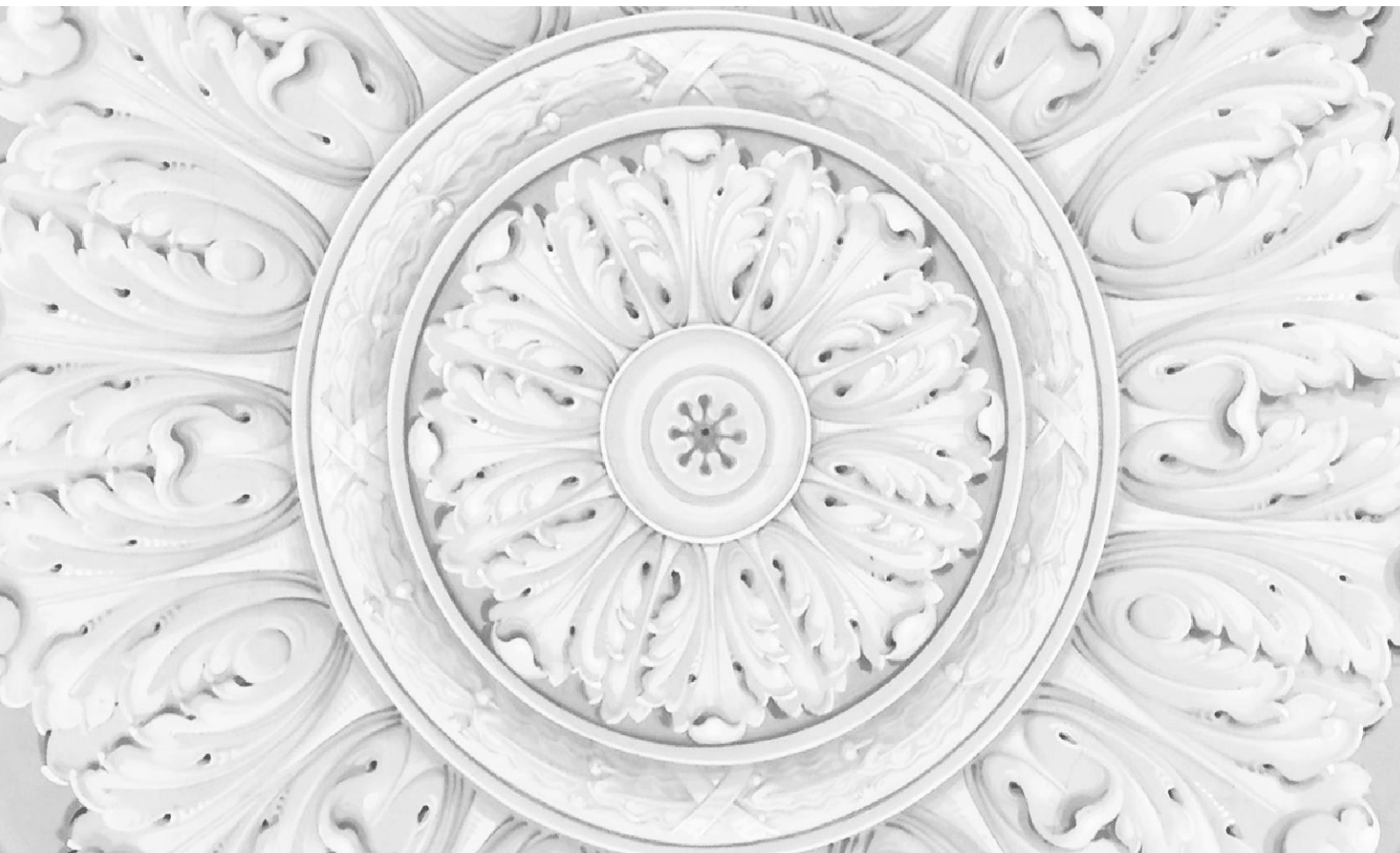




# Bank of Russia

The Central Bank of the Russian Federation



## WORKING PAPER SERIES

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Forecasting the implications of  
foreign exchange reserve  
accumulation with an agent-  
based model

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### Abstract

We develop a stock-flow-consistent agent-based model that comprises a realistic mechanism of money creation and parametrize it to fit actually observed data. The model is used to make out-of-sample projections of broad money and credit developments under the commencement/termination of foreign reserve accumulation by the Bank of Russia. We use direct forecasts from the agent-based model as well as the two-step approach, which implies the use of artificial data to pre-train the Bayesian vector autoregression model. We conclude that the suggested approach is competitive in forecasting and yields promising results.

**Keywords:** Money supply, foreign exchange reserves, forecasting, agent-based model, Russia

**JEL classification:** C53, C63, E51, E58, F31, G21.

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## INTRODUCTION

In a number of emerging market economies, the public sector in recent decades has accumulated sizeable cross-border financial assets, mainly in the form of central banks' foreign exchange reserves. The reserve accumulation has not necessarily been the by-product of fixed exchange rate monetary policy frameworks focused on resisting exchange rate appreciation. Some of this accumulation reflects efforts to bolster the buffer stocks of reserves as a precaution against the possibility of international capital flows suddenly stopping. Accordingly, the monetary authorities in these countries have not abandoned their independent interest rate policy (i.e. the central banks have continued to steer the short-term money market interest rates). To deal with the undesirable effects of foreign exchange interventions (FXIs) in the domestic monetary conditions, they have frequently resorted to sterilization operations, which can be defined in general as a set of policies designed to mitigate the impact of reserve accumulation on domestic interest rates. Even when successful in steering interest rates, such a strategy can potentially have macroeconomic effects, which are discussed in the related literature. We contribute to this strand of research and suggest a novel approach to forecasting the consequences of foreign exchange reserve accumulation by a central bank for the banking system's balance.

Credit and broad money supply developments are only scarcely analysed in the standard literature on FXIs. Instead, the common approach is to examine the outcome of FXIs for reserve money and the central's bank net domestic assets. Presumably, the reason behind such an approach is the tacit existence of a stable relationship between bank reserves and broad money aggregates – the “money multiplier”. The practical applicability of this concept, however, is questioned in the contemporary literature. In our approach, we set up a stock-flow-consistent agent-based model (ABM) that explicitly accounts for the process of money creation.

Another novelty of our approach is the fact that we use our model in actual forecasting exercises. Note that, in the related literature, economically interpretable models usually only serve as a theoretical foundation for time series models. Even in rare cases in which structural models are estimated using actually observed data, they are not used to produce forecasts. Contrarily, we believe that the objective of forecasting the consequences of (previously unobserved) policy measures' implementation is particularly favourable for structural models in terms of competitiveness with time series models. We illustrate this point

by producing out-of-sample forecasts of the effect of the changes in the Bank of Russia's foreign reserve policy on the money and credit supply.

The rest of the paper is structured as follows. Section 1 outlines the flow of funds framework to illustrate the relationship between FXIs and the banking system's balance sheet. It also discusses the Russian experience with the FXI policy and presents the cases to be analysed. Section 2 outlines the ABM set-up. Section 3 describes the estimation procedure. Section 4 presents the results of the forecasting exercises. Section 5 concludes.

## 1. FOREIGN EXCHANGE INTERVENTIONS AND THE BANKING SYSTEM'S BALANCE SHEET

### 1.1 Flow of funds analysis

The banking system's balance sheet (i.e. the aggregate balance sheet comprising both commercial banks and the central bank) may be presented as:

$$\text{CASH} + \text{D} + \text{L}^{\text{PNBS}} + \text{L}^{\text{GOV}} + \text{CAP} = \text{NFA}^{\text{CB}} + \text{NFA}^{\text{B}} + \text{CRED}^{\text{PNBS}} + \text{CRED}^{\text{GOV}} \quad (1)$$

where CASH is the currency in circulation, D is banks' deposits,  $\text{L}^{\text{PNBS}}$  is other liabilities of banks to the private non-banking sector,  $\text{L}^{\text{GOV}}$  is the banking system's liabilities to the government, CAP is banks' capital,  $\text{CRED}^{\text{PNBS}}$  is credit to the private non-banking sector,  $\text{CRED}^{\text{GOV}}$  is claims on the government,  $\text{NFA}^{\text{CB}}$  is the net foreign assets of the central bank and  $\text{NFA}^{\text{B}}$  is the net foreign assets of commercial banks. We rearrange this identity to express money and its counterparts, which we interpret as money growth sources: private credit, external transactions (summarized by the change in net foreign assets of the central bank and commercial banks) and other balance sheet items. We will briefly discuss the economic content of each counterpart and its relationship with FXIs.

$$\underbrace{\text{CASH} + \text{D}}_{\text{Money}} = \underbrace{\text{CRED}^{\text{PNBS}}}_{\text{Private credit}} + \underbrace{\text{CRED}^{\text{GOV}} - \text{L}^{\text{GOV}}}_{\text{Fiscal transactions}} + \underbrace{\text{NFA}^{\text{CB}} + \text{NFA}^{\text{B}}}_{\text{External transactions}} - \underbrace{\text{CAP} - \text{L}^{\text{PNBS}}}_{\text{Other items}} \quad (2)$$

The first counterpart represents money creation through lending (McLeay et al., 2014). When a bank grants a loan, it books the loan as an asset and the newly created deposit as a liability. Therefore, when banks lend to borrowers, they create deposits (initially held by the

borrowers). Deposits may later be used as payment media and thus may be spread among customers of different banks.

The second component represents money creation through fiscal transactions. The sovereign wealth fund in Russia is in the form of the Bank of Russia's liability to the Government ( $L^{\text{GOV}}$ ). The Government may create money by spending the sovereign wealth fund or destroy money by accumulating the sovereign wealth fund. Furthermore, if the banks buy newly issued government bonds, money is created through the increase in credit to the Government ( $\text{CRED}^{\text{GOV}}$ ).

The focus of our paper is on the third counterpart, which represents the inflow of funds into the non-banking sector through external transactions. The non-banking sector may conduct financial and non-financial external transactions. The sum of these transactions constitutes the change in funds owned by the non-banking sector. In the balance of payments, this sum also equals the sum of the banking sector's external transactions, which is reflected in the change in the net foreign assets (NFA) (see Duc et al. (2008), Chung et al. (2015), Kuzin and Schobert (2015) and Ponomarenko (2017a) for a detailed discussion of money creation through external transactions).

Note that there is no immediate effect on money creation at the time of FXI transactions. When a central bank buys foreign reserves from domestic banks, the increase in its NFA is compensated for by the equivalent decrease in the NFA of commercial banks. The banking system's NFA remains unchanged: money is not created.<sup>1</sup> However, there are reasons to expect that commercial banks will not fully accommodate the NFA decrease and will subsequently try to restore the NFA level.<sup>2</sup> In this case, the banking system's NFA will increase and the balance of payments will adjust through a larger current account surplus and/or larger net capital inflows into the non-banking domestic sector (see Ponomarenko (2017b) for the empirical evidence). Both cases imply an inflow of funds and money creation.

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<sup>1</sup> When the reserve accumulation policy implies that the central bank sells domestic assets (i.e. claims on the banking sector) to the foreign sector in exchange for foreign reserves, an increase in foreign assets of the central bank will be offset by an increase in commercial banks' liabilities that they now owe to foreigners. Accordingly, the NFA of the banking system will not change. In the (less common) case in which the central bank sells claims on the non-banking domestic sector to foreigners in exchange for foreign reserves, the NFA of the banking system will increase but will be offset by a decrease in credit to the non-banking sector (see equation (2)), reflecting that money was not created.

<sup>2</sup> The accumulation of net foreign assets/liabilities is usually associated with a widening of currency mismatches, which are undesirable (and in many cases forbidden by banking regulations). See Luca and Petrova (2008) for a discussion of the relationship between banks' net foreign assets and the currency mismatch in domestic assets/liabilities. Another, more general, determinant of flexibility in commercial banks' NFA may be related to capital mobility. Gagnon (2012, 2013) and Bayoumi and Saborowski (2014) point out that, in the presence of capital controls, a balance of payments adjustment to FXIs is more likely to happen through the current account.

In this case, the balance sheet of commercial banks will eventually expand via an increase in deposits on the liability side and claims on the central bank on the asset side.<sup>3</sup> This means that the balance sheet liquidity measures<sup>4</sup> will improve. As pointed out by Disyatat (2011), this may encourage banks to take risks. This hypothesis is in line with the standard practices in asset liability management (Grant, 2011) and is supported by empirical evidence on the macro (Halvorsen and Jacobsen, 2016; Rappoport, 2016) and micro (DeYoung and Jang, 2016; Duijm and Wierds, 2016) levels. We incorporate these aspects of commercial banks' behaviour into our formal model in Section 2.

## 1.2 The Bank of Russia's foreign exchange reserve policy

Arguably, one of the most difficult (although far from unusual) tasks of policy analysis is to predict the effects of policy measures that have not actively been used before. We also believe that these are the circumstances in which a structural economic model may actually compete with state-of-the-art statistical models in forecasting.

To test this proposition, we apply our analysis to Russian data. The Bank of Russia actively accumulated foreign exchange reserves prior to 2008. The scale of FXIs was substantial and played a notable role in money creation (Figure 1). Simultaneously, the Government was accumulating the sovereign wealth fund. However, from 2010, the usage of these policy instruments became notably less intense. This gives us two distinctly different sub-samples with which to test our model.

We conduct the following experiment. We split our time sample into two sub-samples: the first sub-sample comprises data from January 2001 to June 2008 and the second comprises data from January 2010 to December 2013.<sup>5</sup> We parametrize our model using one of the sub-samples and then use it to produce forecasts of the money and credit growth rates over another sub-sample. Accordingly, we may interpret the case of producing the out-of-sample forecasts for the first sub-sample (2001–2008) as predicting the effect of previously unobserved FXIs. Conversely, the out-of-sample forecasts for the second sub-sample (2010–

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<sup>3</sup> In theory (Tobin, 1963; Lavoie, 1999), the "excess" money created by external transactions can subsequently be destroyed by the adjustment of credit. This, however, would require the newly created money to be transferred immediately to the indebted agents, which would use these funds to repay their loans instead of increasing their consumption. The agent-based framework allows us to model this process more realistically.

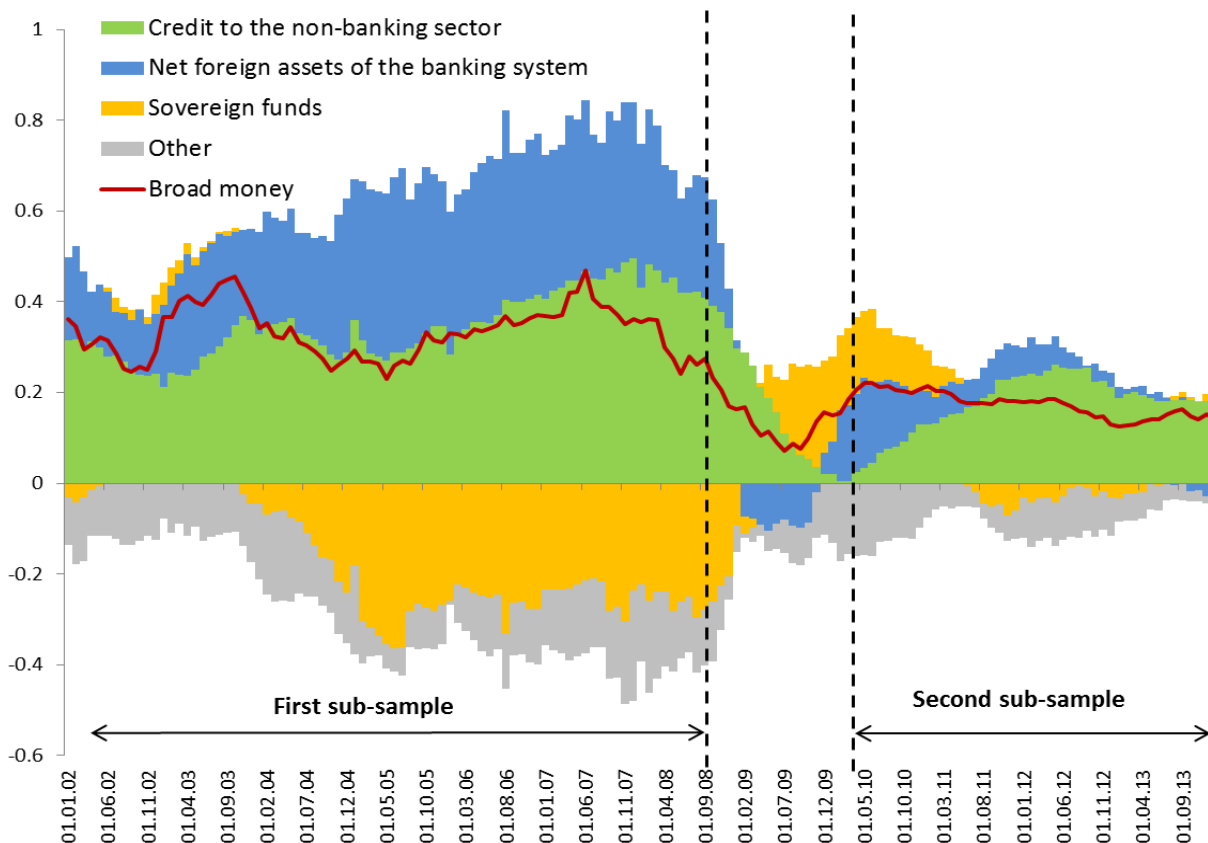
<sup>4</sup> Defined in terms of such indicators as the loans to deposits ratio, net stable funding ratio or liquidity creation (Berger and Bouwman, 2009).

<sup>5</sup> We exclude the observations for 2009 from the analysis due to dramatic exchange rate fluctuations and ensuing changes in foreign currency nominated items on the banking system's balance sheet (which occurred due to both portfolio shifts and the re-evaluation effect). For the same reason, we do not include the observations for 2014–2015. As stated in Section 2, modelling financial dollarization developments is beyond the scope of this paper.



2013) may be regarded as predicting the effect of a termination of the foreign exchange reserve accumulation policy.

**Figure 1. Money growth and its counterparts in Russia**  
(annual flows, percentage of broad money stock)



## 2. THE ABM SET-UP

Theoretical models in the spirit of Kashyap and Stein (1995) are commonly used to illustrate the unconventional monetary policy measures that directly affect banks' balance sheets. However, these models only serve as theoretical foundations and play no role in the empirical analysis (e.g. Butt et al., 2014). Conventional DSGE models may in principal be used for forecasting (although we are not aware of particular examples of DSGE models' application to forecasting the effects of foreign reserve accumulation). However, as pointed out by Borio and Zhu (2012), standard macroeconomic models are not well suited to capturing the risk-taking channel of monetary policy, namely the link between the monetary

policy and the perception and pricing of risk by economic agents.<sup>6</sup> Accommodating realistic behaviour rules is also not a particular strength of the standard analytical tools typically used by macroeconomists. Moreover, in most cases, the workhorse model is a dynamic stochastic general equilibrium model, of which the formulation and numerical solution follow the decisions of an aggregate representative agent in the economy, which behaves similarly to the microscopic agents. Note that, although we may assume that we have sufficient information on the microeconomic behaviour of banks, that is not sufficient to make assumptions about the emergent dynamics of aggregate balance sheet variables.

We therefore employ an agent-based approach, which we think is the most appropriate strategy for our objectives. The merits of agent-based models are discussed in detail by Caiani et al. (2016), Fagiolo and Roventini (2017) and Haldane and Turrell (2018). We find it more convenient (compared with, for example, conventional DSGE models) to set up a stock-flow-consistent agent-based model that accommodates rules of banks' behaviour and can be useful in analysing the balance effects caused by FXIs.

We set up a model focused mostly on the description of the banking sector. There are ample examples of macroeconomic agent-based models with the detailed banking sector in the literature (Ashraf et al., 2017; Chan-Lau, 2017; Popoyan et al., 2017; Krug, 2018, among others). Our model may be regarded as a simplified version of these prototypes. Most notably, our model does not have a detailed real sector (e.g. price setting, production and employment). Instead, the agents simply conduct nominal transactions (transferring their deposits to each other in the process). Our model does not have an interbank reserve market, and fluctuations in the reserve supply do not affect the short-term interest rate. We assume that only an overnight interbank market exists and that the corresponding interest rate always equals the policy rate of the central bank. The fiscal policy is limited to sovereign fund accumulation/spending. On the other hand, transactions with the foreign sector are present in our model and may be regarded as an extension.

Our model is populated by agents ( $E$  exporters and  $N$  producers for domestic markets) and  $B$  banks. The agents own cash and deposits and may take out loans. They may keep their deposits in only one bank but may have loans from any bank. The agents also have foreign debt and foreign financial assets nominated in foreign currency. The initial quantities

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<sup>6</sup> Although DSGE models that address the issue of foreign exchange reserve accumulation are far from unprecedented, they do not fully accommodate the credit and money creation mechanisms and the evolution of banks' balance sheets (see Jakab and Kumhof (2015) for a notable exception). Instead, these models are based on a set of simplifying assumptions. For example, García-Cicco (2011) assumes that the central bank may directly control broad money. Benes et al. (2015) assume that credit spreads are affected by changes in the stock of the central bank's FX reserves.

of these items (and the host banks) are generated randomly in the model's initialization phase but are determined endogenously during the simulation. They also have five fixed characteristics that are determined in the model's initialization phase:

- the market share ( $MS_e$  and  $MS_n$ ), which determines the distribution of revenues on the export and domestic markets;
- the recovery rate ( $RR_e$  and  $RR_n$ ), which determines the value of collateral that is transferred to banks if the agents default on their loans;
- portfolio preferences ( $PP_e$  and  $PP_n$ ), which determine the desired proportion of domestic and foreign financial assets;
- liquidity preferences ( $LP_e$  and  $LP_n$ ), which determine the desired interest rate premium for illiquid deposits;
- internal "break-even" rates ( $IR_n^*$  and  $IR_e^*$ ), which determine the acceptable loan interest rate for a given agent.

The agents gauge their trend income  $Y_{n,t}^p$  depending on their current income  $Y_{n,t}$ , which consists of their revenues in the current period:

$$I_{n,t}^T = \mu I_{n,t-1}^T + (1 - \mu) I_{n,t}$$

All the trend variables in this model are determined using such a law of motion.

The banks have three types of assets (loans, bank reserves and collateral obtained after loan defaults) and three types of liabilities (deposits, capital and net liabilities to the central bank).

Five variables are determined exogenously for each time step:

- The short-term interest rate ( $IR_t$ )
- Foreign exchange reserve purchases by the central bank ( $FXI_t$ )
- Accumulation/spending of the sovereign wealth fund ( $SWF_t$ )
- The global liquidity variable ( $VIX_t$ )
- Export revenues ( $OIL_t$ )

In every time period (representing a month), the sequence of events runs as follows:

1. Domestic transactions are conducted;
2. External transactions are conducted;
3. Commercial banks determine their risk-taking policy and manage their reserves and collateral;
4. Agents manage their domestic financial assets;

5. Loans are extended;
6. Interest payments are made and agents default on loans.

At the end of each time step, aggregate variables (e.g. money and credit) are computed, summing the corresponding microeconomic variables. Let us now turn to a more detailed description of these events.

## 2.1 Domestic transactions and the import demand

The spending of all agents (both exporters and domestic producers<sup>7</sup>) is determined as follows:

$$C_{n,t} = \beta^I I_{n,t}^T + \beta^W D_{n,t} - \beta^D (DSR_{n,t} - DSR^*) I_{n,t}^T + \beta^R \varepsilon_t I_{n,t}^T$$

$D_{n,t}$  is the deposits owned by the agent;  $DSR_{n,t}$  is the agents' current debt service ratio<sup>8</sup> and  $DSR^*$  is the "natural" DSR value; and  $\varepsilon_t$  is a random component of the demand  $\sim U(0,1)$ . Agents' spending cannot be negative or exceed their stock of deposits, but, if the generated desired spending of an agent exceeds the agent's current deposit, the agent will try to obtain a (domestic or external) loan (the volume of the desired loan is  $\beta^{LD} I_{n,t}^T$ ; the desired maturity (years) is determined randomly  $\sim N(5,1)$ ) during other phases of this time step.

The proportion of spending on imports is determined randomly as follows:

$$C_{n,t}^{Im} = \beta^{Im} v_t C_{n,t}, v_t \sim U(0,1)$$

The rest is spent on domestic markets:

$$C_{n,t}^D = C_{n,t} - C_{n,t}^{Im}$$

The income of domestic producers is also determined at this stage by distribution of the pool of spending on domestic markets in accordance with agents' market shares ( $MS_n$ ):

$$I_{n,t} = MS_n (\sum_N^1 C_{n,t}^D + \sum_E^1 C_{e,t}^D)$$

The transactions are settled consistently: spending decreases an agent's deposits (and the reserves of the respective bank) and receiving income increases the deposits (and the reserves of the respective bank).

The sovereign wealth fund is spent or accumulated. The amount of accumulated (spent) funds is determined by the exogenous  $SWF_t$  variable. The deposits of all agents are

<sup>7</sup> For brevity, we only show notations for domestic producers when the equations are exactly analogous for both types of agents.

<sup>8</sup> The debt service ratio is calculated as the sum of the principal and interest payments on all of an agent's loans expected this month as the ratio to permanent income.

reduced (increased) proportionally and the respective banks obtain (lose) the corresponding amount of reserves.

## 2.2 External transactions

The foreign financial assets of the agents ( $FA_n$ ) are remunerated and foreign debt ( $FD_n$ ) is repaid at the foreign interest rate ( $FIR$ ). Repaying foreign debt decreases foreign assets accordingly. The maturity of foreign loans is assumed to equal the  $FDM$ .

Agents that desire a loan will receive foreign loans with probability  $\lambda^{GL} VIX_t$ , where  $VIX_t$  is an exogenous variable representing global liquidity developments. Obtaining a foreign loan increases foreign debt and foreign assets accordingly.

Agents generate the desired capital inflows and outflows ( $CF_{n,t}$ ) by rebalancing their portfolios:

$$CF_{n,t} = \lambda^{CF} (PP_n D_{n,t} / ER_t^T - FA_{n,t})$$

where  $ER_t^T$  is the trend exchange rate (rubles per one unit of foreign currency). The sum of absolute values of negative desired adjustments across all agents constitutes the desired capital inflows ( $\sum_N^1 CF_{n,t}^-$ ). The sum of positive desired adjustments nominated in rubles ( $\sum_N^1 ER_t^T CF_{n,t}^+$ ) across all agents constitutes the desired capital outflows ( $CF_t^+$ ).

Export revenues ( $OIL_t$ ) nominated in foreign currency are an exogenous variable. Spending on imports is the sum of all  $C_{n,t}^{Im}$  determined as described in Section 2.1.

The exchange rate is determined as follows:

$$ER_t = (FXI_t + \sum_N^1 ER_t^T CF_{n,t}^+ + \sum_E^1 ER_t^T CF_{e,t}^+ + \sum_N^1 C_{n,t}^{Im} + \sum_E^1 C_{e,t}^{Im}) / (OIL_t + \sum_N^1 CF_{n,t}^- + \sum_E^1 CF_{e,t}^-)$$

where  $FXI_t$  are foreign exchange purchases by the central bank (nominated in rubles).<sup>9</sup>

After the market-clearing exchange rate is determined, it is used to settle the inflow transactions in ruble terms: agents wishing to increase the share of domestic financial assets in their portfolios transfer  $ER_t CF_{n,t}^-$  worth of funds to their domestic deposits and exporters receive their share of revenues  $I_{e,t} = MS_e ER_t OIL_t$ . These transactions increase the agents' deposits and the reserves of the respective banks. Outflow transactions (imports and capital outflows) decrease the agents' deposits and the reserves of the respective banks.

Note that, in this modelling framework without FXIs, the realized inflows are always equal to the outflows. Therefore, no money or bank reserves are created. However, foreign exchange purchases by the central bank will automatically result in an increase in deposits

<sup>9</sup> If the central bank sells foreign reserves, this item is nominated in foreign currency and is moved to the nominator in the equation above.

and bank reserves. This represents money creation through external transactions under inflexible net foreign reserves of commercial banks, as discussed in Section 1.

Importantly, this assumption means that there are no parameters that directly link FXIs with other variables in the model. Therefore, potentially, the model may be estimated without observing the actual effects of FXIs.

### 2.3 Commercial banks determine the risk-taking policy and manage the reserves and collateral

As discussed in Section 1.1, banks adjust the risk-taking policy in response to their balance sheet developments: they try to improve the balance sheet liquidity by restricting long-term lending and collecting more deposits (preferably “sticky” deposits). In our model, this is represented by banks setting premiums for loans’ and deposits’ interest rates ( $P_{b,t}$ ) depending on the state of balance sheet liquidity and capital adequacy:

$$P_{b,t} = \alpha^L LC_{b,t} + \alpha^{CAP} / CAPRAT_{b,t}$$

$CAPRAT_{b,t}$  is the capital to loans ratio.  $LC_{b,t}$  is the liquidity creation indicator (see Berger and Bouwman (2009) for details) calculated as the ratio between assets and liabilities weighted by liquidity:

$$LC_{b,t} = (\text{Collateral}_{b,t} + \text{Long-term loans}_{b,t} + 0.5 * \text{Short-term loans}_{b,t}) / (0.75 * \text{Core deposits}_{b,t} + 0.5 * \text{Deposits}_{b,t})$$

Loans with a remaining maturity of more than 12 months are considered to be long term; other loans are short term. Core deposits are “sticky” deposits with a lower probability of being transferred to another bank (see Section 2.4). This represents longer maturity as well as other possible features. Note that FXIs improve banks’ balance sheet liquidity (decrease LC) by creating deposits without creating illiquid assets.

We also introduce an ad hoc mechanism to represent competition and market pressure. Namely, after setting the premiums, banks adjust their interest rates in the case that their premiums deviate significantly from the market average ( $P_t^M$ ). The loan rates will also depend on the borrower-specific availability of collateral ( $RR_n$ ).

Eventually, the interest rates on loans and deposits are set using the following rule:

$$IR_{b,n,t}^L = IR_t + IR^{LMU} + \lambda^L P_{b,t} + \lambda^C (P_t^M - P_{b,t}) + \lambda^{B1} (\lambda^{B2} - RR_n)$$

$$IR_{b,t}^D = IR_t + IR^{DMU} + \lambda^L P_{b,t} + \lambda^C (P_t^M - P_{b,t})$$

where  $IR^{LMU}$  and  $IR^{DMU}$  are basic mark-ups.  $\lambda^L = 1$  is for non-core deposits and loans with requested maturity of less than 3 years.

At this stage, remuneration on banks' reserves ( $R_{b,t}$ ) and interest payment on liabilities to the central bank are carried out using the policy rate  $IR_t$ . Remuneration (interest payment) increases (reduces) reserves and increases (reduces) capital accordingly.

Banks borrow an additional amount (reserves) that equals:

$$\Delta R_{b,t} = 0.2D_{b,t} - R_{b,t}$$

where  $D_{b,t}$  is a bank's deposit stock and  $RR$  is the desired reserve to deposit ratio.

Borrowing additional reserves increases the liabilities to the central bank accordingly. Note that reserves' adjustment may be negative and the total liabilities to the central bank may also be negative and become remunerated (representing the liquidity-absorbing facilities of the central bank).

Each month, banks sell a fraction  $\theta$  of their collateral inventories. It is sold to every agent with enough funds in the deposit. The buyer's bank loses the respective amount of deposits and reserves. The inventory-selling bank gains reserves and loses collateral.

## 2.4 Agents manage their domestic financial assets

All agents adjust their cash holdings ( $CH_{n,t}$ ) as follows:

$$\Delta CH_{n,t} = \delta^I I_{n,t}^T + \delta^R \xi_t I_{n,t}^T$$

where  $\xi_t$  is a random component of the cash demand  $\sim U(0,1)$ . An increase in cash holdings reduces the deposits and reserves of the respective bank.

Deposits that mature are automatically extended, and their interest rate is revised to the deposit interest rate currently offered by the respective bank. At this point, the respective agent may choose the deposit type (core or non-core). The agent chooses the core deposit if the interest rate differential exceeds the desired premium (i.e.  $P_{b,t}^{CD} - P_{b,t}^D > LP_n$ ).

All agents randomly (with probability  $1-p^{CD}$  in the case that they currently have core deposits and probability  $1-(p^{CD}-p^D)$  in the case of non-core deposits) explore the deposit market. They randomly choose one of the alternative deposit interest rate offers (with probability  $p^I$  they choose the best offer). In the case that the offered interest rate is higher than their current rate, agents transfer their deposits to the new bank (or revise the deposit interest rate of their current bank). At this point, the maturity (years) is determined randomly  $\sim N(2,0.5)$  and agents may choose to change the deposit type. The newly selected bank gains new deposits and reserves; the previous bank loses both.

## 2.5 Loans are extended

Agents that seek a loan (and do not receive it from abroad) approach a random bank (with probability  $p^l$  they choose the bank with the lowest interest rate premium). Only banks with  $CAPRAT_{b,t}$  exceeding 0.1 may be approached. If an agent's  $IR_n^*$  is higher than the offered  $IR_{b,n,t}^L$ , the loan is created and the deposits of the borrower are increased accordingly. The lending bank loses the respective amount of reserves and the bank in which the borrower's deposit is placed receives them.

## 2.6 Interest payments are made and agents default on loans

Remuneration increases the deposits and reduces the capital of the respective banks. Remuneration and repayment of the loan's main body decrease the borrowers' deposits and the reserves of the bank in which these deposits are placed. The lending bank's reserves and capital (in part of the interest rate payments' amount) increase.

The agents that do not have sufficient funds for repayment default on all of their domestic loans and set their external debt to zero. Domestic banks write off the defaulted loans from their balance sheets. A proportion of the loans' volume is regained as collateral (determined by the borrowers'  $RR_n$ ); the remaining part is capital loss.

## 3. THE ABM ESTIMATION

The estimation of agent-based models is currently an intense area of research, and the state-of-the-art approach is yet to be determined and refined (see Lux and Zwinkels (2017) for a review of the recent advances). Therefore, in our paper, we use a relatively simple and straightforward approach.

We generate 2000 sets of parameters from the distributions reported in the Appendix<sup>10</sup> and use them to generate money and credit series by simulating the model conditional on the actual developments of the observed exogenous variables.<sup>11</sup>

These variables are:

- USD oil prices (representing  $OIL_t$ )
- The Chicago Board Options Exchange Market Volatility Index (as the ratio to mean, representing  $VIX_t$ )

<sup>10</sup> The only difference in initial conditions for the two sub-samples is the starting values of deposits and cash, which are roughly calibrated to match the loans to money ratio observed at the start of the sub-samples.

<sup>11</sup> We start collecting money and credit series after a 10-period-long burn-in period during which the exogenous variables are fixed at the sample means.



- The MIACR overnight interest rate (representing  $IR_t$ )
- Changes in the liabilities of the banking system to the general government (as the ratio to broad money stock, representing  $SWF_t$ )
- Changes in the net foreign assets of the banking system<sup>12</sup> to the general government (as the ratio to broad money stock, representing  $FXI_t$ )

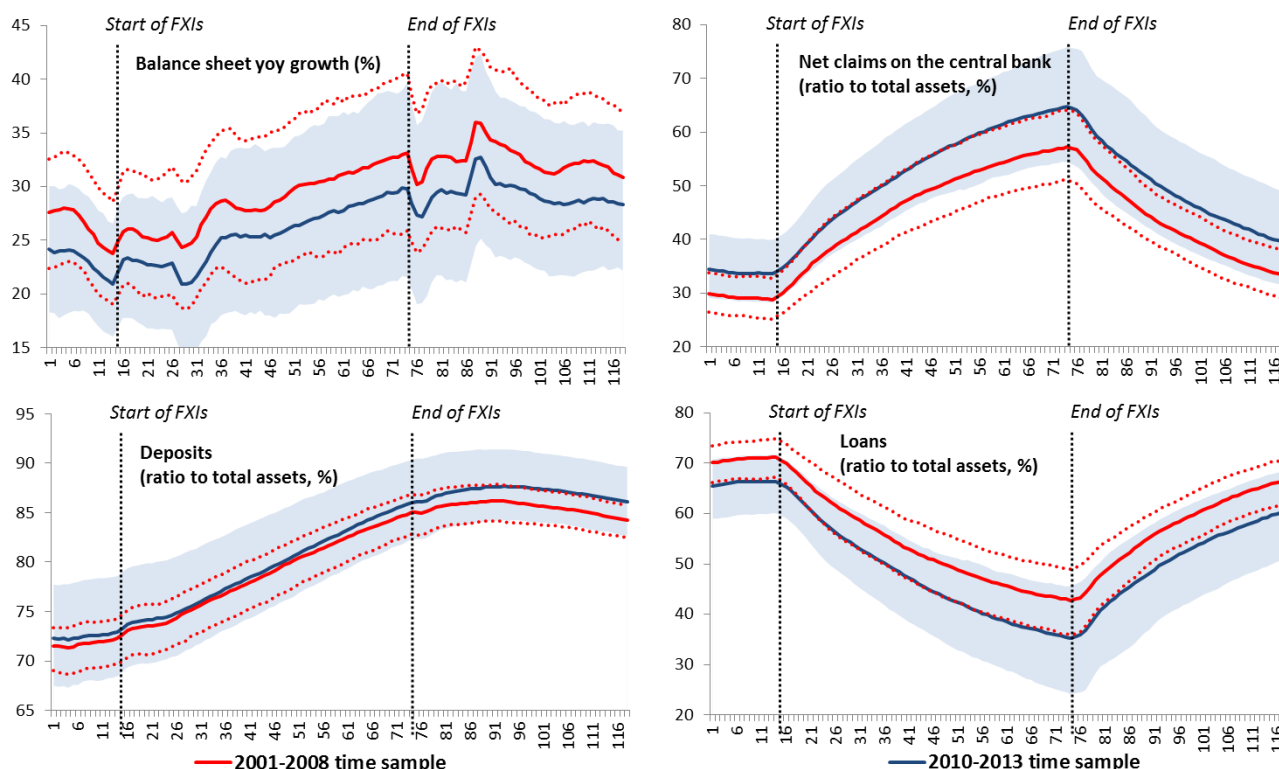
We then use the importance sampling squared algorithm (Tran et al., 2016) with likelihood estimated by averaging 100 draws to evaluate the goodness of fit of generated and actually observed seasonally adjusted series of credit and money stock and to determine the weights for the parameters' sets. We estimate our ABM over two sub-samples: from January 2001 to June 2008 and from January 2010 to December 2013.

We examine the results by comparing the effects of FXIs estimated using the models estimated over two sub-samples. Namely, we generate the series of  $FXI_t \sim N(0.02, 0.01)$  in the period of foreign reserve accumulation and  $\sim N(0.0, 0.01)$  in other periods. Other exogenous variables are fixed at mean values. We proceed by simulating the model conditionally on these exogenous data and observing the developments in commercial banks' balance sheets. The results are presented in Figure 2.

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<sup>12</sup> Over the time samples under analysis, this variable was almost entirely driven by the changes in the Bank of Russia's net foreign assets and therefore may be regarded as a policy variable. Admittedly, when this is not the case (e.g. in times of evolution of domestic financial dollarization), the ABM should be augmented to model the endogenous developments of commercial banks' net foreign assets.

**Figure 2. Effects of foreign reserve accumulation estimated over different time sub-samples**



The model predicts that the rate of commercial banks' balance sheet expansion will pick up when FXIs start. This will happen mostly due to the growth of deposits on the liability side and claims on the central bank on the asset side. The growth rate of loans will be significantly lower but not low enough to compensate for money creation through external transactions by less money creation through lending. Qualitatively, the results are very similar for both sub-samples, although the absolute magnitude of the effects is different. We examine the degree to which these differences affect the model's out-of-sample performance in Section 4.

#### 4. ABM-BASED FORECASTS

We proceed by calculating the out-of-sample forecasts using two estimated versions of ABMs. We employ two approaches to produce these projections. The direct approach is to run the ABM conditional on the actually observed developments of the exogenous variable (after the 10-period-long burn-in period) and collect the realized series of money and stock.

Admittedly, using the ABM directly to produce forecasts may be impractical for actual policy making. This is related to difficulties with re-estimation and with the introduction of observed initial conditions. Therefore, we also utilize a hybrid two-step procedure that

consists of using ABM-based artificial data to train the time series forecasting model.<sup>13</sup> For this purpose, we generate an artificial data set (using the ABM estimated over the training sample) that contains periods of both active reserve foreign reserve accumulation and tranquil periods.<sup>14</sup> We pool this artificial data set with an actual training sample to estimate a time series model.

We use the state-of-the-art Bayesian vector autoregression (BVAR) as a forecasting model. This approach has proved to be efficient for modelling a relatively large number of series with the relatively short time sample available for Russia (see Deryugina and Ponomarenko, 2015). Namely, we combine the Minnesota prior, the “sum-of-coefficients” prior and the “dummy-initial-observation” prior, using the vector of hyperparameters from Giannone et al. (2015). The BVAR comprises seven variables:  $OIL_t$ ,  $VIX_t$ ,  $IR_t$ ,  $SWF_t$ ,  $FXI_t$ , broad money and credit. All the series are in levels (including  $SWF_t$  and  $FXI_t$ ). We use three lags of monthly data. The series are in logs (except  $IR_t$  and  $VIX_t$ ) and seasonally adjusted. We also consider the non-augmented (i.e. estimated without using an artificial data set) BVAR as a benchmark competitor model.

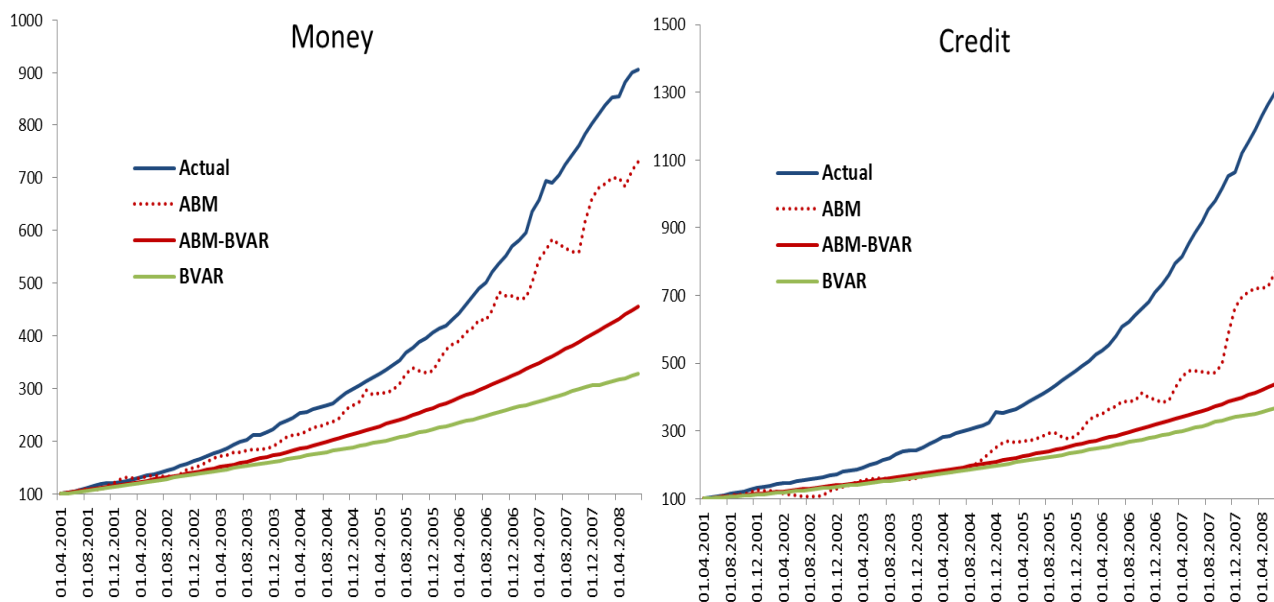
The first forecasting exercise consists of producing one long-term out-of-sample projection (conditional on actually observed the exogenous variables): from the start to the end of the respective forecast samples. The results are presented in Figures 3–4. As could be expected, the BVAR model significantly underestimates the expansion of money and credit over the 2001–2008 sub-sample (the period of active FXIs) and overestimates the balance sheet expansion over the tranquil 2010–2013 sub-sample, while the ABM-based projections are much more realistic. In this exercise, the performance of the hybrid ABM–BVAR does not appear to be better than the stand-alone ABM, although one may notice that the short-term dynamics of its projections are less volatile than those produced by the direct approach and are more consistent with the actually observed data in this respect. Presumably, the priors developed specifically to model economic time series help to filter out the noisy fluctuations produced by the ABM.

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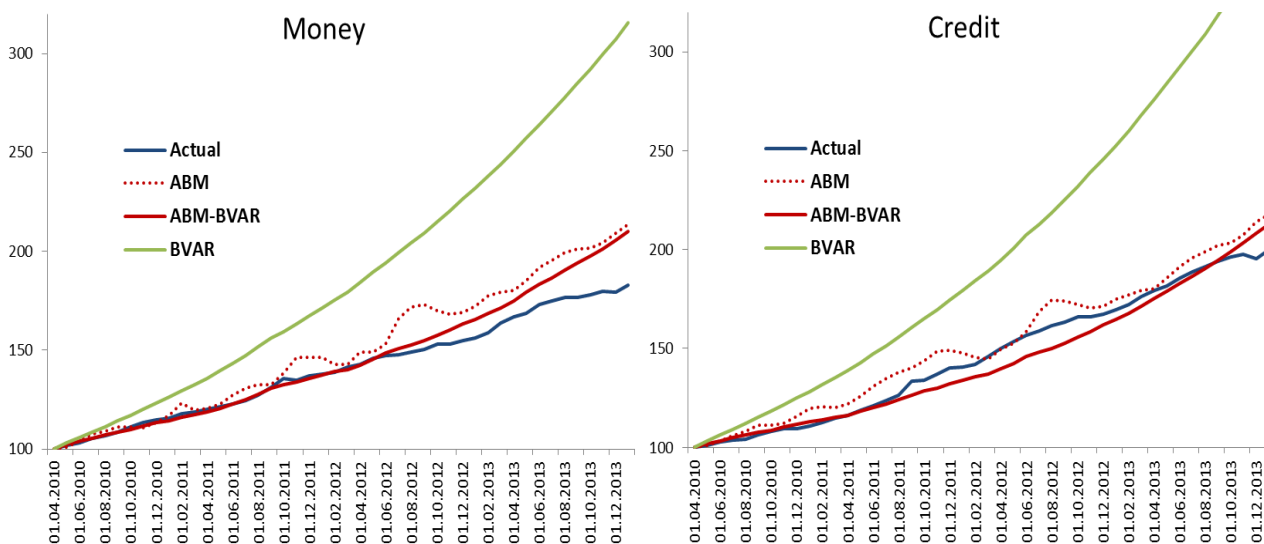
<sup>13</sup> Arguably, this procedure is methodologically close to imposing the DSGE-based priors on VAR models (del Negro and Schorfheide, 2004) or utilizing synthetic data to train neural networks (Jaderberg et al., 2014, 2016; Gupta et al., 2016).

<sup>14</sup> We compile the artificial data set by generating alternate 15-month-long “tranquil” and “active” periods of observations. In tranquil periods,  $SWF_t$  and  $FXI_t$  variables are distributed  $\sim N(0,0.01)$  and in “active” periods  $\sim N(0.02,0.01)$ . Other exogenous variables are fixed at mean values. Endogenous variables (money and credit) are generated by running the ABM conditional on these sets of exogenous variables. The total number of observations in the artificial data set is equal to the number of observations in the respective training sample.

**Figure 3. Out-of-sample projections for the 2001–2008 sub-sample  
(stocks of broad money and credit, March 2001 = 100)**



**Figure 4. Out-of-sample projections for the 2010–2013 sub-sample  
(stocks of broad money and credit, March 2010 = 100)**



In the second exercise, we examine the short-term forecasting performance of our models. We produce conditional projections of cumulated growth of money and credit over

the 12-month horizon. Unlike the first exercise, we use BVAR and ABM-BVAR to produce a set of such projections using each set of observations in the forecast sample as initial conditions (although the models are still estimated only using the training and artificial data sets). In the case of the ABM, we simply measure the cumulated growth over each interval of the projected money and credit stocks calculated in the first exercise. The root mean squared errors (RMSEs) of these projections over different horizons are reported in Table 1. The results are quite straightforward: the ABM-based forecasts outperform BVAR for almost all horizons. Furthermore, in most cases, the hybrid approach outperforms direct forecasting for shorter horizons (up to 6–9 months).

**Table 1. RMSEs of out-of-sample projections without re-estimation  
(ratio to RMSEs of BVAR)**

Horizon (months)	Forecast sample: 2001–2008				Forecast sample: 2010–2013			
	<i>Money</i>		<i>Credit</i>		<i>Money</i>		<i>Credit</i>	
	<i>ABM</i>	<i>ABM-BVAR</i>	<i>ABM</i>	<i>ABM-BVAR</i>	<i>ABM</i>	<i>ABM-BVAR</i>	<i>ABM</i>	<i>ABM-BVAR</i>
1	1.01	1.04	1.41	1.16	2.04	0.70	1.16	0.68
2	1.10	0.98	0.99	1.00	1.80	0.64	1.04	0.58
3	1.14	0.92	0.75	0.89	1.49	0.63	0.88	0.52
4	1.07	0.88	0.67	0.84	1.19	0.62	0.73	0.48
5	0.99	0.83	0.60	0.81	0.96	0.60	0.60	0.46
6	0.87	0.77	0.51	0.78	0.85	0.60	0.51	0.44
7	0.80	0.75	0.52	0.75	0.78	0.61	0.48	0.43
8	0.74	0.73	0.50	0.73	0.68	0.62	0.43	0.42
9	0.70	0.71	0.47	0.72	0.60	0.63	0.38	0.42
10	0.69	0.69	0.47	0.70	0.55	0.64	0.32	0.41
11	0.68	0.66	0.46	0.67	0.54	0.65	0.29	0.40
12	0.61	0.62	0.42	0.66	0.52	0.66	0.28	0.41

The first two exercises show that it may be beneficial to use the ABM in times of policy regime shifts, but the extent to which this approach will remain useful afterwards is not clear. Therefore, we add more realism to the exercises by recursively adding observations from the forecast sample to the data set and re-estimating the ABM-BVAR and BVAR models before producing the projections. The performance of these forecasts is reported in Table 2. As could be expected, in most cases, the accuracy of such recursive projections obtained from ABM-BVAR is greater than that of the direct ABM forecasts (which are the same as in the first two exercises). Most notably, however, the hybrid ABM-BVAR approach in general still outperforms non-augmented BVAR (with the exception of credit forecasts over the 2001–2008 sample). We conclude that the artificial data set that initially helped to estimate the

BVAR does not become a drag on the model's performance when more true observations become available.

**Table 2. RMSEs of out-of-sample projections with recursive re-estimation  
(ratio to RMSEs of the BVAR)**

Horizon (months)	Forecast sample: 2001–2008				Forecast sample: 2010–2013			
	<i>Money</i>		<i>Credit</i>		<i>Money</i>		<i>Credit</i>	
	<b><i>ABM</i></b>	<b><i>ABM-BVAR</i></b>	<b><i>ABM</i></b>	<b><i>ABM-BVAR</i></b>	<b><i>ABM</i></b>	<b><i>ABM-BVAR</i></b>	<b><i>ABM</i></b>	<b><i>ABM-BVAR</i></b>
1	1.30	1.00	1.92	1.20	2.49	0.79	1.56	0.88
2	1.50	0.99	1.51	1.23	2.24	0.71	1.59	0.83
3	1.66	1.00	1.23	1.28	1.81	0.66	1.42	0.77
4	1.58	0.96	1.15	1.27	1.43	0.61	1.20	0.73
5	1.50	0.95	1.07	1.28	1.14	0.56	1.01	0.71
6	1.50	0.95	0.92	1.27	1.01	0.55	0.89	0.69
7	1.26	0.94	0.92	1.24	0.92	0.55	0.84	0.68
8	1.16	0.91	0.91	1.24	0.81	0.56	0.77	0.68
9	1.14	0.92	0.84	1.24	0.71	0.56	0.68	0.68
10	1.06	0.89	0.85	1.15	0.66	0.56	0.60	0.67
11	1.03	0.87	0.82	1.08	0.64	0.56	0.56	0.67
12	0.99	0.84	0.75	1.04	0.63	0.57	0.54	0.68

## CONCLUSIONS

We develop a stock-flow-consistent agent-based model that comprises a realistic mechanism of money creation. The model predicts that foreign reserve accumulation by a central bank (even when sterilized, meaning that it does not affect the short-term interest rates) will result in acceleration of commercial banks' balance sheet expansion rate. This happens due to an increase in money creation through external transactions that is not fully offset by the reduction in money creation through lending.

Importantly, the parsimonious set-up of our ABM arguably gives us an opportunity to parametrize the model and predict the FXIs' effect even without having to observe the realization of such a policy. We illustrate this point by applying our model to Russian data. We split our time sample into two sub-samples: the first sub-sample comprises the period of active foreign reserve accumulation by the Bank of Russia and the second comprises the period when this policy instrument was scarcely used. We estimate our model using one of

the sub-samples and then use it to forecast the effect of commencement/termination of FXIs over another sub-sample.

We estimate the ABM and use the model to produce out-of-sample projections of money and credit developments. We use direct forecasts from the ABM as well as the hybrid approach, which consists of using ABM-based artificial data to train the BVAR model. We find that, in times of policy regime shifts, the ABM produces more accurate long-term projections compared to the state-of-the-art BVAR model. We also show that the ABM-BVAR model outperforms the non-augmented (i.e. estimated without using the ABM-based artificial data set) BVAR in almost all cases. We conclude that the suggested approach is promising and may be employed in practice to predict the effects of foreign reserve accumulation.

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## APPENDIX. ABM PARAMETERS

<i>Description</i>	<i>Parameter</i>	<i>Mean, St. D.</i>	<i>Boundaries</i>
<b>Domestic transactions</b>			
Income	$\beta^I$	$\sim N(0.8, 0.05)$	(0.7, 0.95)
Wealth	$\beta^W$	$\sim N(0.13, 0.025)$	(0.1, 0.25)
Debt	$\beta^D$	$\sim N(1, 0.1)$	(0.5, 2)
“Neutral” DSR	$DSR^*$	$\sim N(0.15, 0.025)$	(0, 0.5)
Random demand	$\beta^R$	$\sim N(0.2, 0.025)$	(0, 1)
Import demand	$\beta^{Im}$	$\sim N(0.33, 0.025)$	(0, 1)
Trend inertia (income)	$\mu$	$\sim N(0.9, 0.025)$	(0.75, 0.95)
Loan demand	$\beta^{LD}$	$\sim N(2, 0.25)$	(0, 10)
<b>External transactions</b>			
Foreign interest rate	$FIR$	$\sim N(5, 2)$	(0, 10)
Foreign debt maturity (years)	$FDM$	$\sim N(5, 1)$	(0, 10)
Global liquidity	$\lambda^{GL}$	$\sim N(0.0025, 0.0005)$	(0, 0.01)
Global liquidity (exporters)	$\lambda^{GL}$	$\sim N(0.0075, 0.0005)$	(0, 0.02)
Capital flows	$\lambda^{CF}$	$\sim N(0.33, 0.05)$	(0, 1)
Portfolio preferences	$PP_n, PP_e$	$\sim N(0.5, 0.1)$	(0, 1)
Trend inertia (exchange rate)	$\mu$	$\sim N(0.9, 0.025)$	(0.75, 0.95)
<b>Banks’ risk taking</b>			
Liquidity	$\alpha^L$	$\sim N(3, 0.5)$	(0, 5)
Capital	$\alpha^{CAP}$	$\sim N(1.5, 0.25)$	(0, 5)
Long-term premium	$\lambda^L$	$\sim N(2, 0.5)$	(0, 5)
Competition (deposits)	$\lambda^C$	$\sim N(0.25, 0.1)$	(0, 1)
Competition (loans)	$\lambda^C$	$\sim N(0.25, 0.1)$	(0, 1)
Collateral	$\lambda^{B1}$	$\sim N(4, 0.5)$	(0, 10)
Neutral “recovery rate”	$\lambda^{B2}$	$\sim N(0.75, 0.1)$	(0, 1)

Basic mark-up (deposits)	$IR^{DMU}$	$\sim N(2, 0.5)$	(0,5)
Basic mark-up (loans)	$IR^{LMU}$	$\sim N(2, 0.5)$	(0,5)
Collateral sales	$\theta$	$\sim N(0.05, 0.01)$	(0.01,1)
<b>Portfolio adjustment</b>			
Liquidity preferences	$LP_e, LP_n$	$\sim N(2, 0.25)$	(0,4)
Cash demand (income)	$\delta^I$	$\sim N(0.3, 0.025)$	(0,0.5)
Cash demand (random)	$\delta^R$	$\sim N(0.1, 0.025)$	(0,0.5)
Withdrawal (core)	$p^{CD}$	$\sim N(0.99, 0.005)$	(0.95,0.999)
Withdrawal (non-core)	$p^D$	$\sim N(0.04, 0.005)$	$p^{CD}-p^D \in$ (0.9,0.999)
Market information	$p^I$	$\sim N(0.5, 0.1)$	(0,1)
<b>Other</b>			
“Natural” interest rates	$IR_n^*$	$\sim N(23, 1)$	(10,30)
Recovery rate	$RR_n$	$\sim N(0.75, 0.025)$	(0,1)
Income at initialization	$I_{n,t}^T$	$\sim N(20, 1)$	(0,40)
Market shares	$MS_n$ are set proportionally to initial income share in the total income of agents of the same type		
Foreign assets at initialization	$FA_{n,t}$	$\sim N(0.2, 0.01)$	(0,1)
Foreign assets at initialization (exporters)	$FA_{e,t}$	$\sim N(0.25, 0.01)$	(0,1)
Loan volume of each agent at initialization		$\sim N(50, 10)$	(0,100)
Deposits at initialization (2001–2008/2010–2013 samples)	$D_{n,t}$	$\sim U(60, 75) / \sim U(30, 45)$	
Deposits at initialization, exporters (2001–2008/2010–2013 samples)	$D_{e,t}$	$\sim U(80, 100) / \sim U(40, 60)$	
Cash holdings at initialization (2001–2008/2010–2013 samples)	$CH_{n,t}$	40/20	

