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FX interventions as a form of unconventional monetary policy

Tobias Cwik and Christoph Winter[*†]

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Abstract

In the aftermath of the Great Financial Crisis (GFC), central banks from several advanced, small, open economies have used FX interventions (FXI) in order to stimulate inflation, given that their policy rates were very low. We present a quantitative DSGE model that allows us to study the effectiveness of this unconventional monetary policy tool. We apply the model to Switzerland, a country that has seen frequent and sizable central bank interventions. The model implies that FXI are effective and long-lasting: FXI of approximately CHF 27 billion (5% of annual GDP) are necessary to prevent the Swiss franc from appreciating by 1.1%. The effect is stronger the longer the central bank can commit to keep its policy rate constant in response to the inflationary effect of the interventions. We also find that FXI create significant additional leeway for monetary policy in small, open economies. This effect can be shown by the "shadow rate", the policy rate required to keep CPI inflation on its realised path without FXI. This "shadow rate" was up to 1 pp below the realised policy rate and close to −1.5% from 2015 to mid-2022 in Switzerland. Our framework also allows us to study the sensitivity of the shadow rate in an environment in which the policy rate is at (or close to) its lower bound. If the persistence of the policy rate increases at the lower bound, the shadow rate rises in absolute terms.

Keywords: Monetary policy, FX intervention, shadow rate, DSGE model
JEL Codes: C54, E52, F41

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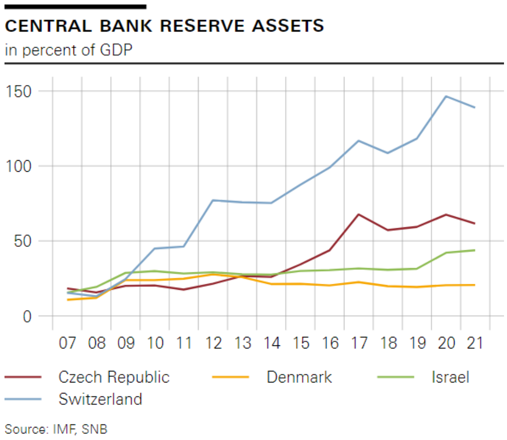


Figure 1: Reserve assets/GDP of central banks from selected advanced, open economies

1 Introduction

In the aftermath of the Great Financial Crisis, many central banks have used so-called unconventional monetary policies in an attempt to stimulate inflation, given that their policy rates were very low. The main examples are purchases of domestic government and corporate bonds, which aimed to lower long-term interest rates and ensure the smooth functioning of financial markets. Commonly, these policies are summarised under the label “Quantitative Easing” (QE). Dell’Ariccia et al. (2018), Bhattarai and Neely (2020) and Kuttner (2018) provide excellent surveys on QE.

However, these QE programmes have been mainly implemented by central banks in large economies.[1] Central banks from small open economies face different options and constraints. First, their domestic bond markets are typically small. Second, the exchange rate channel of monetary policy plays an important role for them. Consequently, they have used a different type of unconventional monetary policy: FX market interventions, that is, purchasing foreign assets with the aim to influence the exchange rate. In Figure 1, we show reserve assets of central banks of several advanced, small, open economies, namely, the Czech Republic, Denmark, Israel and Switzerland.[2]

All of these central banks have seen a substantial increase in their reserve assets following the GFC as a result of large-scale FXI – with the exception of the National Bank of Denmark.[3]

[1] A notable exception is Sweden; see, e.g. De Rezende (2017). In 2009–2010, the Swiss National Bank (SNB) also conducted a bond purchase programme that was very limited in size, see Kettemann and Krogstrup (2014) for details.

[2] According to the Balance of Payments Textbook (IMF, 2016), paragraph 625, “[...]reserve assets are defined as monetary gold held by the authorities of a country, the authorities’ claims on nonresidents, holdings of IMF special drawing rights (SDRs), and a country’s reserve position in the Fund. [...].” Source: `https://www.elibrary.imf.org/display/book/9781557755704/ch12.xml`. Retrieved on 14 April 2023.

[3] After conducting FXI in 2011 and at the beginning of 2015, the National Bank of Demark reduced its foreign asset holdings to stabilise its foreign reserves at 20% of GDP.

Motivated by this fact, we analyse the following question: How effective are FXI in stimulating inflation? To answer this question, we build a quantitative model and apply it to Switzerland. The advantage of our model-based approach is that it enables us to clearly identify the impact of FXI and to separate it from other monetary policy actions. In addition, we use our quantitative model to calculate counterfactuals.

We select Switzerland for the following reasons. First, as shown in Figure 1, the reserve assets of the Swiss National Bank (SNB) have increased to almost 150% of GDP at their peak, more than in the other central banks. Second, in addition to its large FXI, the SNB has also employed a negative policy rate as an additional unconventional monetary policy instrument: in January 2015, the SNB lowered its policy rate to −0.75% and kept it in negative territory until September 2022. Hence, we use our model to study the extent to which lowering the policy rate into negative territory was a substitute for FXI.

Our findings suggest that FXI are effective and long-lasting: FXI of approximately CHF 27 billion (5% of annual GDP) are necessary to prevent the Swiss franc from appreciating by 1.1%. This result assumes a credible commitment to not increasing the policy rate in the three years following the intervention. Larger interventions are needed if the policy rate is expected to rise sooner. If the policy rate is close to its lower bound, it is unlikely to rise in the near term. Therefore, an important result of our analysis is that FXI are more effective when the effective lower bound is binding.

We use the model to compute several counterfactuals, which can be summarised as follows:

- FXI are an effective tool for small, open economies to stabilize inflation around its target. Without FXI, Swiss inflation would have been negative from mid-2010 to 2022.
- FXI create significant additional leeway for monetary policy in small, open economies. This can be shown by the "shadow rate," the policy rate required to keep CPI inflation on its realised path without FXI. This "shadow rate" was up to 1 pp below the realised policy rate and close to −1.5% from 2015 to mid-2022 in Switzerland.
- Our framework also allows us to study the sensitivity of the shadow rate in an environment in which the policy rate is at (or close to) its lower bound. If the persistence of the policy rate increases at the lower bound, the effectiveness of FXI also increases. Nevertheless, the shadow rate rises in absolute terms because policy rate changes become even more powerful if the policy rate is more persistent.
- If Switzerland had avoided negative interest rates from Q1 2015 to Q3 2022, up to CHF 550 billion (approximately USD 630) in FXI would have been needed to keep inflation on its realised path.

Our findings contribute to the literature in numerous ways. First, we add to the literature that uses quantitative models to study the economic impact of unconventional monetary policy instruments, notably Chen et al. (2012), Gertler and Karadi (2011), Gertler and Karadi (2013), Gertler and Kiyotaki (2010). See also the comprehensive survey by Bhattarai and Neely (2020). To date, the focus of this strand of literature has been the impact of QE programs.[4] Our focus is instead on the effectiveness of FXI as an (unconventional) monetary policy instrument in a small, open economy.

Building on the insights of a growing body of theoretical literature,[5] FXI have been introduced into many quantitative DSGE models of small, open economies. Examples include Benes et al. (2015), Liu and Spiegel (2015), Malovana (2015) and more recently Alla et al. (2020), Adrian et al. (2022a), Adrian et al. (2022b), and Montoro and Ortiz (2023).

This body of literature shows that FXI can be effective in absorbing different types of shocks, thereby improving monetary policy trade-offs, and analyses whether and when FXI are welfare enhancing. Our paper is positive in nature – we take it for granted that central banks use FXI and ask to what extent they help increase inflation, as suggested in the seminal work of McCallum (2000) more than two decades ago. Compared to previous quantitative studies, we can estimate all of the key parameters, including the one that determines the effectiveness of FXI.

Second, we contribute to the literature that estimates shadow rates. These studies frequently use a theory of the relationship between interest rates of government bonds of different maturities (see Wu and Xia, 2016). This approach is not suitable for FXI, which mainly work via the exchange rate channel and not via lowering long-term interest rates. We employ an estimated DSGE model and extract the shadow rate through counterfactual experiments, similar to Sims and Wu (2020), who find that the US Federal Reserve's balance sheet expansion during the ZLB period was as effective as a reduction in the policy rate of 2 percentage points.

An extensive body of literature has empirically studied the impact of FXI. Fratzscher et al. (2019) and Menkhoff et al. (2021) provide recent summaries and identify key challenges that typically hamper empirical studies, such as endogeneity problems, missing information on the timing and size of interventions or the focus on short horizons. Our approach is not subject to these issues. With the help of our structural model, we can clearly identify the impact of FXI using publicly available data.

Our paper is structured as follows. In Section 2, we introduce a stylised model to study the mechanism of how FXI affect the exchange rate and thereby the macroeconomy. Section 3 describes the full DSGE model we are using to quantitatively estimate the effectiveness of FXI. In Section 4, we present the data, discuss the model estimation and the resulting parameters. Sections 5 and 6 show the results, and we conclude in Section 7.

[4] Aregger and Leutert (2023a) analyse the role of QE and FXI in countering appreciation pressure in a stylised economy.

[5] See, for example, Gabaix and Maggiori (2015), Amador et al. (2020), Cavallino (2019)), Fanelli and Straub (2021), Hassan et al. (2022) and Itskhoki and Mukhin (2022) and the survey by Maggiori (2021).

2 Stylised model

Any model that has the purpose of studying the impact of FXI needs to break the uncovered interest parity (UIP) condition. Otherwise, (sterilised) FXI – FXI that do not alter the money market rate – are ineffective.[6] We start by presenting a stylised version of a model that breaks the UIP by assuming portfolio adjustment costs, as in Schmitt-Grohé and Uribe (2003). To do so, we extend the model by Yakhin (2022) with FXI, which affect portfolio adjustment costs by changing the foreign bond holdings of domestic households.

Yakhin (2022) considers a small, open economy ("home") populated by a unit mass of households and a government. The economy is perfectly integrated in the world's goods market, in which one perishable good is traded. Households consume the good and trade it in the international markets. We denote consumption by c_t. Each period, households in the home economy are endowed with a random allocation y_t of the good.

There are two currencies, home and foreign. The foreign currency price of the good is P_t^*. Under the assumption of the law of one price, the domestic currency price of the good is $P_t = S_t P_t^*$, where S_t is the nominal exchange rate defined as the $\frac{\text{units domestic currency}}{\text{units foreign currency}}$ ratio. We further simplify the problem by assuming that $P_t^* = 1$ and, hence, $P_t = S_t$.

There are two bonds: a foreign bond B_t^* that pays a risk-free gross return of R_t^* and a domestic bond B_t^G with a risk-free gross return R_t. In the steady state, $R_{SS}^* = R_{SS} = \beta^{-1}$, where β is the subjective discount factor of both domestic households and foreigners.

Domestic bonds B_t^G are issued by the central bank, which also controls their gross return, R_t. Given the small, open economy assumption, only domestic households hold domestic bonds, and their holdings are denoted as B_t^{HH}.[7]

When conducting FXI, the central bank purchases foreign bonds denoted as $B_t^{*,CB}$ from domestic households and issues central bank money in exchange, which we denote as D_t^{CB}. The gross return on central bank money is identical to the gross return on bonds, R_t. Because central bank money yields interest, it is best to think of it as reserves held at the central bank. In our stylised economy, we assume that central bank money is directly held by households and denote their holdings as D_t^{HH}.

The budget constraint of the fiscal authority is given as

$$B_t^G = R_{t-1} B_{t-1}^G + T_t - \tau_t, \tag{1}$$

where τ_t are remittances from the central bank. Under the assumption that the central

[6] Because the SNB operates in a floor system with excess reserves, the money market rate is determined by the interest rate on sight deposits (reserves). Hence, interventions do not need to be sterilised to keep the money market rate close to the SNB's policy rate.

[7] Our model could also be applied in a context in which the central bank sells foreign bonds to the domestic sector to prevent the domestic currency from depreciating. To model the case in which the central bank transacts with foreign residents, our small, open economy model must be extended to a two-country setting.

bank redistributes all of its profits to the fiscal authority, remittances are determined as

$$\tau_t = S_t R^*_{t-1} B^{*,CB}_{t-1} - R_{t-1} D^{CB}_{t-1} + D^{CB}_t - S_t B^{*,CB}_t. \quad (2)$$

The households' maximisation problem is given as

$$\max_{c_t, B^{HH}_t, B^{*,HH}_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t u(c_t) \quad (3)$$

s.t.

$$S_t c_t + B^{HH}_t + D^{HH}_t + (1+\zeta_t) S_t B^{*,HH}_t \quad (4)$$

$$\leq S_t y_t + R_{t-1} B^{HH}_{t-1} + R_{t-1} D^{HH}_{t-1} + S_t R^*_{t-1} B^{*,HH}_{t-1} + \upsilon K_t + T_t, \quad (5)$$

where ζ_t are portfolio adjustment costs that distort foreign bond returns. Portfolio adjustment costs are determined by a time-invariant function $\zeta_t = \zeta(.)$ that depends on the deviation in *aggregate* foreign bond holdings from their respective steady state ($B^{*,HH,AGG}_t - \bar{B}^{*,HH,AGG}$), such that $\zeta(0) = \zeta'(0) = 0$ and $\zeta'(.) > 0$. Because portfolio adjustment costs depend on private households' aggregate foreign bond holdings, they cannot be influenced by individual economic decisions. The assumption that ζ_t is increasing in the (equilibrium) value of the stock of foreign bonds held by domestic savers prevents "excessive" capital outflows and was introduced by Schmitt-Grohé and Uribe (2003) to obtain a well-defined equilibrium.[8]

K_t is the average adjustment cost in the economy, and each household is rebated a portion υ of that cost. Because K_t is a function of the economy's aggregate cost, households do not internalise the effect of their choice of $B^{*,HH}_t$ on K_t in the same way that they do not internalise the effect of their choice on ζ_t.

The households' optimality conditions are as follows:

$$u'(c_t) = \beta R_t \mathbb{E}_t \left(\frac{u'(c_{t+1})}{\Upsilon_{t+1}} \right) \quad (6)$$

$$u'(c_t)[1+\zeta_t] = \beta R^*_t E_t(u'(c_{t+1})) \quad (7)$$

where we defined $\Upsilon_{t+1} \equiv \frac{S_{t+1}}{S_t}$. Combining these two equations gives us a modified version of the uncovered UIP:

$$R_t \mathbb{E}_t \left(\frac{u'(c_{t+1})}{\Upsilon_{t+1}} \right) [1+\zeta_t] = R^*_t \mathbb{E}_t(u'(c_{t+1})) \quad (8)$$

Compared to the standard UIP, the modified version of the UIP is distorted by the term $[1+\zeta_t]$. In the words of Itskhoki and Mukhin (2021), $[1+\zeta_t]$ is a "financial wedge" that, in our case, arises from the presence of portfolio adjustment costs.

[8] The literature usually considers convex portfolio adjustment costs($\zeta''(.) > 0$). See Schmitt-Grohé and Uribe (2003) and Yakhin (2022). However, we subsequently define ζ as a linear function (see 25) in the context of a linear approximation to the UIP, hence $\zeta''(.) = 0$.

Gabaix and Maggiori (2015) and Fanelli and Straub (2021) provide different microfoundations for the financial wedge. In both papers, domestic households hold only domestic bonds and only financial intermediaries have access to international financial markets. Intermediation is subject to frictions, which differ across the two approaches.

Result 1. *The first-order approximation of the UIP is as follows:*

$$i_t^* - \zeta_t - i_t = \log(S_t) - E_t \log(S_{t+1}), \tag{9}$$

where $i_t^* = \log(R_t^*)$ *and* $i_t = \log(R_t)$. *Yakhin (2022) shows that it is identical to the first-order approximation of the UIP in Gabaix and Maggiori (2015) or Fanelli and Straub (2021), if the parameters are appropriately relabelled.*[9]

Another similarity among us, Gabaix and Maggiori (2015) and Fanelli and Straub (2021) is that FXI tend to reduce UIP deviation (i.e. ζ_t), consistent with the empirical evidence in Sandri (2023).

We are now ready to define a market equilibrium in our simple economy.

Aggregate and individual foreign bond holdings are identical because of our assumption that all households are identical:

$$B_t^{*,HH,AGG} = B_t^{*,HH}. \tag{10}$$

Bond market equilibrium implies that the demand for domestic bonds from households and the government's bond supply coincide:

$$B_t^{HH} = B_t^{G}. \tag{11}$$

Similarly, the equilibrium equation for central bank money

$$D_t^{HH} = D_t^{CB}, \tag{12}$$

and

$$K_t = S_t \zeta_t B_t^{*,HH}, \tag{13}$$

denotes aggregate adjustment costs in equilibrium, whereas the balance of payments (BOP) identity in real terms (recall that $S_t = P_t$) is given as

$$B_t^{*,HH} + B_t^{*,CB} = y_t - c_t + R_{t-1}^* B_{t-1}^{*,HH} + R_{t-1}^* B_{t-1}^{*,CB} - \underbrace{(1-\upsilon)\zeta_t B_t^{*,HH}}_{\text{A}} \tag{14}$$

The BOP determines total (net) foreign asset holdings (the net international investment position or NIIP).

There are 5 endogenous variables (c_t, R_t, Υ_t, $B_t^{*,CB}$ and $B_t^{*,HH}$) and 3 equations (Euler, UIP and BOP). The model is closed by specifying a policy rule for the nominal

[9]Yakhin (2022) goes one step further and shows that the equilibrium in all three models – portfolio adjustment costs (Schmitt-Grohé and Uribe (2003)), financial frictions à la Gabaix and Maggiori (2015) or Fanelli and Straub (2021) – are identical. Yakhin's proof rests on the assumption that portfolio adjustment costs are an income loss, whereas we model them as a return loss.

interest rate, R_t, and a policy rule for foreign bond holdings of the central banks (FXI), $B_t^{*,CB}$. Note that the central bank has two different instruments: it can decide about the quantity of central bank money D_t^{CB} (determined by FXI) and about its price R_t. Borio and Disyatat (2009) discuss the conditions under which the central bank can in practice separately set the price and quantity of central bank money, such as by paying interest on reserves.

In the following, we use the equilibrium conditions of our stylised economy to shed more light on the conditions under which FXI are effective and influence the exchange rate. A necessary condition is that FXI affect the amount of private foreign bond holdings $B_t^{*,HH}$.

Result 2. *Under Ricardian equivalence, FXI (i.e. an increase in $B_t^{*,CB}$) reduce private foreign bond holdings $B_t^{*,HH}$ one-to-one as long as $A = 0$.*

Put differently, under Ricardian equivalence, FX purchases by the central bank always reduce the amount of foreign bonds held by the private sector. The proof of the result follows from the BOP (14). Ricardian equivalence implies that government interventions leave c_t unchanged. Our small, open economy assumption together with the fact that our stylised economy is an endowment economy imply that R_{t-1}^* and y_t are exogenous and, thus, unaffected by the FX intervention. The extent to which FXI affect private bond holdings $B_t^{*,HH}$ then depends on the term A – the portion of portfolio adjustment costs that are "lost" because they are not rebated to households (the term A). As long as $A = 0$, there is a one-to-one crowding out because the right-hand side of the BOP (14) is constant. $A = 0$ emerges if either (i) $\upsilon = 1$ (households are fully rebated) or (ii) $\zeta_t = 0$, i.e. FXI are ineffective. If we rule out $\zeta_t = 0$, we obtain $A > 0$ if $\upsilon < 1$. We argue that this is the empirically relevant case. In fact, to match the Swiss data, we set $\upsilon = 0$ (households receive no rebates); see Section 3.8.

In the quantitative model presented below, we relax the implicit assumption that monetary policy – i.e. interest rate changes and FXI – does not have a direct impact on y_t and c_t. In our quantitative model, we assume a production economy, sticky prices and the presence of non-Ricardian households. As a consequence, monetary policy has an impact on both y_t and c_t.

ζ_t determines the strength of FXI; therefore, it is a key model function. Its crucial nature makes it sensible to anticipate its determination and its identification at this stage. Regarding the determination of ζ_t, we assume that it consists of an endogenous and an exogenous part. The endogenous part reflects the impact of FXI as outlined in the stylised model above. The exogenous part reflects external forces ("shocks").

The identification of ζ_t hinges on two equations, the UIP (9) (respectively a modified version of it that better matches the data; see Section 3.2 below) and the BOP (14). The UIP depends on the nominal exchange rate and domestic and foreign policy rates. The BOP depends on net exports $y_t - c_t$ and the share of portfolio adjustment costs that are lost, which are summarised in term A. All elements are influenced by monetary policy, i.e. the interest rate and the exchange rate, but also are subject to various shocks outside the control of monetary policy (e.g. safe-haven shocks); in turn, these shocks may require a monetary policy response, which has been the case in Switzerland (Jordan (2017)).

In Figure 2, we plot total NIIP and its decomposition into reserve and private assets (i.e. total minus SNB reserve assets) relative to GDP. We can distinguish the following episodes:

- Between 2009 to 2013 and between 2019 and 2021, we observe a tight and negative co-movement between reserve assets and private NIIP such that total NIIP remains approximately constant. In light of our previous result, the evidence from this episode suggests that monetary policy (i.e. interest rate changes and FXI) were successful in the sense that they managed to stabilise output and consumption, i.e. the right-hand side of the BOP (14), despite large, safe-haven shocks that occurred during this time.[10]
- Between 2013 and 2015, reserve assets increased, and the private NIIP decreased by more such that total NIIP declined. Monetary policy could not fully compensate for the adverse shocks in this period such that the right-hand side of the BOP (14) declined.
- At the beginning of 2015, the discontinuation of the minimum exchange rate against the euro caused a (real) appreciation in the Swiss franc, which led to valuation losses in the private NIIP. These valuation losses are not visible in the reserve assets because they were more than offset by new FX purchases.[11]
- After the discontinuation of the minimum exchange rate regime and 2019, the private NIIP remained approximately constant, whereas the SNB's reserve assets continued to increase. During this episode, unconventional monetary policy in Switzerland helped increase the right-hand side of the BOP (14) such that left-hand side increased as well.

As the discussion of these episodes shows, the identification of ζ – the function that determines the strength of FXI – depends strongly on the relationship among private NIIP, reserve assets and total NIIP.

As a final remark, we stress that our approach of modelling FXI coincides in many aspects with how QE is usually modelled: a price (here: the exchange rate; QE: usually the long-term interested rate) is distorted by a friction (here: portfolio adjustment costs; QE: different microfoundations lead to the same friction). By purchasing assets, the central bank affects the size of this friction and, thus, the price. In both cases, the central bank is assumed to not face the same frictions as does the private sector.[12]

[10] Yeşin (2015) and Auer and Tille (2016) indeed find that FXI played a prominent role in absorbing the domestic demand for Swiss francs.

[11] To observe the impact of the exchange rate more clearly, consider the nominal version of the BOP (14), $S_tB_t^{*,HH} + S_tB_t^{*,CB} = P_ty_t - P_tc_t + R_{t-1}^*S_tB_{t-1}^{*,HH} + R_{t-1}^*S_tB_{t-1}^{*,CB} - (1-\upsilon)\zeta_tS_tB_t^{*,HH}$.

[12] In our case, even if portfolio adjustment costs existed on the central bank side, they are irrelevant because the exchange rate is determined by a no-arbitrage condition between foreign and domestic bonds held by the private sector (UIP), for which only private adjustment costs matter (unless the portfolio adjustment costs affect the central bank's decision to intervene).

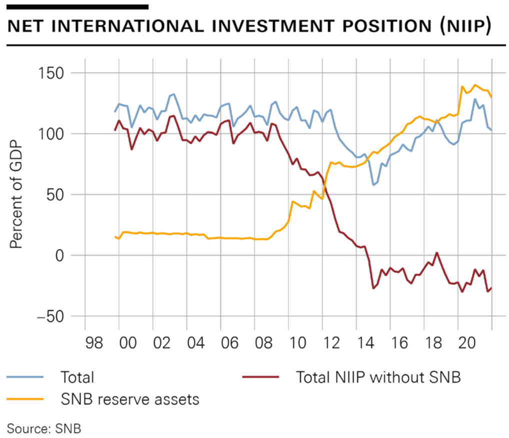


Figure 2: Net international investment position and reserve assets in Switzerland

3 Full model

Our quantitative model is an open-economy version of Eggertsson et al. (2017) and an extension of the small, open economy version of the New Keynesian model presented in Galí and Monacelli (2005) and Rudolf and Zurlinden (2014).

Compared to the stylised model, our quantitative model contains the following additional features:

- firms facing nominal rigidities
- commercial banks that intermediate resources between savers and borrowers and hold sight deposits (reserves) at the central bank
- hand-to-mouth consumers

Modelling firms helps us endogenise production and output. The reasons for adding nominal rigidities are standard. Because of nominal rigidities, changes in the nominal interest rate (nominal exchange rate) affect the real interest rate (real exchange rate) and generate an interest rate channel (exchange rate channel) of monetary policy.

Modelling commercial banks is useful for at least three reasons. First, doing so allows us to model financial intermediation between borrowers and savers, which is costly and gives rise to a bank lending channel of monetary policy. Second, modelling commercial banks also allows us to model the balance sheet of the central bank in a more realistic manner. By modelling banks, we can divide central bank money – the dominant position on the liability side of the central bank – into cash (held by savers) and sight deposits (reserves) held by commercial banks. Third, and most importantly, modelling banks allows us to study theoretically the interaction between FXI and financial intermediation, which is interesting in itself. The question of whether FXI interfere with setting interest rates in the banking sector became even more relevant in the negative interest rate environment in Switzerland between 2005 and 2022. In Section 3.9, we discuss under

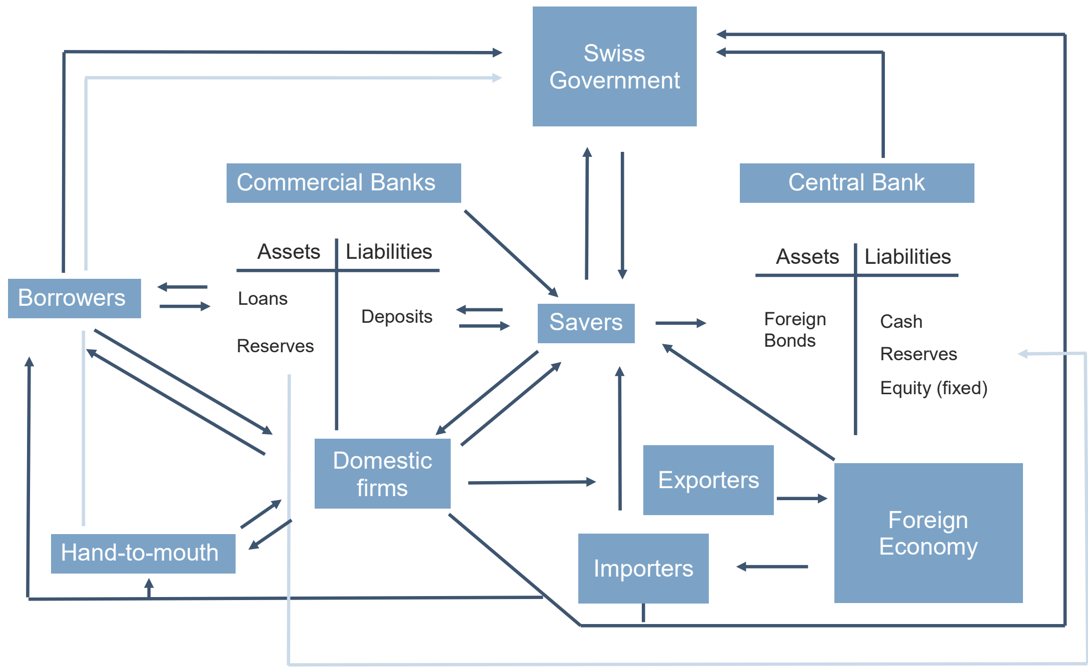


Figure 3: Overview economy

which conditions FXI do not interfere with the transmission of policy rate changes such that the central bank can use FXI as separate policy instruments.

Introducing hand-to-mouth consumers reduces the interest elasticity of aggregate consumption in the model and can help mitigate the forward-guidance puzzle in DSGE models. See Debortoli and Galí (2017), Maliar and Naubert (2019) and Gerke et al. (2020), among others, for a discussion of two-agent New Keynesian (TANK) models.

Figure 3 presents the structure of the full model economy. There are three types of households (borrowers, savers and hand-to-mouth consumers), five types of firms[13], a commercial banking sector, a central bank and a government. Each arrow in Figure 3 represents an interaction between the different sectors of the economy.

In the following, we provide a brief verbal description of the most important arrows. Savers pay taxes to the government and purchase government bonds. Savers also hold deposits at commercial banks and receive interest income in exchange. Moreover, savers invest in foreign bonds. If the central bank intervenes in the FX market, it purchases foreign bonds from domestic savers. Savers then increase their deposits at commercial

[13]Domestic firms that bundle the consumption goods out of domestic final and imported goods, domestic firms that produce final or intermediary goods, importers that import products from the foreign economy to the domestic economy and exporters that export domestic goods to the foreign economy.

banks, which in turn increases commercial banks' holdings of reserves at the central bank.

Borrowers do not own assets apart from cash. Instead, they borrow from commercial banks and pay interest on their loans. All households (borrowers, savers and hand-to-mouth consumers) work for domestic firms and receive labour income, which they spend on domestic and imported goods. Borrowers and savers additionally receive profits generated by the firm's sector. Commercial banks use the deposits they receive from savers to hold reserves at the central bank and grant loans to borrowers. Profits from financial intermediation are distributed to the savers. All types of households pay taxes to the government. The government uses its resources from taxes and new debt issuances to finance its expenditures in the form of domestic and imported goods and to service its outstanding debt. The government also receives profits generated by the central bank.

Lowering the policy rate by the central bank affects the economy via three channels:

- Exchange rate channel (lowering policy rates depreciates the value of domestic currency, which stimulates exports).
- Interest rate channel (intertemporal substitution; consumption today becomes cheaper than consumption tomorrow).
- Bank lending channel (a lower policy rate reduces banks' lending rates and, hence, increases borrowing, albeit less than one-for-one, because more lending increases banks' intermediation costs).

FXI work through only the exchange rate channel.

In the following subsections, we provide more details for the key sectors. We start by describing the households problems.

3.1 Households

The total measure of households is one. There are three types of households: households with wealth, savers s with a share $1-\chi$, and households without wealth with a share χ. Among households without wealth are hand-to-mouth consumers hm with a share χ^{hm} and borrowers b with a share $1-\chi^{hm}$. Therefore, the total number of borrowers is $(1-\chi^{hm})\chi$, and the total number of hand-to-mouth households is $\chi^{hm}\chi$.

Households are indexed by i. Borrowers and savers are forward-looking and maximize consumption given their intertemporal budget constraint. Borrowers are more impatient than savers: $\beta^b < \beta^s$, where β is the discount factor. On the other hand, hand-to-mouth consumers consume their after-tax income every period. The optimization problems of borrowers and savers below follow Benigno et al. (2020) and Eggertsson et al. (2017).

Borrowers' problem. The problem of a borrower household i is given as:

$$\mathrm{E}_0 \sum_{t=0}^{\infty} \left(\beta^b\right)^t U\left(x_t^b(i), n_t^b(i), \frac{M_t^b(i)}{P_t}, \epsilon_t^c, \epsilon_t^{\alpha^m}\right), \tag{15}$$

where U is the utility function, which depends on the deviation in real consumption from a habit $x_t^b(i) = c_t^b(i) - \Lambda c_{t-1}^b$. We assume external habits, ("keeping up with the Joneses"), where c_{t-1}^b is the average consumption of borrowers in the previous period. As explained by Schmitt-Grohé and Uribe (2017), habits introduce persistence into the system, governed by the parameter Λ. $n_t^b(i)$ is labour supply, and $\frac{M_t^b(i)}{P_t}$ are holdings of real money balances. Finally, utility is subject to a shock ϵ_t^c.

Maximisation is subject to the flow budget constraint:

$$\begin{aligned}&\frac{P_t^c}{P_t}c_t^b(i) - \frac{L_t^d(i)}{P_t} + \frac{M_t^b(i)}{P_t} \leq \\ &\frac{W_t^b}{P_t}n_t^b - (1+i_{t-1}^b)\frac{L_{t-1}^d(i)}{P_t} + \frac{M_{t-1}^b(i)}{P_t} - \frac{\Omega\left(M_{t-1}^b(i)\right)}{P_t} + \frac{\Pi_{h,t}^b(i)}{P_t} + \frac{\Pi_{ex,t}^b(i)}{P_t} + \frac{\Pi_{im,t}^b(i)}{P_t} - \tau_t^b(i),\end{aligned} \tag{16}$$

where P_t^c is the price of consumption goods, P_t is the price of domestic goods, $L_t^d(i)$ is the amount of loans taken out in period t, i_{t-1}^b is the borrowing rate, $\Omega\left(M_{t-1}^b(i)\right)$ denotes the costs of holding money (storage costs), W_t^b is the nominal wage per unit of labour, $\Pi_{h,t}^b(i)$ are the profits received from intermediary firms, $\Pi_{ex,t}^b(i)$ are the profits received from exporting firms and $\Pi_{im,t}^b(i)$ are the profits received from importing firms. Finally, $\tau_t^b(i)$ is a lump-sum tax (transfer).

Savers' problem. Each saver household i maximises

$$\mathrm{E}_0\sum_{t=0}^{\infty}(\beta^s)^t\, U\left(x_t^s(i), n_t^s(i), \frac{M_t^s(i)}{P_t}, \epsilon_t^c, \epsilon_t^{\alpha^m}\right), \tag{17}$$

subject to the flow budget constraint

$$\begin{aligned}&\frac{P_t^c}{P_t}c_t^s(i) + \frac{B_t^s(i)}{P_t} + (1+\zeta_t)S_t\frac{B_t^{s,s,*}(i)}{P_t} + \frac{M_t^s(i)}{P_t} + \frac{D_t^s(i)}{P_t} \leq \\ &\frac{W_t^s}{P_t}n_t^s(i) + (1+i_{t-1}^g)\frac{B_{t-1}^s(i)}{P_t} + (1+i_{t-1}^*)S_t\frac{B_{t-1}^{s,s,*}(i)}{P_t} + \frac{M_{t-1}^s(i)}{P_t} - \frac{\Omega(M_{t-1}^s(i))}{P_t} \\ &+ (1+i_{t-1}^s)\frac{D_{t-1}^s(i)}{P_t} + \frac{\Pi_{h,t}^s(i)}{P_t} + \frac{\Pi_{ex,t}^s(i)}{P_t} + \frac{\Pi_{im,t}^s(i)}{P_t} + \frac{Z_t^s(i)}{P_t} - \tau_t^s(i) - \Psi_t.\end{aligned} \tag{18}$$

In the following, we focus on the variables that are new in the savers' problem and that have not been introduced before: B_{t-1}^s represent current-period holdings of domestic government bonds with return $(1+i_{t-1}^g)$, $B_{t-1}^{s,s,*}$ denotes current-period holdings of foreign government bonds with return $(1+i_{t-1}^*)$, and ζ_t denote the portfolio adjustment costs, as in Section 2.

D_{t-1}^s denotes current period holdings of deposits with return $(1+i_{t-1}^s)$. Z_t^s are commercial bank profits, which are solely owned by savers (see Section 3.4). Finally, savers need to pay an additional fixed cost Ψ_t when holding foreign bonds. Differently from ζ_t, Ψ_t does not affect the exchange rate because it does not drive a wedge between the returns on domestic and foreign bonds. More details on Ψ_t are provided in Section 3.8.

We assume that domestic government bonds B^s_{t-1} and deposits D^s_{t-1} at commercial banks are perfect substitutes for savers. Therefore, a no-arbitrage condition requires that the returns on the two assets are identical, implying that $i^s_t = i^g_t$. However, government bonds and deposits differ in how they are created. Whereas government bonds are issued by the fiscal authority (see Section 3.5), deposits are held at commercial banks (see Section 3.4).

Determination of labour supply. Households' labour supply decision is the result of the intratemporal labour-leisure trade-off of borrowers and savers. Hand-to-mouth consumers are assumed to work the same hours as do the other households and receive the same wage.

$$-\frac{U_n\left(x^k_t(i), n^k_t(i), \frac{M^k_t(i)}{P_t}, \epsilon^c_t, \epsilon^{\alpha^m}_t\right)}{U_x\left(x^k_t(i), n^k_t(i), \frac{M^k_t(i)}{P_t}, \epsilon^c_t, \epsilon^{\alpha^m}_t\right)} = \frac{W^k_t}{P^c_t}, \tag{19}$$

where $k \in \{b, s\}$. The left hand side of equation (19) is identical for borrowers and savers. Following Eggertsson et al. (2017) and Benigno et al. (2020), we exploit this fact to simplify the problem further. Under the assumption that U is additively separable in x^k_t, n^k_t and $\frac{M^k_t}{P_t}$ such that $U_n \equiv v'(n^k_t)\epsilon^c_t$ and $U_x \equiv u'(x^k_t)\epsilon^c_t$, equation (19) becomes $\frac{v'(n^k_t)}{u'(x^k_t)} = \frac{W^k_t}{P_t}$. If we further assume that $v(n^k_t) = \frac{(n^k_t)^{1+\eta}}{1+\eta}$ and $u(x^k_t) = 1 - \exp(-qx^k_t)$, (19) can be aggregated into a labour market condition, which is independent of the household type k:

$$\frac{v'(n_t)}{u'(x^{bs}_t)} = \frac{W_t}{P_t}, \tag{20}$$

with $W_t = \left(W^b_t\right)^{\frac{\chi-\chi\chi^{hm}}{1-\chi\chi^{hm}}} \left(W^s_t\right)^{\frac{1-\chi}{1-\chi\chi^{hm}}}$, $n_t = \left(n^b_t\right)^{\frac{\chi-\chi\chi^{hm}}{1-\chi\chi^{hm}}} \left(n^s_t\right)^{\frac{1-\chi}{1-\chi\chi^{hm}}}$ and $x^{bs}_t = \frac{\chi-\chi\chi^{hm}}{1-\chi\chi^{hm}} x^b_t + \frac{1-\chi}{1-\chi^{hm}} x^s_t$. Moreover, $n^b_t = \int_0^{\chi-\chi\chi^{hm}} n^b_t(i)di$, $n^s_t = \int_\chi^1 n^s_t(i)di$, $(\chi-\chi\chi^{hm})x^b_t = \int_0^{\chi-\chi\chi^{hm}} (c^b_t(i) - \Lambda c^b_{t-1})di$ and $(1-\chi)x^s_t = \int_\chi^1 (c^s_t(i) - \Lambda c^s_{t-1})di$.[14]

Equation (20) allows us to treat the labour supply decision "as if" only a single representative household exists. Hence, only the composite labour supply n_t and the composite rate W_t need to be determined in equilibrium, and we can assume that firms hire n_t and pay W_t, which simplifies their problem.

Problem of hand-to-mouth consumers. Each hand-to-mouth consumer i simply consumes his or her after-tax income every period

$$\frac{P^c_t}{P_t} c^{hm}_t(i) \leq \frac{W^{hm}_t}{P_t} n^{hm}_t - \tau^{hm}_t(i). \tag{21}$$

[14]Using $c^{bs}_t = \frac{\chi-\chi\chi^{hm}}{1-\chi\chi^{hm}} c^b_t + \frac{1-\chi}{1-\chi\chi^{hm}} c^s_t$, $(\chi - \chi\chi^{hm})c^b_t = \int_0^{\chi-\chi\chi^{hm}} c^b_t(i)di$ and $(1-\chi)c^s_t = \int_\chi^1 c^s_t(i)di$ together with the results stated in the text, it follows that $x^{bs}_t = c^{bs}_t - \Lambda c^{bs}_{t-1}$.

Because hand-to-mouth consumers are assumed to work the same hours and receive the same wage as the other households, $W_t^{hm} = W_t$ and $n_t^{hm} = n_t$. Aggregate consumption in the economy is given as $c_t = c_t^{bs}\left(1 - \chi\chi^{hm}\right) + c_t^{hm}\chi\chi^{hm}$.

Adding hand-to-mouth consumers reduces – under certain conditions discussed in Debortoli and Galí (2017), Maliar and Naubert (2019) and Gerke et al. (2020) – the interest rate sensitivity of consumption and, hence, mitigates the forward guidance puzzle established by Del Negro et al. (2023).[15]

Modelling money demand. The presence of money, which we interpret as cash, allows households to transfer resources across periods using a non-interest bearing asset, which creates a lower bound on interest rates.[16] To allow for negative interest rates, we assume that there are transaction costs associated to holding cash. We set the lower bound on interest rates to a relatively low value (see Section 4.1). The policy rate in Switzerland was at -0.75% between 2015 and 2022. As we discuss in Section 4.1, evidence shows that the lower bound on the policy rate is much lower than -0.75%, although considerable uncertainty exists regarding its exact value (Grisse, 2023).

We follow the money-in-the-utility function approach and assume that households receive utility from holding real money balances. However, holding money (cash) is associated with storage costs $\Omega\left(M_{t-1}^b\right)$, a fact that allows the deposit rate i^s to become negative. To see this, consider the money demand equation

$$\frac{U_M\left(x_t^s, n_t^s, \frac{M_t^s}{P_t}, \epsilon_t^c, \epsilon_t^{\alpha^m}\right) P_t^c}{U_x\left(x_t^s, n_t^s, \frac{M_t^s}{P_t}, \epsilon_t^c, \epsilon_t^{\alpha^m}\right)} = \frac{i_t^s + \Omega'\left(M_{t-1}^s\right)}{1 + i_t^s}. \tag{22}$$

The lower bond on $\underline{\mathrm{i}}^s$ is defined as the lowest value of i_t^s that satisfies (22). With zero or constant storage costs, $\Omega'\left(M_{t-1}^s\right) = 0$ and $\underline{\mathrm{i}}^s = 0$ as long as a satiation point $\bar{m}$ for real money balances exists, i.e. if $U_M\left(c_t^s, n_t^s, \bar{m}, \epsilon_t^c, \epsilon_t^{\alpha^m}\right) = 0 \ \forall \ \frac{M_t^s}{P_t} \geq \bar{m}$.

If $\Omega'\left(M_{t-1}^s\right) > 0$, $\underline{\mathrm{i}}^s < 0$. We assume that storage costs are linear such that $\Omega'\left(M_{t-1}^s\right) = \gamma^m$, hence $\underline{\mathrm{i}}^s = -\gamma^m$.

3.2 Exchange rate determination

In the long run, relative PPP holds and, thus, the nominal exchange rate is determined by the inflation differential between the domestic and the foreign economy. However, relative PPP does not hold in the short run because of sticky import prices, as explained later in Section 3.6.

[15] Whether adding hand-to-mouth consumers, who just consume their wage bill (and profits, if they receive part of them) and do not smooth their consumption intertemporally, reduces the interest sensitivity of consumption depends on the cyclicality of the wage bill (and on the countercyclicality of profits). In our case, hand-to-mouth consumers do not receive profits. We also analyse the case in which hand-to-mouth consumers receive profits. In that case, aggregate consumption turns out to be unchanged, and only our estimated intertemporal elasticity of substitution becomes counterfactually large.

[16] Cash is also an important liability for most central banks. Therefore, by modelling cash, we can model the central bank's balance sheet (see Section 3.3) in a more realistic manner.

In the short run, the exchange rate S_t is determined by the uncovered interest rate parity condition (UIP). The UIP is a no-arbitrage condition that ensures that domestic savers are indifferent between investing in foreign or domestic bonds. The UIP can be derived by combining the first-order conditions for domestic and foreign bonds that emerge from the optimisation problem of savers; see Equation 8 in the stylised model.

Taking logs, the UIP is as follows (see also Equation 9 in the stylised model):

$$i_t^* - \zeta_t - i_t^g = \log(S_t) - \mathrm{E}_t \log(S_{t+1}). \tag{23}$$

Well-known is that this UIP specification is inconsistent with several empirical findings on the impact of interest rates on exchange rates that are otherwise puzzling, in particular the delayed-overshooting puzzle (the fact that the exchange rate follows a hump-shaped pattern after an interest rate change). See Rudolf and Zurlinden (2014), Christiano et al. (2011) and Bacchetta and van Wincoop (2019).[17] Therefore, we follow Adolfson et al. (2008) and use the following modification:

$$i_t^* - \zeta_t - i_t^g = \log(S_t) - (1-\varphi)\mathrm{E}_t \log(S_{t+1}) - \varphi \log(S_{t-1}), \tag{24}$$

where $\varphi \in (0,1)$. The drawback of this specification is that φ is not microfounded. Our motivation to consider $\varphi \in (0,1)$ is purely empirical. Indeed, in Section 4.3, we argue that the data show a strong preference for this specification.

To understand the role of φ, consider the case of no delayed overshooting, $\varphi = 0$. If the central bank lowers i_t^g, investments in domestic government bonds become less attractive than investments in foreign bonds. Therefore, domestic savers must expect the domestic currency to appreciate to compensate them for the lower domestic interest rate, i.e. $\log(S_t) - \mathrm{E}_t \log(S_{t+1}) > 0$. This implies that an immediate depreciation, $\Delta \log(S_t) > 0$, is needed to be compatible with an expected appreciation. In the case of $\varphi > 0$, the domestic currency depreciates for some time before it appreciates. A higher φ is associated with a longer the depreciation period.

The central bank can also influence S_t through the impact of its FXI on the costs of holding foreign bonds ζ_t. An FX intervention in which the central bank purchases foreign bonds from domestic savers decreases ζ_t, and the effective return on holding foreign bonds $i_t^* - \zeta_t$ increases. As a result, the domestic exchange rate depreciates.

More specifically, the linearised equation of ζ_t is as follows:

$$\zeta_t = \underbrace{\lambda^{\zeta}\left(\frac{B_t^{s,*}}{P_t^*} - \frac{B^{s,*}}{P^*}\right)}_{\text{endogenous component}} + \underbrace{\zeta + \log\left(\epsilon_t^{\zeta}\right)}_{\text{exogenous component}}, \tag{25}$$

where ζ is the steady-state value of ζ_t, $\left(\frac{B_t^{s,*}}{P_t^*} - \frac{B^{s,*}}{P^*}\right)$ is the deviation in aggregate domestic savers' foreign bond holdings from the steady state (in % of GDP, which is normalised to 1 in the steady state and determined by $B_t^{s,*} = (1-\chi)B_t^{s,s,*}$), $\lambda^{\zeta} > 0$ measures the

[17] Scholl and Uhlig (2008) argue that the delayed-overshooting puzzle is robust to different identification schemes for monetary policy shocks.

impact of this deviation on ζ_t and, thereby, the effectiveness of FXI. ϵ_t^{ζ} is an exogenous shock. ζ_t is time-variant due to the shock process ϵ_t^{ζ}.

3.3 Central bank

We assume that the central bank operates in a floor system, in which commercial banks hold excess reserves at the central bank.[18] In this system, the policy rate set by the central bank equals the interest rate on reserves i_t^r, which is determined by the following Taylor rule:

$$\frac{1+i_t^r}{1+i^r} = \left(\frac{1+i_{t-1}^r}{1+i^r}\right)^{\rho^m} \left(\left(\frac{1+\pi_t^c}{1+\pi^c}\right)^{\phi^\pi} \left(\frac{y_{h,t}}{y_h}\right)^{\phi^y}\right)^{1-\rho^m} \left(\frac{y_{h,t}}{y_{h,t-1}}\right)^{\phi^{dy}} \epsilon_t^r, \tag{26}$$

where π_t^c is CPI inflation (q/q), $y_{h,t}$ denotes domestic production (GDP) and ϵ_t^r is an AR(1) process (see Smets and Wouters (2007)). The fact that commercial banks hold excess reserves also implies that they can change their policy rates without changing reserves, i.e. without buying or selling foreign bonds.

FXI – the second policy instrument of the central bank – are not rule-based. Therefore, the deviation in real foreign bond holdings of the central bank from the steady state follows an AR(1) process.

$$\log\left(\frac{B_t^{cb,*}P}{B^{cb,*}P_t}\right) = \rho^{B^{cb,*}} \log\left(\frac{B_{t-1}^{cb,*}P}{B^{cb,*}P_{t-1}}\right) + \varepsilon_t^{B^{cb,*}} \tag{27}$$

Because FXI are unsterilised, they affect the amount of excess reserves that commercial banks hold at the central bank. Under certain conditions, which we state in Section 3.9 (see Corollary 1), FXI do not affect market interest rates (e.g. commercial banks' borrowing and lending rates or the government bond rate), and market interest rates are determined only by the interest rate on reserves. We next derive τ_t^{cb}, the remittances that the central bank distributes to the fiscal authority (see Section 3.5). We start by stating the central bank's balance sheet at the end of period t:

$$B_t^{cb,*}S_t = R_t + M_t + EK, \tag{28}$$

where $B_t^{cb,*}$ are foreign bond holdings of the central bank, R_t are reserve holdings of commercial banks, M_t denotes cash in circulation and EK denotes central banks' equity, which is assumed to be fixed in the current version of the model.

Because equity is constant, remittances to the fiscal authority τ_t^{cb} are the real profits

[18] Although this assumption corresponds to the Swiss case, it is inconsequential as long as the central bank can use its policy rate and FXI as two separate instruments.

that the central bank generates in period t:[19]

$$\tau_t^{cb} = \underbrace{i_{t-1}^{*} S_t \frac{B_{t-1}^{cb,*}}{P_t} - i_{t-1}^{r} \frac{R_{t-1}}{P_t}}_{\text{A}} + \underbrace{\frac{\Delta R_t}{P_t} + \frac{\Delta M_t}{P_t}}_{\text{B}} - \underbrace{S_t \frac{\Delta B_t^{cb,*}}{P_t}}_{\text{C}}. \tag{29}$$

Profits arise when the return on holding foreign bonds is higher than the interest rate on reserves (term A) (the interest rate on cash is zero) and from the expansion in the monetary base (term B). Foreign bond purchases (term C) reduce profits. Because foreign bonds purchases are financed by an increase in the monetary base (recall that equity is assumed to be fixed), terms B and C exactly offset each other. Thus, an appreciation in the domestic currency (a decrease in S_t) reduces profits because, ceteris paribus, it reduces term A.

3.4 Commercial banks

The modelling of commercial banks follows Eggertsson et al. (forthcoming). We follow the simpler version derived in Eggertsson et al. (2017), which nevertheless captures all of the essential details. A continuum of identical commercial banks is distributed along the unit interval. Commercial banks are owned by savers. All profits generated by commercial banks are immediately redistributed, which makes their problem static. In period $t-1$, commercial banks accept deposits from savers, which are either lent to borrowers or held as reserves at the central bank. At the beginning of period t, loans, deposit and reserves are repaid, and profits accrue.

Lending is costly, where the real costs are given as $\Gamma\left(\frac{l_{t-1}}{\bar{l}_{t-1}}\right) = \left(\frac{l_{t-1}}{\bar{l}_{t-1}}\right)^{\nu^1}$ such that $\Gamma'\left(\frac{l_{t-1}}{\bar{l}_{t-1}}\right) > 0$ and $\Gamma''\left(\frac{l_{t-1}}{\bar{l}_{t-1}}\right) > 0$, where $l_{t-1} \equiv \frac{L_{t-1}}{P_{t-1}}$ denotes the supply of real loans. The costs of lending $\Gamma\left(\frac{l_{t-1}}{\bar{l}_{t-1}}\right)$ capture – in reduced form – credit market imperfections. Commercial banks are perfectly competitive and take the interest rates i_{t-1}^{b}, i_{t-1}^{r} and i_{t-1}^{s} as given.

Each commercial bank maximises real profits

$$\frac{Z_t}{P_t} = i_{t-1}^{b} \frac{L_{t-1}}{P_t} + i_{t-1}^{r} \frac{R_{t-1}}{P_t} - i_{t-1}^{s} \frac{D_{t-1}}{P_t} - \Gamma\left(\frac{l_{t-1}}{\bar{l}_{t-1}}\right) \tag{30}$$

subject to the commercial bank's balance sheet

$$\frac{R_{t-1}}{P_t} + \frac{L_{t-1}}{P_t} = \frac{D_{t-1}}{P_t}. \tag{31}$$

[19] Ricardian equivalence does not hold in the model. Therefore, the timing of the distribution of profits is relevant. Because the loan rates paid by borrowers is higher than the interest rate on government bonds, borrowers prefer that profits are distributed as early as possible, i.e. in the current period. This is the case that we study.

Plugging (31) into (30) gives

$$\frac{Z_t}{P_t} = (i^b_{t-1} - i^s_{t-1})\frac{L_{t-1}}{P_t} + (i^r_{t-1} - i^s_{t-1})\frac{R_{t-1}}{P_t} - \Gamma\left(\frac{l_{t-1}}{\bar{l}_{t-1}}\right)$$

or

$$z_t = \frac{(i^b_{t-1} - i^s_{t-1})}{(1+\pi_t)} l_{t-1} + \frac{(i^r_{t-1} - i^s_{t-1})}{(1+\pi_t)} r_{t-1} - \Gamma\left(\frac{l_{t-1}}{\bar{l}_{t-1}}\right),$$

where we use $z_t \equiv \frac{Z_t}{P_t}$, $l_{t-1} \equiv \frac{L_{t-1}}{P_{t-1}}$, $r_{t-1} \equiv \frac{R_{t-1}}{P_{t-1}}$.

Profit maximisation implies that real loans l_{t-1} are chosen such that:

$$\frac{(i^b_t - i^s_t)}{(1+\pi_{t+1})} = \frac{1}{\bar{l}_t}\Gamma'\left(\frac{l_t}{\bar{l}_t}\right). \tag{32}$$

3.5 Fiscal authority

The fiscal authority consumes g_t units of the final consumption good at a price P^c_t, where g_t is exogenously determined by the following AR(1) process:

$$\log\left(\frac{g_t}{g}\right) = \rho^g \log\left(\frac{g_{t-1}}{g}\right) + \varepsilon^g_t. \tag{33}$$

Government expenditures are financed by issuing bonds B_t, which are repaid by levying a lump-sum tax τ_t on borrowers and savers. The lump-sum tax is a function of government debt to stabilise it over time

$$\tau_t = \tau\left(\frac{B_{t-1}P}{BP_{t-1}}\right)^{\tau_2}. \tag{34}$$

The fiscal authority also receives remittances τ^{cb}_t from the central bank. Therefore, the government's budget constraint is as follows:

$$\frac{P^c_t}{P_t} g_t \leq \frac{B_t}{P_t} - (1 + i^g_{t-1})\frac{B_{t-1}}{P_t} + \tau_t + \tau^{cb}_t. \tag{35}$$

3.6 Firm sector

The firms sector is standard for a small, open economy model; see, e.g. Galí and Monacelli (2005). Firms can be broadly separated into five categories: firms that bundle consumption goods (private and government) out of domestic final goods and imported goods, domestic firms that produce final or intermediary goods, importers and exporters. The optimisation problems of the five firms are shown in Appendix A.

Prices for domestic and imported (intermediate) goods are sticky. Nominal rigidities in the import sector make sure that import price responses to exchange rate fluctuations and foreign price changes are in line with the data.

3.7 Foreign economy

The foreign economy consists of three sectors: a representative household, which maximizes consumption given habits and log utility and a firm sector with an intermediate and a final good producing firm. The intermediate good firm sets prices given price stickiness à la Calvo (1983) and indexation. Finally, the foreign central bank sets the interest rate in the economy subject to a Taylor rule, which is analogous to the one in the domestic economy. The model equations are provided in Appendix B. The notation is equivalent to the domestic economy. We add a * to highlight foreign variables.

3.8 Equilibrium

In the equilibrium section, we highlight the aggregate resource constraint, which determines the evolution of the NIIP in the model. Although more complex, the equation mimics the dynamics of the balance of payments (BOP) equation (14) in the stylised model and can replicate the evolution of the NIIP shown in Figure 2.

$$\underbrace{S_t\frac{B_t^{s,*}}{P_t} - S_t\frac{B_{t-1}^{s,*}}{P_t}}_{\text{change in private NIIP}} + \underbrace{S_t\frac{B_t^{CB,*}}{P_t} - S_t\frac{B_{t-1}^{CB,*}}{P_t}}_{\text{change in reserve assets}} = \underbrace{ex_t - \frac{P_{f,t}}{P_t}im_t + \frac{\Pi_{im,t}}{P_t} + \frac{S_t\Pi_{ex,t}^{s}(i)}{P_t}}_{\text{trade balance}}$$
$$+ \underbrace{i_{t-1}^{*}S_t\frac{B_{t-1}^{s,*}}{P_t} + i_{t-1}^{*}S_t\frac{B_{t-1}^{CB,*}}{P_t}}_{\text{factor payments from abroad}} - \underbrace{\left(\frac{\Omega(M_{t-1})}{P_t} + \Gamma\left(\frac{l_{t-1}}{\bar{l}_{t-1}}\right) + \zeta_t S_t\frac{B_{t-1}^{s,*}}{P_t} + \Psi_t\right)}_{\text{storage/transaction costs}}. \tag{36}$$

Compared to the stylised model, Ψ_t appears on the right-hand side of the aggregate resource constraint reduces the total net return on net foreign asset holdings – in addition to the financial wedge ζ_t – and is given as the following equation: $\Psi_t = \left(\Psi\epsilon_t^{\Psi}\right) S_t\frac{B_{t-1}^{s,*}}{P_t}$, where ϵ_t^{Ψ} is an exogenous shock process, and Ψ the steady-state loss in total net return. Ψ_t renders negative the total net return on net foreign assets, which is required to account for the empirical fact that the total net international investment position of Switzerland has been stable (see Figure 2) despite persistent current account surpluses (Stoffels and Tille, 2018). According to Stoffels and Tille (2018), current account surpluses have been offset by valuation losses on foreign assets stemming from the steady, real appreciation in the Swiss franc. In our steady state, the real exchange rate is constant by construction. Other factors that might account for the total net return loss captured in the model by Ψ_t are differences in the asset and, thus, the return structure of foreign assets versus foreign liabilities, among other things.

The other nonlinear equilibrium conditions are stated in Appendix B in real form.

3.9 Discussion I: Independence of the two policy instruments FXI and financial intermediation

An important assumption in our model is that the central bank has two separate instruments: the policy rate i^r and FXI. The derivation of the commercial banks' problem in section 3.4 helps us validate this assumption theoretically. In this section, we show that as long as the lower bound $\underline{i}^s$ does not bind, FXI do not affect i^s and i^g. They affect i^b if and only if they affect the demand for loans.

We make two assumption. First, we assume that the lower bound $\underline{i}^s$ does not bind. Second, we make sure that the problem is well-behaved by assuming that we are in an equilibrium in which $i^r_{t-1} = i^s_{t-1}$.[20]

Using these assumptions, we can derive the following proposition:

Proposition 1. *Commercial banks are indifferent to the amount of real deposits d_t if and only if $i^r_{t-1} = i^s_{t-1}$.*

Proof. "if": if $i^r_{t-1} = i^s_{t-1}$, commercial banks make neither profits nor losses from accepting deposits and simultaneously holding them as reserves at the central bank. Hence, they are indifferent. "only if": if commercial banks are indifferent, it must be that $i^r_{t-1} = i^s_{t-1}$. Suppose not. If either $i^r_{t-1} > i^s_{t-1}$ (or $i^r_{t-1} < i^s_{t-1}$), commercial banks cannot be indifferent because they are better off by accepting more (fewer) deposits and by increasing (decreasing) their reserve holdings at the central bank, which contradicts the claim. □

In other words, Proposition 1 ensures that the additional deposits generated when the central bank purchases foreign bonds from domestic savers do not change the behaviour or the profitability of commercial banks and, thereby, do not affect i^s or i^g. Commercial banks can simply pass on these additional deposits to the central bank.

The following corollary summarises the impact of FXI on market interest rates:

Corollary 1. *Abstracting from general equilibrium effects (i.e. keeping i^r constant), FXI do not have an impact on i^s and i^g. They affect i^b if and only if they affect the demand for loans.*

Proof. Because $i^s_{t-1} = i^r_{t-1}$ and $i^s_{t-1} = i^g_{t-1}$, only i^b_{t-1} could in principle depend on FXI. i^b_{t-1} depends on the aggregate demand for loans via condition (32). □

FXI might affect the loan demand for several reasons, e.g. because the weaker exchange rate raises production and, hence, the profits of domestic firms, which are partly distributed to borrowers. Indeed, in our quantitative exercise, i^b rises as a result of FXI, thereby dampening their effect.[21]

[20] If commercial banks also hold government bonds, $i^r_{t-1} = i^g_{t-1}$ would follow by no-arbitrage, such that commercial banks are indifferent between government bonds and reserves. Because government bonds and deposits are perfect substitutes, $i^s_{t-1} = i^g_{t-1}$, implying that $i^r_{t-1} = i^s_{t-1}$.

[21] Fuhrer et al. (2021) document that, beyond a certain threshold, an increase in reserves actually lowers commercial banks' lending spreads (the difference between banks' lending rate and the risk-free rate) because banks attempt to increase their loan volume by lending more aggressively. Compared to our model, in which the spread increases, the economic impact of FXI is amplified.

What happens instead if the effective lower bound $\underline{\mathrm{i}}^s$ binds? In this case, $i^r_{t-1} < \underline{\mathrm{i}}^s$, and Proposition 1 and, hence, Corollary 1 cease to apply. Banks are no longer indifferent to the amount of deposits, and FXI might affect their profitability and ability to intermediate between savers and borrowers. An extended version of our commercial banking sector is required to analyse the consequences of FXI in this scenario in greater detail.[22]

In the following, we show that $i^r_{t-1} = i^s_{t-1}$ is a suitable assumption for Switzerland.

3.10 Discussion II: Lower bound $\underline{\mathrm{i}}^s$ in the Swiss context

In January 2015, the SNB imposed an interest rate of −0.75% on sight deposits (reserves) held by commercial banks, which means that we also need to assume that i^s_{t-1} is at −0.75%. International evidence and evidence for Switzerland suggest that commercial banks are reluctant to lower i^s_t below zero (see, e.g. Eggertsson et al., forthcoming and the references included therein). Nevertheless, we argue that $i^r_{t-1} = i^s_{t-1}$ is an appropriate assumption for Switzerland in the context of our model for the following reasons.

- Because only sight deposits exceeding an exemption threshold are subject to the negative interest rate at the SNB, the effective interest rate paid by the banking system as a whole is considerably higher (in absolute terms) than −0.75%.[23]
- Many commercial banks in Switzerland charged customers for deposits that exceed a certain threshold (Baeriswyl et al., 2021, and Fuster et al., 2021) and/or they indirectly passed on negative rates by increasing fees (Basten and Mariathasan, 2020).
- No evidence shows that bank lending decreased after the SNB lowered its policy rate to −0.75% – see, e.g. Schelling and Towbin (2020) and Baeriswyl et al. (2021) – something that we expect if a binding lower bound on deposits hampers financial intermediation.

To conclude, no evidence shows that FXI have caused a higher spread between banks' borrowing and lending rates or that FXI have decreased bank lending. Finally, note that assuming $i^r_{t-1} = i^s_{t-1}$ ensures that the interest rate on government bonds i^g_{t-1} follows the policy rate into negative territory (because $i^s_{t-1} = i^g_{t-1}$), which is consistent with the empirical evidence provided by Grisse and Schumacher (2018) for Switzerland. Eggertsson et al. (forthcoming) present similar evidence from Sweden. This link is crucial for the exchange rate channel of monetary policy because i^g_{t-1} enters the UIP (see equation 24).

[22] Whether the effect of FXI is positive or negative depends on the details of the banking sector. In Eggertsson et al. (2017), if $i^r_{t-1} < \underline{\mathrm{i}}^s$, holding reserves becomes costly, and commercial banks prefer to hold more cash, which decreases their profits and, hence, increases the costs of financial intermediation. On the one hand, additional FXI might increase the costs of financial intermediation in this case because they increase banks' financial burden. On the other hand, additional reserves improve the average quality of banks' collateral, which might foster credit creation, a point made by Lenel et al. (2019).

[23] A back-of-the-envelope calculation suggests that the effective interest rate on sight deposits was −0.16% in 2021 (profits on Swiss franc positions by the SNB divided by average amount of sight deposits).

4 Estimation

We estimate the model using Bayesian methods on Swiss data, as surveyed for example in An and Schorfheide (2007). A Bayesian estimation combines prior information on the parameters with the likelihood function of the model to form the posterior distribution. We construct the likelihood using the Kalman filter based on the model's state space representation of the rational expectations solution. In the remainder of this section, we first show the set of model parameters that we calibrate to the Swiss and foreign economy. Then we describe the data used for estimation before we present the estimated parameters prior and posterior distributions.

4.1 Calibrated parameters

We calibrate the steady states of a few key model variables to pre-financial crisis data before we solve analytically for the steady states of the other variables. Thereby, we normalize steady-state quarterly GDP to one, $y_h = 1$. Table 1 summarizes the calibrated steady-state and parameter settings. The steady-state foreign asset position of the SNB relative to quarterly GDP, $\frac{B^{cb,*}}{y_h}$, is 60% in the model, which reflects the average foreign asset position from 2000 until the financial crisis. We set the government debt to the quarterly GDP ratio, $\frac{B}{y_h}$, to 142.4%, the value in 2007. Steady-state cash holdings relative to quarterly GDP, $\frac{M}{y_h}$, are 32% for both savers and borrowers. This equals the ratio of banknotes in circulation to GDP immediately before the crisis. The ratio of household bank loans to quarterly GDP, $\frac{L}{y_h}$, was 368% on average from 1999 until 2009. Both the Swiss and foreign government spending to GDP ratios, $\frac{G}{y_h}, \frac{G^*}{y_h}$, are calibrated to 20%.

The share of consumers without wealth, χ, is calibrated to match the share of the Swiss population with wealth less than 50000 Swiss franc.[24] The markups of domestic, importing and foreign firms are 10% in the steady state. We assume that the resulting profits of Swiss firms are distributed to borrowers and savers according to their population share. Hand-to-mouth consumers do not receive any profits. Swiss savers are more patient than borrowers with a discount factor of $\beta^s = 0.998$ compared to $\beta^b = 0.9926$. They are also more patient than foreign households, which implies a steady-state real interest rate differential of an annualised 0.7% between the foreign and the Swiss economy. This differential is picked up by the steady-state adjustment costs, $\zeta = \frac{\beta^s}{\beta^*} - 1$. This calibration ensures that the steady-state real effective returns in the foreign and domestic economies are equal. Therefore, in the steady state, domestic savers are indifferent between saving in Switzerland and abroad. We calibrate the steady-state total net return loss in the aggregate resource constraint to $\Psi = 0.04 - \zeta$. This value leads to a reasonable pre-financial crisis private NIIP ratio of 100% of annual GDP, which matches the data in Figure 2.

Steady-state inflation in Switzerland is calibrated to 1% on an annual basis, $\pi^c = \pi = 0.0025$, reflecting the average of the quantitative band that the SNB equalises with

[24] See the Swiss wealth statistic of the Swiss Federal Tax Administration.

Parameter		Value
$\frac{B^{cb,*}}{y_h}$	SS CB foreign asset to GDP ratio	0.6
$\frac{B}{y_h}$	SS government debt to GDP ratio	1.424
$\frac{M}{y_h}$	SS cash to GDP ratio	0.32
$\frac{L}{y_h}$	SS bank loans to GDP ratio	3.68
$\frac{G}{y_h}$	SS government spending to GDP ratio	0.2
$\frac{G^*}{y_h}$	Foreign SS government spending to GDP ratio	0.2
χ	Share of consumers without wealth	0.55
λ_h	SS mark-up domestic firms	1.1
λ_f	SS mark-up importing firms	1.1
λ_x	SS mark-up exporting firms	1
λ_*	SS mark-up foreign firms	1.1
β^s	Discount factor savers	0.998
β^b	Discount factor borrowers	0.9926
β^*	Foreign discount factor	0.9963
π^c	SS CPI inflation	0.0025
π	SS domestic inflation	0.0025
π^*	SS foreign inflation	0.005
γ^o	Degree of openness	0.6
γ^m	Storage costs cash	0.005

Table 1: Selected calibrated parameters

	Prior			Posterior			
	Dist	Mean	Std	Mean	Std	5%	95%
q	gamm	0.750	0.3000	1.180	0.2543	0.7782	1.5640
Λ	beta	0.500	0.1000	0.795	0.0409	0.7284	0.8609
χ^{hm}	beta	0.500	0.2000	0.906	0.0266	0.8635	0.9492
η	gamm	1.000	0.1000	0.843	0.0729	0.7231	0.9622
σ^m	norm	1.000	0.2000	0.106	0.0178	0.0764	0.1349
λ^ζ	gamm	0.500	0.2500	0.001	0.0002	0.0009	0.0014
φ	beta	0.500	0.1500	0.603	0.0565	0.5100	0.6929
θ	gamm	1.000	0.1000	0.883	0.0654	0.7745	0.9897
ϕ	beta	0.750	0.0500	0.897	0.0133	0.8750	0.9187
ϕ^f	beta	0.750	0.0500	0.865	0.0162	0.8394	0.8917
ι^p	beta	0.500	0.1000	0.371	0.0740	0.2497	0.4936
ι^f	beta	0.500	0.1000	0.332	0.0729	0.2101	0.4492
τ^2	invg	0.100	0.1000	0.257	0.0567	0.1636	0.3497
ν^1	gamm	6.000	0.5000	6.079	0.4831	5.2658	6.8570
ρ^m	beta	0.800	0.0500	0.933	0.0087	0.9191	0.9476
ϕ^π	gamm	1.500	0.0500	1.489	0.0497	1.4083	1.5690
ϕ^y	gamm	0.500	0.0500	0.439	0.0448	0.3667	0.5128
ϕ^{dy}	gamm	0.100	0.0500	0.008	0.0035	0.0024	0.0134
$\Lambda^\star$	beta	0.500	0.1000	0.317	0.1367	0.1153	0.5033
$\eta^\star$	gamm	1.000	0.1000	1.032	0.0985	0.8713	1.1890
$\theta^\star$	gamm	1.000	0.1000	0.508	0.0150	0.4888	0.5295
$\phi^\star$	beta	0.750	0.0500	0.827	0.0239	0.7884	0.8666
$\iota^\star$	beta	0.500	0.1000	0.400	0.0752	0.2775	0.5254
$\rho^{m,\star}$	beta	0.800	0.1000	0.883	0.0201	0.8501	0.9154
$\phi^{\pi,\star}$	gamm	1.500	0.1000	1.557	0.1020	1.3902	1.7277
$\phi^{y,\star}$	gamm	0.500	0.1000	0.278	0.0623	0.1776	0.3764
$\phi^{dy,\star}$	gamm	0.200	0.1000	0.005	0.0022	0.0012	0.0079

Table 2: Parameter prior and posterior distributions: Structural parameters

price stability. Foreign steady-state inflation, π^*, equals 2% on an annual basis. The resulting inflation differential of 1% per annum between Switzerland and the foreign economy determines the steady-state nominal appreciation of the Swiss franc relative to the US dollar and the euro in the model. To obtain the degree of openness, γ^o, we sum up nominal imports and exports in each period, divide this value by twice the Swiss GDP and take the average over the sample period. Finally, we set the storage costs of cash, γ^m, such that the effective lower bound on the deposit rate is -2% annualised, $\underline{\mathrm{i}}^s = -0.005$. This is the lower bound of the interval estimated by Kolcunova and Havranek (2018) for the Czech Republic. In fact, the de-facto lower bound resulting in our quantitative application is slightly higher than -2% because, according to our utility function, a household's marginal utility is declining but always positive:

$$U\left(x_t^k, n_t^k, \frac{M_t^k}{P_t}, \epsilon_t^c, \epsilon_t^{\alpha^m}\right) = \left[1 - e^{(-qx_t^k)} + \alpha^{m,k}\epsilon_t^{\alpha^m}\frac{1}{1-\frac{1}{\sigma^m}}\left(\frac{M_t^k}{P_t}\right)^{1-\frac{1}{\sigma^m}} - \alpha^n\frac{1}{1+\eta}(n_t^k)^{1+\eta}\right]\epsilon_t^c, \tag{37}$$

where $k \in \{b, s\}$. Hence, no satiation point $\bar{m}$ exists for real money balances, at which $U_M\left(c_t^k, n_t^k, \bar{m}, \epsilon_t^c, \epsilon_t^{\alpha^m}\right) = 0 \;\forall\; \frac{M_t^k}{P_t} \geq \bar{m}$. However, the existence of a satiation point was assumed in the derivation of the lower bound in Section 3.1.

4.2 Data

We use quarterly data for Switzerland, the US and the euro area from the fourth quarter of 1999 to the third quarter of 2022 to estimate the model. The following thirteen observables are employed: growth in Swiss real GDP, growth in Swiss real consumption, growth in Swiss real bank loans, growth in Swiss real bank notes in circulation, the real effective exchange rate, Swiss real total NIIP without SNB reserve assets, SNB reserve assets, Swiss domestic inflation, Swiss CPI inflation, the SNB policy rate and real GDP growth, CPI inflation and the policy rates for the US and the euro area. We start the sample in the fourth quarter of 1999 because quarterly data on the NIIP are only available since Q4 1999. The foreign economy is a composite of the US and euro area. The relative weights of the US and the euro area (20% US, 80% euro area) reflect the relative export and import shares vis-à-vis Switzerland.

4.3 Prior and posterior distributions

Prior distributions. Overall, we estimate 27 structural parameters and 13 shock processes. Tables 2 and 3 summarise the prior and posterior distributions for each parameter. Foreign economy parameters are labelled by an asterisk. Columns 2–4 show the prior settings. In general, we use the Beta distribution for those parameters that span only the unit interval. For parameters that should be positive, we use a Gamma distribution. For the standard deviation of shock innovations, we use the Inverse Gamma distribution.

The preference parameter in the utility function q is centred around 0.75, the value chosen in Eggertsson et al. (2017). We also use their input to calibrate the prior mean of the marginal intermediation cost parameter ν^1 to 6. Indexation and habit parameters, ι and Λ, are centred around 0.5. We also set the prior of χ^{hm} to 0.5, which implies that 50% of all households without wealth are hand-to-mouth consumers and 50% are borrowers. The same is true for the persistence parameter in the UIP φ, for which we select the same prior settings as in Adolfson et al. (2008). Because no evidence exists of the key parameter λ^{ζ}, which governs the effectiveness of FXI, we opt for a loose prior centred around 0.5. However, we exclude a contractionary effect of FXI on the exchange rate by choosing a gamma distribution. The Calvo parameters for domestic, import and foreign prices are centred around 0.75, a value consistent with an average period of one year between price adjustments. This corresponds to the average duration of price rigidity reported for Switzerland in Kaufmann (2009). The prior means for the Taylor rule parameters in the domestic economy, $\rho^m = 0.8$, $\phi^\pi = 1.5$, $\phi^y = 0.5$ and $\phi^{dy} = 0.1$, reflect interest rate smoothing, a reaction to inflation consistent with the Taylor principle and a moderate reaction to the output gap and output growth. The priors for the Taylor rule parameters in the foreign economy are chosen analogously.[25] The persistence parameters in the shock processes are centred around 0.75 with the exception of the persistence parameters in the markup shocks, ρ^{λ^h}, ρ^{λ^f} and $\rho^{\lambda^{h,*}}$, and the persistence parameters in the monetary policy shocks, ρ^r and $\rho^{r,*}$. The reason for setting a lower prior persistence in these shock processes is to pick up high frequency movements only in inflation and the interest rate and to allow the New Keynesian Phillips curves and Taylor rules explain the remaining variations.

Posterior distributions and exchange rate persistence (φ). The posterior estimates point to a high degree of price stickiness in the domestic and foreign economies, consistent with other recent DSGE model estimates of price stickiness (see Adolfson et al., 2008 or Rudolf and Zurlinden, 2014). Price stickiness in Switzerland is found to be higher for domestic prices than for import prices with posterior means of $\phi = 0.9$ and $\phi^f = 0.87$. This reflects the observation that import prices are more volatile than domestic prices.

Whereas the posterior distributions show a low degree of price indexation in the Swiss and foreign economy, there is a significant degree of persistence in the exchange rate behaviour with a posterior mean estimate for φ of 0.6. This finding confirms delayed overshooting in the Swiss exchange rate market. More generally, the data strongly prefer a model in which $\varphi > 0$ (corresponding to the modified UIP (24)) than a model in which $\varphi = 0$ (corresponding to the standard UIP (23)). The model with exchange rate persistence ($\varphi > 0$) has a log marginal likelihood of -1700 relative to a log marginal likelihood of -1721 for the model without exchange rate persistence ($\varphi = 0$).[26] This is also documented by a posterior probability of 1.0.[27] To compute the log marginal likelihood of the model with $\varphi = 0$, we re-estimate the entire model setting $\varphi = 0$, leaving the steady-state parametrisation unchanged. Intuitively, to match the data in the absence

[25]See the prior distributions in Smets and Wouters (2007) for the US and Rudolf and Zurlinden (2014) for Switzerland.

[26]We use the Laplace approximation to calculate the log marginal likelihoods.

[27]See Koop (2003) for a definition of posterior model probability.

	Prior			Posterior			
	Dist	Mean	Std	Mean	Std	5%	95%
ρ^{c}	beta	0.750	0.1000	0.913	0.0296	0.8672	0.9592
ρ^{ζ}	beta	0.750	0.1000	0.338	0.0680	0.2272	0.4480
ρ^{g}	beta	0.750	0.1000	0.945	0.0074	0.9338	0.9578
$\rho^{\bar{l}}$	beta	0.750	0.1000	0.533	0.0864	0.3884	0.6740
ρ^{λ^h}	beta	0.300	0.1000	0.248	0.0757	0.1211	0.3665
ρ^{λ^f}	beta	0.300	0.1000	0.411	0.0970	0.2536	0.5689
ρ^{α^m}	beta	0.750	0.1000	0.988	0.0047	0.9812	0.9961
ρ^{Ψ}	beta	0.750	0.1000	0.282	0.0576	0.1845	0.3739
ρ^{r}	beta	0.500	0.1000	0.420	0.0670	0.3106	0.5302
$\rho^{B^{cb,*}}$	beta	0.750	0.1000	0.990	0.0040	0.9838	0.9964
ρ^{g^*}	beta	0.750	0.1000	0.849	0.0202	0.8161	0.8821
$\rho^{\lambda^{h,*}}$	beta	0.300	0.1000	0.795	0.0603	0.7096	0.8830
$\rho^{r,*}$	beta	0.500	0.1000	0.747	0.0478	0.6734	0.8231
σ^{c}	invg	2.000	2.0000	1.297	0.2143	0.9680	1.6210
σ^{ζ}	invg	3.000	4.0000	1.085	0.1532	0.8378	1.3276
σ^{g}	invg	3.000	4.0000	12.603	0.9983	10.9693	14.2121
$\sigma^{\bar{l}}$	invg	3.000	4.0000	16.177	1.7791	13.2292	18.9941
σ^{λ^h}	invg	0.500	1.0000	1.033	0.1729	0.7633	1.2935
σ^{λ^f}	invg	0.500	1.0000	3.380	0.4202	2.6960	4.0466
σ^{α^m}	invg	3.000	4.0000	11.837	2.1758	8.3948	15.0849
σ^{Ψ}	invg	3.000	4.0000	261.905	13.3150	239.9879	284.6348
σ^{r}	invg	0.500	1.0000	0.086	0.0075	0.0736	0.0978
$\sigma^{B^{cb,*}}$	invg	3.000	4.0000	42.819	3.2147	37.4850	47.8663
σ^{g^*}	invg	3.000	4.0000	11.630	1.0628	9.8844	13.3696
$\sigma^{\lambda^{h,*}}$	invg	0.500	1.0000	1.558	0.2732	1.1136	1.9840
$\sigma^{r,*}$	invg	0.500	1.0000	0.113	0.0153	0.0878	0.1369

Table 3: Parameter prior and posterior distributions: Shock process parameters

of the lagged exchange rate in the UIP, the model requires a higher persistence of the shock process ϵ_t^{ζ}, ρ^{ζ} (0.8 instead of 0.3).[28] In other words, if $\varphi = 0$, the shock process must explain a larger fraction of the variation in the data, resulting in an inferior fit.

The parameter λ^{ζ}, which governs the effectiveness of FXI on the exchange rate is well identified with a posterior mean of 0.001. We find a high degree of interest rate smoothing in the domestic and foreign economies with the posterior means $\rho^m = 0.93$ and $\rho^{m,*} = 0.88$. Together with the low posterior mean estimates for the reaction to output growth $\phi^{dy} = 0.008$ and $\phi^{dy,*} = 0.005$, these estimates reflect the monetary policy environment from the financial crisis until the COVID-19 pandemic, during which time policy rates were close to the effective lower bound and very rarely adjusted. The interest rate elasticity of cash σ^m is estimated to a small value with a posterior mean of 0.1. This implies that the elevated Swiss cash holdings can only be explained to a limited degree by low interest rates in the model. The domestic trade elasticity θ is slightly below the prior mean elasticity (θ=0.88), whereas the foreign trade elasticity θ^* is lower at 0.51. The latter estimate implies a moderate reaction of Swiss exports to exchange rate movements. Both trade elasticity estimates are in line with Rudolf and Zurlinden (2014). The posterior estimate of the marginal intermediation cost parameter ν^1 lies very close to the prior mean, the value chosen in Eggertsson et al. (2017). The share of hand-to-mouth consumers among all households without wealth χ^{hm} is estimated at 0.9. This high estimate reduces the interest rate sensitivity of aggregate consumption in the model because hand-to-mouth consumers react only to disposable income. Finally, the posterior estimate of q=1.2 implies an intertemporal elasticity of substitution in a borrower's and a saver's consumption (IES) of 1. The value is larger than the one assumed in Eggertsson et al. (2017) and Curdia and Woodford (2011) and lies within the range of plausible estimates as documented in, for example, the literature overview of Thimme (2016). Moreover, the IES of 1 in the model leads to an impulse response of GDP after a monetary policy shock, which is consistent with Swiss empirical evidence (see Figure 6 and the empirical evidence in Cwik et al., 2022).

4.4 Discussion I: Empirical plausibility of ζ_t

ζ_t – the "friction" that makes FXI effective – is in line with empirical measures for FX market frictions. We use two empirical measures. The first measure is ex-ante UIP deviations.[29] Because they are calculated ex-ante, they depend on external exchange rate

[28] The remaining parameters for the estimation with $\varphi = 0$ are available on request.

[29] The UIP deviations are defined as the ex-ante expected excess return when transferring Swiss money at the spot rate into foreign currency, investing it at the three-month foreign policy rate and then transferring it back into Swiss franc using the expected exchange rate in a three-month period compared to a three-month investment at the Swiss policy rate. The foreign policy rate and exchange rates are computed as the weighted average of US and euro area data, as discussed in Section 4.2. We need expectations of the Swiss franc exchange rate vis-à-vis the euro area and the US to compute the UIP deviations. Following Bacchetta et al. (2023), we use 3-month ahead expectations from the Consensus panel for the EURCHF and EURUSD and calculate the effective expected Swiss exchange rate according to the following formula: $S_{t+1}^{exp} = \left(S_{t+1}^{exp,EURCHF}\right)^{0.8} * \left(\frac{S_{t+1}^{exp,EURCHF}}{S_{t+1}^{exp,EURUSD}}\right)^{0.2}$.

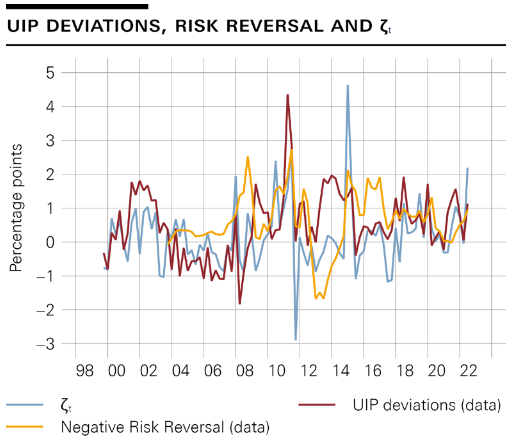


Figure 4: Comparison ζ_t and empirical measures of FX market frictions

expectations, which do not necessarily need to be consistent with overall financial market expectations. Therefore, we also calculate the Swiss franc risk reversal, which does not depend on expectations. The risk reversal is a measure for crash risk Brunnermeier et al. (2009) events that cause a sharp depreciation in the foreign currency. If investor do not reap arbitrage opportunities inherent in the UIP deviations because they fear "crashes" (Brunnermeier et al., 2009) or "disasters" (Farhi et al., 2009), the risk reversal should be a good proxy for frictions in FX arbitrage.[30]

Figure 4 shows that ζ_t co-moves closely with the empirical UIP deviation and the (negative) of the risk reversal.[31] Although the fit is not perfect, it should be noted that we do not use either the empirical UIP deviations nor the risk reversal as an observable in our estimation.

4.5 Discussion II: Decomposition of ζ_t

As stated in relation to equation (25), in the model, ζ_t consists of an endogenous and an exogenous component. In the following, we discuss the determinants and the identification of the two components in greater detail.

We start by discussing the exogenous component, which is not influenced by FXI. It is shown in the left panel in Figure 5, together with ζ_t. The exogenous component and

[30]The Swiss franc risk reversal is a composite of the EURCHF and the USDCHF risk reversals with the same country weights used to calculate the UIP deviations.

[31]We plot the negative of the risk reversal because the EURCHF or the USDCHF risk reversal becomes more negative in times of stress, whereas ζ_t becomes more positive by construction. For example, the EURCHF risk reversal is a price of a call EURCHF option (right to buy euros and sell Swiss franc at a certain rate) minus the price of a put EURCHF option (right to sell euros and buy Swiss francs at a certain rate). A Swiss saver who owns foreign bonds wants to insure against an appreciation in the Swiss franc by purchasing put EURCHF and USDCHF options. In times of stress, buying insurance against an appreciation in the Swiss franc becomes more expensive. Hence, put options become more valuable, and the risk reversal tends to become more negative.

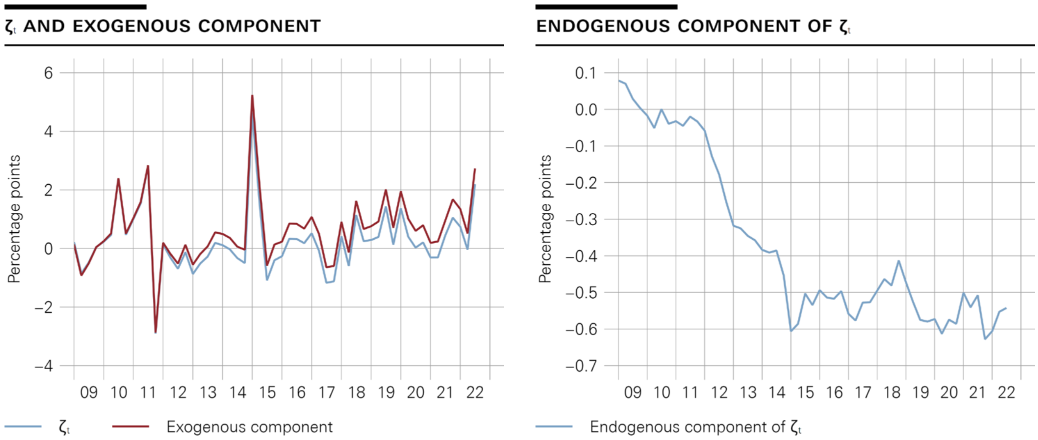


Figure 5: Comparison ζ_t, exogenous component and endogenous component

ζ_t are observed to co-move closely, suggesting that the exogenous component (here, in particular, ϵ_t^{ζ}) is important to understand the behaviour of ζ_t over time.

The timing of the ups and downs in the exogenous component, which are entirely due to ϵ_t^{ζ}, suggests that ϵ_t^{ζ} reflects political events. From the point of view of Swiss savers, the European debt crisis in 2011 and the victory of the far-left Syriza party in the elections in Greece in January 2015 made it more likely that the euro area would break up.[32] Consequently, according to our estimation, both ϵ_t^{ζ} and ζ_t increased in January 2015.[33] After mid-2012, insurance costs declined for some time, in part because the ECB had announced the Outright Monetary Transactions (OMT) programme.[34] Other events had a more limited impact on the insurance costs and, thus, also on ϵ_t^{ζ}.[35]

We now turn to the endogenous component of ζ_t shown in the right panel in Figure 5. This component represents the difference between the exogenous component and ζ_t in the left panel in Figure 5. Consistent with our theoretical assumptions, FXI reduce UIP deviations. Starting from zero at the time of the financial crisis, the endogenous component has become more negative over time due to FXI conducted by the SNB. However, compared to the exogenous component, the magnitude of the endogenous

[32]Syriza threatened to end what they called the “vicious circle of austerity”; see `https://www.dw.com/en/a-timeline-of-greeces-long-road-to-recovery/a-45118014` (retrieved on 7 January 2021).

[33]The discontinuation of the minimum exchange rate by the SNB in January 2015 also contributed to the increase in insurance costs.

[34]As Dell’Ariccia et al. (2018) put it: “Together, the announcement of the OMT program and Draghi’s ‘whatever it takes’ speech reversed the sovereign-debt market self-destructing spiral. And this was accomplished without ever making purchases under the program, since to date, not a single member country has made a formal request.” (p. 115)

[35]For example, the increase in insurance costs after mid-2013 was probably due to the challenge to the legality of the OMT programme in front of the German constitutional court and later in front of the European Court of Justice (`https://en.wikipedia.org/wiki/2000s_European_sovereign_debt_crisis_timeline`, retrieved on 7 January 2021). The decrease in ζ_t in 2017 is due to Macron’s victory in the presidential elections in France. The agreement on the EU recovery fund in July 2020 also helped decrease ζ_t.

component is small, indicating that FXI account only for a limited part of ζ_t. This finding is consistent with the observation that FXI have been attenuating but not fully offsetting the impact of political events on the Swiss franc exchange rate, a conclusion that is in line with our discussion on the development of the NIIP (see Figure 2 in Section 2).

5 Effectiveness of policy rate changes and FXI

In this section, we discuss the impact of the two policy instruments on the model economy. The following impulse responses start when the model economy is in equilibrium and are used to analyse the effect of changes in the two policy instruments in the absence of other shocks. This allows for a study of the effect of their transmission on the nominal exchange rate, real economic activity and inflation.

5.1 Transmission of a policy rate change

We start by describing the impact of an expansionary monetary policy shock large enough to temporarily decrease the policy rate by 100 bp (annualised). The path of the policy rate is depicted in the upper-left panel in Figure 6. In our experiment, the policy rate remains at approximately 100 bp below its initial value for three quarters before returning to its initial level.

The decline in the policy rate stimulates GDP and inflation through the exchange rate channel, the interest rate channel and the bank lending channel. The interest rate channel increases GDP and inflation by lowering the interest rates for savers. Lower interest rates stimulate consumption, which in turn increases domestic demand and domestic prices. In addition, the bank lending channel decreases the borrowing rate albeit less than one for one, which allows borrowers to take out more loans. The exchange rate channel increases GDP and inflation by weakening the Swiss franc. As the upper-right panel in Figure 6 shows, the reduction in the policy rate leads to a depreciation in the Swiss franc of up to 4% after five quarters. Although the Swiss franc starts to appreciate after seven quarters, it remains permanently lower, even after the policy rate has returned to its initial level. The reason is that the policy intervention permanently increases consumer prices in Switzerland. Because consumer prices abroad remain constant, purchasing power parity implies that the Swiss franc becomes permanently weaker. As a result of the depreciation, Swiss products become more competitive, and net exports increase, increasing aggregate demand. The increase in domestic demand raises domestic inflation, whereas the weaker Swiss franc increases imported inflation. All of the channels cause GDP to increase by 2% at the peak, which is reached after three quarters (see the lower-left panel in Figure 6). Inflation increases by 1% after four quarters, as shown in the lower-right panel in Figure 6.

To the best of our knowledge, no recent empirical evidence exists on the effect of monetary policy on GDP and inflation in Switzerland. In a parallel paper, we aim to close this gap (see Cwik et al., 2022). Our findings in the two papers are broadly

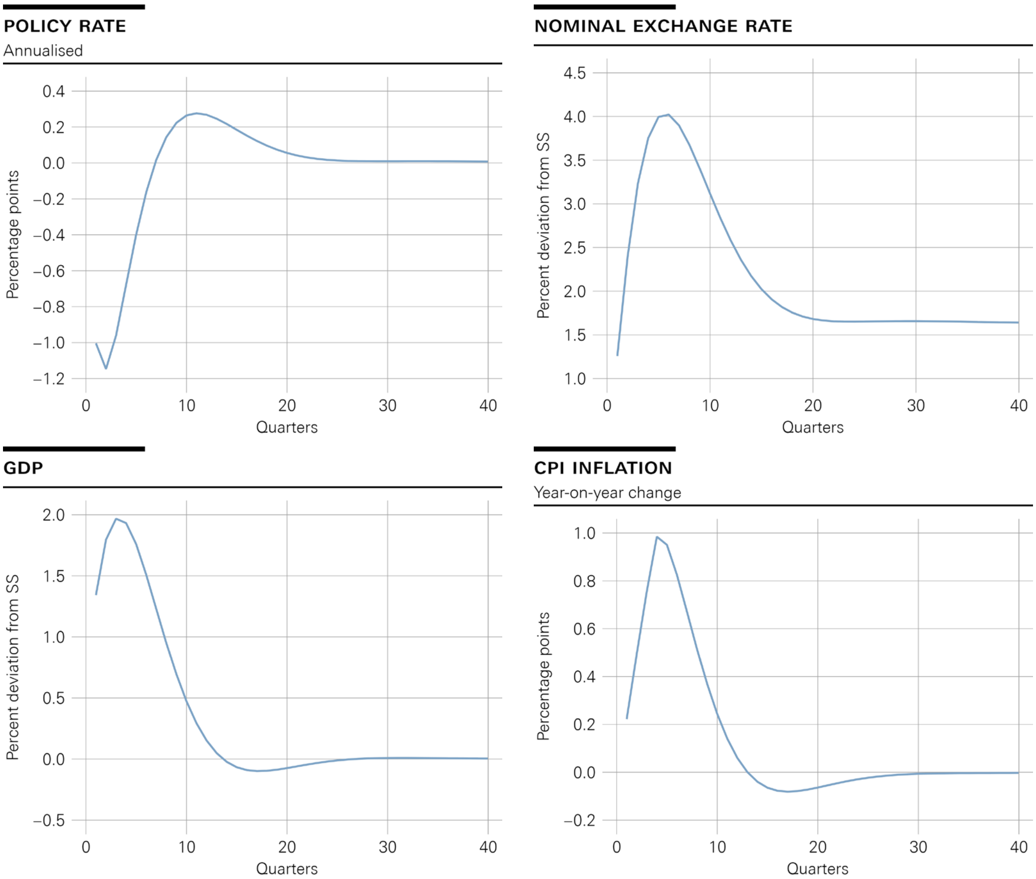


Figure 6: Expansionary policy rate shock

consistent with each other.[36] Fink et al. (2020) and Grisse (2020) analyse the effect of monetary policy on the Swiss franc. They report a depreciation of 2–4 % on impact, which is consistent with our findings. The degree of overshooting implied in our model is consistent with that in Scholl and Uhlig (2008) and Hettig et al. (2019).

5.2 Transmission of FXI

We now describe the effects of an FX intervention in the model. In our experiment, the SNB expands its balance sheet permanently by purchasing foreign bonds worth approximately CHF 27 billion (approximately 5% of annual GDP).[37]

When purchasing foreign bonds, the SNB reduces the amount of foreign bonds held by Swiss savers. By construction, the costs of holding foreign bonds for Swiss savers decline; hence, their effective return on foreign bonds increases, which depreciates the Swiss franc.

Because the weaker Swiss franc stimulates Swiss GDP and inflation, the Taylor rule dictates that the policy rate increases and partially crowds out the positive effect of the FX intervention. In this case, the Swiss franc depreciates by up to 0.4% after 10 quarters, as shown in the unrestricted scenario in the upper-right panel in Figure 7. Typically, however, the SNB intervenes in the FX rate market while keeping the policy rate constant. Therefore, we simulate the effect of an FX intervention for several different scenarios for how long the policy rate stays constant, as shown in the top left-hand panel in Figure 7. For example, the red lines show the effects when the policy rate is constant for one year, whereas the orange lines depict the effects when the policy rate is constant for two years. One can see that the impact of FXI on the Swiss franc depends crucially on how long the policy rate stays constant.[38]

In the top right-hand panel in Figure 7, we plot the paths of the Swiss franc for these policy rate paths. If the policy rate stays constant for three years, the Swiss franc depreciates by up to 1.1% following the intervention. If the policy rate stays constant for five years, the Swiss franc depreciates by up to 3% following the intervention, and GDP increases by 1% at the peak, which is reached after three quarters (see the lower-left panel in Figure 7). A general message that emerges from this discussion is that an FX intervention works best if the policy rate is kept constant in the years following the intervention and if the central bank can credibly commit to this future policy path at the time of the intervention. A corollary of this finding is that when the policy rate is stuck at its effective lower bound, FXI are more effective because the policy rate is unlikely to increase soon thereafter.

[36] Ramey (2016) provides an extensive survey of the effects of monetary policy in closed economies. According to her Table 1, the effects of policy rate changes on GDP are highly heterogeneous and encompass our results.

[37] We approximate a permanent expansion of the SNB balance sheet by setting the AR(1) coefficient in the shock process for FXI very close to 1. FXI are expressed in terms of real quarterly GDP averaged from 1999 Q4 to 2008 Q4, which amounts to approximately CHF 544 billion.

[38] We simulate the impulse responses under perfect foresight, i.e. agents in the model know how long the policy rate remains constant and act accordingly.

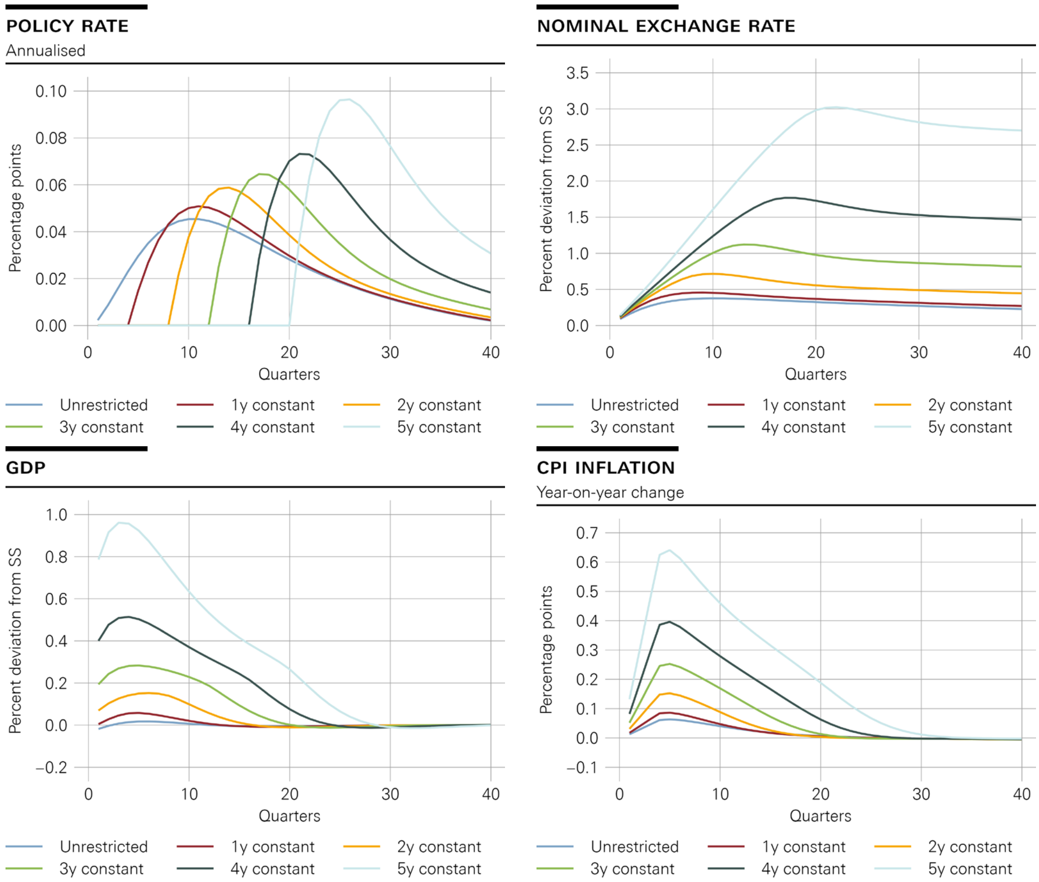


Figure 7: Expansionary FX intervention shock (5% of GDP)

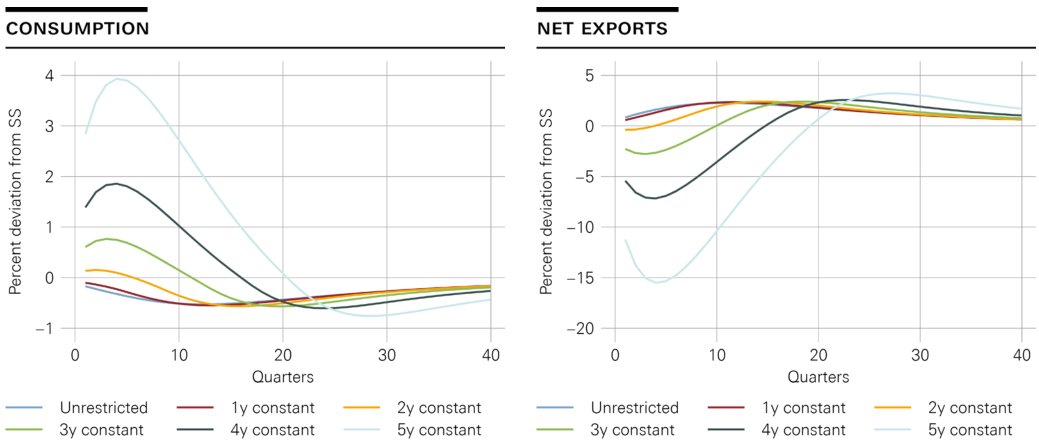


Figure 8: Expansionary FX intervention shock (5% of GDP)

As can be seen from the top right-hand panel in Figure 7, the impact of FXI on the nominal exchange rate is hump-shaped. This is due to the presence of the lagged exchange rate on the right-hand side of the UIP (see equation 24). Without the lag, i.e. if φ equal zero, the exchange rate depreciates on impact and appreciates afterwards. However, it would remain permanently weaker because the FX intervention has permanently increased consumer prices in Switzerland, but they remain constant abroad. Purchasing power parity then implies that the Swiss franc is permanently weaker. $\varphi > 0$ gives rise to the hump-shaped response, which becomes more pronounced as the impact of the FX intervention on Swiss consumer prices strengthens.

To assess the relative effectiveness of policy rate changes and FXI, we compare the peak effects of the two instruments on the nominal exchange rate. On the one hand, we find that a reduction in the SNB policy rate by 100 bp over three quarters causes the exchange rate to depreciate by 4% at the peak, which is reached after five quarters (see the top right-hand panel in Figure 6). On the other hand, an FX intervention worth approximately CHF 27 billion (5% of annual Swiss GDP) causes the exchange rate to depreciate by 1.1% at the peak if the policy rate remains constant in the three years following the intervention. Thus, a temporary reduction in the policy rate of 25 bp or an FX intervention of CHF 24 billion have the same effect on the exchange rate.

While changes in the policy rate affect GDP and inflation through the interest rate and exchange rate channels, FX interventions only operate through the exchange rate channel. In both cases, the bank lending channel dampens the expansionary effect of a policy rate reduction or FX purchases by increasing the spread between the lending rate i^b and the deposit rate i^s. The bank lending channel arises from the increase in output, which raises the income of borrowers. This allows them to take out more loans, and the volume of loans increases, as does the spread between i_t^b and i_t^s.

The expansionary effect of FXI on GDP and inflation can be seen in the bottom panel in Figure 7. Inflation rises by between 0.1% and 0.6% at the peak depending on how long the policy rate is held constant. The increase in inflation is mainly driven by the depreciation in the Swiss franc, which makes imports more expensive. Sticky prices imply that importers price in the full future path of the exchange rate, and inflation should increase from the first quarter onwards. However, because of indexation and that we show year-on-year inflation, the inflation response is hump-shaped, peaking five quarters after the exchange rate intervention. Empirical estimates for Switzerland suggest that the exchange rate pass-through is approximately 0.15 (see Stulz, 2007 and Oktay, 2022). A comparison of the peak responses of the nominal exchange rate and inflation shows that our model-implied pass-through is broadly in line with this evidence.

GDP increases by between 0.02% and 1% depending again on our assumption of the behaviour of the policy rate. To better understand how GDP reacts, we plot the impact of an FX intervention on consumption and net exports in Figure 8. Turning first to consumption (left-hand panel), we see that consumption increases if the policy rate is held constant for more than a year. In this case, the real interest rate declines because the policy rate is held constant as the inflation rate increases, causing the real interest rate to fall. If the policy rate is allowed to respond to the expansionary effect of the

FX intervention, the real interest rate rises because the Taylor principle requires that the nominal interest rate rises by more than the inflation rate. Given that Switzerland has a small, open economy with a high degree of openness, the consumption response also shapes the response of imports and, hence, the response of net exports shown in the right-hand panel. The direct impact of the exchange rate on external rebalancing, however, is comparably small.[39]

To our knowledge, although no evidence exists on the quantitative effects of FXI on GDP and inflation, we can compare the impact on the exchange rate through the empirical literature. Although considerable heterogeneity exists, the literature generally agrees that FXI have a sizable impact on exchange rates. Adler et al. (2019) use instrumental variables and estimate the impact of FXI on the exchange rate for a panel of 52 countries. They find a purchase of foreign currency of 1 percentage point of GDP causes the nominal exchange rate to depreciation in the range of [1.7%,2.0%]. Interestingly, when the authors split the sample between emerging market and advanced economies, the results for the emerging market economies hold even when the group is considered in isolation, whereas the impact of FXI become insignificant for advanced economies. This finding suggests that FXI are less effective for the latter group, possibly because domestic and foreign assets can be substituted more easily (in our model, this means that portfolio adjustment costs are lower) in advanced economies (Miyajima and Montoro (2013)). Consequently, the available evidence for Switzerland suggests that the effects of FXI are weaker. Kugler (2020) finds that an increase in sight deposits (reserves) of 1 percentage point of GDP depreciates the Swiss franc in the range of [0.33%,0.72%]. According to our model, FXI equivalent to 1 percentage point of GDP depreciate the Swiss franc in the range of [0.08%,0.6%] depending on how long the policy rate is held constant.

Other paper measure the impact of FXI in terms of USD. Ribon (2017) estimates that FX purchases equal to the monthly average of 830 million USD contributed to a depreciation in the effective exchange rate of approximately 0.6% in Israel. In our case, an intervention of the same size depreciates the Swiss franc in the range of [0.01%,0.09%] and, hence, by substantially less. Our results are more in line with the recent paper by Menkhoff et al. (2021), who analyse FXI by the Bank of Japan. They report that an intervention of 1.7 billion USD depreciates the USD/JPY by 0.2%. In our case, an intervention equivalent to 1.7 billion USD depreciates the Swiss franc in the range of [0.02%,0.18%]. Menkhoff et al. (2021) estimate that the effect of an intervention is very persistent, as do Caspi et al. (2022).[40]

In conclusion, the literature reflects considerable heterogeneity. Different countries, sample periods and data frequencies make the results difficult to compare. Our results show that an important source of heterogeneity is the length of time the policy rate is held constant after the intervention. Although the empirical literature implicitly assumes

[39]For this reason, it is difficult to compare our results to those in the literature that measures the impact of currency depreciations on external rebalancing. See Adler et al. (2020).

[40]Caspi et al. (2022) focus on the impact of an intervention (versus no intervention); therefore, their quantitative results are difficult to compare with ours.

sterilised FXI, which implies a constant policy rate at the time of the intervention, empirically controlling for anticipation effects of future policy rate changes may be difficult, which may lead to heterogeneity across studies.

6 Counterfactual experiments

In this section, we present the results of our counterfactual experiments, in which we study alternative paths of the policy rate and SNB reserve asset holdings.

6.1 The Swiss economy without FXI

With the help of our model, we now compute the path that the Swiss economy would have taken if the SNB had not intervened in the FX market. In this exercise, we assume that the path of the policy rate corresponds to the realised path. In a second exercise, we calculate the path for the Swiss economy if the SNB had refrained from using any unconventional monetary policy instruments. In this case, in addition to not intervening in the FX market, the SNB would have kept its policy rate at zero from 2015 to the third quarter of 2022.

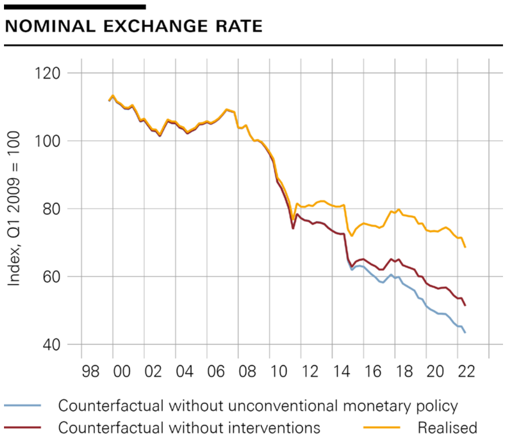
The following steps are necessary to compute the first exercise.

1. Where would the Swiss economy, i.e. the exchange rate, GDP and inflation, be in the absence of FXI?

2. Where would the policy rate be in the absence of FXI? The answer shows how much lower monetary policy would have endogenously set the policy rate in the absence of FXI to respond to lower inflation. This is governed in the model by the Taylor rule.

3. The magnitude of contractionary policy rate shocks needed to bring the policy rate back to the realised path is calculated.

To compute these steps, we proceed as follows. We run a historical shock decomposition for the nominal exchange rate, GDP, CPI inflation and the policy rate, i.e. we decompose the historical deviations in the variables from their steady-state values into the contributions from the various shocks in the model. The contribution of the FX intervention shock, $\varepsilon_t^{B^{cb,*}}$, to the historical deviations in the nominal exchange rate, GDP and CPI inflation determines the first component of the exercise. The contribution of the FX intervention shock to the historical deviations in the policy rate shows how much lower the policy rate would have been over the sample period without FXI (see Step 2). To compute the third step, we let the Kalman filter calculate the contractionary monetary policy rate shocks necessary to bring the policy rate back to the realised path. To arrive at the desired counterfactual, we subtract both the decline in the nominal exchange rate (respectively GDP or CPI inflation) obtained from the first step and the decline in these variables due to the contractionary policy rate shocks in the third step from the observed path of these variables.



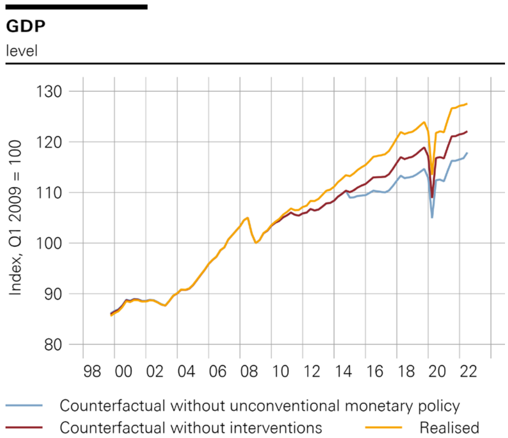


Figure 9: Swiss economy without FXI

The second exercise without any unconventional monetary policy instruments is computed similarly. We add further contractionary shocks in the third step to bring the policy rate path to zero from 2015 to the third quarter of 2022. This leads to additional downward pressure on GDP and CPI inflation.

Without unconventional monetary policy, the appreciation in the nominal exchange rate would have been much stronger in recent years. According to Figure 9 (left panel), the counterfactual exchange rate paths would have followed the same path as the realised one before the SNB started to intervene in the FX rate market. After the financial crises, the realised and counterfactual paths began to diverge. Had the SNB not intervened in the FX market, the nominal exchange rate would have appreciated 17 pp more until the third quarter of 2022 (red line). Without any unconventional monetary policy, i.e. without FXI and negative interest rates, the exchange rate would have appreciated even 25 pp more (blue line).[41]

A stronger Swiss franc would have depressed net exports. As a result, GDP would have been lower. The right panel in Figure 9 shows the realised and counterfactual paths for GDP. Without FXI, the GDP level would have been up to 5.5 pp below its realised path (red line). Without any unconventional monetary policy measures, GDP would have been 10.5 pp below its realised path (blue line).

Figure 10 (left-hand panel) shows that without FXI, inflation would have declined to

[41] Between September 2011 and January 2015, the SNB maintained a minimum exchange rate at CHF 1.20 per euro. Whether this policy changes the "average" relationship between FXI and the exchange rate estimated by our model depends on the credibility of the floor. Jermann (2017) and Hanke et al. (2019) use option prices to calculate the credibility of this policy and derive the counterfactual EURCHF exchange rate, i.e. the exchange rate that would have prevailed without the floor. Because their estimates for the counterfactual exchange rate depend on a different information set than our finding (option prices vs. development of reserve assets), they provide a useful cross-check. While Jermann (2017) finds that the counterfactual exchange rate is less than 5% lower than the actual exchange rate towards the end of the minimum exchange rate regime, Hanke et al. (2019) estimate that the difference is approximately 12%, which is broadly consistent with our results.

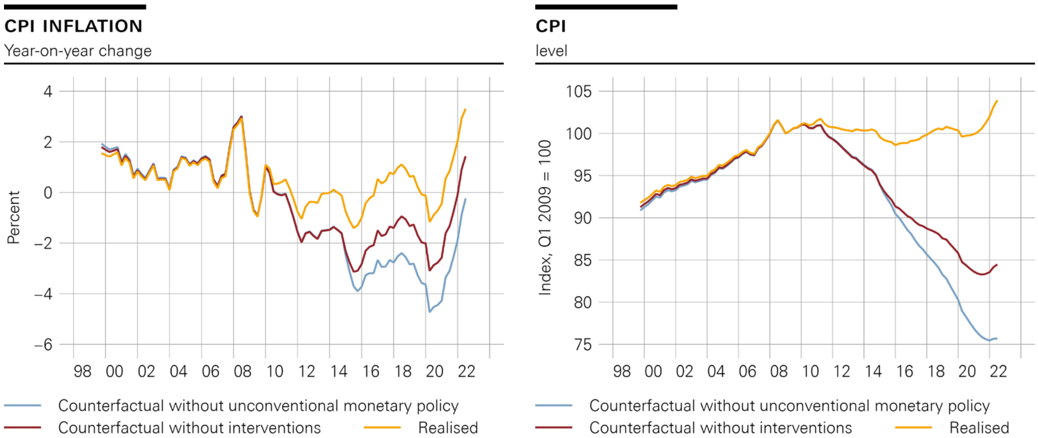


Figure 10: CPI without FXI

−3% in Q3 2015 (red line) and would have been negative from mid-2010 to 2022. In the absence of unconventional monetary policy, inflation would have fallen to −4% in the second quarter of 2020. This result suggests that both FXI and negative interest rates are effective tools for stabilising inflation around the quantitative band that the SNB equates with price stability. The right-hand panel shows the consequences for the CPI level: both negative interest rates and unconventional monetary policy helped stabilise the CPI at approximately its 2008–2009 level. Without these measures, the CPI would have fallen by 25%. Important to note is that inflation expectations remain anchored in our counterfactual experiments. It is likely that inflation expectations would have become unanchored if the SNB had not used unconventional monetary policy instruments. In this case, the decline in prices could have been much more drastic.

6.2 Additional FXI to avoid negative interest rates

Had the SNB not lowered its policy rate into negative territory in 2015 (Figure 11, left panel), considerable additional asset purchases would have been necessary to keep inflation on its realised path. This can be seen from the right panel. Instead of CHF 940 billion, the SNB would have held foreign assets worth CHF 1500 billion by Q3 2020.[42]

6.3 A shadow policy rate

In our third counterfactual experiment, we compute a shadow rate for Switzerland. We define the shadow rate as the path of the SNB policy rate required to keep inflation on

[42]The spike in foreign assets in Q1 2015 in the counterfactual experiment results because the interest rate – higher in the counterfactual experiment – immediately lowers the exchange rate and, thus, the inflation rate. In contrast, FXI affect the exchange rate and, hence, inflation only with a lag of several quarters. Because we require that the inflation path in the counterfactual experiment equals the realised path in all periods, foreign asset holdings must "overshoot" in the first period to compensate immediately for the higher interest rate.

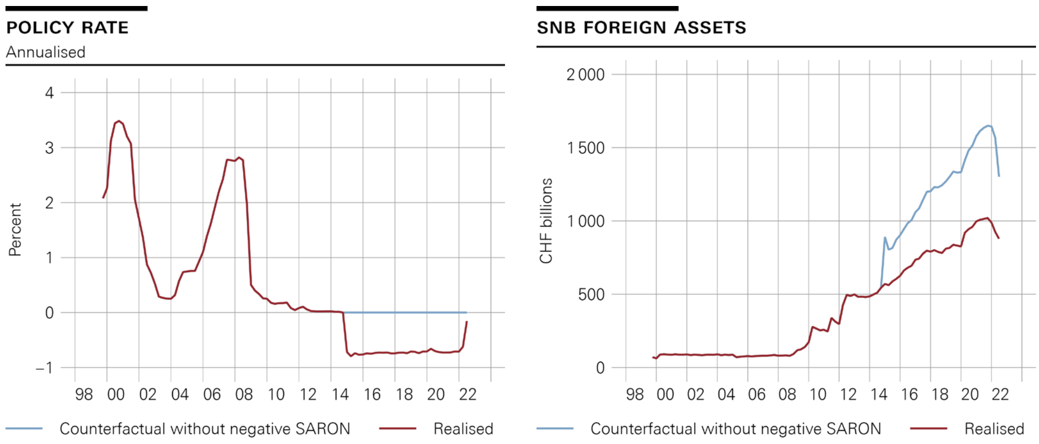


Figure 11: SNB foreign assets without negative policy rate

its realised path in the absence of FXI.

The following steps necessary to compute the shadow rate are similar but not identical to the steps in the first counterfactual (see Subsection 6.1).

1. Where would the policy rate be in the absence of FXI? The answer shows how much lower monetary policy would have endogenously set the policy rate in the absence of FXI due to the Taylor rule. This is the first component of the shadow rate.

2. Where would inflation be in the absence of FXI?

3. The magnitude of expansionary policy rate shocks needed to compensate for the fall in inflation caused by the absence of FXI. This is the second component of the shadow rate.

To compute these steps, we work with the historical shock decomposition as outlined in subsection 6.1. The contribution of the FX intervention shock to the historical deviations of the policy rate determines the first component of the shadow rate. The contribution of the FX intervention shock to the historical deviations of CPI inflation shows how much lower CPI inflation would have been over the sample period without FXI (see Step 2). To compute the third step, we let the Kalman filter compute the expansionary monetary policy rate shocks necessary to compensate the fall in CPI inflation due to the missing FXI (determined in Step 2). To arrive at the shadow rate, we subtract both the endogenous fall in the policy rate in the first step and the lower policy rate path to compensate the fall in CPI inflation in the third step from the observed policy rate path.

The left panel in Figure 12 shows the shadow rate in comparison to the observed policy rate. The right panel in Figure 12 plots the difference between the two rates. The shadow rate lies up to 1 pp below the observed policy rate. Hence, to achieve the observed inflation path without FXI, the SNB would have had to set its policy rate well

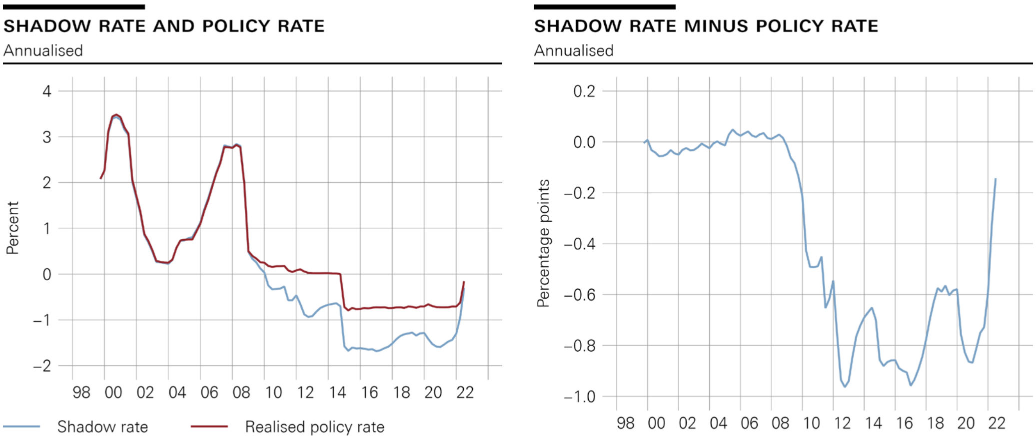


Figure 12: Shadow rate

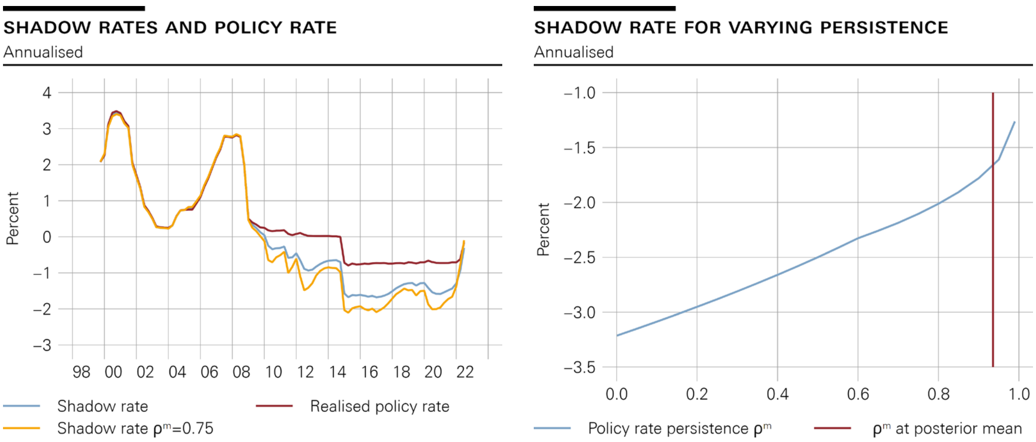


Figure 13: Shadow rate and policy rate persistence

below −1% from Q1 2015 onwards. To put into perspective the path of the shadow rate, note that the SNB policy rate was approximately 2.75% in 2008 before the financial crisis. From Q1 2015 onwards to Q2 2022, it was at −0.75%, which is a decrease of 3.5 pp. Additional expansionary monetary policy through FXI equivalent to approximately 1 pp would correspond to almost 30% of the total decrease in the policy rate since the financial crisis. In other words, FXI created significant additional leeway for monetary policy in Switzerland.

Shadow rate and policy rate persistence. From the financial crisis until the COVID-19 pandemic, policy rates in Switzerland and other advanced economies were close to the effective lower bound and, thus, adjusted very rarely by monetary policy makers. This shapes expectations in the model of how persistent the policy rate is and leads to a high posterior estimate for the interest rate smoothing parameter in the

Taylor rule, ρ^m, of 0.93.[43] We now analyse the effectiveness of interventions relative to interest rate changes as measured by the shadow rate if the policy rate was adjusted more frequently.

The orange line in the left panel in Figure 13 shows an alternative path for the shadow rate. The path is calculated while setting $\rho^m = 0.75$ instead of 0.93. All other parameters are kept at their posterior mean. The red and blue lines show the same realised policy rate and shadow rate as in Figure 12. One can see that the shadow rate declines significantly to -2% in Q1 2015, when the policy rate is expected to be less persistent.

The right panel in Figure 13 underscores this finding. It depicts the minimum point of the shadow rate over the sample period when ρ^m is varied between 0 and 0.99 and all other parameters are kept at their posterior mean. As a comparison, we also plot the minimum point of the shadow rate when all parameters are at the posterior mean. This is the vertical red line in Figure 13. If the policy rate were completely flexible, $\rho^m = 0$, the minimum point of the shadow rate, would be as low as -3.2%.

Why does less persistence in the policy rate lead to a lower path for the shadow rate? Three effects are at work. First, with a lower smoothing parameter in the Taylor rule, the policy rate endogenously falls more in the absence of FXI. Second, FXI are less effective with less interest rate smoothing. The policy rate increases faster after FX is purchased and, thus, crowds out more of the stimulus on inflation. Third, monetary policy rate shocks are less effective when the interest rate is less sticky. The policy rate is expected to return faster to its steady state after a monetary policy rate shock occurs, generating less stimulus for the real economy and inflation. Therefore, more monetary policy shocks are needed to yield the same effect on inflation. The first and third effect lead to a more negative shadow rate and dominate, whereas the second effect partially compensates. Overall, the results indicate that the shadow rate would be significantly more negative in an environment of less persistent policy rates.

We conclude from this exercise that although the absolute effectiveness of FXI increases when the economy is close to the lower bound (and the persistence of the policy rate is high), its effectiveness relative to policy rate changes decreases precisely because policy rate changes become more powerful if they are more persistent.

7 Conclusion

In the aftermath of the financial crises, central banks of several advanced, small, open economies used FXI to stimulate economic activity and inflation, given that their policy rates were already very low. We present a quantitative DSGE model that allows us to study the effectiveness of this unconventional monetary policy tool. We apply the model to Switzerland, a country that has experienced frequent and sizeable interventions by its central bank.

With the help of the model, we can quantify the effectiveness of FXI and find that they are an effective tool to stabilize inflation around the target. The effectiveness of

[43] See subsection 4.3 for a discussion of the posterior estimates of the model parameters.

FXI increases the longer the central bank can commit to keep its policy rate constant in response to the inflationary effects of interventions. Counterfactual experiments reveal that FXI can create significant additional leeway for monetary policy in small, open economies as shown by the shadow rate. Moreover, in an environment in which the policy rate is at (or close to) its lower bound, the shadow rate rises in absolute terms. Negative interest rates helped prevent FXI of CHF 550 billion (approximately 630 billion USD).

Our work can be extended in several directions. While we focus on the effectiveness of discretionary FXI, comparing the findings to rule-based interventions such as the effect of FXI during the minimum exchange rate period of 2011–2015 would be interesting. In addition, FX announcements have played a crucial role during the minimum exchange rate period and afterwards. We expect that incorporating these channels would strengthen the effectiveness of FXI.[44]

[44]The empirical literature documents that FXI are more effective when accompanied by clear communication; see, e.g. Fischer and Zurlinden (1999), Fratzscher et al. (2019) and Aregger and Leutert (2023b).

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Appendix A Firms sector

We provide the essence for each group of firms in the following.

A.1 Final good producers

There is a representative final good firm that produces $y_{h,t}$ using intermediary goods of firm j, $y_{h,t,j}$ as an input. The production technology is given as

$$y_{h,t} = \left(\int_0^1 (y_{h,t,j})^{\frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{\epsilon}{\epsilon-1}}. \tag{38}$$

We assume that $\epsilon > 1$, such that the markup charged by intermediate goods firms, remains finite. In a first step, we derive the demand of the representative final good firm for the domestic intermediary good $y_{h,t,j}$ as a function of $y_{h,t}$ by solving its profit maximisation problem with respect to $y_{h,t,j}$, which is given as

$$\max_{y_{h,t,j}} P_{h,t} \left(\int_0^1 (y_{h,t,j})^{\frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{\epsilon}{\epsilon-1}} - \int_0^1 P_{h,t,j} y_{h,t,j}, \tag{39}$$

with the respective first-order condition for an intermediate good j

$$P_{h,t} \frac{\epsilon}{\epsilon-1} \frac{\epsilon-1}{\epsilon} \left(\int_0^1 (y_{h,t,j})^{\frac{\epsilon-1}{\epsilon}} dj \right)^{\frac{\epsilon}{\epsilon-1}-1} (y_{h,t,j})^{\frac{\epsilon-1}{\epsilon}-1} = P_{h,t,j}, \tag{40}$$

which, after some manipulations, leads to the demand function for the intermediate good j:

$$y_{h,t,j} = \left(\frac{P_{h,t,j}}{P_{h,t}} \right)^{-\epsilon} y_{h,t}. \tag{41}$$

The demand function for variety j is decreasing in its own price $P_{h,t,j}$ and increasing in the aggregate price level $P_{h,t}$. ϵ denotes the price elasticity. Demand is proportional to aggregate output $y_{h,t}$.

The demand function can be used in the derivation of the aggregate price index for domestic goods. To see this, note that nominal output can be written as

$$P_{h,t} y_{h,t} = \int_0^1 P_{h,t,j} y_{h,t,j} dj.$$

Plugging in the demand function (41) gives

$$P_{h,t} y_{h,t} = \int_0^1 P_{h,t,j} \left(\frac{P_{h,t,j}}{P_{h,t}} \right)^{-\epsilon} y_{h,t} dj.$$

Simplifying leads us to

$$P_{h,t} y_{h,t} = (P_{h,t})^{\epsilon} y_{h,t} \int_0^1 P_{h,t,j}^{1-\epsilon} dj,$$

and finally to

$$P_{h,t} = \left(\int_0^1 (P_{h,t,j})^{1-\epsilon} dj \right)^{\frac{1}{1-\epsilon}}. \tag{42}$$

$P_{h,t}$ denotes the unit price of domestic output. Therefore, we define $P_t \equiv P_{h,t}$.

A.2 Consumption good producers

Consumption good producers bundle the final domestic good and the final imported good (see Section A.4) using a CES aggregator with constant returns to scale. There is a continuum of price-taking firms. Because of constant returns to scale, we can focus on a representative final goods firm.

There are two types of consumption good producers. The first type produces private consumption goods, and the second one government consumption goods.[45]

The CES aggregator of consumption good producers' private consumption good is a CES composite of home and imported goods, defined as

$$c_t = \left[(1-\gamma^o)^{\frac{1}{\theta}} (y_{h,t})^{\frac{\theta-1}{\theta}} + \gamma^{o\frac{1}{\theta}} (y_{f,t})^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}} \tag{43}$$

$y_{h,t}$ and $y_{f,t}$ are final goods and imported goods, respectively. γ^o denotes the import share and θ the trade elasticity.

The demand for final goods and imported goods in the production of private consumption goods is given as

$$y^c_{f,t} = \gamma^o \left(\frac{P_{f,t}}{P^c_t} \right)^{-\theta} c_t, \tag{44}$$

and the aggregate price index for consumption goods can be shown to be

$$P^c_t = \left[(1-\gamma^o) P^{1-\theta}_{h,t} + \gamma^o P^{1-\theta}_{f,t} \right]^{\frac{1}{1-\theta}}. \tag{45}$$

Government consumption goods are produced using the same technology as in (43), resulting in the following demand functions:

$$y^g_{h,t} = (1-\gamma^o) \left(\frac{P_{h,t}}{P^g_t} \right)^{-\theta} g_t \tag{46}$$

and

$$y^g_{f,t} = \gamma^o \left(\frac{P_{f,t}}{P^g_t} \right)^{-\theta} g_t. \tag{47}$$

The aggregate price index for government consumption goods is given as

[45] The term "goods" also refers to services.

$$P_t^g = \left[(1-\gamma^o)P_{h,t}^{1-\theta} + \gamma^o P_{f,t}^{1-\theta}\right]^{\frac{1}{1-\theta}}. \tag{48}$$

Evidently, $P_t^g = P_t^c$.

A.3 Intermediate good firms

An intermediate good firm j produces $y_{h,j,t}$ using the following production technology:

$$y_{h,j,t} = n_{j,t},$$

where $n_{j,t} = (n_{j,t}^s)^{1-\chi}(n_{j,t}^b)^{(1-\chi^{hm})\chi}(n_{j,t}^{hm})^{\chi^{hm}\chi}$.

It is convenient to split the optimisation problem of the firm into two parts. First, we study the static cost minimisation problem for firm j, and it chooses the cost-minimizing labour input for a given level of production.

The Lagrangian associated with this problem is as follows:

$$\min_{n_{j,t}} \text{Cost} = W_t n_{j,t} + \Theta_{j,t}\left[y_{h,j,t} - n_{j,t}\right] \tag{49}$$

where W_t is the nominal rental rate of labour in period t given as

$$W_t = (W_t^s)^{1-\chi}(W_t^b)^{(1-\chi^{hm})\chi}(W_t^{hm})^{\chi^{hm}\chi} \tag{50}$$

and $\Theta_{j,t}$ denotes the Lagrange multiplier of the technology constraint. The first-order condition is as follows

$$W_t = \Theta_{j,t}. \tag{51}$$

In a second stage, firm j sets output $y_{h,j,t}$ and price $P_{h,j,t}$ to maximize its profits $\Pi_{h,j,t}$:

$$\max_{P_{h,j,t},y_{h,j,t}} \Pi_{h,j,t} = P_{h,j,t}y_{h,j,t} - W_t n_{j,t}.$$

It respects the demand function (41) and the cost-minimizing input choice that follows from condition (51). We can use condition (51) to rewrite the profit-maximization problem of firm j in real terms

$$\max_{P_{h,j,t},y_{h,j,t}} \frac{\Pi_{h,j,t}}{P_t} = \frac{P_{h,j,t}}{P_t}y_{h,j,t} - mc_{h,t}y_{h,j,t}$$

where we define $mc_{h,t} \equiv \frac{\Theta_t}{P_t}$ as the real marginal costs. By plugging in the demand function (41), this problem can be simplified further.

We now introduce price rigidities. Intermediate producers are not freely able to adjust their prices in each period. We follow Calvo (1983) and assume that in each period, firms face a fixed probability of being allowed to change their price. Let $(1-\phi)$ be the probability that a firm can adjust its price. A firm might get stuck with probability ϕ, ϕ^2, ..., ϕ^g for $1, 2, \ldots g$ periods. In this case, we assume partial indexation: a fraction ι^p of firms adjust their price according to last period's inflation π_{t-1}, i.e. $P_{h,j,t} =$

$(1+\pi_{t-1})P_{h,j,t-1}$, while the remaining fraction $(1-\iota^p)$ adjust their price according to steady-state inflation π, i.e. $P_{h,j,t} = (1+\pi)P_{h,j,t-1}$. We use the following definition: $\pi_t \equiv \frac{P_{h,t}}{P_{h,t-1}} - 1$.

The pricing problem then becomes dynamic:

$$\max_{P_{h,j,t}} \mathrm{E}_t \sum_{g=0}^{\infty} (\beta\phi)^g \frac{\iota_{t+g}}{\iota_t} \left(\frac{((1+\pi_{t-1})^g P_{h,j,t})^{\iota^p} ((1+\pi)^g P_{h,j,t})^{1-\iota^p}}{P_{t+g}} \left(\frac{((1+\pi_{t-1})^g P_{h,j,t})^{\iota^p} ((1+\pi)^g P_{h,j,t})^{1-\iota^p}}{P_{t+g}} \right)^{-\epsilon} y_{h,t+g} \right)$$
$$-\mathrm{E}_t \sum_{g=0}^{\infty} (\beta\phi)^g \frac{\iota_{t+g}}{\iota_t} \left(mc_{h,t+g} \left(\frac{((1+\pi_{t-1})^g P_{h,j,t})^{\iota^p} ((1+\pi)^g P_{h,j,t})^{1-\iota^p}}{P_{t+g}} \right)^{-\epsilon} y_{h,t+g} \right). \tag{52}$$

Here, $\iota_{t+g} \equiv (\varpi u'(c^b_{t+g}) + (1-\varpi)u'(c^s_{t+g}))$ is the weighted marginal utility of consumption. Following Eggertsson et al. (2017), we assume that $\beta \equiv \chi \left(1-\chi^{hm}\right) \beta^b + (1-\chi)\beta^s$, i.e. intermediated goods firms are under the control of both borrowers and savers. As a consequence, the factor used by intermediate good firms to discount their future profits is a weighted average of the discount factors of borrowers and savers.

We can show that all adjusting firms update to the same reset price $P^{\#}_t$, which is given as

$$P^{\#}_t = \frac{\epsilon}{\epsilon-1} \frac{X_{1,h,t}}{X_{2,h,t}}, \tag{53}$$

where

$$X_{1,h,t} = \iota_t mc_{h,t} P^{\epsilon}_{h,t} y_{h,t} + \phi\beta((1+\pi_{t-1})^{\iota^p}(1+\pi)^{1-\iota^p})^{-\epsilon} \mathrm{E}_t X_{1,h,t+1} \tag{54}$$

and

$$X_{2,h,t} = \iota_t \left(P_{h,t}\right)^{\epsilon-1} y_{h,t} + \phi\beta((1+\pi_{t-1})^{\iota^p}(1+\pi)^{1-\iota^p})^{1-\epsilon} \mathrm{E}_t X_{2,h,t+1} \tag{55}$$

Note that if $\phi = 0$, $P^{\#}_{h,t}$ reduces to

$$P^{\#}_t = \frac{\epsilon}{\epsilon-1} \Theta_t \tag{56}$$

since, by definition, $mc_{h,t}P_{h,t} = \Theta_t$. If prices are fully flexible, the optimal price is a fixed markup $\frac{\epsilon}{\epsilon-1}$ over nominal marginal costs Θ_t.

We define the markup as $\lambda_h \equiv \frac{\epsilon}{\epsilon-1}$. To allow for cost-push shocks, we make the markup time-varying. See Appendix B.

A.4 Importing firms

As in Vukotic (2007), we assume that there is continuum of importing firms indexed by j on the unit interval. Importing firm j buys a homogenous final good abroad at price P^*_t and transforms it into a differentiated imported good by rebranding. The outcome of this process is denoted as $y_{f,t,j}$. We assume that the rebranding process does not require resources and is, thus, costless.

Then, similar to the production of domestic final goods, there is a representative final good firm that produces $y_{f,t}$ using $y_{f,t,j}$ as inputs. The production technology is given as:

$$y_{f,t} = \left(\int_0^1 (y_{f,t,j})^{\frac{\epsilon_f - 1}{\epsilon_f}} dj \right)^{\frac{\epsilon_f}{\epsilon_f - 1}}. \tag{57}$$

Total imports are given as

$$im_t = \int_0^1 y_{f,t,j} dj. \tag{58}$$

The derivation in the demand and the price index for imported foreign goods is similar to the domestic final good sector presented above and results in

$$y_{f,t,j} = \left(\frac{P_{f,t,j}}{P_{f,t}} \right)^{-\epsilon_f} y_{f,t} \tag{59}$$

and

$$P_{f,t} = \left(\int_0^1 (P_{f,t,j})^{1-\epsilon_f} dj \right)^{\frac{1}{1-\epsilon_f}}. \tag{60}$$

The profit-maximization problem of importing firm j in real terms is

$$\max_{P_{f,j,t}, y_{f,j,t}} \frac{\Pi_{f,j,t}}{P_t} = \frac{P_{f,j,t}}{P_t} y_{f,j,t} - mc_{f,t} y_{f,j,t},$$

where we define $mc_{f,t} \equiv \frac{P_t^* S_t}{P_t}$ as the real marginal costs. By plugging in the demand function (59), this problem can be simplified further.

As for domestic intermediate goods, we can introduce price rigidities following Calvo (1983). Let $(1 - \phi^f)$ be the probability that an importing firm can adjust its price. A firm might be stuck with probability ϕ^f, ${\phi^f}^2$, ..., ${\phi^f}^g$ for $1, 2, \ldots g$ periods. In this case, we assume partial indexation: a fraction ι^f of firms adjust their price according to last period's inflation $\pi_{f,t-1}$, i.e. $P_{f,j,t} = (1 + \pi_{f,t-1}) P_{f,j,t-1}$, while the remaining fraction $(1 - \iota^f)$ adjust their price according to steady-state inflation π_f, i.e. $P_{f,j,t} = (1 + \pi_f) P_{f,j,t-1}$. We define $\pi_{f,t} \equiv \frac{P_{f,t}}{P_{f,t-1}} - 1$. The pricing problem then becomes dynamic:

$$\begin{aligned} &\max_{P_{f,j,t}} \mathrm{E}_t \sum_{g=0}^{\infty} \left(\beta \phi^f\right)^g \frac{\iota_{t+g}}{\iota_t} \left(\frac{((1+\pi_{f,t-1})^g P_{f,j,t})^{\iota^f} ((1+\pi_f)^g P_{f,j,t})^{1-\iota^f}}{P_{t+g}} \left(\frac{((1+\pi_{f,t-1})^g P_{f,j,t})^{\iota^f} ((1+\pi_f)^g P_{f,j,t})^{1-\iota^f}}{P_{f,t+g}} \right)^{-\epsilon_f} y_{f,t+g} \right) \\ &- \mathrm{E}_t \sum_{g=0}^{\infty} \left(\beta \phi^f\right)^g \frac{\iota_{t+g}}{\iota_t} \left(mc_{f,t+g} \left(\frac{((1+\pi_{f,t-1})^g P_{f,j,t})^{\iota^f} ((1+\pi_f)^g P_{f,j,t})^{1-\iota^f}}{P_{f,t+g}} \right)^{-\epsilon_f} y_{f,t+g} \right). \end{aligned} \tag{61}$$

Here, $\iota_{t+g} \equiv (\varpi u'(c_{t+g}^b) + (1 - \varpi) u'(c_{t+g}^s))$ and $\beta \equiv \chi \left(1 - \chi^{hm}\right) \beta^b + (1 - \chi) \beta^s$, as in the case of intermediate goods.

We can show that all adjusting firms update to the same reset price $P_{f,t}^{\#}$, which is given as

$$P_{f,t}^{\#} = \frac{\epsilon_f}{\epsilon_f - 1} \frac{X_{1,f,t}}{X_{2,f,t}}, \tag{62}$$

where

$$X_{1,f,t} = \iota_t mc_{f,t} P_t P_{f,t}^{\epsilon_f} y_{f,t} + \phi^f \beta((1+\pi_{f,t-1})^{\iota^f}(1+\pi_f)^{1-\iota^f})^{-\epsilon_f} \mathrm{E}_t X_{1,f,t+1} \tag{63}$$

and

$$X_{2,f,t} = \iota_t \left(P_{f,t}\right)^{\epsilon_f} y_{f,t} + \phi^f \beta((1+\pi_{f,t-1})^{\iota^f}(1+\pi_f)^{1-\iota^f})^{1-\epsilon_f} \mathrm{E}_t X_{2,f,t+1} \tag{64}$$

We define the markup as $\lambda_f \equiv \frac{\epsilon_f}{\epsilon_f - 1}$. To allow for cost-push shocks, we make the markup time-varying. See Appendix B.

A.5 Exporting firms

There is a continuum of exporting firms indexed by j on the unit interval. Each firm buys a homogenous final domestic good in the home country at the price $P_{h,t}$ and ships it to the foreign country. In the foreign country, each firm differentiates the good by rebranding. The outcome of this process is denoted as $y_{e,t,j}$. This process does not require resources and is, thus, costless. Finally, the exporting firm sells these differentiated goods abroad to a representative final export good firm, which produces a homogenous final export good $y_{e,t}$ using $y_{e,t,j}$ as inputs. Its production technology is given as:

$$y_{e,t} = \left(\int_0^1 (y_{e,t,j})^{\frac{\epsilon_{ex}-1}{\epsilon_{ex}}} dj \right)^{\frac{\epsilon_{ex}}{\epsilon_{ex}-1}}. \tag{65}$$

Total exports are given as

$$ex_t = \int_0^1 y_{e,t,j} dj. \tag{66}$$

The derivation in the demand and the price index for the export goods is similar to the final good sector presented above and leads to

$$y_{e,t,j} = \left(\frac{P_{e,t,j}}{P_{e,t}} \right)^{-\epsilon_{ex}} y_{e,t} \tag{67}$$

and

$$P_{e,t} = \left(\int_0^1 \left(P_{e,t,j}\right)^{1-\epsilon_{ex}} dj \right)^{\frac{1}{1-\epsilon_{ex}}}, \tag{68}$$

Since prices are flexible, all exporting firms charge the same price (derivation omitted):

$$P_{e,t} = P_{e,t,j} = \frac{\epsilon_{ex}}{\epsilon_{ex} - 1} \frac{P_t}{S_t}. \tag{69}$$

We define the markup as $\lambda_x \equiv \frac{\epsilon_{ex}}{\epsilon_{ex}-1}$. We further assume that the domestic economy is negligible in size, implying that γ^*, i.e. the share of domestic goods in the production of foreign consumption goods, is equal to zero. Therefore, it follows that the demand for the final export good in the foreign economy is given as

$$y_{e,t} = \left(\frac{P_{e,t}}{P_t^*} \right)^{-\theta^*} y_t^* \tag{70}$$

where θ^* is the elasticity of substitution between domestic and foreign goods in the foreign economy, and y_t^* is the output in the rest of the world.

Profits in domestic currency are given as

$$\Pi_{e,j,t} = S_t \left(\frac{\epsilon_{ex}}{\epsilon_{ex} - 1} - 1 \right) \frac{P_{h,t}}{S_t} y_{e,t} = \left(\frac{\epsilon_{ex}}{\epsilon_{ex} - 1} - 1 \right) P_{h,t} y_{e,t} \tag{71}$$

Appendix B Nonlinear model equations

Domestic economy

Households

$$\exp\left((-q)\ \left(c_t^s - \Lambda\, c_{t-1}^s\right)\right)\ \epsilon_t^c = \beta^s\ \left(1 + i_t^g\right)\ \frac{\exp\left((-q)\ \left(c_{t+1}^s - \Lambda c_t^s\right)\right)\ \epsilon_{t+1}^c}{1 + \pi_{t+1}^c} \tag{72}$$

$$\exp\left((-q)\ \left(c_t^b - \Lambda\, c_{t-1}^b\right)\right)\ \epsilon_t^c = \beta^b\ \left(1 + i_t^b\right)\ \frac{\epsilon_{t+1}^c\ \exp\left((-q)\ \left(c_{t+1}^b - \Lambda\, c_t^b\right)\right)}{1 + \pi_{t+1}^c} \tag{73}$$

$$\frac{1}{\kappa_{h,t}}\, c_t^{hm} = w b_t^{hm} - \tau^h m_t \tag{74}$$

$$\frac{\alpha^n\ (n_t)^\eta}{q\ \exp\left((-q)\ \left(c_t^{bs} - h\, c_{t-1}^{bs}\right)\right)} = \kappa_{h,t}\, w_t \tag{75}$$

$$\frac{\alpha^{ms}\, \epsilon_t^{\alpha^m}\ (m_t^s)^{-\frac{1}{\sigma^m}}}{\kappa_{h,t}\, q\ \exp\left((-q)\ \left(c_t^s - h\, c_{t-1}^s\right)\right)} = \frac{i_t^g + \gamma^m}{1 + i_t^g} \tag{76}$$

$$\frac{\alpha^{mb}\, \epsilon_t^{\alpha^m}\ (m_t^b)^{-\frac{1}{\sigma^m}}}{\kappa_{h,t}\, q\ \exp\left((-q)\ \left(c_t^b - h\, c_{t-1}^b\right)\right)} = \frac{i_t^b + \gamma^m}{1 + i_t^b} \tag{77}$$

$$b_t = b_t^s\ (1 - \chi) \tag{78}$$

$$z_t = z_t^s\ (1 - \chi) \tag{79}$$

$$d_t = d_t^s\ (1 - \chi) \tag{80}$$

$$b_t^{s,*} = b_t^{s,s,*}\ (1 - \chi) \tag{81}$$

$$m_t^b + \frac{1}{\kappa_{h,t}} c_t^b - l_t^d = w b_t^b - \frac{\left(1 + i_{t-1}^b\right)\ l_{t-1}^d}{1 + \pi_t} + \frac{m_{t-1}^b}{1 + \pi_t} - \Omega(m_{t-1}^b) + \Pi_{h,t}^{r,b} + \Pi_{ex,t}^{r,b} + \Pi_{im,t}^{r,b} - \tau_t^b \tag{82}$$

$$l_t = l_t^d\, \chi \left(1 - \chi^{hm}\right) \tag{83}$$

$$\Omega(m^s_{t-1}) = \frac{\gamma^m \, m^s_{t-1}}{1+\pi_t} \tag{84}$$

$$\Omega(m^b_{t-1}) = \frac{\gamma^m \, m^b_{t-1}}{1+\pi_t} \tag{85}$$

$$\frac{1+i^g_t}{1+i^*_t} = \frac{(s_{t+1})^{1-\varphi} \, (s_{t-1})^{\varphi} \, \left(1+\pi^c_{t+1}\right)^{1-\varphi} \, (1+\pi^*_t)^{\varphi} \, (1+\pi^c)^{2\,\varphi}}{(1+\zeta_t) \, s_t \, \left(1+\pi^*_{t+1}\right)^{1-\varphi} \, (1+\pi^c_t)^{\varphi} \, (1+\pi^*)^{2\,\varphi}} \tag{86}$$

$$1+\zeta_t = (1+\zeta) \, \exp\left(\lambda^{\zeta} \, \left(b^{s,*}_t - b^{s,*}\right)\right) \, \epsilon^{\zeta}_t \tag{87}$$

$$\Delta S_t = \frac{s_t \, (1+\pi^c_t)}{(1+\pi^*_t) \, s_{t-1}} \tag{88}$$

$$c^{bs}_t = c^b_t \, \frac{\chi(1-\chi^{hm})}{1-\chi\chi^{hm}} + c^s_t \, \frac{1-\chi}{1-\chi\chi^{hm}} \tag{89}$$

$$c_t = c^{bs}_t \, \left(1-\chi\chi^{hm}\right) + c^{hm}_t \, \chi\chi^{hm} \tag{90}$$

$$n_t \, w_t = w b^b_t \tag{91}$$

$$n_t \, w_t = w b^s_t \tag{92}$$

$$n_t \, w_t = w b^{hm}_t \tag{93}$$

$$\tau^b_t = \tau_t \tag{94}$$

$$\tau^s_t = \tau_t \tag{95}$$

$$\tau^{hm}_t = \tau_t \tag{96}$$

$$m_t = m^b_t \, \chi \left(1-\chi^{hm}\right) + m^s_t \, (1-\chi) \tag{97}$$

$$\iota_t = \varpi \exp\left((-q) \, \left(c^b_t - h \, c^b_{t-1}\right)\right) \, q \, + (1-\varpi) \exp\left((-q) \, \left(c^s_t - h \, c^s_{t-1}\right)\right) \, q \tag{98}$$

$$\Omega(m_t) = \chi \left(1-\chi^{hm}\right) \Omega(m^b_t) + (1-\chi) \, \Omega(m^s_t) \tag{99}$$

Firm sector

$$y_t = \frac{n_t}{v_t^p} \tag{100}$$

$$y_t = y_{h,t}^c + y_{h,t}^g + ex_t \tag{101}$$

$$mc_t = w_t \tag{102}$$

$$(1+\pi_t)^{\frac{1}{1-\lambda_{h,t}}} = (1-\phi)\left(1+\pi_t^{\#}\right)^{\frac{1}{1-\lambda_{h,t}}} + \phi\left((1+\pi_{t-1})^{\iota^p}\ (1+\pi)^{1-\iota^p}\right)^{\frac{1}{1-\lambda_{h,t}}} \tag{103}$$

$$x_{1,t} = y_t\, \iota_t\, mc_t + \phi\, \beta\left((1+\pi_{t-1})^{\iota^p}\ (1+\pi)^{1-\iota^p}\right)^{\frac{\lambda_{h,t}}{1-\lambda_{h,t}}} (1+\pi_{t+1})^{\frac{\lambda_{h,t}}{\lambda_{h,t}-1}}\ x_{1,t+1} \tag{104}$$

$$x_{2,t} = \iota_t\, y_t + \left((1+\pi_{t-1})^{\iota^p}\ (1+\pi)^{1-\iota^p}\right)^{\frac{1}{1-\lambda_{h,t}}}\ \phi\, \beta\ (1+\pi_{t+1})^{\frac{1}{\lambda_{h,t}-1}}\ x_{2,t+1} \tag{105}$$

$$1+\pi_t^{\#} = \frac{x_{1,t}\ (1+\pi_t)\ \lambda_{h,t}}{x_{2,t}} \tag{106}$$

$$1+\pi_t^c = \left((1-\gamma^o)\ ((1+\pi_t)\ \kappa_{h,t-1})^{1-\theta} + \gamma^o\ ((1+\pi_{f,t})\ \kappa_{f,t-1})^{1-\theta}\right)^{\frac{1}{1-\theta}} \tag{107}$$

$$\begin{aligned} x_{1,f,t} &= \iota_t\, mc_{f,t}\left(y_{f,t}^c + y_{f,t}^g\right) \\ &\quad + (1+\pi_{t+1})\ \beta\, \phi^f\left(\left(1+\pi_{t-1}^f\right)^{\iota^f}\left(1+\pi^f\right)^{1-\iota^f}\right)^{\frac{\lambda_{f,t}}{1-\lambda_{f,t}}}\left(1+\pi_{t+1}^f\right)^{\frac{\lambda_{f,t}}{\lambda_{f,t}-1}}\ x_{1,f,t+1} \end{aligned} \tag{108}$$

$$x_{2,f,t} = \iota_t\left(y_{f,t}^c + y_{f,t}^g\right) + \left(1+\pi_{t+1}^f\right)^{\frac{\lambda_{f,t}}{\lambda_{f,t}-1}}\ \beta\, \phi^f\left(\left(1+\pi_{t-1}^f\right)^{\iota^f}\left(1+\pi^f\right)^{1-\iota^f}\right)^{\frac{1}{1-\lambda_{f,t}}}\ x_{2,f,t+1} \tag{109}$$

$$1+\pi_{f,t}^{\#} = \frac{x_{1,f,t}\ \frac{(1+\pi_t)\,\lambda_{f,t}}{\kappa_{f,h,t-1}}}{x_{2,f,t}} \tag{110}$$

$$mc_{f,t} = \frac{s_t}{\kappa_{h,t}} \tag{111}$$

$$(1+\pi_{f,t})^{\frac{1}{1-\lambda_{f,t}}} = \left(1-\phi^f\right)\left(1+\pi^{\#}_{f,t}\right)^{\frac{1}{1-\lambda_{f,t}}} + \phi^f \left((1+\pi_{f,t-1})^{\iota^f}\,(1+\pi_f)^{1-\iota^f}\right)^{\frac{1}{1-\lambda_{f,t}}} \quad (112)$$

$$1+\pi_{f,t} = \frac{(1+\pi^c_t)\,\kappa_{f,t}}{\kappa_{f,t-1}} \quad (113)$$

$$\kappa_{f,h,t} = \frac{\kappa_{f,t}}{\kappa_{h,t}} \quad (114)$$

$$c_t = \kappa_{h,t}\,y^c_{h,t} + \kappa_{f,t} y^c_{f,t} \quad (115)$$

$$y^c_{h,t} = c_t\,(1-\gamma^o)\,\kappa_{h,t}^{(-\theta)} \quad (116)$$

$$y^c_{f,t} = c_t\,\gamma^o\,\kappa_{f,t}^{(-\theta)} \quad (117)$$

$$y^g_{h,t} = (1-\gamma^o)\,\kappa_{h,t}^{(-\theta)}\,g_t \quad (118)$$

$$y^g_{f,t} = \gamma^o\,\kappa_{f,t}^{(-\theta)}\,g_t \quad (119)$$

$$im_t = \left(y^c_{f,t} + y^g_{f,t}\right)\,v^p_t \quad (120)$$

$$ex_t = \left(\frac{\kappa_{h,t}\,\lambda_x}{s_t}\right)^{(-\theta^*)}\,y^*_t \quad (121)$$

$$\Pi^r_{im,t} = \left(y^c_{f,t} + y^g_{f,t}\right)\left(\kappa_{f,h,t} - \frac{s_t}{\kappa_{h,t}}\,v^p_t\right) - \frac{(\lambda_f - 1)\,im}{\kappa_h}\,s \quad (122)$$

$$\Pi^r_{ex,t} = (\lambda_x - 1)\,ex_t \quad (123)$$

$$\Pi^r_{h,t} = y_t - w_t n_t \quad (124)$$

$$\Pi^{r,b}_{h,t} = \frac{1}{1-\chi\chi^{hm}}\Pi^r_{h,t} \quad (125)$$

$$\Pi^{r,s}_{h,t} = \frac{1}{1-\chi\chi^{hm}}\Pi^r_{h,t} \quad (126)$$

$$\Pi^{r,b}_{ex,t} = \frac{1}{1-\chi\chi^{hm}} \Pi^{r}_{ex,t} \tag{127}$$

$$\Pi^{r,s}_{ex,t} = \frac{1}{1-\chi\chi^{hm}} \Pi^{r}_{ex,t} \tag{128}$$

$$\Pi^{r,b}_{im,t} = \frac{1}{1-\chi\chi^{hm}} \Pi^{r}_{im,t} \tag{129}$$

$$\Pi^{r,s}_{im,t} = \frac{1}{1-\chi\chi^{hm}} \Pi^{r}_{im,t} \tag{130}$$

$$nx_t = ex_t - \kappa_{f,h,t}\, im_t \tag{131}$$

Commercial banks

$$i^g_t = i^s_t \tag{132}$$

$$r_t = d_t - l_t \tag{133}$$

$$z_t = \frac{i^b_{t-1} - i^s_{t-1}}{1+\pi_t}\, l_{t-1} - \Gamma_{t-1} \tag{134}$$

$$\frac{i^b_t - i^s_t}{1+\pi_{t+1}} = \frac{\Gamma'_t}{\bar{l}_t} \tag{135}$$

$$i^s_t = i^r_t \tag{136}$$

$$\Gamma_t = \left(\frac{l_t}{\bar{l}_t}\right)^{\nu^1} \tag{137}$$

$$\Gamma'_t = \nu^1 \left(\frac{l_t}{\bar{l}_t}\right)^{\nu^1 - 1} \tag{138}$$

Fiscal authority

$$\frac{g_t}{\kappa_{h,t}} = \tau_t + b_t - \frac{\left(1+i^g_{t-1}\right)}{1+\pi_t} b_{t-1} + \tau^{CB}_t \tag{139}$$

$$\tau_t = \tau \left(\frac{b_{t-1}}{b}\right)^{\tau^2} \tag{140}$$

Central bank

$$\frac{1+i^r_t}{1+i^r} = \left(\frac{1+i^r_{t-1}}{1+i^r}\right)^{\rho^m} \left(\left(\frac{1+\pi^c_t}{1+\pi^c}\right)^{\phi^\pi} \left(\frac{y_t}{y}\right)^{\phi^y}\right)^{1-\rho^m} \left(\frac{y_t}{y_{t-1}}\right)^{\phi^{dy}} \epsilon^r_t \tag{141}$$

$$m_t + r_t = \tau^{CB}_t + \frac{m_{t-1}}{1+\pi_t} + \frac{\left(1+i^r_{t-1}\right)}{1+\pi_t} r_{t-1} + \frac{s_t}{\kappa_{h,t}} b^{cb,*}_t - \frac{\left(1+i^*_{t-1}\right) \frac{s_t}{\kappa_{h,t}}}{1+\pi^*_t} b^{cb,*}_{t-1} \tag{142}$$

$$\frac{s_t}{\kappa_{h,t}} b^{cb,*}_t = m_t + r_t + EK \tag{143}$$

Equilibrium

$$\begin{aligned} &\frac{s_t}{\kappa_{h,t}} b^{s,*}_t - \frac{\frac{s_t\left(1+i^*_{t-1}\right)}{\kappa_{h,t}}}{1+\pi^*_t} b^{s,*}_{t-1} + \frac{s_t}{\kappa_{h,t}} b^{cb,*}_t - \frac{\left(1+i^*_{t-1}\right)}{1+\pi^*_t} \frac{s_t}{\kappa_{h,t}} b^{cb,*}_{t-1} \\ &= \Pi^r_{im,t} + \Pi^r_{ex,t} + ex_t - \frac{\kappa_{f,h,t}\, im_t}{v^p_t} - \left(\Omega(m_{t-1}) + \Gamma_{t-1} + \frac{\zeta_t\, s_t}{\kappa_{h,t}} b^{s,*}_t + \Psi_t\right) \end{aligned} \tag{144}$$

Foreign economy

$$\frac{1}{c^*_t - \Lambda^*\, c^*_{t-1}} = \frac{\left(1+i^*_t\right)}{1+\pi^*_{t+1}} \frac{\beta^*}{c^*_{t+1} - c^*_t\, \Lambda^*} \tag{145}$$

$$\frac{w^*_t}{c^*_t - \Lambda^*\, c^*_{t-1}} = \alpha^{n,*} \left(n^*_t\right)^{\eta^*} \tag{146}$$

$$y_t^* = \frac{n_t^*}{v^{p,*}} \tag{147}$$

$$c_t^* + g_t^* = y_t^* \tag{148}$$

$$mc_t^* = w_t^* \tag{149}$$

$$(1+\pi_t^*)^{\frac{1}{1-\lambda_{h,t}^*}} = (1-\phi^*)\,\left(1+\pi_t^{\#,*}\right)^{\frac{1}{1-\lambda_{h,t}^*}} + \phi^*\,\left(\left(1+\pi_{t-1}^*\right)^{\iota^*}\,(1+\pi^*)^{1-\iota^*}\right)^{\frac{1}{1-\lambda_{h,t}^*}} \tag{150}$$

$$x_{1,t}^* = \frac{y_t^*\,mc_t^*}{c_t^*} + \beta^*\,\phi^*\,\left(1+\pi_{t+1}^*\right)^{\frac{\lambda_{h,t}^*}{\lambda_{h,t}^*-1}}\,\left(\left(1+\pi_{t-1}^*\right)^{\iota^*}\,(1+\pi^*)^{1-\iota^*}\right)^{\frac{\lambda_{h,t}^*}{1-\lambda_{h,t}^*}}\,x_{1,t+1}^* \tag{151}$$

$$x_{2,t}^* = \frac{y_t^*}{c_t^*} + \left(\left(1+\pi_{t-1}^*\right)^{\iota^*}\,(1+\pi^*)^{1-\iota^*}\right)^{\frac{1}{1-\lambda_{h,t}^*}}\,\beta^*\,\phi^*\,\left(1+\pi_{t+1}^*\right)^{\frac{1}{\lambda_{h,t}^*-1}}\,x_{2,t+1}^* \tag{152}$$

$$1+\pi_t^{\#,*} = \frac{x_{1,t}^*\,(1+\pi_t^*)\,\lambda_{h,t}^*}{x_{2,t}^*} \tag{153}$$

$$\frac{1+i_t^*}{1+i^*} = \left(\frac{1+i_{t-1}^*}{1+i^*}\right)^{\rho^{m,*}}\,\left(\left(\frac{1+\pi_t^*}{1+\pi^*}\right)^{\phi^{\pi,*}}\,\left(\frac{y_t^*}{y^*}\right)^{\phi^{y,*}}\right)^{1-\rho^{m,*}}\,\left(\frac{y_t^*}{y_{t-1}^*}\right)^{\phi^{dy,*}}\,\epsilon_t^{m,*} \tag{154}$$

Shock processes

$$\log\left(\epsilon_t^c\right) = \rho^c\,\log\left(\epsilon_{t-1}^c\right) + 0.01\,\varepsilon_t^c \tag{155}$$

$$\log\left(\epsilon_t^\zeta\right) = \rho^\zeta\,\log\left(\epsilon_{t-1}^\zeta\right) + 0.01\,\varepsilon_t^\zeta \tag{156}$$

$$\log\left(\epsilon_t^{\alpha^m}\right) = \rho^{\alpha^m}\,\log\left(\epsilon_{t-1}^{\alpha^m}\right) + 0.01\,\varepsilon_t^{\alpha^m} \tag{157}$$

$$\log\left(\epsilon_t^\Psi\right) = \rho^\Psi\,\log\left(\epsilon_{t-1}^\Psi\right) + 0.01\,\varepsilon_t^\Psi \tag{158}$$

$$\log\left(\frac{g_t}{g}\right) = \rho^g\,\log\left(\frac{g_{t-1}}{g}\right) + 0.01\,\varepsilon_t^g \tag{159}$$

$$\log\left(\frac{b_t^{cb,*}}{b^{cb,*}}\right) = \rho^{B^{cb,*}} \log\left(\frac{b_{t-1}^{cb,*}}{b^{cb,*}}\right) + 0.01\,\varepsilon_t^{B^{cb,*}} \tag{160}$$

$$\log\left(\frac{\bar{l}_t}{\bar{l}}\right) = \rho^{\bar{l}} \log\left(\frac{\bar{l}_{t-1}}{\bar{l}}\right) + 0.01\,\varepsilon_t^{\bar{l}} \tag{161}$$

$$\log\left(\frac{\lambda_{h,t}}{\lambda_h}\right) = \rho^{\lambda^h} \log\left(\frac{\lambda_{h,t-1}}{\lambda_h}\right) + 0.01\,\varepsilon_t^{\lambda^h} \tag{162}$$

$$\log\left(\frac{\lambda_{f,t}}{\lambda_f}\right) = \rho^{\lambda^f} \log\left(\frac{\lambda_{f,t-1}}{\lambda_f}\right) + 0.01\,\varepsilon_t^{\lambda^f} \tag{163}$$

$$\log\left(\epsilon_t^r\right) = \rho^r \log\left(\epsilon_{t-1}^r\right) + 0.01\,\varepsilon_t^r \tag{164}$$

$$\log\left(\frac{g_t^*}{g^*}\right) = \rho^{g^*} \log\left(\frac{g_{t-1}^*}{g^*}\right) + 0.01\,\varepsilon_t^{g^*} \tag{165}$$

$$\log\left(\frac{\lambda_{h,t}^*}{\lambda_h^*}\right) = \rho^{\lambda^{h,*}} \log\left(\frac{\lambda_{h,t-1}^*}{\lambda_h^*}\right) + 0.01\,\varepsilon_t^{h,*} \tag{166}$$

$$\log\left(\epsilon_t^{r,*}\right) = \rho^{r,*} \log\left(\epsilon_{t-1}^{r,*}\right) + 0.01\,\varepsilon_t^{r,*} \tag{167}$$

Measurement equations

$$obs_t^{dy} = 100\frac{(y_t - y_{t-1})}{y_{t-1}} + obs^{dy} \tag{168}$$

$$obs_t^{dc} = 100\frac{(c_t - c_{t-1})}{c_{t-1}} + obs^{dc} \tag{169}$$

$$obs_t^{dy,*} = 100\frac{\left(y_t^* - y_{t-1}^*\right)}{y_{t-1}^*} + obs^{dy,*} \tag{170}$$

$$obs_t^{\pi} = 100\frac{(\pi_t - \pi)}{1+\pi} + obs^{\pi} \tag{171}$$

$$obs_t^{\pi^c} = 100\frac{(\pi_t^c - \pi^c)}{1+\pi^c} + obs^{\pi^c} \tag{172}$$

$$obs_t^{\pi,*} = 100\frac{(\pi_t^* - \pi^*)}{1+\pi^*} + obs^{\pi,*} \tag{173}$$

$$obs_t^{R} = 100\frac{(i_t^r - i^r)}{1+i^r} + obs^{R} \tag{174}$$

$$obs_t^{R,*} = 100\frac{(i_t^* - i^*)}{1+i^*} + obs^{R,*} \tag{175}$$

$$obs_t^{dl} = 100\frac{(l_t - l_{t-1})}{l_{t-1}} + obs^{dl} \tag{176}$$

$$obs_t^{dm} = 100\frac{(m_t - m_{t-1})}{m_{t-1}} + obs^{dm} \tag{177}$$

$$obs^s{}_t = 100\frac{(s_t - s)}{s} \tag{178}$$

$$obs_t^{b^{s,*}} = 100\frac{\left(b_t^{s,*} - b^{s,*}\right)}{b^{s,*}} \tag{179}$$

$$obs_t^{b^{cb,*}} = 100\frac{\left(b_t^{cb,*} - b^{cb,*}\right)}{b^{cb,*}} \tag{180}$$

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