incentive constraint

$$V_t(s_{ht}, b_{ht}, s_{ft}, b_{ft}, n_t) \geq \theta\left(Q_t s_{ht} + \Delta q_t b_{ht} + \frac{Q^*_t s_{ft} + \Delta q^*_t b_{ft}}{e_t}\right). \quad \text{(B.2)}$$

The domestic banker's value function at the end of each period is given by

$$V_t(s_{ht}, b_{ht}, s_{ft}, b_{ft}, n_t) = \mathbb{E}_t \Lambda_{t,t+1}\left[(1-\sigma)n_{t+1} + \sigma W_{t+1}(n_{t+1})\right], \quad \text{(B.3)}$$

with the law of motion of net worth

$$\begin{aligned} n_{t+1} = \quad & (R_{k,t+1} - R_t)Q_t s_{ht} + (R_{b,t+1} - R_t)q_t b_{ht} + R_t n_t \\ & + \left(\frac{R^*_{k,t+1}}{e_{t+1}} - \frac{R_t}{e_t}\right) Q^*_t s_{ft} + \left(\frac{R^*_{b,t+1}}{e_{t+1}} - \frac{R_t}{e_t}\right) q^*_t b_{ft}. \end{aligned} \quad \text{(B.4)}$$

We obtain the solution to value functions by guess and verify. First, we conjecture that V_t is linear in all arguments:

$$\begin{aligned} & V_t\left(s_{ht}, b_{ht}, s_{ft}, b_{ft}, n_t\right) \\ = & \mu_{st} Q_t s_{ht} + \mu_{bt} q_t b_{ht} + \mu_{s^*t} Q^*_t s_{ft} + \mu_{b^*t} q^*_t b_{ft} + \nu_t n_t + \vartheta_t. \end{aligned} \quad \text{(B.5)}$$

Similarly, we conjecture that W_t is a linear function of net worth:

$$W_t\left(n_t\right) = \phi_{wt} n_t + v_{wt}. \quad \text{(B.6)}$$

Let $\widetilde{\Lambda}_{t,t+1}$ be the banker's "augmented" stochastic discount factor, equal to the product of $\Lambda_{t,t+1}$ and the multiplier $\Omega_{t,t+1} = 1 - \sigma + \sigma\phi_{w,t+1}$. Plugging (B.6) and the net worth equation (B.4) into the value function (B.3), we obtain the expression of V_t in terms of the guess of W_t:

$$V_t\left(s_{ht},b_{ht},s_{ft},b_{ft},n_t\right)=\mathbb{E}_t\left[\Lambda_{t,t+1}\left(1-\sigma+\sigma\phi_{w,t+1}\right)n_{t+1}\right]+\sigma\mathbb{E}_t\left[\Lambda_{t,t+1}v_{w,t+1}\right]$$

$$=\ \mathbb{E}_t\left\{\tilde{\Lambda}_{t,t+1}\left[\left(R_{k,t+1}-R_t\right)Q_t s_{ht}+\left(R_{b,t+1}-R_t\right)q_t b_{ht}+\left(\frac{R^*_{k,t+1}}{e_{t+1}}-\frac{R_t}{e_t}\right)Q^*_t s_{ft}\right]\right\}$$

$$+\mathbb{E}_t\left\{\tilde{\Lambda}_{t,t+1}\left[\left(\frac{R^*_{b,t+1}}{e_{t+1}}-\frac{R_t}{e_t}\right)q^*_t b_{ft}+R_t n_t\right]\right\}+\sigma\mathbb{E}_t\left[\Lambda_{t,t+1}v_{w,t+1}\right].$$

By matching the coefficients of the above equation with the linear conjecture of V_t in equation (B.5), the corresponding coefficients are obtained as:

$$\mu_{st}=\mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1}\left(R_{k,t+1}-R_t\right)\right],$$

$$\mu_{bt}=\mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1}\left(R_{b,t+1}-R_t\right)\right],$$

$$\mu_{s^*t}=\mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1}\left(\frac{R^*_{k,t+1}}{e_{t+1}}-\frac{R_t}{e_t}\right)\right],$$

$$\mu_{b^*t}=\mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1}\left(\frac{R^*_{b,t+1}}{e_{t+1}}-\frac{R_t}{e_t}\right)\right],$$

$$\nu_t=\mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1}R_t\right],$$

$$\vartheta_t=\sigma\mathbb{E}_t\left[\Lambda_{t,t+1}v_{w,t+1}\right].$$

Next, let λ_t be the Lagrange multiplier associated with the incentive constraint (B.2), and define the Lagrangian for the maximization problem in (B.1) as follows:

$$\mathcal{L}_t=V_t\left(s_{ht},b_{ht},s_{ft},b_{ft},n_t\right)-\frac{\kappa_1}{2}\left(\frac{Q^*_t s_{ft}-Q^*_{ss}\bar{s}_f}{e_t n_t}\right)^2 n_t-\frac{\kappa_2}{2}\left(\frac{q^*_t b_{ft}-q^*_{ss}\bar{b}_f}{e_t n_t}\right)^2 n_t$$

$$+\lambda_t\left[V_t\left(s_{ht},b_{ht},s_{ft},b_{ft},n_t\right)-\theta\left(Q_t s_{ht}+\Delta q_t b_{ht}+\frac{Q^*_t s_{ft}+\Delta q^*_t b_{ft}}{e_t}\right)\right].$$

The first-order conditions with respect to asset positions are given by:

$$\frac{\partial\mathcal{L}_t}{\partial s_{ht}}=\left(1+\lambda_t\right)\mu_{st}Q_t-\lambda_t\theta Q_t=0,$$

$$\frac{\partial\mathcal{L}_t}{\partial b_{ht}}=\left(1+\lambda_t\right)\mu_{bt}q_t-\lambda_t\theta\Delta q_t=0,$$

$$\frac{\partial\mathcal{L}_t}{\partial s_{ft}}=\left(1+\lambda_t\right)\mu_{s^*t}Q^*_t-\kappa_1\frac{Q^*_t s_{ft}-Q^*_{ss}\bar{s}_f}{e_t n_t}\left(\frac{Q^*_t}{e_t}\right)-\lambda_t\theta\frac{Q^*_t}{e_t}=0,$$

$$\frac{\partial \mathcal{L}_t}{\partial b_{ft}} = (1+\lambda_t)\,\mu_{b^*t} q_t^* - \kappa_2 \frac{q_t^* b_{ft} - q_{ss}^* \bar{b}_f}{e_t n_t}\left(\frac{q_t^*}{e_t}\right) - \lambda_t \theta \frac{\Delta q_t^*}{e_t} = 0.$$

By plugging the expressions of the coefficients of the conjectured solution V_t in (B.5) into the first-order conditions, the solutions to the expected excess returns on domestic risky assets and portfolio positions of foreign assets are obtained as follows:

$$\mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1}\left(R_{k,t+1} - R_t\right)\right] = \frac{\lambda_t}{1+\lambda_t}\theta,$$

$$\mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1}\left(R_{b,t+1} - R_t\right)\right] = \Delta \cdot \frac{\lambda_t}{1+\lambda_t}\theta,$$

$$Q_t^* s_{ft} = Q_{ss}^* \bar{s}_f + \left\{(1+\lambda_t)\,\mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1}\left(\frac{R_{k,t+1}^* e_t}{e_{t+1}} - R_t\right)\right] - \lambda_t \theta\right\}\frac{n_t}{\kappa_1} e_t,$$

$$q_t^* b_{ft} = q_{ss}^* \bar{b}_f + \left\{(1+\lambda_t)\,\mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1}\left(\frac{R_{b,t+1}^* e_t}{e_{t+1}} - R_t\right)\right] - \lambda_t \theta \Delta\right\}\frac{n_t}{\kappa_2} e_t.$$

Note that when the incentive constraint (B.2) is nonbinding, i.e. $\lambda_t = 0$, the expected excess returns on domestic risky assets are both zero, and the deviations in the optimal foreign asset holdings from steady-state values increase with the expected excess returns on foreign assets relative to domestic deposit rate in terms of the home currency.

To solve the value functions, we solve the risk-weighted holdings of domestic assets, $Q_t s_{ht} + \Delta q_t b_{ht}$ first, by plugging the first-order conditions into the incentive constraint. Plug the guessed solution (B.5) into the incentive constraint (B.2), use the condition $\mu_{bt} = \Delta \mu_{st}$, and rearrange the terms, we can obtain

$$(\theta - \mu_{st})\left(Q_t s_{ht} + \Delta q_t b_{ht}\right) \leq \left(\mu_{s^*t} - \frac{\theta}{e_t}\right) Q_t^* s_{ft} + \left(\mu_{b^*t} - \frac{\theta \Delta}{e_t}\right) q_t^* b_{ft} + \nu_t n_t + \vartheta_t.$$

By moving the terms of $Q_t^* s_{ft}$ and $q_t^* b_{ft}$ to the left-hand side and divide both sides with $\theta - \mu_{st}$, we get the following incentive constraint:

$$\frac{\nu_t n_t + \vartheta_t}{\theta - \mu_{st}} \geq Q_t s_{ht} + \Delta q_t b_{ht} + \frac{\theta - e_t \mu_{s^*t}}{\theta - \mu_{st}} \cdot \frac{Q_t^* s_{ft}}{e_t} + \frac{\theta - \mu_{b^*,t} e_t / \Delta}{\theta - \mu_{st}} \cdot \frac{\Delta q_t^* b_{ft}}{e_t}.$$

Moreover, by plugging in the expressions of $Q_t^* s_{ft}$ and $q_t^* b_{ft}$, the above inequality yields the following solution

$$Q_t s_{ht} + \Delta q_t b_{ht} \leq \phi_t n_t + \psi_t, \tag{B.7}$$

with the coefficient term ϕ_t given as:

$$\phi_t = \frac{\kappa_1^{-1}\left(\mu_{s^*t} e_t - \theta\right)\left[(1+\lambda_t)\,\mu_{s^*t} e_t - \lambda_t \theta\right] + \kappa_2^{-1}\left(\mu_{b^*t} e_t - \theta \Delta\right)\left[(1+\lambda_t)\,\mu_{b^*t} e_t - \lambda_t \theta \Delta\right] + \mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1} R_t\right]}{\theta - \mu_{st}}, \tag{B.8}$$

and the intercept term ψ_t given as:

$$\psi_t = \frac{\left(\mu_{s^*t} - \frac{\theta}{e_t}\right) Q^*_{ss}\bar{s}_f + \left(\mu_{b^*t} - \frac{\theta\Delta}{e_t}\right) q^*_{ss}\bar{b}_f + \sigma\mathbb{E}_t\left[\Lambda_{t,t+1}v_{w,t+1}\right]}{\theta - \mu_{st}}. \tag{B.9}$$

Similarly, by plugging the first-order conditions into the maximization problem in (B.1), we obtain the expression for the coefficient term ϕ_{wt} as

$$\begin{aligned}\phi_{wt} = & \frac{\left[(1-\lambda_t)\mu_{s^*t}e_t + \lambda_t\theta\right]\left[(1+\lambda_t)\,\mu_{s^*t}e_t - \lambda_t\theta\right]}{2\kappa_1} \\ & + \frac{\left[(1-\lambda_t)\mu_{b^*t}e_t + \lambda_t\Delta\theta\right]\left[(1+\lambda_t)\,\mu_{b^*t}e_t - \lambda_t\theta\Delta\right]}{2\kappa_2} \\ & + \mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1}R_t\right] + \phi_t\mu_{st},\end{aligned} \tag{B.10}$$

and the intercept term v_{wt} as

$$v_{wt} = \mu_{st}\psi_t + \mu_{s^*t}Q^*_{ss}\bar{s}_f + \mu_{b^*t}q^*_{ss}\bar{b}_f + \sigma\mathbb{E}_t\left[\Lambda_{t,t+1}v_{w,t+1}\right]. \tag{B.11}$$

In addition, by plugging the first-order conditions and equation (B.7) into (B.5), we can write the value function V_t as a linear function of n_t as follows:

$$V_t = \phi_{vt}n_t + v_{vt},$$

where the solution to the coefficient term ϕ_{vt} is

$$\begin{aligned}\phi_{vt} = & \frac{\mu_{s^*t}e_t}{\kappa_1}\left[(1+\lambda_t)\,\mu_{s^*t}e_t - \lambda_t\theta\right] + \frac{\mu_{b^*t}e_t}{\kappa_2}\left[(1+\lambda_t)\,\mu_{b^*t}e_t - \lambda_t\theta\Delta\right] \\ & + \mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1}R_t\right] + \phi_t\mu_{st},\end{aligned}$$

and the solution to the intercept term v_{vt} is

$$v_{vt} = \mu_{st}\psi_t + \mu_{s^*t}Q^*_{ss}\bar{s}_f + \mu_{b^*t}q^*_{ss}\bar{b}_f + \sigma\mathbb{E}_t\left[\Lambda_{t,t+1}v_{w,t+1}\right].$$

Up to this point, we have completed the guess and verify process for the solution to value functions of domestic banks. Given the symmetry of the model, we omit the details and only list the essential results of the solution to foreign banks in the following part.

The foreign banker's value function $W^*_t(n^*_t)$ before the portfolio decisions is defined as:

$$W^*_t(n^*_t) = \max_{s^*_{ht}, b^*_{ht}, s^*_{ft}, b^*_{ft}} V^*_t(s^*_{ht}, b^*_{ht}, s^*_{ft}, b^*_{ft}, n^*_t) - \left\{\frac{\kappa_1}{2}\left[\frac{e_t(Q_t s^*_{ht} - Q_{ss}\bar{s}^*_h)}{n^*_t}\right]^2 + \frac{\kappa_2}{2}\left[\frac{e_t(q_t b^*_{ht} - q_{ss}\bar{b}^*_h)}{n^*_t}\right]^2\right\} n^*_t, \tag{B.12}$$

subject to the incentive constraint on asset positions:

$$V_t^*(s_{ht}^*, b_{ht}^*, s_{ft}^*, b_{ft}^*, n_t^*) \geq \theta \left[Q_t^* s_{ft}^* + \Delta q_t^* b_{ft}^* + (Q_t s_{ht}^* + \Delta q_t b_{ht}^*) e_t \right]. \tag{B.13}$$

The foreign banker's value function at the end of each period is given by

$$V_t^*(s_{ht}^*, b_{ht}^*, s_{ft}^*, b_{ft}^*, n_t^*) = \mathbb{E}_t \Lambda_{t,t+1}^* \left[(1-\sigma) n_{t+1}^* + \sigma W_{t+1}^*(n_{t+1}^*) \right],$$

with the law of motion of foreign banks' net worth:

$$\begin{aligned} n_{t+1}^* = {} & (R_{k,t+1}^* - R_t^*) Q_t^* s_{ft}^* + (R_{b,t+1}^* - R_t^*) q_t^* b_{ft}^* + R_t^* n_t^* \\ & + (R_{k,t+1} e_{t+1} - R_t^* e_t) Q_t s_{ht}^* + (R_{b,t+1} e_{t+1} - R_t^* e_t) q_t b_{ht}^*. \end{aligned}$$

We guess and verify a linear solution to V_t^* as follows:

$$\begin{aligned} & V_t^* \left(s_{ht}^*, b_{ht}^*, s_{ft}^*, b_{ft}^*, n_t^* \right) \\ & = \mu_{st}^* Q_t s_{ht}^* + \mu_{bt}^* q_t b_{ht}^* + \mu_{s^*t}^* Q_t^* s_{ft}^* + \mu_{b^*t}^* q_t^* b_{ft}^* + \nu_t^* n_t^* + \vartheta_t^*. \end{aligned} \tag{B.14}$$

For W_t^*, the linear guess is:

$$W_t^* \left(n_t^* \right) = \phi_{wt}^* n_t^* + v_{wt}^*. \tag{B.15}$$

Matching the coefficients of the above equation with the guess of V_t^* in equation (B.14) yields the following expressions:

$$\mu_{s^*t}^* = \mathbb{E}_t \left[\tilde{\Lambda}_{t,t+1}^* \left(R_{k,t+1}^* - R_t^* \right) \right],$$

$$\mu_{b^*t}^* = \mathbb{E}_t \left[\tilde{\Lambda}_{t,t+1}^* \left(R_{b,t+1}^* - R_t^* \right) \right],$$

$$\mu_{st}^* = \mathbb{E}_t \left[\tilde{\Lambda}_{t,t+1}^* \left(R_{k,t+1} e_{t+1} - R_t^* e_t \right) \right],$$

$$\mu_{bt}^* = \mathbb{E}_t \left[\tilde{\Lambda}_{t,t+1}^* \left(R_{b,t+1} e_{t+1} - R_t^* e_t \right) \right],$$

$$\nu_t^* = \mathbb{E}_t \left[\tilde{\Lambda}_{t,t+1}^* R_t^* \right],$$

$$\vartheta_t^* = \sigma \mathbb{E}_t \left[\Lambda_{t,t+1}^* v_{t+1}^* \right].$$

Next, let λ_t^* be the Lagrange multiplier associated with the incentive constraint (B.13). The maximization problem in (B.12) yields the following set of first-order conditions.

$$\mathbb{E}_t \left[\tilde{\Lambda}_{t,t+1}^* \left(R_{k,t+1}^* - R_t^* \right) \right] = \frac{\lambda_t^* \theta}{1 + \lambda_t^*},$$

$$\mathbb{E}_t\left[\tilde{\Lambda}^*_{t,t+1}\left(R^*_{b,t+1}-R^*_t\right)\right]=\frac{\lambda^*_t\theta\Delta}{1+\lambda^*_t},$$

$$Q_t s^*_{ht}=Q_{ss}\bar{s}^*_h+\left\{\left(1+\lambda^*_t\right)\mathbb{E}_t\left[\tilde{\Lambda}^*_{t,t+1}\left(\frac{R_{k,t+1}e_{t+1}}{e_t}-R^*_t\right)\right]-\lambda^*_t\theta\right\}\frac{n^*_t}{\kappa_1}\frac{1}{e_t},$$

$$q_t b^*_{ht}=q_{ss}\bar{b}^*_h+\left\{\left(1+\lambda^*_t\right)\mathbb{E}_t\left[\tilde{\Lambda}^*_{t,t+1}\left(\frac{R_{b,t+1}e_{t+1}}{e_t}-R^*_t\right)\right]-\lambda^*_t\theta\Delta\right\}\frac{n^*_t}{\kappa_2}\frac{1}{e_t}.$$

When the incentive constraint (B.13) is nonbinding, i.e. $\lambda^*_t=0$, the expected excess returns on foreign risky assets are both zero, and the deviations in the optimal domestic asset holdings from steady-state values increase with the expected excess returns on domestic assets relative to foreign deposit rate in terms of the foreign currency.

For the foreign banks, the risk-weighted holdings of foreign assets, $Q^*_t s^*_{ft}+\Delta q^*_t b^*_{ft}$, can be derived as follows by plugging the first-order conditions into the incentive constraint. The solution is

$$Q^*_t s^*_{ft}+\Delta q^*_t b^*_{ft}\leq\phi^*_t n^*_t+\psi^*_t,$$

where the equality holds if $\lambda^*_t>0$. Furthermore, the associated slope coefficient is given by

$$\phi^*_t=\frac{\kappa_1^{-1}\left(\mu^*_{st}e_t^{-1}-\theta\right)\left[\left(1+\lambda^*_t\right)\mu^*_{st}e_t^{-1}-\lambda^*_t\theta\right]+\kappa_2^{-1}\left(\mu^*_{bt}e_t^{-1}-\theta\Delta\right)\left[\left(1+\lambda^*_t\right)\mu^*_{bt}e_t^{-1}-\lambda^*_t\theta\Delta\right]+\mathbb{E}_t\left[\tilde{\Lambda}^*_{t,t+1}R^*_t\right]}{\theta-\mu^*_{s^*t}},\tag{B.16}$$

and the corresponding intercept is given by

$$\psi^*_t=\frac{\left(\mu^*_{st}-\theta e_t\right)Q_{ss}\bar{s}_h+\left(\mu^*_{bt}-\theta\Delta e_t\right)q_{ss}\bar{b}_h+\sigma\mathbb{E}_t\left[\Lambda^*_{t,t+1}v^*_{w,t+1}\right]}{\theta-\mu^*_{s^*t}}.\tag{B.17}$$

Similarly, the slope coefficient ϕ^*_{wt} in the linear solution to $W^*_t(n^*_t)$ is given by

$$\begin{aligned}\phi^*_{wt}=&\frac{\left[(1-\lambda^*_t)\mu^*_{st}e_t^{-1}+\lambda^*_t\theta\right]\left[\left(1+\lambda^*_t\right)\mu^*_{st}e_t^{-1}-\lambda^*_t\theta\right]}{2\kappa_1}\\&+\frac{\left[(1-\lambda^*_t)\mu^*_{bt}e_t^{-1}+\lambda^*_t\Delta\theta\right]\left[\left(1+\lambda^*_t\right)\mu^*_{bt}e_t^{-1}-\lambda^*_t\theta\Delta\right]}{2\kappa_2}\\&+\mathbb{E}_t\left[\tilde{\Lambda}^*_{t,t+1}R^*_t\right]+\phi^*_t\mu^*_{s^*t},\end{aligned}$$

and the associated intercept term v^*_{wt} is given as

$$v^*_{wt}=\mu^*_{s^*t}\psi^*_t+\mu^*_{st}Q_{ss}\bar{s}_h+\mu^*_{bt}q_{ss}\bar{b}_h+\sigma\mathbb{E}_t\left[\Lambda^*_{t,t+1}v^*_{w,t+1}\right].$$

Finally, the value function V^*_t in equilibrium can also be expressed as a linear function of

n_t^*, and the solution is

$$V_t^* = \phi_{vt}^* n_t^* + v_{vt}^*,$$

with the slope coefficient ϕ_{vt}^* given by

$$\phi_{vt}^* = \frac{\mu_{st}^*}{\kappa_1 e_t}\left[(1+\lambda_t^*)\,\mu_{st}^* e_t^{-1} - \lambda_t^* \theta\right] + \frac{\mu_{bt}^*}{\kappa_2 e_t}\left[(1+\lambda_t^*)\,\mu_{bt}^* e_t^{-1} - \lambda_t^* \theta \Delta\right]$$
$$+\mathbb{E}_t\left[\tilde{\Lambda}_{t,t+1}^* R_t^*\right] + \phi_t^* \mu_{s^*t}^*,$$

and the intercept term v_{vt}^* given by

$$v_{vt}^* = \mu_{s^*t}^* \psi_t^* + \mu_{st}^* Q_{ss} \bar{s}_h + \mu_{bt}^* q_{ss} \bar{b}_h + \sigma \mathbb{E}_t\left[\Lambda_{t,t+1}^* v_{w,t+1}^*\right].$$

Up to this point, we obtain the solutions for portfolio choices and linear value functions for both domestic and foreign banks.

B.3 FX Dealers

We follow Gabaix and Maggiori (2015) and assume that FX dealers intermediate the excess dollar demand period by period for the sake of simplicity. At the end of each period, FX dealers distribute the net profits to the households in two countries based on fixed shares η and $1-\eta$. We consider the case with fixed Γ, which captures the degree of limited risk-bearing capacity of FX dealers. As in Gabaix and Maggiori (2015), we assume that FX dealers maximize the real expected return from longing foreign short-term debts ($d_{st}e_t$) and shorting US short-term debt ($-d_{st}$) at period t:

$$V_t^d = \max_{d_{st}} \mathbb{E}_t\left[\left(\eta \Lambda_{t,t+1} + (1-\eta)\Lambda_{t,t+1}^* \frac{e_{t+1}}{e_t}\right)\left(\frac{R_t^* e_t}{e_{t+1}} - R_t\right)\right] d_{st},$$

subject to the financial constraint:

$$V_t^d \geq \Gamma_t d_{st}^2 e_t.$$

Here, to simplify the algebra, we follow Gabaix and Maggiori (2015) directly and simply assume that the divertable proportion of asset position d_{st} is $\Gamma_t\,|d_{st}e_t|$. By plugging the value function into the constraint and rearranging, we can find that the FX dealer's optimal position on US short-term debt is $d_{st} = \frac{1}{\Gamma_t}\mathbb{E}_t\left[\left(\eta \Lambda_{t,t+1} + (1-\eta)\Lambda_{t,t+1}^* \frac{e_{t+1}}{e_t}\right)\left(\frac{R_t^*}{e_{t+1}} - \frac{R_t}{e_t}\right)\right]$.

In equilibrium, the currency market clearing condition is

$$D_{dt} = D_{st},$$

where the US dollar supply D_{st} is the aggregation of d_{st} across FX dealers, and the US dollar demand D_{dt} is the sum of net US exports, net buying volume of US risky assets, dollar debt repaid by FX dealers from the previous period, and FX dealers' net profits rebated to US households:

$$
\begin{aligned}
D_{dt} = & \underbrace{(Q_t S^*_{Ht} - Q_{t-1} S^*_{H,t-1} R_{kt}) - (Q^*_t S_{Ft} - Q^*_{t-1} S_{F,t-1} R^*_{kt})/e_t}_{\text{net equity inflows to US}} \\
& + \underbrace{(q_t B^*_{Ht} - q_{t-1} B^*_{H,t-1} R_{bt}) - (q^*_t B_{Ft} - q^*_{t-1} B_{F,t-1} R^*_{bt})/e_t}_{\text{net bond inflows to US}} \\
& + \underbrace{\gamma_y \frac{(p^*_{Ht} e_t)^{1-\eta_y}}{e_t} Y^*_t - \gamma_y \left(\frac{p_{Ft}}{e_t}\right)^{1-\eta_y} Y_t}_{\text{net exports of US}} + \underbrace{R_{t-1} D_{s,t-1}}_{\text{dollar debt payoff}} + \underbrace{\eta \left(\frac{R^*_{t-1} e_{t-1}}{e_t} - R_{t-1}\right) D_{s,t-1}}_{\text{profits rebated to US households}}.
\end{aligned}
$$

Here, it is worth mentioning that the definition of net portfolio flows is consistent with the data construction in Bertaut and Tryon (2007) and Bertaut and Judson (2014). Since we assume that the final good producers import varieties of retail goods from both domestic and foreign countries, the real value of net US exports is defined as

$$
\begin{aligned}
& \int_0^1 \frac{P^*_{Ht}(i)}{P_t \mathcal{E}_t} Y^*_{Ht}(i) di - \int_0^1 \frac{P_{Ft}(i)}{P_t} Y_{Ft}(i) di \\
= & \gamma_y \left(\frac{P^*_{Ht}}{P^*_t}\right)^{\theta_y - \eta_y} \frac{1}{P_t \mathcal{E}_t} \int_0^1 \frac{(P^*_{Ht}(i))^{1-\theta_y}}{(P^*_t)^{-\theta_y}} Y^*_t di - \gamma_y \left(\frac{P_{Ft}}{P_t}\right)^{\theta_y - \eta_y} \int_0^1 \frac{(P_{Ft}(i))^{1-\theta_y}}{P_t^{1-\theta_y}} Y_t di \\
= & \gamma_y \frac{P^*_t}{P_t \mathcal{E}_t} \left(\frac{P^*_{Ht}}{P^*_t}\right)^{1-\eta_y} Y^*_t - \gamma_y \left(\frac{P_{Ft}}{P_t}\right)^{1-\eta_y} Y_t \\
= & \gamma_y \frac{(p^*_{Ht} \cdot e_t)^{1-\eta_y}}{e_t} Y^*_t - \gamma_y \left(\frac{p_{Ft}}{e_t}\right)^{1-\eta_y} Y_t.
\end{aligned}
$$

Moreover, the FX dealers need to repay their dollar debt with accrued interest $R_{t-1} D_{s,t-1}$ from the previous period and rebate net profits $\eta \left(\frac{R^*_{t-1} e_{t-1}}{e_t} - R_{t-1}\right) D_{s,t-1}$ to US households.

B.4 Intermediate Goods Producers

The competitive intermediate goods producers take as given the real wage rate and the real equity return to banks, and produce output according to the following Cobb-Douglas technology:

$$Y_{mt} = A_t (u_t K_t)^{\alpha} L_{pt}^{1-\alpha},$$

where u_t is the rate of capital utilization. The capital stock K_t depreciates at a rate $\delta(u_t) = \delta 0 + \delta 1(u_t - 1) + \frac{\delta 2}{2}(u_t - 1)^2$. Then the aggregate capital accumulates according to

$$K_{t+1} = I_t + (1 - \delta(u_t))K_t.$$

Given the intermediate goods prices p_{mt} and capital goods price Q_t, the producers choose u_t to maximize the gross output of production $p_{mt}Y_{mt} + (1 - \delta(u_t))Q_tK_t$. Then first-order condition for capital utilization rate is

$$\delta'(u_t)Q_tK_t = p_{mt}\alpha\frac{Y_{mt}}{u_t}.$$

Since the production function is constant returns to scale in capital and labor, it follows that the producers face a constant price of intermediate goods, which is equal to the marginal cost of production:

$$\begin{aligned} p_{mt} &= \min_{K_t, L_t}\left\{Z_tK_t + w_tL_{pt};\text{ s.t. } A_t(u_tK_t)^{\alpha}L_{pt}^{1-\alpha} = 1.\right\} \\ &= \frac{1}{A_t}\left(\frac{Z_t}{\alpha u_t}\right)^{\alpha}\left(\frac{w_t}{1-\alpha}\right)^{1-\alpha}. \end{aligned}$$

The corresponding labor demand is given by

$$w_t = \frac{(1-\alpha)p_{mt}Y_t}{L_{pt}},$$

and the capital demand is given by

$$Z_t = \frac{\alpha p_{mt}Y_t}{K_t}.$$

B.5 Capital Producers

The capital producers are competitive in each country. They take as given the price of capital goods Q_t (Q_t^*) and choose the output of new capital goods I_t (I_t^*) to maximize the profits. Due to the existence of capital adjustment cost, the output decisions are intertemporally related. Thus, for the domestic capital producers, their objective is to maximize the discounted sum of future profits in the home market, which is given by

$$\max_{\{I_{t+k}\}_{k=0}^{\infty}} \mathbb{E}_t \sum_{k=0}^{\infty} \Lambda_{t,t+k}\left\{Q_{t+k}I_{t+k} - \left[1 + f\left(\frac{I_{t+k}}{I_{t+k-1}}\right)\right]I_{t+k}\right\},$$

where $f(I_t/I_{t-1})$ is the adjustment cost per unit of new capital goods produced. The adjustment cost is quadratic in the net growth of new capital output, i.e. $f(I_t/I_{t-1}) = \frac{\kappa_i}{2}(I_t/I_{t-1}-1)^2$. By taking the derivative of the discounted sum of future profits with respect to I_t, the first-order condition of optimal new capital goods in period t is given by

$$Q_t = 1 + f\left(\frac{I_t}{I_{t-1}}\right) + \frac{I_t}{I_{t-1}} f'\left(\frac{I_t}{I_{t-1}}\right) - \mathbb{E}_t \Lambda_{t,t+1} \left(\frac{I_{t+1}}{I_t}\right)^2 f'\left(\frac{I_{t+1}}{I_t}\right).$$

Note that the last term captures the impact of new capital goods I_t today on future production cost of capital via the adjustment cost function. We assume that the profits of capital producers are rebated as lump-sum payments to households.

Symmetrically, the first-order condition of foreign capital producers is given by

$$Q_t^* = 1 + f\left(\frac{I_t^*}{I_{t-1}^*}\right) + \frac{I_t^*}{I_{t-1}^*} f'\left(\frac{I_t^*}{I_{t-1}^*}\right) - \mathbb{E}_t \Lambda_{t,t+1}^* \left(\frac{I_{t+1}^*}{I_t^*}\right)^2 f'\left(\frac{I_{t+1}^*}{I_t^*}\right).$$

B.6 Retail Firms

Given the CES technology of Y_t in (17) and (18), the domestic final good producers minimize within-period cost of production:

$$P_t Y_t = \int_0^1 \left[P_{Ht}(i) Y_{Ht}(i) + P_{Ft}(i) Y_{Ft}(i)\right] di,$$

where $P_{Ht}(i)$ and $P_{Ft}(i)$ are the nominal home-currency prices of the home and foreign retail good i in home market. The cost minimization implies the isoelastic demand functions:

$$Y_{Ht}(i) = (1-\gamma_y)\left(\frac{P_{Ht}}{P_t}\right)^{-\eta_y}\left(\frac{P_{Ht}(i)}{P_{Ht}}\right)^{-\theta_y} Y_t \text{ and } Y_{Ft}(i) = \gamma_y \left(\frac{P_{Ft}}{P_t}\right)^{-\eta_y}\left(\frac{P_{Ft}(i)}{P_{Ft}}\right)^{-\theta_y} Y_t, \tag{B.18}$$

where P_{Ht} and P_{Ft} are the aggregate price indices of baskets:

$$P_{Ht} = \left[\int_0^1 P_{Ht}(i)^{1-\theta_y} di\right]^{\frac{1}{1-\theta_y}} \quad \text{and} \quad P_{Ft} = \left[\int_0^1 P_{Ft}(i)^{1-\theta_y} di\right]^{\frac{1}{1-\theta_y}}.$$

The retail input choices by foreign final good producers is characterized by a symmetric demand schedule. In particular, the demand for home and foreign retail goods by foreign final good producers is given by:

$$Y_{Ht}^*(i) = \gamma_y \left(\frac{P_{Ht}^*}{P_t^*}\right)^{-\eta_y} \left(\frac{P_{Ht}^*(i)}{P_{Ht}^*}\right)^{-\theta_y} Y_t^* \text{ and } Y_{Ft}^*(j) = (1-\gamma_y) \left(\frac{P_{Ft}^*}{P_t^*}\right)^{-\eta_y} \left(\frac{P_{Ft}^*(j)}{P_{Ft}^*}\right)^{-\theta_y} Y_t^*, \tag{B.19}$$

where $P_{Ht}^*(i)$ and $P_{Ft}^*(i)$ are the nominal foreign-currency prices of the home and foreign retail good i in the foreign market, and where P_{Ht}^* and P_{Ft}^* are the associated aggregate price indices of good baskets:

$$P_{Ht}^* = \left[\int_0^1 P_{Ht}^*(i)^{1-\theta_y} di\right]^{\frac{1}{1-\theta_y}} \quad \text{and} \quad P_{Ft}^* = \left[\int_0^1 P_{Ft}^*(i)^{1-\theta_y} di\right]^{\frac{1}{1-\theta_y}}.$$

The retail firms are monopolistically competitive and set the optimal goods prices according to nominal rigidities as in Calvo (1983). They choose the optimal reset price $P_{Ht}(i)$ and $P_{Ht}^*(i)$ to maximize the discounted value of total real profits, which is given by

$$\begin{aligned}
&\mathbb{E}_t \sum_{k=0}^{\infty} \phi_p^k \Lambda_{t,t+k} \left\{ \left[\frac{P_{Ht}(i)}{P_{t+k}} - p_{m,t+k}\right] Y_{H,t+k}(i) \right. \\
&\left. + \left[\frac{P_{Ht}^*(i)}{\left(\iota\mathcal{E}_t + (1-\iota)\,\mathcal{E}_{t+k}\right) P_{t+k}} - p_{m,t+k}\right] Y_{H,t+k}^*(i) \right\},
\end{aligned}$$

where $\iota \in \{0,1\}$ with $\iota = 1$ corresponding to the case of PCP (producer currency pricing) and $\iota = 0$ to the case of LCP (local currency pricing). From equations (B.18) and (B.19), the demand for good i in domestic and foreign markets are given by

$$\begin{aligned}
Y_{H,t+k}(i) &= (1-\gamma_y) \left(\frac{P_{H,t+k}}{P_{t+k}}\right)^{-\eta_y} \left(\frac{P_{Ht}(i)}{P_{H,t+k}}\right)^{-\theta_y} Y_{t+k}, \\
Y_{H,t+k}^*(i) &= \gamma_y \left(\frac{P_{H,t+k}^*}{P_{t+k}^*}\right)^{-\eta_y} \left(\frac{\mathcal{E}_{t+k} P_{Ht}^*(i)}{\left(\iota\mathcal{E}_t + (1-\iota)\,\mathcal{E}_{t+k}\right) P_{H,t+k}^*}\right)^{-\theta_y} Y_{t+k}^*,
\end{aligned}$$

where Y_{t+k} and Y_{t+k}^* denote the aggregate demand in home and foreign country at period $t+k$.

Denote the optimal reset prices of home retailer i as $\hat{P}_{Ht}(i)$ and $\hat{P}_{Ht}^*(i)$. By taking derivatives of the retailer's objective function with respect to the good prices $P_{Ht}(i)$ and $P_{Ht}^*(i)$, we can obtain the first-order necessary conditions for the retailer's profit maximization problem as following:

$$\sum_{k=0}^{\infty} \phi_p^k \Lambda_{t,t+k} \left[\frac{\hat{P}_{Ht}(i)}{P_{t+k}} - \frac{\theta_y}{\theta_y - 1} \cdot p_{m,t+k}\right] Y_{H,t+k}(i) = 0, \tag{B.20}$$

and

$$\sum_{k=0}^{\infty} \phi_p^k \Lambda_{t,t+k} \left[\frac{\hat{P}_{Ht}^*(i)}{\left(\iota \mathcal{E}_t + (1-\iota)\, \mathcal{E}_{t+k}\right) P_{t+k}} - \frac{\theta_y}{\theta_y - 1} \cdot p_{m,t+k} \right] Y_{H,t+k}^*(i) = 0. \tag{B.21}$$

Due to the identical marginal production cost $p_{m,t+k}$ and the symmetric demand functions $Y_{H,t+k}(i)$ and $Y_{H,t+k}^*(i)$, the optimal reset prices are the same across retailers in the same country. Thus we omit the goods index i of the optimal reset prices as long as it does not cause any confusion. The optimal reset prices do not have a closed-form solution, but can be expressed in a recursive form as follows. We first define following variables:

$$\begin{aligned}
X_{1,Ht} &= \sum_{k=0}^{\infty} \phi_p^k \Lambda_{t,t+k} p_{m,t+k} \left(P_{t+k}\right)^{\eta_y} \left(P_{H,t+k}\right)^{\theta_y - \eta_y} Y_{t+k}, \\
X_{2,Ht} &= \sum_{k=0}^{\infty} \phi_p^k \Lambda_{t,t+k} \left(P_{t+k}\right)^{\eta_y - 1} \left(P_{H,t+k}\right)^{\theta_y - \eta_y} Y_{t+k}, \\
X_{1,Ht}^* &= \sum_{k=0}^{\infty} \phi_p^k \Lambda_{t,t+k} p_{m,t+k} \left(\frac{P_{H,t+k}^*}{P_{t+k}^*} \right)^{-\eta_y} \left(\frac{\mathcal{E}_{t+k}}{\left(\iota \mathcal{E}_t + (1-\iota)\, \mathcal{E}_{t+k}\right) P_{H,t+k}^*} \right)^{-\theta_y} Y_{t+k}^*, \\
X_{2,Ht}^* &= \sum_{k=0}^{\infty} \phi_p^k \Lambda_{t,t+k} \frac{\left(P_{H,t+k}^* / P_{t+k}^*\right)^{-\eta_y}}{\left(\iota \mathcal{E}_t + (1-\iota)\, \mathcal{E}_{t+k}\right) P_{t+k}} \left(\frac{\mathcal{E}_{t+k}}{\left(\iota \mathcal{E}_t + (1-\iota)\, \mathcal{E}_{t+k}\right) P_{H,t+k}^*} \right)^{-\theta_y} Y_{t+k}^*.
\end{aligned}$$

These variables can be written recursively as

$$\begin{aligned}
X_{1,Ht} &= p_{mt} (P_t)^{\eta_y} (P_{Ht})^{\theta_y - \eta_y} Y_t + \phi_p \Lambda_{t,t+1} X_{1,H,t+1}, \\
X_{2,Ht} &= (P_t)^{\eta_y - 1} (P_{Ht})^{\theta_y - \eta_y} Y_t + \phi_p \Lambda_{t,t+1} X_{2,H,t+1}, \\
X_{1,Ht}^* &= p_{mt} (P_t^*)^{\eta_y} \left(P_{Ht}^*\right)^{\theta_y - \eta_y} Y_t^* + \phi_p \Lambda_{t,t+1} \left(\frac{\mathcal{E}_t}{\mathcal{E}_{t+1}} \right)^{\theta_y \cdot \iota} X_{1,H,t+1}^*, \\
X_{2,Ht}^* &= \frac{1}{P_t \mathcal{E}_t} (P_t^*)^{\eta_y} \left(P_{Ht}^*\right)^{\theta_y - \eta_y} Y_t^* + \phi_p \Lambda_{t,t+1} \left(\frac{\mathcal{E}_t}{\mathcal{E}_{t+1}} \right)^{(\theta_y - 1) \cdot \iota} X_{2,H,t+1}^*.
\end{aligned}$$

Hence, by rearranging terms in equations (B.20) and (B.21) and replacing the terms with the above notations, the optimal nominal reset prices of home retailers can be written as

$$\begin{aligned}
\hat{P}_{Ht} &= \frac{\theta_y}{\theta_y - 1} \frac{X_{1,Ht}}{X_{2,Ht}}, \\
\hat{P}_{Ht}^* &= \frac{\theta_y}{\theta_y - 1} \frac{X_{1,Ht}^*}{X_{2,Ht}^*}.
\end{aligned}$$

Moreover, the optimal reset prices in real terms can be expressed as follows. Define $x_{1,Ht} = X_{1,Ht}/(P_t)^{\theta_y}$, $x_{2,Ht} = X_{2,Ht}/(P_t)^{\theta_y - 1}$, $\hat{p}_{Ht} = \hat{P}_{Ht}/P_t$, $p_{Ht} = P_{Ht}/P_t$, the real reset price for home-produced home goods is given by

$$\hat{p}_{Ht} = \frac{\theta_y}{\theta_y - 1}\frac{x_{1,Ht}}{x_{2,Ht}},$$
$$x_{1,Ht} = p_{mt} p_{Ht}^{\theta_y-\eta_y} Y_t + \phi_p \Lambda_{t,t+1} x_{1,H,t+1} (\Pi_{t+1})^{\theta_y},$$
$$x_{2,Ht} = p_{Ht}^{\theta_y-\eta_y} Y_t + \phi_p \Lambda_{t,t+1} x_{2,H,t+1} (\Pi_{t+1})^{\theta_y - 1}.$$

Note that p_{Ht} and $\hat{p}_{Ht}$ are, respectively, the aggregate price index and optimal reset price in real home currency of home retail goods in the home market. Similarly, define $x^*_{1,Ht} = X^*_{1,Ht}/(P^*_t)^{\theta_y}$, $x^*_{2,Ht} = X^*_{2,Ht} P_t \mathcal{E}_t/(P^*_t)^{\theta_y}$, $\hat{p}^*_{Ht} = \hat{P}^*_{Ht}/(P_t\mathcal{E}_t)$, $p^*_{Ht} = P^*_{Ht}/(P_t\mathcal{E}_t)$, the real reset price for home-produced foreign goods is given by

$$\hat{p}^*_{Ht} = \frac{\theta_y}{\theta_y - 1}\frac{x^*_{1,Ht}}{x^*_{2,Ht}},$$
$$x^*_{1,Ht} = p_{mt}(p^*_{Ht} \cdot e_t)^{\theta_y-\eta_y} Y^*_t + \phi_p \Lambda_{t,t+1} \left(\frac{\mathcal{E}_t}{\mathcal{E}_{t+1}}\right)^{\theta_y \cdot \iota} x^*_{1,H,t+1} (\Pi^*_{t+1})^{\theta_y},$$
$$x^*_{2,Ht} = (p^*_{Ht} \cdot e_t)^{\theta_y-\eta_y} Y^*_t + \phi_p \Lambda_{t,t+1} \left(\frac{\mathcal{E}_t}{\mathcal{E}_{t+1}}\right)^{1+(\theta_y-1)\cdot\iota} x^*_{2,H,t+1} \frac{(\Pi^*_{t+1})^{\theta_y}}{\Pi_{t+1}}.$$

Note that p^*_{Ht} and $\hat{p}^*_{Ht}$ are, respectively, the aggregate price index and optimal reset price in real home currency of home retail goods in the foreign market.

For the foreign retailers, the optimal reset prices in real terms can be derived in a similar way. The first-order conditions for their optimal reset prices are given by

$$\sum_{k=0}^{\infty} \phi_p^k \Lambda^*_{t,t+k} \left[\frac{\hat{P}^*_{Ft}(i)}{P^*_{t+k}} - \frac{\theta_y}{\theta_y - 1} \cdot p^*_{m,t+k}\right] Y^*_{F,t+k}(i) = 0,$$

and

$$\sum_{k=0}^{\infty} \phi_p^k \Lambda^*_{t,t+k} \left[\frac{(\iota\mathcal{E}_t + (1-\iota)\,\mathcal{E}_{t+k})\,\hat{P}_{Ft}(i)}{P^*_{t+k}} - \frac{\theta_y}{\theta_y - 1} \cdot p^*_{m,t+k}\right] Y_{F,t+k}(i) = 0,$$

where $\hat{P}^*_{Ft}(i)$ and $\hat{P}_{Ft}(i)$ are the optimal nominal reset prices of foreign retail good i in foreign and domestic markets, and they are also identical across foreign retailers. To obtain the real value of these reset prices, let us denote $\hat{p}^*_{Ft} = \hat{P}^*_{Ft}/P^*_t$, $p^*_{Ft} = P^*_{Ft}/P^*_t$, $\hat{p}_{Ft} = \hat{P}_{Ft}\mathcal{E}_t/P^*_t$, $p_{Ft} = P_{Ft}\mathcal{E}_t/P^*_t$. Note that p^*_{Ft} and $\hat{p}^*_{Ft}$ are the aggregate price index and optimal reset price in real foreign currency of foreign retail goods sold in the foreign market, and p_{Ft} and $\hat{p}_{Ft}$ are the aggregate price index and optimal reset price in real foreign currency of foreign retail goods sold in the home market. The optimal reset prices in real terms can be written in the following recursive form:

$$\hat{p}^*_{Ft} = \frac{\theta_y}{\theta_y - 1}\frac{x^*_{1,F,t}}{x^*_{2,F,t}},$$
$$x^*_{1,Ft} = p^*_{mt}(p^*_{Ft})^{\theta_y-\eta_y}Y^*_t + \phi_p\Lambda^*_{t,t+1}x^*_{1,F,t+1}(\Pi^*_{t+1})^{\theta_y},$$
$$x^*_{2,Ft} = (p^*_{Ft})^{\theta_y-\eta_y}Y^*_t + \phi_p\Lambda^*_{t,t+1}x^*_{2,F,t+1}(\Pi^*_{t+1})^{\theta_y-1},$$

and

$$\hat{p}_{Ft} = \frac{\theta_y}{\theta_y - 1}\frac{x_{1,F,t}}{x_{2,F,t}},$$
$$x_{1,Ft} = p^*_{mt}\left(\frac{p_{Ft}}{e_t}\right)^{\theta_y-\eta_y}Y_t + \phi_p\Lambda^*_{t,t+1}\left(\frac{\mathcal{E}_{t+1}}{\mathcal{E}_t}\right)^{\theta_y\cdot\iota}x_{1,F,t+1}(\Pi_{t+1})^{\theta_y},$$
$$x_{2,Ft} = \left(\frac{p_{Ft}}{e_t}\right)^{\theta_y-\eta_y}Y_t + \phi_p\Lambda^*_{t,t+1}\left(\frac{\mathcal{E}_{t+1}}{\mathcal{E}_t}\right)^{1+(\theta_y-1)\cdot\iota}x_{2,F,t+1}\frac{(\Pi_{t+1})^{\theta_y}}{\Pi^*_{t+1}}.$$

B.7 Aggregation

This section characterizes the evolution of aggregate price indices of retail goods baskets, aggregate demand and budget constraint of each country.

Price aggregation. In principle, we need a market clearing condition for each retail good variety, since the prices can be heterogeneous. Thanks to the homothetic preference and i.i.d. opportunity of resetting prices, we are able to derive the aggregate price dynamics in a recursive form. In particular, the laws of motion of nominal price indices of home retail goods baskets sold in each country are given by

$$P_{Ht} = \left[\int_0^1 P_{Ht}(i)^{1-\theta_y}di\right]^{\frac{1}{1-\theta_y}} = \left[(1-\phi_p)\left(\hat{P}_{Ht}\right)^{1-\theta_y} + \phi_p\left(P_{H,t-1}\right)^{1-\theta_y}\right]^{\frac{1}{1-\theta_y}},$$
$$P^*_{Ht} = \left[\int_0^1 P^*_{Ht}(i)^{1-\theta_y}di\right]^{\frac{1}{1-\theta_y}} = \left[(1-\phi_p)\left(\hat{P}^*_{Ht}\right)^{1-\theta_y} + \phi_p\left(P^*_{H,t-1}\right)^{1-\theta_y}\right]^{\frac{1}{1-\theta_y}}.$$

Denote the real price indices of home baskets in home currency as $p_{Ht} = P_{Ht}/P_t$ and $p^*_{Ht} =$

$\frac{P^*_{Ht}}{P_t \mathcal{E}_t}$, the above equations imply

$$p_{Ht} = \left[(1 - \phi_p) \left(\hat{p}_{Ht} \right)^{1-\theta_y} + \phi_p \left(\frac{p_{H,t-1}}{\Pi_t} \right)^{1-\theta_y} \right]^{\frac{1}{1-\theta_y}}, \tag{B.22}$$

$$p^*_{Ht} = \left[(1 - \phi_p) \left(\hat{p}^*_{Ht} \right)^{1-\theta_y} + \phi_p \left(\frac{p^*_{H,t-1}}{\Pi_t} \cdot \frac{\mathcal{E}_{t-1}}{\mathcal{E}_t} \right)^{1-\theta_y} \right]^{\frac{1}{1-\theta_y}}. \tag{B.23}$$

Note that the nominal exchange rate is $\mathcal{E}_t = \frac{e_t P^*_t}{P_t}$, then it follows that

$$\frac{\mathcal{E}_t}{\mathcal{E}_{t-1}} = \frac{\Pi^*_t}{\Pi_t} \cdot \frac{e_t}{e_{t-1}}.$$

For the foreign producers, denote the real price indices of foreign retail goods baskets in foreign currency as $p^*_{Ft} = P^*_{Ft}/P^*_t$ and $p_{Ft} = \frac{P_{Ft}\mathcal{E}_t}{P^*_t}$. The laws of motion for these price indices are similar to the home goods baskets:

$$p^*_{Ft} = \left[(1 - \phi_p) \left(\hat{p}^*_{Ft} \right)^{1-\theta_y} + \phi_p \left(\frac{p^*_{F,t-1}}{\Pi^*_t} \right)^{1-\theta_y} \right]^{\frac{1}{1-\theta_y}}, \tag{B.24}$$

$$p_{Ft} = \left[(1 - \phi_p) \left(\hat{p}_{Ft} \right)^{1-\theta_y} + \phi_p \left(\frac{p_{F,t-1}}{\Pi^*_t} \cdot \frac{\mathcal{E}_t}{\mathcal{E}_{t-1}} \right)^{1-\theta_y} \right]^{\frac{1}{1-\theta_y}}. \tag{B.25}$$

At the country level, the price index of aggregate home demand satisfies:

$$\begin{aligned} 1 &= \left[(1 - \gamma_y) \left(\frac{P_{Ht}}{P_t} \right)^{1-\eta_y} + \gamma_y \left(\frac{P_{Ft}}{P_t} \right)^{1-\eta_y} \right]^{\frac{1}{1-\eta_y}} \\ &= (1 - \gamma_y) \left(p_{Ht} \right)^{1-\eta_y} + \gamma_y \left(\frac{p_{Ft}}{e_t} \right)^{1-\eta_y}, \end{aligned}$$

where in the second and third equality, we apply the definitions of p_{Ht}, p_{Ft} and e_t given above. Similarly, the real price index of aggregate foreign demand should satisfy

$$1 = (1 - \gamma_y) \left(p^*_{Ft} \right)^{1-\eta_y} + \gamma_y \left(p^*_{Ht} \cdot e_t \right)^{1-\eta_y}.$$

The above relations allow us to pin down the inflation rates of aggregate price indices at country level via the aggregate prices (B.22), (B.23), (B.24) and (B.25). In particlar, the domestic inflation rate is given by

$$1 = (1-\gamma_y)\left[(1-\phi_p)\left(\hat{p}_{Ht}\right)^{1-\theta_y} + \phi_p\left(\frac{p_{H,t-1}}{\Pi_t}\right)^{1-\theta_y}\right]^{\frac{1-\eta_y}{1-\theta_y}}$$

$$+\gamma_y\left[(1-\phi_p)\left(\frac{\hat{p}_{Ft}}{e_t}\right)^{1-\theta_y} + \phi_p\left(\frac{p_{F,t-1}}{\Pi_t\cdot e_{t-1}}\right)^{1-\theta_y}\right]^{\frac{1-\eta_y}{1-\theta_y}},$$

and the foreign inflation rate is given by

$$1 = (1-\gamma_y)\left[(1-\phi_p)\left(\hat{p}^*_{Ft}\right)^{1-\theta_y} + \phi_p\left(\frac{p^*_{F,t-1}}{\Pi^*_t}\right)^{1-\theta_y}\right]^{\frac{1-\eta_y}{1-\theta_y}}$$

$$+\gamma_y\left[(1-\phi_p)\left(\hat{p}^*_{Ht}\cdot e_t\right)^{1-\theta_y} + \phi_p\left(\frac{p^*_{H,t-1}\cdot e_{t-1}}{\Pi^*_t}\right)^{1-\theta_y}\right]^{\frac{1-\eta_y}{1-\theta_y}}.$$

Demand aggregation. For each variety of goods sold by retail firms, we have a market clearing condition: $Y_t(i) = Y_{Ht}(i) + Y^*_{Ht}(i)$. The variable $Y_t(i)$ is the total output of this retail good, and the demand by domestic and foreign markets are given by

$$Y_{Ht}(i) = (1-\gamma_y)\left(\frac{P_{Ht}}{P_t}\right)^{-\eta_y}\left(\frac{P_{Ht}(i)}{P_{Ht}}\right)^{-\theta_y} Y_t,$$

$$Y^*_{Ht}(i) = \gamma_y\left(\frac{P^*_{Ht}}{P^*_t}\right)^{-\eta_y}\left(\frac{P^*_{Ht}(i)}{P^*_{Ht}}\right)^{-\theta_y} Y^*_t,$$

where the country-level aggregate demand is

$$Y_t = C_t + \left[1 + f\left(\frac{I_t}{I_{t-1}}\right)\right] I_t + G + \left\{\frac{\kappa_1}{2}\left[\frac{Q^*_t\left(S_{Ft}-\bar{S}_F\right)}{e_t N_t}\right]^2 + \frac{\kappa_2}{2}\left[\frac{q^*_t\left(B_{Ft}-\bar{B}_F\right)}{e_t N_t}\right]^2\right\} N_t,$$

and

$$Y^*_t = C^*_t + \left[1 + f\left(\frac{I^*_t}{I^*_{t-1}}\right)\right] I^*_t + G^* + \left\{\frac{\kappa_1}{2}\left[\frac{Q_t e_t\left(S^*_{Ht}-\bar{S}^*_H\right)}{N^*_t}\right]^2 + \frac{\kappa_2}{2}\left[\frac{q_t e_t\left(B^*_{Ht}-\bar{B}^*_H\right)}{N^*_t}\right]^2\right\} N^*_t.$$

We can integrate the demand for intermediate goods across retailers and obtain the aggregate output of intermediate goods producers, which allows us to pin down the aggregate labor and capital demand. In particular, let $Y_{mt} = \int_0^1 Y_t(i)di$ and $Y^*_{mt} = \int_0^1 Y^*_t(i)di$ be the aggregate output of intermediate goods producers in home and foreign country, which represent the aggregate supply at country level. The home aggregate output of intermediate goods can be expressed as

$$Y_{mt} = \int_0^1 Y_t(i)di = (1-\gamma_y)p_{Ht}^{\theta_y-\eta_y}\zeta_{Ht}Y_t + \gamma_y(p_{Ht}^* \cdot e_t)^{\theta_y-\eta_y}\zeta_{Ht}^*Y_t^*,$$

where ζ_{Ht} and ζ_{Ht}^* are measures of price dispersion of home retail goods sold in home and foreign markets:

$$\zeta_{Ht} = \int_0^1 \left(\frac{P_{Ht}(i)}{P_t}\right)^{-\theta_y} di,$$

$$\zeta_{Ht}^* = \int_0^1 \left(\frac{P_{Ht}^*(i)}{P_t^*}\right)^{-\theta_y} di.$$

Since the price resetting opportunity is i.i.d. across retailers, we can derive the law of motion of the price dispersion measure ζ_{Ht} as follows:

$$\begin{aligned}\zeta_{Ht} &= (1-\phi_p)\left(\hat{p}_{Ht}\right)^{-\theta_y} + \int_{1-\phi_p}^1 \left(\frac{P_{H,t-1}(i)}{P_t}\right)^{-\theta_y} di \\ &= (1-\phi_p)\left(\hat{p}_{Ht}\right)^{-\theta_y} + \left(\frac{P_{t-1}}{P_t}\right)^{-\theta_y} \int_{1-\phi_p}^1 \left(\frac{P_{H,t-1}(i)}{P_{t-1}}\right)^{-\theta_y} di.\end{aligned}$$

Via the law of large numbers, this reduces to

$$\zeta_{Ht} = (1-\phi_p)\left(\hat{p}_{Ht}\right)^{-\theta_y} + \phi_p \Pi_t^{\theta_y}\zeta_{H,t-1}.$$

Similarly, the law of motion of price dispersion measure ζ_{Ht}^* can be written as

$$\zeta_{Ht}^* = (1-\phi_p)\left(\hat{p}_{Ht}^* \cdot e_t\right)^{-\theta_y} + \phi_p \left(\Pi_t^*\right)^{\theta_y}\zeta_{H,t-1}^*.$$

On the other hand, the foreign country's aggregate output of intermediate goods can be expressed as

$$Y_{mt}^* = (1-\gamma_y)(p_{Ft}^*)^{\theta_y-\eta_y}\zeta_{Ft}^*Y_t^* + \gamma_y\left(\frac{p_{Ft}}{e_t}\right)^{\theta_y-\eta_y}\zeta_{Ft}Y_t,$$

where the price dispersion measures are given by

$$\begin{aligned}\zeta_{Ft}^* &= (1-\phi_p)\left(\hat{p}_{Ft}^*\right)^{-\theta_y} + \phi_p\left(\Pi_t^*\right)^{\theta_y}\zeta_{F,t-1}^*, \\ \zeta_{Ft} &= (1-\phi_p)\left(\frac{\hat{p}_{Ft}}{e_t}\right)^{-\theta_y} + \phi_p\left(\Pi_t\right)^{\theta_y}\zeta_{F,t-1}.\end{aligned}$$

Country budget constraint. As in Itskhoki and Mukhin (2021), the model equilibrium requires a budget constraint for the home country, which is derived as follows.

First, the aggregate profits of domestic retail firms are given by

$$\begin{aligned}
&\int_0^1 \left(\frac{P_{Ht}(i)}{P_t} - p_{mt}\right) Y_{Ht}(i)di + \int_0^1 \left(\frac{P^*_{Ht}(i)}{\mathcal{E}_t P_t} - p_{mt}\right) Y^*_{Ht}(i)di \\
&= \int_0^1 \left[\frac{P_{Ht}(i)}{P_t} Y_{Ht}(i) + \frac{P_{Ft}(i)}{P_t} Y_{Ft}(i)\right] di + \int_0^1 \frac{P^*_{Ht}(i)}{\mathcal{E}_t P_t} Y^*_{Ht}(i)di - \int_0^1 \frac{P_{Ft}(i)}{P_t} Y_{Ft}(i)di - p_{mt} Y_{mt} \\
&= Y_t + NX_t - p_{mt} Y_{mt},
\end{aligned}$$

where NX_t represents the net exports of US. In the second line we use the domestic intermediate goods market clearing condition $Y_{mt} = \int_0^1 \left[Y_{Ht}(i) + Y^*_{Ht}(i)\right] di$, and in the third line we use the domestic final goods producers' zero-profit condition $P_t Y_t = \int_0^1 [P_{Ht}(i) Y_{Ht}(i) + P_{Ft}(i) Y_{Ft}(i)] di$ and the definition of US net exports $NX_t = \int_0^1 \frac{P^*_{Ht}(i)}{\mathcal{E}_t P_t} Y^*_{Ht}(i)di - \int_0^1 \frac{P_{Ft}(i)}{P_t} Y_{Ft}(i)di$.

Given the expression of retailers' profits, we can write the nonfinancial and financial firms' aggregate payouts to the home households DIV_t as

$$\begin{aligned}
DIV_t = & \underbrace{(1-\sigma)N_{et}}_{\text{Net worth of home exit banks}} - \underbrace{\left\{\frac{\kappa_1}{2}\left[\frac{Q^*_t(S_{Ft} - \bar{S}_F)}{e_t N_t}\right]^2 + \frac{\kappa_2}{2}\left[\frac{q^*_t(B_{Ft} - \bar{B}_F)}{e_t N_t}\right]^2\right\} N_t}_{\text{Home banks' holding cost}} \\
& + \underbrace{\eta\left(\frac{R^*_{t-1} e_{t-1}}{e_t} - R_{t-1}\right) D_{s,t-1}}_{\text{Dealers' profits to home HH}} + \underbrace{Q_t I_t - \left[1 + f\left(\frac{I_t}{I_{t-1}}\right)\right] I_t}_{\text{Home capital producers' profits}} \\
& + \underbrace{Y_t + NX_t - p_{mt} Y_{mt}}_{\text{Home retailers' profits}}, \qquad \text{(B.26)}
\end{aligned}$$

where N_{et} represents the aggregate net worth of existing banks at the beginning of period t before occupation shocks. From equation (5), the expression of N_{et} is given by

$$\begin{aligned}
N_{et} &= R_{kt} Q_{t-1} S_{H,t-1} + R_{bt} q_{t-1} B_{H,t-1} + \frac{R^*_{kt}}{e_t} Q^*_{t-1} S_{F,t-1} + \frac{R^*_{bt}}{e_t} q^*_{t-1} B_{F,t-1} - R_{t-1} D_{t-1} \\
&= \left[Z_t + (1-\delta) Q_t\right] K_t - R_{kt} Q_{t-1} S^*_{H,t-1} + R_{bt} q_{t-1}(B_{t-1} - B^*_{H,t-1} - B_{g,t-1}) \\
&\quad + \frac{R^*_{kt}}{e_t} Q^*_{t-1} S_{F,t-1} + \frac{R^*_{bt}}{e_t} q^*_{t-1} B_{F,t-1} - R_{t-1} D_{t-1}, \qquad \text{(B.27)}
\end{aligned}$$

where the first line is the definition of N_{et}, and in the second line we use the definition $R_{kt} \equiv \frac{Z_t + (1-\delta) Q_t}{Q_{t-1}}$, the equity market clearing condition $K_t = S_{t-1} = S_{H,t-1} + S^*_{H,t-1}$ and the long-term bond market clearing condition $B_t = B_{Ht} + B^*_{Ht} + B_{gt}$. In addition, combining (B.27) with the law of motion of aggregate bank net worth N_t, we can rewrite the expression of N_t as

$$N_t = \sigma N_{et} + X. \qquad \text{(B.28)}$$

Next, by aggregating individual bank balance sheet (4) and replacing N_t with equation (B.28), we obtain the following equation for domestic banks' aggregate balance sheet:

$$Q_t S_{Ht} + q_t B_{Ht} + \frac{Q_t^* S_{Ft} + q_t^* B_{Ft}}{e_t} = \sigma N_{et} + X + D_t. \tag{B.29}$$

Finally, we add up domestic households' budget constraint (1), domestic banks' aggregate balance sheet (B.29) and domestic consolidated government budget constraint (19), resulting after rearranging in:

$$\begin{aligned}
&C_t + G + \left[1 + f\left(\frac{I_t}{I_{t-1}}\right)\right] I_t + \left\{\frac{\kappa_1}{2}\left[\frac{Q_t^*(S_{Ft} - \bar{S}_F)}{e_t N_t}\right]^2 + \frac{\kappa_2}{2}\left[\frac{q_t^*(B_{Ft} - \bar{B}_F)}{e_t N_t}\right]^2\right\} N_t - Y_t \\
&= \left(Q_t S_{Ht}^* - R_{kt} Q_{t-1} S_{H,t-1}^*\right) - \left(Q_t^* S_{Ft} - R_{kt}^* Q_{t-1}^* S_{F,t-1}\right)/e_t \\
&\quad + \left(q_t B_{Ht}^* - R_{bt} q_{t-1} B_{H,t-1}^*\right) - \left(q_t^* B_{Ft} - R_{bt}^* q_{t-1}^* B_{F,t-1}\right)/e_t \\
&\quad + \eta\left(\frac{R_{t-1}^* e_{t-1}}{e_t} - R_{t-1}\right) D_{s,t-1} + NX_t + R_{t-1}\tilde{D}_{s,t-1} - \tilde{D}_{st},
\end{aligned} \tag{B.30}$$

where $\tilde{D}_{st} \equiv D_{ht} - D_t - D_{gt}$ is the home country's holdings of US short-term debt issued by FX dealers in the international financial market. In the derivation, we substitute the expressions for DIV_t and N_{et}, and employ the intermediate goods producers' zero-profit condition $p_{mt} Y_{mt} = w_t L_t + Z_t K_t$, the equity market clearing condition $K_{t+1} = S_t = S_{H,t} + S_{H,t}^*$, the long-term bond market clearing condition $B_t = B_{Ht} + B_{Ht}^* + B_{gt}$.

The first line of equation (B.30) represents the net demand for domestic final goods, which is zero given the domestic final goods market clearing condition (21). In addition, combine (B.30) with the US short-term debt market clearing condition $D_{st} = \tilde{D}_{st}$, we obtain the home country budget constraint:

$$\begin{aligned}
D_{st} &= \left(Q_t S_{Ht}^* - R_{kt} Q_{t-1} S_{H,t-1}^*\right) - \left(Q_t^* S_{Ft} - R_{kt}^* Q_{t-1}^* S_{F,t-1}\right)/e_t \\
&\quad + \left(q_t B_{Ht}^* - R_{bt} q_{t-1} B_{H,t-1}^*\right) - \left(q_t^* B_{Ft} - R_{bt}^* q_{t-1}^* B_{F,t-1}\right)/e_t \\
&\quad + \eta\left(\frac{R_{t-1}^* e_{t-1}}{e_t} - R_{t-1}\right) D_{s,t-1} + NX_t + R_{t-1} D_{s,t-1},
\end{aligned} \tag{B.31}$$

Note that this equation aligns with the currency market clearing condition in (**??**) and (13). The reason is that equation (B.31) achieves the market clearing of US short-term debt in the international financial market, with the right-hand side being home country's demand $\tilde{D}_{st}$ from equation (B.30), and the left-hand side representing FX dealers' supply. Through FX dealers' zero-capital balance sheet, equation (B.31) inherently implies the clearing of currency market.

A paralell equation to (B.30) for foreign country is

$$
\begin{aligned}
& C_t^* + G^* + \left[1 + f\left(\frac{I_t^*}{I_{t-1}^*}\right)\right] I_t^* + \left\{\frac{\kappa_1}{2}\left[\frac{e_t Q_t (S_{Ht}^* - \bar{S}_H^*)}{N_t^*}\right]^2 + \frac{\kappa_2}{2}\left[\frac{e_t q_t (B_{Ht}^* - \bar{B}_H^*)}{N_t^*}\right]^2\right\} N_t^* - Y_t^* \\
= & \left(Q_t^* S_{Ft} - R_{kt}^* Q_{t-1}^* S_{F,t-1}\right) - \left(Q_t S_{Ht}^* - R_{kt} Q_{t-1} S_{H,t-1}^*\right) \cdot e_t \\
& + \left(q_t^* B_{Ft} - R_{bt}^* q_{t-1}^* B_{F,t-1}\right) - \left(q_t B_{Ht}^* - R_{bt} q_{t-1} B_{H,t-1}^*\right) \cdot e_t \\
& - R_{t-1}^* D_{s,t-1} e_{t-1} + (1-\eta)\left(\frac{R_{t-1}^* e_{t-1}}{e_t} - R_{t-1}\right) D_{s,t-1} e_t + NX_t^* + D_{st} e_t \\
= & -e_t \cdot (D_{dt} - D_{st}),
\end{aligned}
$$

where NX_t^* is the net exports of foreign country. In the first equality, we apply FX dealers' zero-capital balance sheet. In the second equality, we use $NX_t^* = -NX_t \cdot e_t$. The foreign final goods market clearing condition implies that the foreign country budget constraint is also given by $D_{dt} = D_{st}$. As stated in Itskhoki and Mukhin (2021), this is a version of *Walras Law* in our economy with FX dealers, making the foreign country budget constraint a redundant equation in the equilibrium system.

B.8 Definition of Equilibrium

In the model equilibrium, each type of agents solve their own maximization problem, and all the markets clear. Therefore, we define the model equilibrium as follows.

Definition. Given sequences of monetary shocks $\{\varepsilon_{it}, \varphi_{gt}\}$, a *competitive equilibrium* is a path of home household decisions $\{C_t, L_t, D_{ht}, X\}$, foreign household decisions $\{C_t^*, L_t^*, D_{ht}^*, X^*\}$, home producer decisions $\{K_t, L_{pt}, I_t, Y_t, Y_{Ht}, Y_{Ft}, Y_{Ht}(i), Y_{Ft}(i), Y_{mt}\}$, foreign producer decisions $\left\{K_t^*, L_{pt}^*, I_t^*, Y_{Ht}^*, Y_{Ft}^*, Y_{Ht}^*(i), Y_{Ft}^*(i), Y_{mt}^*\right\}$, home bank decisions $\{s_{ht}, b_{ht}, s_{ft}, b_{ft}, n_t\}$, foreign bank decisions $\left\{s_{ht}^*, b_{ht}^*, s_{ft}^*, b_{ft}^*, n_t^*\right\}$, aggregate quantities $\{S_{Ht}, S_{Ht}^*, B_{Ht}, B_{Ht}^*, S_{Ft}, S_{Ft}^*, B_{Ft}, B_{Ft}^*, N_t, N_t^*\}$, FX dealer decisions $\{D_{st}\}$, prices $\{e_t, w_t, w_t^*, Z_t, Z_t^*, Q_t, Q_t^*, q_t, q_t^*, p_{Ht}, p_{Ht}^*, p_{Ft}, p_{Ft}^*\}$, asset returns $\{R_{kt}, R_{bt}, R_t, R_{kt}^*, R_{bt}^*, R_t^*\}$, inflation rates $\{\Pi_t, \Pi_t^*\}$, fiscal and monetary variables $\left\{G, B_{gt}, T_t, i_t, G^*, B_{gt}^*, T_t^*, i_t^*\right\}$, such that at every period t: (1) households, producers, banks and FX dealers maximize their objective functions taking as given equilibrium prices, taxes, and transfers; (2) the government budget constraint and monetary policy rules hold; (3) all markets clear: intermediate goods markets, retail goods markets, final goods markets, capital goods markets, labor markets, liquid asset (deposits and short-term bond) markets, the markets for firm equity, the markets for long-term government bonds and the market for balance of payment.

B.9 An Alternative Model without Final Good Producers

This section develops an alternative model without final good producers as in Itskhoki and Mukhin (2021). The model differs from the baseline model in the following three aspects. First, the households' intertemporal decisions are the same as the baseline model, while within a period they consume varieties of goods from home and foreign producers directly. Second, there are no final good producers, and the retailers and intermediate good firms are integrated into a continuum of goods producers. Third, the input of capital producers, government expenditure and the holding cost of bank portfolio adjustment, are the composite of home and foreign varieties of goods with the same aggregator as households' consumption. We provide more details on the setup of households and goods producers below.

Households. The home households allocate their within-period consumption expenditure $P_t C_t$ between home and foreign varieties of goods $C_{jt}(i)$, for $j \in \{H, F\}$ and $i \in [0, 1]$ via a two-layer CES aggregator:

$$C_t = \left[(1-\gamma_c)^{\frac{1}{\eta_c}} C_{Ht}^{\frac{\eta_c - 1}{\eta_c}} + \gamma_c^{\frac{1}{\eta_c}} C_{Ft}^{\frac{\eta_c-1}{\eta_c}}\right]^{\frac{\eta_c}{\eta_c-1}} \tag{B.32}$$

and

$$C_{jt} = \left[\int_0^1 C_{jt}(i)^{\frac{\theta_c-1}{\theta_c}} di\right]^{\frac{\theta_c}{\theta_c-1}} \quad \text{for } j \in \{H, F\}, \tag{B.33}$$

where C_{Ht} and C_{Ft} are baskets of individual home and foreign produced goods, $\eta_c > 1$ measures the elasticity of substitution between home and foreign goods, $\gamma_c \in \left[0, \frac{1}{2}\right)$ measures the degree of home bias, $\theta_c > 1$ measures the elasticity of substitution between goods within baskets.

The households minimize expenditure $P_t C_t = \int_0^1 \left[P_{Ht}(i) C_{Ht}(i) + P_{Ft}(i) C_{Ft}(i)\right] di$ subject to the CES aggregator (B.32) and (B.33), where $P_{Ht}(i)$ and $P_{Ft}(i)$ are the nominal home-currency prices of the home and foreign variety i in the home market. This implies the following isoelastic demand functions:

$$C_{Ht}(i) = (1-\gamma_c)\left(\frac{P_{Ht}}{P_t}\right)^{-\eta_c}\left(\frac{P_{Ht}(i)}{P_{Ht}}\right)^{-\theta_c} C_t \text{ and } C_{Ft}(i) = \gamma_c \left(\frac{P_{Ft}}{P_t}\right)^{-\eta_c}\left(\frac{P_{Ft}(i)}{P_{Ft}}\right)^{-\theta_c} C_t,$$

where P_{Ht} and P_{Ft} are the aggregate price indices of goods baskets:

$$P_{Ht} = \left[\int_0^1 P_{Ht}(i)^{1-\theta_c} di \right]^{\frac{1}{1-\theta_c}} \quad \text{and} \quad P_{Ft} = \left[\int_0^1 P_{Ft}(i)^{1-\theta_c} di \right]^{\frac{1}{1-\theta_c}}.$$

The expenditure allocation of the foreign households is characterized by a symmetric demand schedule. In particular, the demand for home and foreign goods by foreign households is given by:

$$C^*_{Ht}(i) = \gamma_c \left(\frac{P^*_{Ht}}{P^*_t} \right)^{-\eta_c} \left(\frac{P^*_{Ht}(i)}{P^*_{Ht}} \right)^{-\theta_c} C^*_t \text{ and } C^*_{Ft}(i) = (1-\gamma_c) \left(\frac{P^*_{Ft}}{P^*_t} \right)^{-\eta_c} \left(\frac{P^*_{Ft}(i)}{P^*_{Ft}} \right)^{-\theta_c} C^*_t,$$

where $P^*_{Ht}(i)$ and $P^*_{Ft}(i)$ are the nominal foreign-currency prices of the home and foreign variety i in the foreign market, and where P^*_{Ht} and P^*_{Ft} are the aggregate price indices of baskets:

$$P^*_{Ht} = \left[\int_0^1 P^*_{Ht}(i)^{1-\theta_c} di \right]^{\frac{1}{1-\theta_c}} \quad \text{and} \quad P^*_{Ft} = \left[\int_0^1 P^*_{Ft}(i)^{1-\theta_c} di \right]^{\frac{1}{1-\theta_c}}.$$

Goods producers. The goods producers are monopolistically competitive. Each of them produces a variety of good $i \in [0,1]$ and sells the output in home and foreign markets, according to the production function

$$Y_t(i) = A_t K^\alpha_t(i) L^{1-\alpha}_{pt}(i).$$

The goods producers take as given the real wage rate w_t and the real capital return Z_t to banks, and set the optimal goods prices subject to nominal rigidities as in Calvo (1983). Since the production function is contant returns to scale in capital and labor, it follows that the producers face a constant marginal cost of production, which is given by the cost minimization problem:

$$\begin{aligned} MC_t &= \min_{K_t, L_t} \left\{ Z_t K_t + w_t L_{pt}; \text{s.t. } A_t K^{1-\alpha}_t L^\alpha_{pt} = 1. \right\} \\ &= \frac{1}{A_t} \left(\frac{Z_t}{\alpha} \right)^\alpha \left(\frac{w_t}{1-\alpha} \right)^{1-\alpha}. \end{aligned}$$

The corresponding labor demand and capital demand are given by

$$w_t = \frac{(1-\alpha) MC_t Y_t(i)}{L_{pt}(i)},$$

and

$$Z_t = \frac{\alpha MC_t Y_t(i)}{K_t(i)}.$$