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Excess reserves, monetary policy and financial volatility

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ABSTRACT

This paper examines the real and financial effects of reserves in a Dynamic Stochastic General Equilibrium (DSGE) model with monopoly banking and credit market imperfections. The framework explicitly accounts for the fact that commercial banks hold excess reserves and they incur costs in holding these assets. The model also accounts for imperfect substitutability between bank funding sources and it shows that this feature is an important channel through which reserve requirement shocks can affect real variables. Numerical experiments show that an increase in reserve requirements creates a countercyclical effect for real economic activity. The results also indicate that the combination of an augmented Taylor rule which responds to excess reserves and a countercyclical reserve requirement rule is optimal to mitigate macroeconomic and financial volatility associated with liquidity shocks.

1. Introduction

Excess reserves have been a common feature of the banking system of many countries across the world.[1] In developed countries, the phenomenon of excess reserves has become more apparent since the global financial crisis. However, in developing economies, the problem of excess reserves is more prevalent. For several years, the banking system of some developing countries has recorded high persistent liquidity. Given its importance to the monetary transmission process, several researchers have empirically examined the determinants of excess liquidity in developing economies. Contributions along these lines include Maynard and Moore (2005) for Barbados, Saxegaard (2006) for Sub-Saharan Africa, Khemraj (2007, 2009) for Guyana, Anderson-Reid (2011) for Jamaica, Pontes and Sol Murta (2012) for Cape Verde, Jordan et al. (2012) for The Bahamas and Primus et al. (2014) for Trinidad and Tobago.[2]

Despite the impact excess reserves can have on the transmission mechanism of monetary policy, there have been few attempts to examine the role of reserves in a general equilibrium framework. Two of the analytical contributions in this area are Samake (2010) and Christiano et al. (2014). Although both studies incorporated excess reserves into a general equilibrium model with banking, they did not model the fact that banks incur costs in holding these assets. It is important to have a well-defined demand for excess reserves to explicitly account for the rate of return on reserves and any opportunity cost of holding reserves.

This paper therefore explicitly models excess reserves in a New Keynesian Dynamic Stochastic General Equilibrium (DSGE) framework with monopoly banking, credit market imperfections and a cost channel. The model extends and modifies the framework in Agénor and Alper (2012), and integrates aspects of Glocker and Towbin (2012) and Agénor et al. (2013). The notable features of this model are: it accounts for imperfect substitutability between bank funding sources—deposits and central bank borrowing; excess reserves are endogenous, as banks voluntarily demand these assets; and there are convex costs associated with holding reserves. The framework is used to examine an augmented Taylor rule and an endogenous countercyclical reserve requirement rule separately, as well as the optimal combination of the both rules jointly, to manage real and financial volatility associated with a liquidity shock. This research represents an essential contribution as it is the first

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[1] In most financial systems, excess liquidity refers to the maintenance by banks of a higher level of funds than is normally required to meet their statutory reserve requirements and settlement balances. Excess liquidity (or excess reserves) is measured as the difference between total bank reserves and required bank reserves. For this reason, the terms excess liquidity and excess reserves are used interchangeably in the literature.

[2] Excess bank liquidity is also a problem for large developing countries, such as Brazil, Russia, India, China and Nigeria. Some of the other developing countries with the problem of excess reserves include Botswana (see Akinboade and Zachariah, 1997), Egypt (see Fielding and Shortland, 2005), Mexico (see Jallath-Coria et al., 2005), Tanzania (see Aikaeli, 2006), Turkey (see Tabak and Bankasi, 2006), Indonesia (see Bathaluddin et al., 2012), Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama and the Dominican Republic (see Deléchat et al., 2012), and Morocco (see El Hamma and Ejbari, 2013).

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attempt to apply a New Keynesian general equilibrium model with a financial sector, which accounts for the fact that banks incur costs in holding excess reserves, to examine the macroeconomic effects of excess liquidity and reserve requirements, as well as optimal interest rate and reserve requirement rules.

The reasons for excess liquidity can be categorized into structural and cyclical factors. One structural factor is a low degree of financial development. Therefore, excess liquidity tends to be more persistent in countries with underdeveloped financial markets, such as inefficient payment systems, or an underdeveloped market for government securities (see Saxegaard, 2006). Regarding the cyclical factors, one of the main sources of excess reserves is foreign currency inflows (Ganley, 2004). Current account inflows arise mainly through revenues received from commodity exports. Therefore, exporters of minerals, such as Botswana, and oil exporting economies, such as Nigeria and Trinidad and Tobago, observe huge current account surpluses when commodity prices are high on world markets. Capital account inflows may arise from aid-related transfers, foreign direct investment and portfolio inflows. In many developing countries, the problem of excess reserves arises from both structural and cyclical factors.

In an attempt to withdraw excess liquidity from the financial system, central banks have used open market operations and issued central bank bills. Central banks have also issued long-term securities (bonds) and implemented special deposit facilities. In addition, reserve requirements have been used frequently to manage liquidity.[3] For instance, between 2006 and 2009, the central banks of China and India increased reserve requirements to mop up excess liquidity. One disadvantage to note however is that reserve requirements act as a tax on the financial sector (Montoro and Moreno, 2011).

One of the key concerns for policymakers in countries where the banking system has high persistent excess reserves is the ineffectiveness of monetary policy. Excess liquidity impedes the monetary transmission mechanism and undermines the ability of monetary policy to stabilize the economy. It is important for excess bank reserves to be managed because tight liquidity conditions are necessary for the central bank to have leverage over the commercial banks to achieve its monetary objectives. Thus, changes in the policy interest rate can be reflected in the interest rates in the banking sector if commercial banks do not hold substantial liquidity above the legal requirement. Also, the central bank can effectively perform the function of monopoly supplier of domestic currency if the banking system is not plagued with excess liquidity (Ganley, 2004).[4] Another concern for policymakers is how to manage macroeconomic and financial volatility, amid high financial system liquidity. For example, in the presence of excess reserves, if demand conditions improve, banks can expand lending with consequences for inflation and financial stability. Moreover, excess reserves impose costs to commercial banks and policymakers. For instance, surplus reserves held as cash in vault or at the central bank that are not remunerated or remunerated below market interest rates can reduce bank profitability. Also, banks with large reserves may face large equity requirements to prevent socially costly risk-sharing on assets (Martin et al., 2013). In addition, policymakers incur more debt by increasing the issuance of securities to absorb excess reserves. This has contributed to increases in public sector debt in many countries, such as Jamaica (Anderson-Reid, 2011).

To quantify the macroeconomic effects of excess reserves, the model is calibrated for a middle-income country—due to the fact that the banking system in some of these economies has recorded high persistent liquidity. Specifically, the framework is used to examine the financial and real effects of a productivity shock, an increase in the base policy interest rate, a shock to the reserve requirement ratio and an exogenous increase in bank liquidity (taking the form of a shock to deposits). Furthermore, the model is used to investigate the volatility of the key variables following a liquidity shock when two alternative policy rules are used: an augmented Taylor rule; and a countercyclical reserve requirement rule. These two rules are also used to examine the optimal combination of policy rules when there is an increase in liquidity. The results show that as the base policy rate and the refinance rate rise following a negative supply shock and a contractionary monetary shock, the opportunity cost of holding excess reserves increases. Notably, a positive shock to required reserves leads to a contraction in output—which implies that changes in reserve requirements are countercyclical. The findings also indicate that using an augmented Taylor rule simultaneously with a countercyclical reserve requirement rule is the optimal combination of instruments to mitigate macroeconomic and financial volatility associated with liquidity shocks.

The rest of this paper is organized as follows. Section 2 presents the model and Section 3 outlines the symmetric equilibrium. The key steady-state and log-linearized equations of the model are presented in Section 4. Section 5 provides a discussion of the calibration for a "typical" middle-income country. In Section 6, impulse response functions are used to discuss the findings from the policy experiments and other shocks to the model. Section 7 considers two policy rules for mitigating real and financial volatility, and it examines optimal interest rate and reserve requirement rules. The final section provides a summary of the main results.

2. The model

Consider an economy which contains seven classes of agents: identical infinitely-lived households indexed by $h \in [0, 1]$, a final good-producing firm, a continuum of intermediate good-producing firms indexed by $j \in [0, 1]$, a capital good producer, a commercial bank (a bank, for short), the central bank (whose responsibility is to regulate the commercial bank) and the government.[5] Households consume and supply labour to intermediate good-producing firms. Intermediate good-producing firms use the labour provided by households and capital (which is rented from the capital good producer) to produce a unique good that is sold on the monopolistically competitive market. The final good-producing firm aggregates imperfectly substitutable intermediate goods into a single final good which is used for consumption, investment or government spending. In this model, wages are fully flexible and adjust to clear the market.

The commercial bank, which is owned by households, supplies credit in advance to intermediate good-producing firms to finance their short-term working capital needs. The bank also supplies credit to the capital good producer for investment financing. The bank's supply of loans is perfectly elastic at the prevailing lending rate. The bank pays interest on household deposits and central bank loans. In addition, the bank is required to hold minimum reserves against deposits at the central bank, and it has an explicit

[3] See Montoro and Moreno (2011); Robitaille (2011); Tovar et al. (2012) for further discussions.

[4] For instance, under tight liquidity conditions, if the central bank lowers the policy interest rate, deposit and lending rates should be reduced. Lower deposit rates should lead to a drop in demand for that category of assets, thereby stimulating consumption today, while a fall in loan rates is expected to increase demand for loans. If banks do not have sufficient liquidity to satisfy the increase in demand for loans, they would borrow from the central bank to finance any shortfall.

[5] In effect, the household and capital good producer can be thought of as one unit in this model, and this unit ignores the potential benefit of housing as collateral in capital good production while making housing choices. This point is further discussed later.

demand for excess reserves. The bank determines the total reserve ratio, the deposit rate and the lending rate, and borrows from the central bank to finance any shortfall in funding. The central bank supplies all the credit demanded by the bank at a rate that includes a premium, above the base policy rate. The penalty rate depends on the ratio of central borrowing to deposits, whereas the base policy rate is determined through a Taylor rule. It is important to note that because there is a perfectly elastic supply of liquidity, the bank is not subject to (random) withdrawal risk which has been a key factor in reserve management models.[6] Therefore, increased uncertainty about the size of cash withdrawals does not influence the quantity of excess bank reserves in this model.

The financial sector of the model incorporates features that are relevant to the structure of middle-income countries. First, commercial banks in these economies have a voluntary demand for excess reserves, which the framework accounts for, given the bank's explicit demand for excess reserves. Second, in some of these countries, commercial banks are required to hold primary and secondary reserves at the central bank. Given that secondary reserves are remunerated in a few countries, the model extends this to consider the case of interest being paid on the bank's total reserve holding at the central bank. Third, in many middle-income countries, the financial system is sufficiently developed so monetary policy can operate through the manipulation of a short-term interest rate. Therefore, the central bank in this model sets its policy rate using a Taylor-type rule. Finally, the banking system (as in most developing countries) has credit market imperfections and due to asymmetric information problems, lending to firms is collateralized.

2.1. Households

Each household, h, chooses consumption, labour supply to intermediate good-producing firms and real monetary assets. The objective of a representative household is to maximize the following utility function,

$$U = E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \frac{[C_{ht}]^{1-\sigma^{-1}}}{1-\sigma^{-1}} + \eta_N \ln(1-N_{ht}) + \eta_X \ln X_{ht} \right\}, \tag{1}$$

where C_{ht} is household consumption, N_{ht} is the share of total time endowment (normalized to unity) household h spent working, X_{ht} is a composite index of real monetary assets, $\sigma > 0$ gives the intertemporal elasticity of substitution in consumption, η_N, $\eta_X > 0$ are preference parameters with respect to leisure and money holdings respectively, $\beta \in (0, 1)$ is the discount factor and E_t is the expectation operator conditional on the information available at the beginning of period t.

The composite monetary asset is a combination of real cash balances, M^H_{ht}, and real bank deposits, D_{ht}, which can be represented by the following Cobb-Douglas function,

$$X_{ht} = (M^H_{ht})^{\nu} D_{ht}^{1-\nu}, \tag{2}$$

where $\nu \in (0, 1)$.

Real wealth of household h at the end of period t, A_{ht}, is given by,

$$A_{ht} = M^H_{ht} + D_{ht} + B^H_{ht}, \tag{3}$$

where B^H_{ht} denotes holdings of one-period real government bonds.

At the beginning of period t, each household enters with M^H_{ht-1} level of cash. Real cash balances yield no return, while deposits and government bonds yield gross returns of $(1+i^D_t)$ and $(1+i^B_t)$, respectively. Therefore, the total real returns from holding deposits and government bonds from period $t-1$, adjusted for the rate of inflation, are denoted respectively by $(1+i^D_{t-1})D_{ht-1}(P_{t-1}/P_t)$ and $(1+i^B_{t-1})B^H_{ht-1}(P_{t-1}/P_t)$, where P_t represents the price of the final good.

In addition, households supply labour to intermediate good-producing firms, for which they receive a total real factor payment $\omega_t N_{ht}$, where ω_t denotes the economy-wide real wage. Each household owns an intermediate good-producing firm so all the profits made by that firm, J^I_{ht}, are paid to the respective household. Also, each household receives a fixed fraction $\varphi_h \in (0, 1)$ of the bank's profits, J^B_t, and the capital good producer's profits, J^K_t, with $\int_0^1 \varphi_h dh = 1$. Each household is also required to pay a lump-sum tax, whose real value is T_{ht}.

The real budget constraint of household h is,

$$M^H_{ht} + D_{ht} + B^H_{ht} \le \omega_t N_{ht} - T_{ht} + M^H_{ht-1}\left(\frac{P_{t-1}}{P_t}\right) + (1+i^D_{t-1})D_{ht-1}\left(\frac{P_{t-1}}{P_t}\right)$$
$$+ (1+i^B_{t-1})B^H_{ht-1}\left(\frac{P_{t-1}}{P_t}\right) + J^I_{ht} + \varphi_h J^B_t + J^K_t - C_{ht}. \tag{4}$$

Each household maximizes lifetime utility with respect to C_{ht}, N_{ht}, M^H_{ht}, D_{ht} and B^H_{ht}, taking i^D_t, i^B_t, P_t, and T_{ht} as given. Maximizing (1) subject to (4) yields the following first order conditions,

$$C_{ht}^{-1/\sigma} = \beta E_t \left[(C_{ht+1})^{-1/\sigma} \left(\frac{1+i^B_t}{1+\pi_{t+1}}\right) \right], \tag{5}$$

$$N_{ht} = 1 - \frac{\eta_N (C_{ht})^{1/\sigma}}{\omega_t}, \tag{6}$$

$$M^H_{ht} = \frac{\eta_X \nu (C_{ht})^{1/\sigma}(1+i^B_t)}{i^B_t}, \tag{7}$$

$$D_{ht} = \frac{\eta_X (1-\nu)(C_{ht})^{1/\sigma}(1+i^B_t)}{i^B_t - i^D_t}, \tag{8}$$

where $\pi_{t+1} = (P_{t+1} - P_t)/P_t$ is the inflation rate.

Eq. (5) is the standard Euler equation which describes the optimal consumption path. Eq. (6) represents the optimal labour supply which is positively related to the real wage and negatively related to consumption. Eq. (7) shows that the demand for real cash balances depends positively on consumption and negatively on the opportunity cost of holding cash (measured by the rate of return on government bonds). Eq. (8) denotes the real demand for deposits which is positively related to consumption and the deposit rate, and negatively related to the bond rate.

2.2. Final good-producing firm

The final good producer assembles a continuum of imperfectly substitutable intermediate goods Y_{jt}, indexed by $j \in (0, 1)$, to produce the final good Y_t, which is used for private consumption, government consumption and investment. The production technology for combining intermediate goods to produce the final good is given by the standard (Dixit and Stiglitz, 1977) technology,

$$Y_t = \left\{ \int_0^1 [Y_{jt}]^{(\theta-1)/\theta} dj \right\}^{\theta/(\theta-1)}, \tag{9}$$

where $\theta > 1$ represents the elasticity of demand for each intermediate good.

Given the prices of intermediate goods, P_{jt}, and the final good price, P_t, the final good-producing firm chooses the quantities of intermediate goods to maximize its profits. The first-order condition with respect to Y_{jt} is,

$$Y_{jt} = \left(\frac{P_{jt}}{P_t}\right)^{-\theta} Y_t. \tag{10}$$

[6] In reserve management models, the optimal level of reserves demanded by commercial banks is a function of deposit fluctuations (see Morrison, 1966; Poole, 1968; and Baltensperger, 1980 for further discussions).

Eq. (10) gives the demand for each intermediate good j. Substituting (10) in (9) and imposing a zero-profit condition, the final good price is represented by,

$$P_t = \left[\int_0^1 (P_{jt})^{1-\theta} dj \right]^{1/(1-\theta)}. \tag{11}$$

2.3. Intermediate good-producing firms

Each intermediate good-producing firm, j, produces a perishable good which is sold on a monopolistically competitive market. To produce these goods, each firm rents capital at the price r_t^K from the capital good producer and combines it with labour. The technology faced by each intermediate good-producing firm is given by the Cobb-Douglas production function,

$$Y_{jt} = A_t K_{jt}^{\alpha} N_{jt}^{1-\alpha}, \tag{12}$$

where N_{jt} is household $h = j$ labour hours, K_{jt} is the amount of capital rented by the firm, $\alpha \in (0, 1)$ is the elasticity of output with respect to capital and A_t is a serially uncorrelated technology shock which follows a first-order autoregressive process, $A_t = A_{t-1}^{\rho_A} \exp\left(\xi_t^A\right)$, where $\rho_A \in (0, 1)$ and $\xi_t^A \sim N(0, \sigma_{\xi^A})$.

In order to pay wages in advance, firm j takes a loan from the bank at the beginning of the period. The amount borrowed is,

$$L_{jt}^{F,W} = \kappa^W \omega_t N_{jt}, \tag{13}$$

where $L_{jt}^{F,W}$ represents the real value of loans demanded by intermediate good producers for all $t \geq 0$ and $\kappa^W \in (0, 1)$. It is assumed that short-term loans for working capital are contracted at a rate i_t^C, which reflects the cost of borrowing from the central bank. The wage bill, inclusive of interest payments is $(1 + i_t^C)\kappa^W \omega_t N_{jt} + (1 - \kappa^W)\omega_t N_{jt}$. Rearranging this gives $(1 + \kappa^W i_t^C)\omega_t N_{jt}$, which shows the firm's wage bill includes a constant share of financing of working capital needs. Thus, κ^W indicates the strength of the cost channel; if $\kappa^W = 0$, no cost channel exists.

Intermediate good producers solve a two stage problem. In the first stage, given input prices, firms integrate capital and labour in a perfectly competitive market in order to minimize their total costs. The first-order conditions with respect to N_{jt} and K_{jt} equate the marginal products of capital and labour to their relative prices, from which the capital-labour ratio is obtained,

$$\frac{K_{jt}}{N_{jt}} = \left(\frac{\alpha}{1-\alpha}\right) \left[\frac{(1 + \kappa^W i_t^C)\omega_t}{r_t^K} \right]. \tag{14}$$

The unit real marginal cost is,

$$mc_{jt} = \frac{\left[(1 + \kappa^W i_t^C)\omega_t\right]^{1-\alpha} (r_t^K)^{\alpha}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha} A_t}. \tag{15}$$

In the second stage, each firm chooses prices, P_{jt}, to maximize the discounted real value of current and future profits. Nominal price stickiness is introduced along the lines of Rotemberg (1982), by assuming that intermediate good-producing firms incur a cost in adjusting prices. These price adjustment costs, PAC_{jt}, which are measured in terms of aggregate output, Y_t, take the form,

$$PAC_{jt} = \frac{\phi_F}{2} \left(\frac{P_{jt}}{P_{jt-1}} - 1 \right)^2 Y_t, \tag{16}$$

where $\phi_F \geq 0$ is the degree of price stickiness.

Thus, the profit maximization problem for the intermediate good producer is,

$$\max_{P_{jt}} E_t \sum_{t=0}^{\infty} \beta^t \Lambda_t J_{jt}^I, \tag{17}$$

where $\beta^t \Lambda_t$ is the firm's discount factor for period t, with Λ_t representing the marginal utility gained from consuming an additional unit of profit. Real profits, J_{jt}^I, are defined as,

$$J_{jt}^I = Y_{jt} - mc_{jt} Y_{jt} - PAC_{jt}. \tag{18}$$

Substituting (10) and (16) in (18) and taking mc_{jt}, P_t and Y_t as given, the first-order condition with respect to P_{jt} is,

$$\begin{aligned} &(1-\theta)\Lambda_t \left(\frac{P_{jt}}{P_t}\right)^{-\theta} \frac{Y_t}{P_t} + \theta \Lambda_t mc_{jt} \left(\frac{P_{jt}}{P_t}\right)^{-\theta-1} \frac{Y_t}{P_t} \\ &-\Lambda_t \phi_F \left\{ \left(\frac{P_{jt}}{P_{jt-1}} - 1 \right) \frac{Y_t}{P_{jt-1}} \right\} \\ &+\beta \phi_F E_t \left\{ \Lambda_{t+1} \left(\frac{P_{jt+1}}{P_{jt}} - 1 \right) \left(\frac{P_{jt+1}}{P_{jt}^2} \right) Y_{t+1} \right\} = 0. \end{aligned} \tag{19}$$

Eq. (19) gives the adjustment process of the nominal price P_{jt}. When there is no price adjustment cost ($\phi_F = 0$), the price equals a mark-up over the real marginal cost,

$$P_{jt} = \left(\frac{\theta}{\theta - 1} \right) mc_{jt} P_t. \tag{20}$$

In a symmetric equilibrium $P_{jt} = P_t$ for all j; hence the real marginal cost equals the reciprocal of the mark-up, $mc_t = (\theta - 1)/\theta$.

2.4. Capital good producer

In the economy, all the capital is owned by the capital good producer who employs a linear production function to produce capital goods. At the beginning of each period, the capital good producer purchases I_t of the final good from the final good producer. Because payments for these final goods must be made in advance, the capital good producer borrows from the bank,

$$L_t^{F,I} = I_t, \tag{21}$$

where $L_t^{F,I}$ denotes real loans made to the capital good producer for investment purposes. The total cost faced by the capital good producer at the end of period t for buying an amount I_t of the final good is $(1 + i_t^L)I_t$, where i_t^L is the lending rate.

The capital good producer combines undepreciated capital from the previous period, with investment to produce new capital goods. New capital goods, denoted as K_{t+1}, are given by,

$$K_{t+1} = I_t + (1-\delta)K_t - \frac{\Theta_K}{2} \left(\frac{K_{t+1}}{K_t} - 1 \right)^2 K_t, \tag{22}$$

where $K_t = \int_0^1 K_{jt} dj$, $\delta \in (0, 1)$ gives the constant rate of depreciation and $\Theta_K > 0$ measures the magnitude of adjustment costs. The capital good producer rents the new capital stock to intermediate good-producing firms at the rate r_t^K.

The capital good producer chooses the amount of capital stock in order to maximize the value of the discounted stream of dividend payments to the household. The optimization problem of the capital good producer is given by,[7]

$$\max_{K_{t+1}} E_t \sum_{t=0}^{\infty} \beta^t \Lambda_t J_t^K, \tag{23}$$

[7] As noted earlier, the household and capital good producer in this model can be thought of as a single unit with respect to housing choices. Agénor et al. (2013) assume further that in case of default the capital seized by the bank is returned immediately and in its entirety to the household, who turns it back instantly to the capital good-producing firm. As a result, and as implicitly assumed in (24), the capital good producer does not internalize the risk of default, that is, the possibility that it could lose the fraction of the housing stock that it used to secure bank loans. See Agénor et al. (2014) for an alternative treatment.

where real profits, J_t^K, can be denoted as,

$$J_t^K = r_t^K K_t - (1 + i_t^L) I_t. \tag{24}$$

Maximizing (23) subject to (22), and substituting the first order condition for B_{ht}^H from the household problem $[\beta E_t(\Lambda_{t+1}/1 + \pi_{t+1}) = \Lambda_t / 1 + i_t^B]$ gives,

$$E_t r_{t+1}^K = (1 + i_t^L) E_t \left\{ \left[1 + \Theta_K \left(\frac{K_{t+1}}{K_t} - 1 \right) \right] \left(\frac{1 + i_t^B}{1 + \pi_{t+1}} \right) \right\} - E_t \left\{ (1 + i_{t+1}^L) \left[(1 - \delta) + \frac{\Theta_K}{2} \left[\left(\frac{K_{t+2}}{K_{t+1}} \right)^2 - 1 \right] \right] \right\}. \tag{25}$$

Eq. (25) shows the expected rental rate of capital is a function of the current and expected loan rates, the cost of adjusting capital across periods, the bond rate, the depreciation rate and the inflation rate. The opportunity cost of investing in physical capital is measured by the real rate of return on government bonds. If the capital good producer does not borrow at the beginning of the period, and there are no adjustment costs ($\Theta_K = 0$),

$$E_t r_{t+1}^K = E_t \left(\frac{1 + i_t^B}{1 + \pi_{t+1}} \right) - 1 + \delta. \tag{26}$$

Eq. (26) is the standard arbitrage condition which implies that capital is produced up to the point where the (expected) rental rate of capital is equal to the (expected) real interest rate on government bonds plus depreciation.

2.5. Commercial bank

The bank receives deposits, D_t, from households at the start of each period. These deposits are used to finance loans to intermediate good-producing firms for wage payments and to the capital good producer for investment. Given households' deposits and total loans to firms, to finance any shortfall in funding, the bank borrows from the central bank, L_t^B, for which it pays a net interest rate i_t^C. Assets of the commercial bank at the beginning of period t consist of total real loans to firms, L_t^F, and real total reserve holdings, TR_t, whereas its liabilities comprise of real loans from the central bank and real deposits. The bank's balance sheet is thus,

$$L_t^F + TR_t = L_t^B + D_t. \tag{27}$$

Total reserves comprise of excess reserves, ER_t, and required reserves, RR_t, which are the compulsory minimum amount of reserves the bank must hold at the central bank. Thus,

$$TR_t = ER_t + RR_t, \tag{28}$$

where total reserves are a portion μ_t^{TR} of deposits and required reserves are a percent μ_t of deposits. Therefore, $TR_t = \mu_t^{TR} D_t$ and $RR_t = \mu_t D_t$; where μ_t^{TR}, $\mu_t \in (0, 1)$. Using these in (28), excess reserves are therefore determined residually,[8]

$$ER_t = (\mu_t^{TR} - \mu_t) D_t. \tag{29}$$

Reserves held at the central bank are remunerated at the rate i^M,[9] where $i^M < i_t^C$.[10] The bank therefore chooses the total reserve ratio, the deposit rate and the lending rate to maximize its present discounted value of real profits. Hence, the bank's profit maximization problem is,

$$\max_{\{\mu_t^{TR}, 1+i_t^D, 1+i_t^L\}} E_{t^-} \sum_{t=0}^{\infty} \beta^t \Lambda_t J_t^B, \tag{30}$$

where, E_{t^-} is the expectations operator based on information available at the beginning of period t and J_t^B represents real bank profits at the end of period t.

Therefore, expected real bank profits can be defined as,

$$E_{t^-}\left(J_t^B\right) = (1 + \kappa^W i_t^C) L_t^{F,W} + Q_t^F (1 + i_t^L) L_t^{F,I} + (1 - Q_t^F) \kappa^C K_t + (1 + i^M) TR_t - (1 + i_t^D) D_t - (1 + i_t^C) L_t^B - \Phi(\mu_t^{TR} - \mu_t) D_t, \tag{31}$$

where $\kappa^C \in (0, 1)$ and $Q_t^F \in (0, 1)$ is the repayment probability.

From Eq. (31), the first term on the right-hand side, $(1 + \kappa^W i_t^C) L_t^{F,W}$, shows repayment on loans to intermediate good-producing firms. The second term, $Q_t^F (1 + i_t^L) L_t^{F,I}$, represents expected repayment on loans to the capital good producer, providing that there is no default. The third term, $(1 - Q_t^F) \kappa^C K_t$, denotes the bank's earnings in case of default, where $1 - Q_t^F$ represents the probability of default. This term therefore shows real effective collateral, given by a fraction (κ^C) of the real capital stock. The expression $(1 + i^M) TR_t$ denotes the principal plus interest gained from total reserves, whereas $(1 + i_t^D) D_t$ represents the principal and interest paid on real deposits, and $(1 + i_t^C) L_t^B$ reflects the gross repayments to the central bank. Similar to Glocker and Towbin (2012), the final term, $\Phi(\mu_t^{TR} - \mu_t) D_t$, is included to represent the convex costs of holding reserves, which are proportional to the amount of real deposits. Thus,

$$\Phi(\mu_t^{TR} - \mu_t) = -\Phi_{C1}(\mu_t^{TR} - \mu_t) + \frac{\Phi_{C2}}{2}(\mu_t^{TR} - \mu_t)^2 + \varepsilon_t^R. \tag{32}$$

From Eq. (32), Φ_{C1} and Φ_{C2} are cost function parameters. The linear term, $\Phi_{C1}(\mu_t^{TR} - \mu_t)$, determines steady-state deviations from the required reserve ratio. A positive deviation from the ratio may generate small benefits because holding excess reserves reduces the costs of liquidity management. Intuitively, if the bank fails to meet the reserve requirement it has to face the penalty rate for funds borrowed from the central bank. The quadratic term, $\Phi_{C2}/2(\mu_t^{TR} - \mu_t)^2$, indicates that negative deviations from the required ratio may generate large costs. For instance, the central bank may impose a higher penalty rate in cases where there are large negative deviations from its target, and at the same time, cease remuneration of excess reserves.[11] The last term, ε_t^R, represents a cost shock.

From the balance sheet constraint (27), and given that L_t^F and D_t are determined by the private agents' behaviour, borrowing from the central bank can be solved for residually:

$$L_t^B = L_t^F - (1 - \mu_t^{TR}) D_t. \tag{33}$$

Using (32) and (33) in (31) gives the bank's static optimization problem,

$$\max_{\{\mu_t^{TR}, 1+i_t^D, 1+i_t^L\}} \{(1 + \kappa^W i_t^C) L_t^{F,W} + Q_t^F (1 + i_t^L) L_t^{F,I} + (1 - Q_t^F) \kappa^C K_t + (1 + i^M) \mu_t^{TR} D_t - (1 + i_t^D) D_t - (1 + i_t^C) \left[L_t^F - (1 - \mu_t^{TR}) D_t \right] - \left[-\Phi_{C1}(\mu_t^{TR} - \mu_t) + \frac{\Phi_{C2}}{2} (\mu_t^{TR} - \mu_t)^2 + \varepsilon_t^R \right] D_t \}. \tag{34}$$

The first-order condition with respect to μ_t^{TR} is,

$$\mu_t^{TR} = \mu_t + \frac{\left(1 + i^M\right) + \Phi_{C1} - \left(1 + i_t^C\right)}{\Phi_{C2}}. \tag{35}$$

[8] In principle, the bank should determine directly excess reserves; however, it is more convenient to solve for total reserves first, and use this solution to determine excess reserves.

[9] A few studies have discussed how interest on reserves can be used as a policy instrument (see Goodfriend, 2002; Ennis and Weinberg, 2007; Keister et al., 2008; Keister and McAndrews, 2009; and Kashyap and Stein, 2012).

[10] In line with practical evidence, the interest rate on reserves is set lower than the refinance rate. It is important to note that if reserves are remunerated at the policy interest rate, the distortionary effect associated with an increase in reserve requirements can be reduced.

[11] These responses, however, are not explicitly accounted for in the model.

The difference between the total reserve ratio and the required reserve ratio, $\mu_t^{TR} - \mu_t$, represents the bank's excess reserve ratio, μ_t^{ER}, which is given by,

$$\mu_t^{ER} = \frac{\left(1+i^M\right) + \Phi_{C1} - \left(1+i_t^C\right)}{\Phi_{C2}}. \tag{36}$$

The first-order condition with respect to $1+i_t^D$ is,

$$(1+i^M)\mu_t^{TR}\left(\frac{\partial D_t}{\partial\left(1+i_t^D\right)}\right) - (1+i_t^D)\left(\frac{\partial D_t}{\partial\left(1+i_t^D\right)}\right) - D_t$$
$$+(1+i_t^C)(1-\mu_t^{TR})(\frac{\partial D_t}{\partial\left(1+i_t^D\right)}) - \Phi(\cdot)(\frac{\partial D_t}{\partial\left(1+i_t^D\right)}) = 0,$$

using $\eta_D = \left[\partial D_t/\partial\left(1+i_t^D\right)\right]\left[\left(1+i_t^D\right)/D_t\right]$ to represent the constant interest elasticity of the supply of deposits by the household results in,

$$1+i_t^D = (1+\frac{1}{\eta_D})^{-1}[(1+i_t^C) - \mu_t^{TR}(i_t^C - i^M)$$
$$+\Phi_{C1}(\mu_t^{TR} - \mu_t) - \frac{\Phi_{C2}}{2}(\mu_t^{TR} - \mu_t)^2]. \tag{37}$$

The first-order condition with respect to $1+i_t^L$ is,

$$Q_t^F L_t^{F,I} + Q_t^F(1+i_t^L)\frac{\partial L_t^{F,I}}{\partial(1+i_t^L)} - (1+i_t^R)\frac{\partial L_t^{F,I}}{\partial(1+i_t^L)} = 0,$$

using $\eta_L = \left[\partial L_t^{F,I}/\partial(1+i_t^L)\right]\left[(1+i_t^L)/L_t^{F,I}\right]$ to denote the interest elasticity of demand for loans for investment yields,

$$1+i_t^L = \frac{1+i_t^C}{Q_t^F[\eta_L^{-1}+1]}. \tag{38}$$

Eq. (36) shows that μ_t^{ER} increases with i^M but falls with i_t^C. Therefore, the excess reserve ratio is decreasing in the spread between the interest rate on reserves and the cost of borrowing from the central bank (the refinance rate). By holding an additional unit of excess reserves at the central bank, the bank benefits by gaining $1+i^M$; at the same time, it saves because it does not have to borrow from the central bank to meet reserve requirements. By contrast, the bank also incurs costs for holding the extra unit of excess reserves. Therefore, Eq. (36) balances the costs and the benefits of holding excess reserves. From Eq. (37), the (gross) interest rate on deposits depends on the marginal cost of borrowing from the central bank, which is lowered in the presence of remunerated reserves by the difference between the refinance rate and the interest rate on reserves. The deposit rate also depends on the costs associated with holding excess reserves. Eq. (38) shows that the (gross) lending rate depends positively on the marginal cost of borrowing from the central bank and negatively on the repayment probability, Q_t^F.

The repayment probability is taken to depend positively on "micro" and "macro" factors, namely, the real effective collateral-loan ratio and economic activity. Therefore, Q_t^F increases with the collateral provided by firms and falls with the amount borrowed. Hence,

$$Q_t^F = \phi_0\left(\frac{\kappa^C K_t}{L_t^{F,I}}\right)^{\phi_1}\left(\frac{Y_t}{Y}\right)^{\phi_2}, \tag{39}$$

where ϕ_0, ϕ_1, $\phi_2 > 0$ and (Y_t/Y) represents the output gap, with Y denoting the steady-state value of output[12] under fully flexible prices.

[12] Similar to other studies (see, for instance, Meh and Moran, 2010), the output gap is measured in terms of deviations from its steady-state value.

2.6. Central bank

The central bank's assets consist of government bonds, B_t^C, and loans to the commercial bank, L_t^B, whereas its liabilities consist of total reserves, TR_t, and currency supplied to households and firms, M_t^s. Therefore, the central bank's balance sheet is given by,

$$B_t^C + L_t^B = TR_t + M_t^s. \tag{40}$$

Using $TR_t = \mu_t^{TR} D_t$ and rearranging, Eq. (40) becomes,

$$M_t^s = B_t^C + L_t^B - \mu_t^{TR} D_t. \tag{41}$$

Eq. (41) shows the supply of currency is matched by government bonds and central bank loans extended to the commercial bank, less the fraction of deposits held at the central bank.

In this economy, the central bank sets its base policy interest rate, i_t^R, using a Taylor-type rule of the form,

$$1+i_t^R = \left(1+i_{t-1}^R\right)^{\chi} + \left[(1+i^R)\left(\frac{1+\pi_t}{1+\pi^T}\right)^{\phi_\pi}\left(\frac{Y_t}{Y}\right)^{\phi_Y}\right]^{1-\chi} + \epsilon_t, \tag{42}$$

where $\chi \in (0, 1)$ measures the degree of interest rate smoothing, i^R is the steady-state value of the base policy interest rate, π_t is current inflation, $\pi^T \geq 0$ is the central bank's inflation target, $\phi_\pi, \phi_Y > 0$ measure the relative weights on inflation deviations from its target and the output gap, respectively, and ϵ_t is a serially correlated shock with constant variance, which follows a first order autoregressive process of the form,

$$\epsilon_t = \epsilon_{t-1}^{\rho_\epsilon} \exp(\xi_t^\epsilon), \tag{43}$$

where $\rho_\epsilon \in (0, 1)$ and $\xi_t^\epsilon \sim N(0, \sigma_{\xi^\epsilon})$ is a serially correlated random shock with zero mean.

Similar to Agénor et al. (2015), the actual cost of borrowing for the commercial bank incorporates a penalty rate, θ_t^B, which is in addition to the base policy rate:

$$1+i_t^C = (1+i_t^R)(1+\theta_t^B). \tag{44}$$

The penalty rate depends positively on the ratio of central bank borrowing to deposits:

$$\theta_t^B = \theta_0^B\left(\frac{L_t^B}{D_t}\right), \tag{45}$$

where $\theta_0^B > 0$. The penalty rate will rise in two cases: first, if there is an increase in the amount borrowed from the central bank; and second, if there is a fall in deposits. This indicates that the composition of bank liabilities affects the rate at which it borrows from the central bank. Therefore, by distinguishing between the base policy rate and the actual rate at which commercial banks can borrow from the central bank, the model accounts for imperfect substitutability between bank funding sources—deposits and central bank borrowing. Because higher reserve requirements reduce the deposit rate, and this in turn causes a fall in household demand for deposits, this policy action will increase the penalty rate and subsequently, the refinance rate. A higher cost for central bank liquidity has a direct positive effect on the loan rate. This channel is particularly important to generate a countercyclical effect of higher reserve requirements.

2.7. Government

The government purchases the final good, collects taxes, and issues one-period risk-free bonds, B_t, which are held by the central bank, B_t^C, and households, B_t^H. Total bonds can be denoted by, $B_t = B_t^C + B_t^H$. The government's real budget constraint is given by,

$$B_t + T_t + i_{t-1}^C L_{t-1}^B \frac{P_{t-1}}{P_t} + i_{t-1}^B B_{t-1}^C \frac{P_{t-1}}{P_t} - i^M TR_{t-1} \frac{P_{t-1}}{P_t}$$
$$= G_t + (1 + i_{t-1}^B) B_{t-1} \frac{P_{t-1}}{P_t}, \tag{46}$$

where G_t denotes real government spending and T_t represents real lump-sum tax revenues. The sum of the terms $i_{t-1}^C L_{t-1}^B (P_{t-1}/P_t)$, $i_{t-1}^B B_{t-1}^C (P_{t-1}/P_t)$ and $i^M TR_{t-1}(P_{t-1}/P_t)$ (adjusted for the rate of inflation) comes from the assumption that the net income earned by the central bank from lending to the commercial bank, holding government bonds and holding reserves from the commercial bank, respectively, is transferred to the government at the end of each period.

Government purchases represent a constant fraction, $\psi \in (0, 1)$, of output of the final good,

$$G_t = \psi Y_t. \tag{47}$$

3. Symmetric equilibrium

In a symmetric equilibrium, all firms producing intermediate goods are identical so they produce the same output, and prices are the same across firms. Also, all households supply the same number of labour hours. Therefore, $K_{jt} = K_t$, $N_{jt} = N_t$, $Y_{jt} = Y_t$, $P_{jt} = P_t$, for all $j \in (0, 1)$.

It is necessary for equilibrium conditions in the credit, deposit, goods and cash markets to be satisfied.[13] The supply of loans by the commercial bank and supply of deposits by households are perfectly elastic at the prevailing interest rates; as a result, the markets for loans and deposits always clear. To satisfy equilibrium in the goods markets, production must be equal to aggregate demand. Thus, using (16),

$$Y_t = C_t + G_t + I_t + \frac{\phi_F}{2}\left(\frac{1+\pi_t}{1+\pi} - 1\right)^2 Y_t. \tag{48}$$

The equilibrium condition of the market for cash is,

$$M_t^s = M_t^H + M_t^F, \tag{49}$$

where $M_t^F = \int_0^1 M_{jt}^F dj$ represents the total cash holdings of intermediate good-producing firms and the capital good producer. It is assumed that bank loans to all firms are extended in the form of cash such that, $L_t^F = M_t^F$. Substituting this in (49), $M_t^s = M_t^H + L_t^F$. Replacing M_t^s from (41) gives,

$$B_t^C + L_t^B - \mu_t^{TR} D_t = M_t^H + L_t^F. \tag{50}$$

Using L_t^B from (33) into (50) gives,

$$\overline{B}^C = M_t^H + D_t. \tag{51}$$

Given that the total stock of bonds held by the central bank is constant, Eq. (51) implies that real cash balances are inversely related to real bank deposits. This equation also represents the money market equilibrium condition, from which the equilibrium bond rate is obtained.

4. Steady state and log-linearization

This section presents some of the key steady-state and log-linearized equations of the model.

The steady-state deposit and lending rates are given by,

$$1 + i^D = \left(1 + \frac{1}{\eta_D}\right)^{-1}\Bigg[(1+i^C) - \mu^{TR}(i^C - i^M) + \Phi_{C1}(\mu^{TR} - \mu) - \frac{\Phi_{C2}}{2}(\mu^{TR} - \mu)^2\Bigg],$$

$$1 + i^L = \frac{1 + i^C}{Q^F\left[\eta_L^{-1} + 1\right]}.$$

In the steady state, the repayment probability is inversely related to the firm's assets over its liabilities,

$$Q^F = \phi_0 \left(\frac{\kappa^C K}{L^{F,I}}\right)^{\phi_1}.$$

The steady-state value of the excess reserve ratio is given by,

$$\mu^{ER} = \frac{\left(1 + i^M\right) + \Phi_{C1} - (1 + i^C)}{\Phi_{C2}}.$$

In order to solve the model, each variable is log-linearized around a non-stochastic, zero-inflation steady state.[14] The log-linearized deposit and lending rates are denoted by,[15]

$$\hat{\imath}_t^D = \frac{1}{(1+i^D)}\left(1 + \frac{1}{\eta_D}\right)^{-1}\Big\{\left(1 - \mu^{TR}\right)(1+i^C)\hat{\imath}_t^C - \mu^{TR}\hat{\mu}_t^{TR}(i^C - i^M) + \left[\Phi_{C1} - \Phi_{C2}\left(\mu^{TR} - \mu\right)\right]\left(\mu^{TR}\hat{\mu}_t^{TR} - \mu\hat{\mu}_t\right)\Big\},$$

$$\hat{\imath}_t^L = \hat{\imath}_t^C - \hat{Q}_t^F,$$

where, a linear approximation of the repayment probability gives,

$$\hat{Q}_t^F = \phi_2 \hat{Y}_t + \phi_1\left(\hat{K}_t - \hat{L}_t^{F,I}\right).$$

The log-linearized excess reserve ratio is,

$$\hat{\mu}_t^{ER} = \frac{-(1+i^C)\hat{\imath}_t^C}{\Phi_{C2}\ \mu^{ER}}.$$

5. Calibration

To examine the general equilibrium effects of excess reserves, this section provides an illustrative calibration of the model for a representative middle-income country. A summary of the parameter values is provided in Table 1. Regarding the parameters related to the household, the discount factor, β, is set at 0.985. The intertemporal elasticity of substitution, σ, is taken to be 0.5, which is in line with estimates for developing countries. The preference parameter for leisure, η_N, is calibrated at 1.8, whereas the preference parameter for composite monetary assets, η_X, is set at 0.02, which is consistent with the values used in existing studies for other developing countries. Furthermore, the relative share of cash in narrow money, ν, is calibrated to be 0.2, close with estimates obtained for developing countries, such as Chile in 2012. These values yield a cash plus deposit to output ratio of 42%.

For the production side, the elasticity of demand for intermediate goods, θ, is 10.0, which corresponds to a steady-state markup rate of 11.1%, while the share of capital in output of intermediate goods, α, is set at 0.3, and is consistent with estimates for developing countries. Given that in this model firms finance a fraction of their working capital needs by bank borrowing, the cost channel parameter, κ^W, is set at 0.75. Using the method proposed in Keen and Wang (2007), the value of the adjustment cost parameter for prices, ϕ_F, is calculated as 65. As is standard in the literature, the

[13] The equilibrium condition of the market for government bonds is eliminated by Walras' Law.

[14] Log-linearized variables are denoted by a hat.

[15] The reserve requirement ratio is exogenous in this model. Therefore, $\hat{\mu}_t = 0$ except for the case when there is a shock to the variable.

Table 1
Calibrated parameter values: benchmark case.

Parameter	Value	Description
β	0.985	Discount factor
σ	0.5	Elasticity of intertemporal substitution
η_N	1.8	Relative preference for leisure
η_X	0.02	Relative preference for money holdings
ν	0.2	Share parameter in index of money holdings
θ	10.0	Elasticity of demand, intermediate goods
α	0.3	Share of capital in output, intermediate goods
ϕ_F	65	Adjustment cost parameter, prices
Θ_K	18	Adjustment cost parameter, investment
δ	0.034	Depreciation rate of capital
κ^C	0.05	Effective collateral-loan ratio
κ^W	0.75	Share of financing working capital
Φ_{C1}	0.35	Linear cost function parameter
Φ_{C2}	7.5	Quadratic cost function parameter
ϕ_1	0.02	Elasticity of risk premium with respect to collateral
ϕ_2	0.2	Elasticity of risk premium with respect to cyclical output
μ	0.14	Reserve requirement rate
χ	0	Degree of persistence in interest rate rule
ϕ_π	1.5	Response of base policy rate to inflation deviations
ϕ_Y	0.2	Response of base policy rate to output growth
ψ	0.2	Share of government spending in output
θ_0^B	0.01	Sensitivity of the penalty rate to borrowing-deposit ratio
$\rho_A(\rho_\epsilon)$	0.4	Degree of persistence, supply shock (shock to base policy rate)

depreciation rate for capital, δ, is set equal to 0.034, and the adjustment cost parameter for investment, Θ_K, is set at 18.

With regards to the parameters characterizing bank behaviour, the effective collateral-loan ratio, κ^C, is set at a low value of 0.05. This value is consistent with the data observed for middle-income countries. There is little information on the values for the cost function parameters, Φ_{C1} and Φ_{C2}, and therefore these coefficients are calibrated such that the differential between the steady-state total reserve ratio and the required reserve ratio is 4.5%. This value is close to the actual spread observed in the data for middle-income countries where excess reserves are a common feature of the banking system. Using this approach gives a value of 0.35 for Φ_{C1} and 7.5 for Φ_{C2} . The elasticity of the repayment probability with respect to collateral, ϕ_1, is set at a relatively low value, 0.02; whereas the elasticity of the repayment probability with respect to cyclical output, ϕ_2, is set at 0.2, as in Agénor et al. (2012).

For the variables related to the central bank, the required reserve ratio, μ, is set at 14%, which is an average of the ratio observed in a number of developing countries.[16] The lagged value of the policy rate in the interest rate rule, χ, is set to 0, which implies that there is direct interest rate smoothing from the central bank's policy response. The parameters for the response of the base policy rate to inflation deviations from its target and to output growth, ϕ_π and ϕ_Y, are set to 1.5 and 0.2, respectively, which are standard values estimated for Taylor-type rules in middle-income countries. The sensitivity of the penalty rate to the ratio of central bank borrowing to deposits, θ_0^B, is set at a low value of 0.01. The degree of persistence in the supply shock, ρ_A, and the shock to the base policy rate, ρ_ϵ, are both set to 0.4. Finally, the share of government spending in output, ψ, is set at 0.2, which is close to the actual value observed for middle-income countries, such as South Africa.

The calibration implies that in the steady state, the ratio of excess reserves to total reserves is 24.5%, which is close to the value observed in the recent data for countries with high persistent excess liquidity, such as Jamaica. Further, in the steady state, the proportion of deposits held as total reserves is 18.5%. The steady-state value of the repayment probability is 97%, which implies the default probability is around 3%. The steady-state ratio of consumption to output is 63%, which is a close approximation of the value observed for middle-income countries.

6. Policy analysis

6.1. Negative supply shock

Fig. 1 shows the impulse response functions of some of the main variables of the model following a one percent negative productivity shock. The direct effect of the shock is an immediate decline in output, and a rise in the marginal production costs, which in turn exerts an upward pressure on prices. As a result of the rise in inflation, the base policy rate which is determined by the Taylor rule rises. The higher base policy rate leads to a direct increase in the refinance rate, which in turn raises the deposit rate and the demand for bank deposits, and reduces borrowing from the central bank. From the central bank's balance sheet, a fall in loans to the commercial bank reduces the supply of currency, and therefore to restore equilibrium in the money market, the demand for cash must fall. Because the central bank's real bond holdings which determine the total monetary assets are fixed, the bond rate adjusts to clear the money market. Therefore, to reduce the demand for cash, the bond rate increases, which, through intertemporal substitution, leads to a fall in the level of current consumption. Overall, the higher rate of return on deposits and bonds increases households' demand for these financial assets, and lowers their consumption.

A key point to note is that based on the calibration, the cost channel exists ($\kappa^W > 0$). Thus, owing to the fact that marginal costs depend directly on the refinance rate, an increase in this rate tends to further raise firms' marginal costs as it increases the labour costs of production. Furthermore, the increase in the refinance rate also translates to an immediate rise in the loan rate, which lowers the demand for investment and the level of physical capital over time. The collateral-to-loan ratio increases on impact as loans for investment fall by more than the value of collateral. Because the collateral effect is dominated by the cyclical output effect, the repayment probability falls, causing the loan rate to increase further, which in turn exerts an upward pressure on the rental rate of capital. Based on the calibration, the higher rental rate of capital offsets the fall in the level of physical capital, and the rise in both labour supply and the refinance rate, causing real wages to increase upon the impact of the shock.[17] The rise in real wages, subsequently, creates further upward pressure on firms' marginal costs.

In this model, excess reserves are positively related to their rate of return, but depend negatively on the refinance rate. Therefore, because the interest rate paid on reserves is fixed by the central bank, an increase in the marginal cost of borrowing from the central bank lowers the level of excess reserves. As the refinance rate and the other interest rates in the banking sector increase, the costs of holding excess reserves are higher. Put differently, there is a higher opportunity cost of holding excess reserves when the marginal cost of borrowing from the central bank increases. Thus, provided that the interest rate on reserves remains unchanged, the rise in other short-term interest rates indicates that banks can earn a higher return from investing in other assets, so they reduce

[16] The reserve requirement ratio represents an average of the rate for Cape Verde, China, Croatia, India, Jamaica, Malawi, Nigeria, and Trinidad and Tobago in 2012.

[17] The values of capital, labour supply, the refinance rate and the rental rate of capital were calculated. The results showed that the increase in the rental rate of capital offsets the total (negative) value of all the other variables, bringing about an increase in real wages.

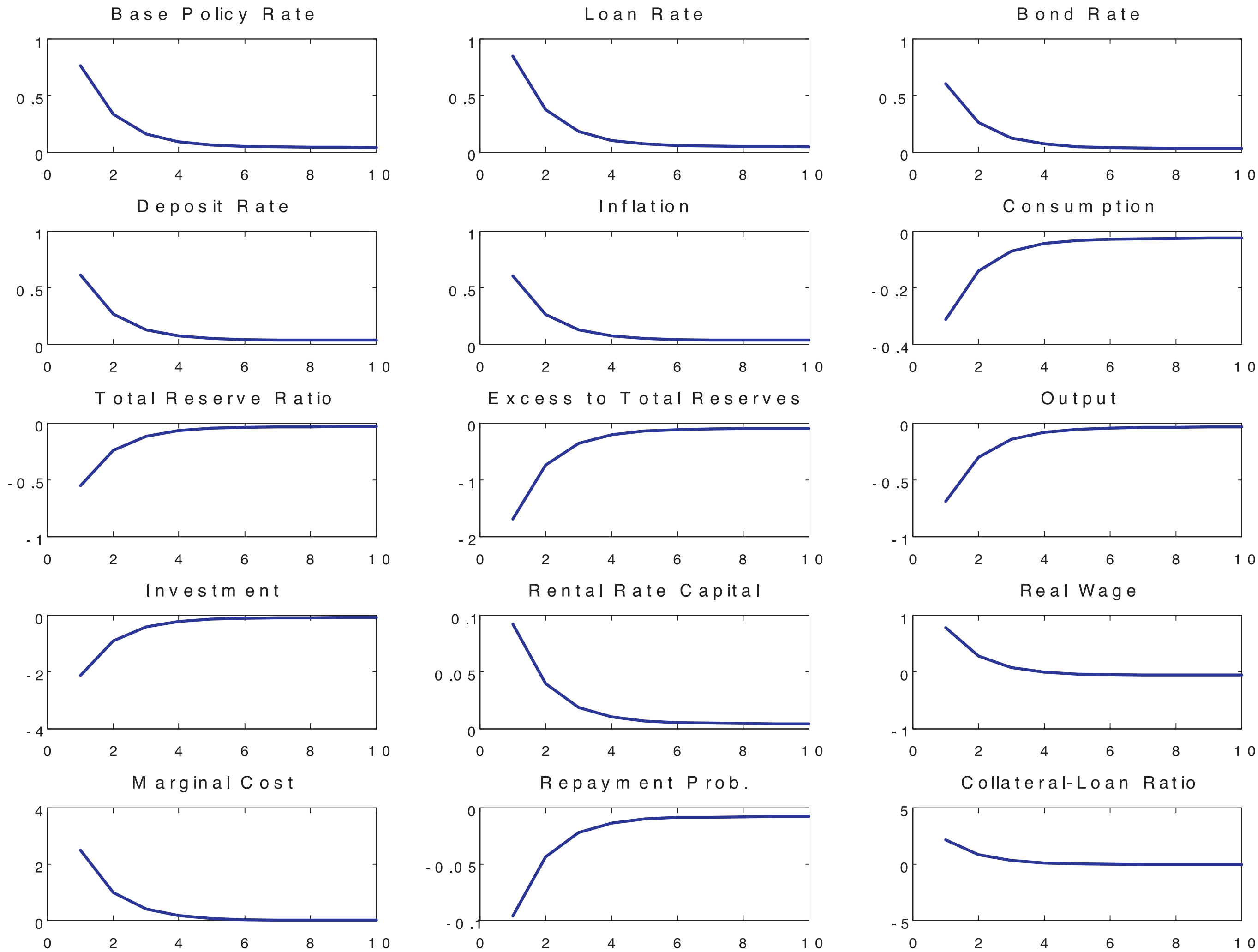

Fig. 1. Negative supply shock. Absolute deviations from baseline, unless otherwise indicated.

demand for excess reserves. Given that the excess reserve ratio decreases, and that the required reserve ratio remains constant, the total reserve ratio also falls.

6.2. Monetary policy shocks

This section examines the transmission of two monetary policy shocks: an increase in the base policy rate and an increase in the reserve requirement ratio.

Fig. 2 illustrates the general equilibrium effects of a one percent increase in the base policy rate. A rise in the policy rate raises the cost of borrowing from the central bank, which in turn, increases the deposit and loan rates immediately. As in the previous case, the rise in the deposit rate increases households' demand for bank deposits. The higher level of bank deposits lowers both central bank borrowing and the money supply. Consequently, the government bond rate increases to reduce demand for cash and to restore equilibrium in the money market. In response to the rise in the bond rate, current consumption and output fall. At the same time, a higher loan rate leads to a reduction in loans for investment, which in turn causes the collateral-to-loan ratio to increase. However, as the drop in output dominates the rise in the collateral-to-loan ratio, the repayment probability falls. In this case, real wages fall by more than the value of physical capital, placing downward pressure on the rental rate of capital. The decline in marginal costs, which results from the drop in the rental rate of capital and real wages, creates a downward pressure on inflation. Furthermore, similar to the case of the negative productivity shock, the higher refinance rate increases the opportunity cost of holding excess reserves. As a consequence, the bank demands less excess reserves. The reduction in the quantity of excess reserves leads to an immediate fall in the level of total bank reserves.

Fig. 3 shows the effects of a one percent increase in the minimum reserve requirement ratio, μ_t. Given that the required reserve rate is exogenous in this model, to assess the impact of an increase, it is assumed that μ_t is stochastic and follows a first-order autoregressive process of the form: $\mu_t = \mu_{t-1}^{\rho_\mu} \exp\left(\xi_t^\mu\right)$. The impulse response functions show that an increase in reserve requirements does indeed lead to a reduction in the excess reserve ratio.[18] In general, because the required reserve ratio goes up and the excess reserve ratio falls, the net effect on the total reserve ratio is *a priori* ambiguous; given our calibration, the net effect is positive, as shown in the simulations.[19] In the model, because the deposit rate is set as a mark-down on the total reserve ratio, a rise in total reserves leads to a fall in the interest rate on deposits. The drop in

[18] Agénor and El Aynaoui (2010), using a simple (static) model with credit market imperfections, also found that raising reserve requirements can help to sterilize excess liquidity.

[19] This policy action is desirable because it reduces the level of excess reserves in the banking system—despite the fact that total reserves increase as a result of a higher level of required reserves.

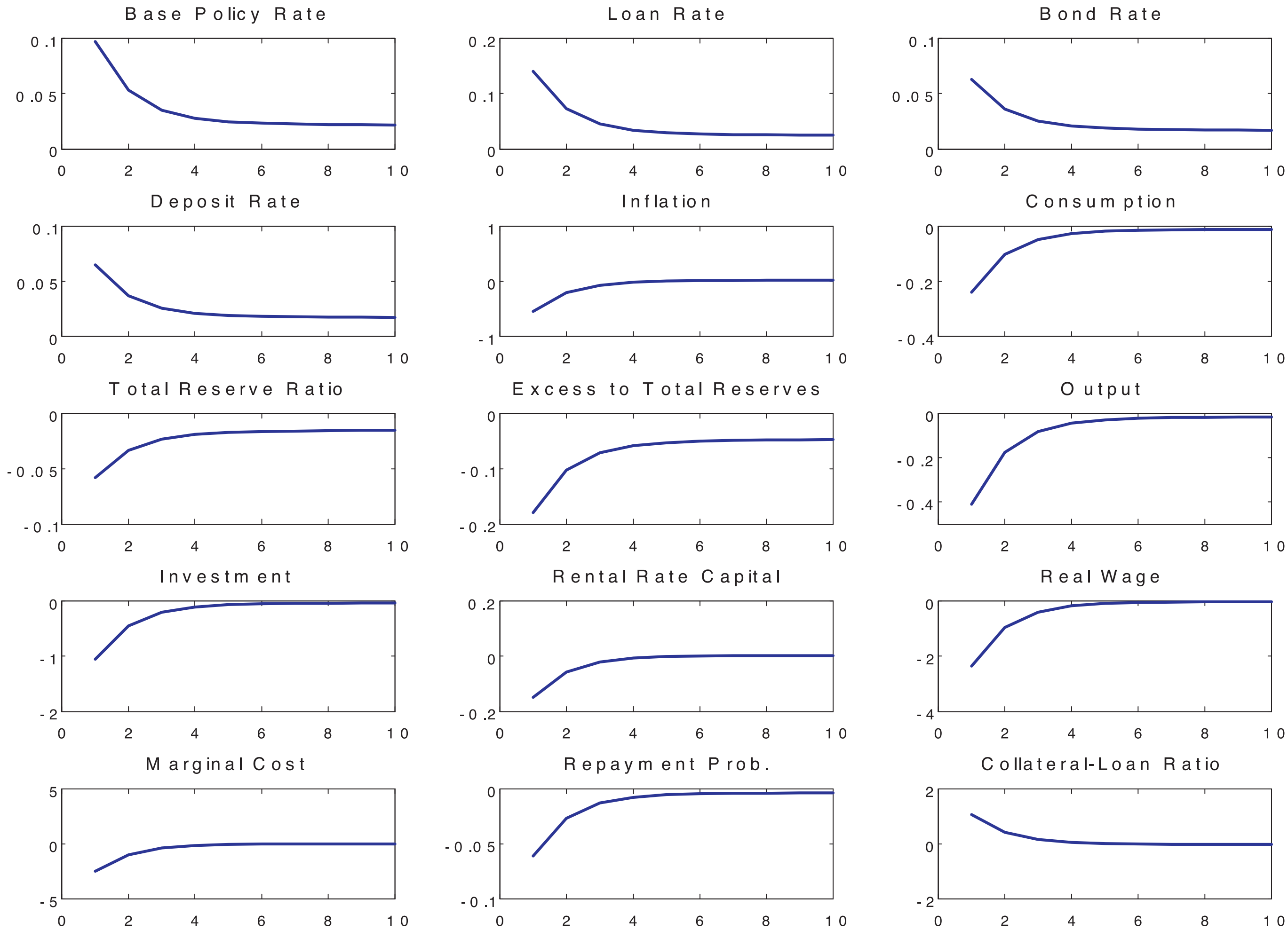

Fig. 2. Positive shock to base policy rate. Absolute deviations from baseline, unless otherwise indicated.

the deposit rate tends to reduce households' incentive to save, so bank deposits fall causing borrowing from the central bank and the money supply to increase. Because there is intertemporal substitution between bank funding sources, the fall in deposits and the rise in central bank borrowing cause the penalty rate to increase, and this subsequently raises the cost of borrowing from the central bank. Owing to the fact that the loan rate is determined optimally as a mark-up over the marginal cost of borrowing from the central bank, the higher refinance rate leads to a direct increase in the cost at which private agents can borrow. Equilibrium in the money market requires an increase in the demand for cash, which is brought about through a reduction in the bond rate, which in turn leads to a higher level of current consumption and demand, thereby raising inflation. The base policy rate increases in response to the rise in prices.

The rise in the loan rate leads to a higher rental rate of capital and a lower capital stock over time. Primarily owing to the higher rental rate of capital, real wages increase. Also, the higher lending rate leads to a reduction in investment loans and a rise in the collateral-to-loan ratio, which raises the repayment probability. Because the increase in the cost of borrowing from the central bank dominates the response of the repayment probability, the loan rate rises further. Marginal costs rise because of the increase in the refinance rate, higher real wages and the rise in the rental rate of capital. The increase in firms' production costs creates a further upward pressure on prices, which ultimately leads to an amplified rise in the base policy rate.

In the current framework, a higher reserve requirement rate makes deposits more expensive and it has a direct impact on lending rates. In this case, as shown in the simulations, the fall in investment dominates the rise in consumption, bringing about a contraction in output. Thus, this experiment provides evidence that imperfect substitutability between bank funding sources is a key channel through which reserve requirement shocks may prove countercyclical. Similar to this result, a number of other studies have found that reserve requirements are countercyclical. For instance, Agénor et al. (2015) used a dynamic stochastic model, in which bank funding sources are imperfect substitutes, to examine the effects of a reserve requirement rule. The authors found that under a credit-based reserve requirement rule, a drop in the world risk-free interest rate is countercyclical in the sense that it mitigates the expansion in output, amongst other things. In another study Glocker and Towbin (2015) showed that a shock to the required reserve ratio in Brazil leads to an increase in unemployment and a contraction in economic activity. Carvalho et al. (2013) also examined the impact of higher reserve requirements in Brazil and found that a shock to the required reserve ratio creates a liquidity shortage, which in turn, raises banks' funding costs and lending rates. Overall the shock results in a contraction in output. Furthermore, in the case of a decrease in reserve requirements, a study by Areosa and Coelho (2013) showed that the countercyclical effect on output also holds.

It is important to note that higher reserve requirements can also generate a procyclical effect. Consider the case where bank

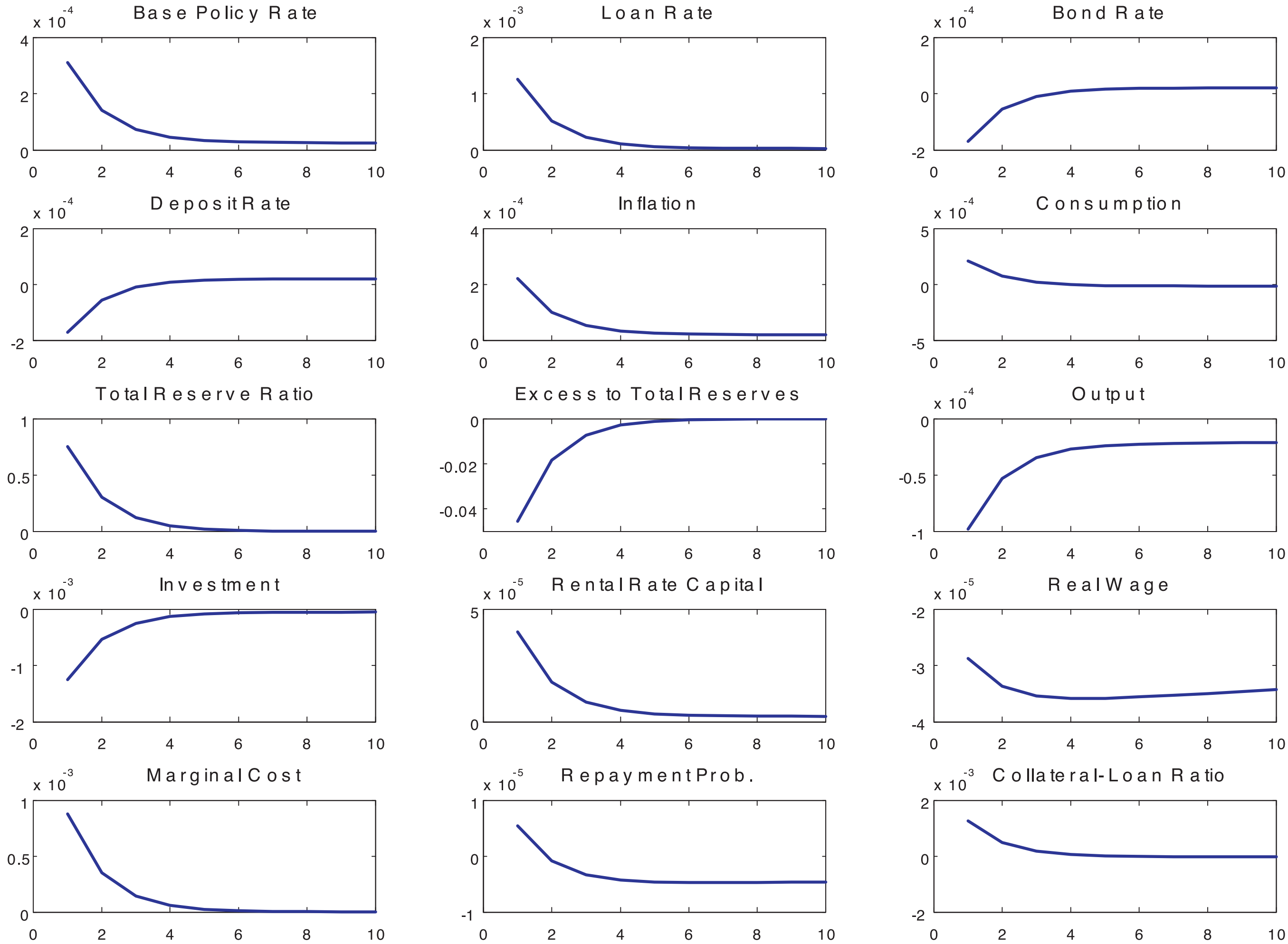

Fig. 3. Positive shock to reserve requirements. Absolute deviations from baseline, unless otherwise indicated.

funding sources (deposits and central bank liquidity) are perfect substitutes. Because an increase in the required reserve ratio lowers the interest rate that represents the opportunity cost of current versus future consumption, household savings fall. If banks are subject to higher reserve requirements they will borrow from the central bank at the prevailing interest rate to compensate for the shortfall in liquidity. In this case, on impact of the shock, banks' cost of funds and the loan rate are not affected. Also, if the intertemporal substitution effects are strong, the decline in the deposit rate will cause current consumption and aggregate demand to increase.

The procyclical effect of reserve requirements is observed in several studies. For instance, Glocker and Towbin (2012) found that under an interest rate rule, an increase in reserve requirements widens the spread between lending and deposit rates.[20] The higher lending rate reduces investment, whereas the fall in the deposit rate stimulates consumption. Based on the calibration, the effect of the increase in consumption dominates the fall in investment, causing output to rise. This implies that changes in reserve requirements are procyclical, with respect to economic activity.[21] Similarly, Agénor and Pereira da Silva (2014) and Gonzalez-Rozada and Sola (2014) found that an increase in the reserve requirement ratio leads to a procyclical effect with respect to output.

6.3. Liquidity shock

As illustrated in Fig. 4, the direct effect of an exogenous one percent increase in bank deposits is an immediate rise in the ratio of excess reserves to total reserves. Given that required reserves remain constant, the increase in excess reserves leads to a rise in total reserves. The higher level of bank deposits also reduces borrowing from the central bank, thereby lowering money supply. Similar to the cases of the supply shock and the shock to the base policy rate, to restore equilibrium in the money market, the bond rate rises, which, through intertemporal substitution, results in a reduction in current consumption and a fall in output. In response to the drop in output, the base policy interest rate falls, leading to a reduction in the refinance rate, which in turn puts downward pressure on the loan rate. The lower lending rate reduces the rental rate of capital, which in turn increases the demand for physical capital. As observed previously, the fall in the rental rate of capital reduces real wages; in turn, the fall in both variables results in a drop in the firms' marginal costs and thus inflation. The decrease in prices leads to an amplified drop in the base policy rate. Also, the lower loan rate stimulates investment, leading to a fall in the collateral-to-loan ratio, which combined with the contraction in output, causes the repayment probability to fall. The lower

[20] Montoro and Moreno (2011) and Tovar et al. (2012) also pointed out that an increase in required reserves acts as a tax on banks, so the spread between deposit and lending rates widens.

[21] See Baltensperger (1982) and Horrigan (1988) for further discussions on the impact of changes in reserve requirements on economic stability.

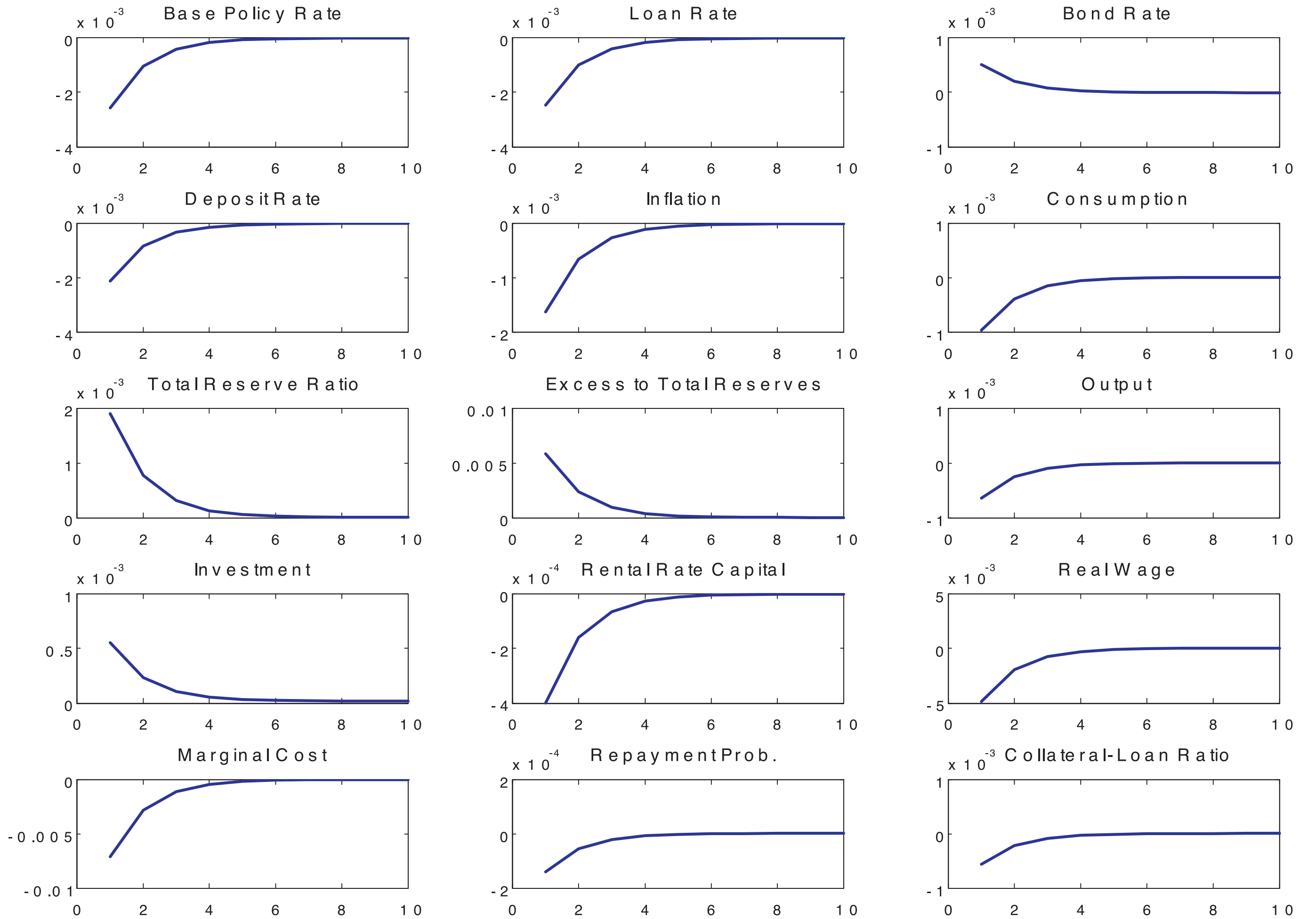

Fig. 4. Positive shock to bank deposits. Absolute deviations from baseline, unless otherwise indicated.

refinance rate attenuates the response of the repayment probability to the shock, leading to an amplified decline in the lending rate.

7. Simple policy rules

7.1. An augmented Taylor rule

This experiment considers the case where the central bank adjusts its policy rate directly in response to changes in excess reserves. The rationale for this is to examine how effective a policy rule which responds to fluctuations in excess reserves may be in mitigating volatility in the real and financial variables of the model, under a one percent shock to deposits. To examine this, the standard Taylor rule (42) is replaced by an augmented interest rate rule, which in log-linear form is given by,

$$\hat{\imath}_t^R = \chi \hat{\imath}_{t-1}^R + (1-\chi)[\phi_\pi(\hat{\pi}_t) + \phi_Y(\hat{Y}_t) + \phi_{\varsigma,i}(\widehat{ER\_TR}_t)] + \epsilon_t, \quad (52)$$

where $\widehat{ER\_TR}_t$ denotes the ratio of excess reserves to total reserves. Primus (2012) estimated an augmented Taylor rule for Trinidad and Tobago which included a measure of excess reserves. The results from her study showed the relative weight corresponding to deviations in the ratio of excess reserves to total reserves from its steady state, $\phi_{\varsigma,i}$, takes a negative value. The negative coefficient indicates that in response to an increase in excess reserves, the central bank lowers the base policy rate to reduce incentive for banks to hold excess liquidity. Intuitively, if the policy rate is low, commercial banks would tend to reduce their holdings of excess reserves. By contrast, if this rate is high, banks would voluntarily hold excess reverses as a measure of precaution to avoid any shortfall in liquidity. A reduction in the base policy rate is also expected to lower the refinance rate, and thereafter, the deposit rate, which in turn discourages household deposits.

To assess the impact of an augmented policy rule in mitigating volatility following a liquidity shock, the asymptotic standard deviations and the relative standard deviations of the main variables under the augmented Taylor rule and the standard Taylor rule are compared. To conduct this experiment, alternative values of -0.1 and -0.2 are used for $\phi_{\varsigma,i}$. The results from Table 2 indicate that the augmented Taylor rule is effective in reducing the volatility of key macroeconomic variables such as inflation, output and consumption. In addition, the base policy rate, the loan rate, the deposit rate, and the ratio of excess reserves to total reserves are slightly more volatile. Further, under the augmented rule, the more volatile negative reaction of the loan rate stimulates investment; as a result, fluctuations in investment rise.

7.2. A countercyclical reserve requirement rule

This experiment investigates the macroeconomic and financial effects of a one percent liquidity shock under a countercyclical reserve requirement rule that relates changes in the required reserve ratio to deviations in the ratio of excess reserves to total reserves. Therefore, in this approach, the required reserve ratio is endogenous and serves a countercyclical role for managing volatility in excess reserves. A number of studies have discussed how reserve

Table 2
Standard deviations under standard Taylor rule and augmented Taylor rule.

Variable	Standard Taylor rule	Augmented Taylor rule			
	$\phi_{\zeta,i}=0$	$\phi_{\zeta,i}=-0.1$		$\phi_{\zeta,i}=-0.2$	
	Sd. Dev.	Sd. Dev.*	Rel. S.D.**	Sd. Dev.	Rel. S.D.
Inflation	0.0018	0.0014	0.7778	0.0010	0.5556
Output	0.0007	0.0004	0.5714	0.0002	0.2857
Consumption	0.0010	0.0009	0.9000	0.0007	0.7000
Investment	0.0006	0.0013	2.1667	0.0020	3.3333
Base policy rate	0.0028	0.0029	1.0357	0.0029	1.0357
Loan rate	0.0027	0.0028	1.0370	0.0029	1.0741
Bond rate	0.0006	0.0005	0.8333	0.0005	0.8333
Deposit rate	0.0023	0.0023	1.0000	0.0024	1.0435
Total reserve ratio	0.0021	0.0021	1.0000	0.0021	1.0000
Excess-total reserves	0.0064	0.0065	1.0156	0.0066	1.0313

Notes: *Sd. Dev. is the standard deviation; ** Rel. S.D. denotes the relative standard deviation.

Table 3
Standard deviations when the reserve requirement ratio is exogenous and endogenous.

Variable	Exogenous reserve requirement rate	Endogenous reserve requirement rule			
	$\phi_{\zeta,\mu}=0$	$\phi_{\zeta,\mu}=1.2$		$\phi_{\zeta,\mu}=1.5$	
	Sd. Dev.	Sd. Dev.*	Rel. S.D.**	Sd. Dev.	Rel. S.D.
Inflation	0.0018	0.0018	1.0000	0.0018	1.0000
Output	0.0007	0.0007	1.0000	0.0007	1.0000
Consumption	0.0010	0.0010	1.0000	0.0010	1.0000
Investment	0.0006	0.0006	1.0000	0.0006	1.0000
Base policy rate	0.0028	0.0028	1.0000	0.0028	1.0000
Loan rate	0.0027	0.0027	1.0000	0.0027	1.0000
Bond rate	0.0006	0.0006	1.0000	0.0006	1.0000
Deposit rate	0.0023	0.0023	1.0000	0.0023	1.0000
Total reserve ratio	0.0021	0.0015	0.7143	0.0011	0.5238
Excess-total reserves	0.0064	0.0039	0.6094	0.0027	0.4219

Notes: *Sd. Dev. is the standard deviation; ** Rel. S.D. denotes the relative standard deviation.

requirements can be used countercyclically to mitigate macroeconomic fluctuations (see for instance, Montoro and Moreno, 2011). Reserve requirements have also been used by many central banks as a liquidity tool to sterilize excess reserves and mitigate financial volatility. Consider the case where the central bank is assumed to set the reserve requirement rule according to the following,

$$\hat{\mu}_t = \chi^{\mu}\hat{\mu}_{t-1} + (1-\chi^{\mu})\mu + \phi_{\zeta,\mu}(\widehat{ER\_TR}_t). \tag{53}$$

where $\chi^{\mu}\,\epsilon(0,\,1)$ denotes the degree of persistence in the policy rule and $\phi_{\zeta,\,\mu}$, which measures deviations in the ratio of excess reserves to total reserves from its steady state, is an indicator of cyclical conditions. For illustrative purposes a value of 0.12 is used for χ^{μ}, and $\phi_{\zeta,\,\mu}$ is set at 1.2 initially, then a value of 1.5 is considered. Thus, there is a relatively low degree of persistence in changes of the required reserve ratio. Also, the positive value for $\phi_{\zeta,\,\mu}$ indicates that when there is an increase in excess bank liquidity, the central bank will raise the reserve requirement ratio to reduce the quantity of excess reserves in the banking system.

To assess whether the countercyclical rule can help to reduce volatility, the asymptotic standard deviations and the relative standard deviations of the main variables are compared when the reserve requirement ratio is endogenous and exogenous. The results from Table 3 show that although the countercyclical reserve requirement rule is successful in reducing fluctuations in excess reserves and total reserves, this policy rule has no effect on the real variables of the model.

7.3. Optimal simple rules and financial volatility

This section considers jointly the effects of two policy rules for managing financial volatility: an augmented Taylor rule and a countercyclical reserve requirement rule—which are presented in Eqs. (52) and (53) above, respectively. As both policy rules respond to the ratio of excess reserves to total reserves, it is assumed that the central bank is concerned with mitigating fluctuations in liquidity for some financial stability reason. In an environment where commercial banks hold excess reserves, it is particularly important that central banks devise rules which take the liquidity situation into account. This is because the presence of excess bank liquidity weakens the monetary transmission mechanism and has resulted in a sluggish pass through of the short-term interest rate to real and financial variables. Also, excess idle funds held in vaults or as non-remunerated reserves at the central bank reduce bank profitability. Banks may be tempted to compensate for this loss by lowering credit standards or softening collateral requirements in order to stimulate the demand for loans and attract customers. In turn, a weakening of credit standards may make banks more vulnerable to default risk in a downturn.

Similar to Agénor and Zilberman (2015), to determine the optimal policy responses, it is assumed that the central bank's objective is to minimize two exogenous loss functions. In this case, the central bank is concerned with macroeconomic stability and financial stability. Macroeconomic stability, given in the first loss function, is defined in terms of the volatility of inflation and output. In the second loss function, the central bank is also concerned about financial stability and as a result, the credit-to-output ratio is included in the loss function. Thus, financial stability is measured in terms of the volatility in the credit-to-GDP ratio—which has been widely used as a financial indicator. The loss functions are given by,

$$\mathcal{L}_t^1 = V\left(\hat{\pi}_t\right) + 0.25V(\hat{Y}_t), \tag{54}$$

$$\mathcal{L}_t^2 = V\left(\hat{\pi}_t\right) + 0.25V(\hat{Y}_t) + 0.2V(\widehat{L}_t^F - \widehat{Y}_t), \tag{55}$$

Table 4
Central bank losses and optimal policy parameters.

	Loss function $\mathcal{L}_t^1$	Loss function $\mathcal{L}_t^2$
Regime I	$\phi_\pi = 3$	$\phi_\pi = 3$
	$\phi_{\zeta,i} = -$	$\phi_{\zeta,i} = -$
	$\phi_{\zeta,\mu} = -$	$\phi_{\zeta,\mu} = -$
	$\mathcal{L}_t^1 = 0.936$	$\mathcal{L}_t^2 = 1.090$
Regime II	$\phi_\pi = 3$	$\phi_\pi = 3$
	$\phi_{\zeta,i} = -0.6$	$\phi_{\zeta,i} = -0.2$
	$\phi_{\zeta,\mu} = -$	$\phi_{\zeta,\mu} = -$
	$\mathcal{L}_t^1 = 0.268$	$\mathcal{L}_t^2 = 0.391$
Regime III	$\phi_\pi = 3$	$\phi_\pi = 3$
	$\phi_{\zeta,i} = -$	$\phi_{\zeta,i} = -$
	$\phi_{\zeta,\mu} = 0.29$	$\phi_{\zeta,\mu} = 0.67$
	$\mathcal{L}_t^1 = 0.935$	$\mathcal{L}_t^2 = 1.090$
Regime IV	$\phi_\pi = 3$	$\phi_\pi = 3$
	$\phi_{\zeta,i} = -0.2$	$\phi_{\zeta,i} = -0.2$
	$\phi_{\zeta,\mu} = 0.29$	$\phi_{\zeta,\mu} = 0.1$
	$\mathcal{L}_t^1 = 0.158$	$\mathcal{L}_t^2 = 0.377$

Note: The values for $\mathcal{L}_t^1$ and $\mathcal{L}_t^2$ are raised to the negative power of 6 (10^{-6}).

where $V(x_t)$ denotes the volatility of deviations of x_t from its steady state. Similar to other studies, a weight of 0.25 is attached to output volatility (see for instance Walsh, 2003), whereas a higher weight is attached to inflation volatility. The weight attached to financial stability takes a low value of 0.2.

The loss functions are computed under four policy regimes: Under Regime I, the central bank considers a standard Taylor rule so the required reserve rule is held constant. In this case, only the optimal response to inflation, ϕ_π, is solved for from Eq. (52). Regime II considers an augmented Taylor rule, so in this case the optimal response to inflation, ϕ_π, and the ratio of excess reserves to total reserves, $\phi_{\zeta,\, i}$, are solved. The required reserve rule is also held constant in this case. Under Regime III, the standard Taylor rule and a reserve requirement rule are considered jointly. Therefore, from Eqs. (52) and (53), the optimal response to inflation, ϕ_π, and the ratio of excess reserves to total reserves, $\phi_{\zeta,\, \mu}$, are computed. Under Regime IV, the augmented interest rate rule and the required reserve rule are adjusted simultaneously as the central bank's policy tools. Therefore, ϕ_π, $\phi_{\zeta,\, i}$ and $\phi_{\zeta,\, \mu}$ are solved for optimally.[22] The aim of this experiment is to determine whether a countercyclical reserve requirement rule can be an effective complement to interest rate policy to reduce macroeconomic and financial volatility following a liquidity shock. Put differently, does Regime IV dominate the other regimes? Furthermore, this experiment will indicate whether an augmented Taylor rule which responds to excess reserves, combined with a reserve requirement rule, performs better in that it minimizes central bank losses, when compared to a standard Taylor rule, combined with a reserve requirement rule.

Table 4 shows the central bank losses and optimal policy parameters under the four policy regimes, using a grid step of 0.1 and assuming that the upper bound for $\phi_\pi = 3$. The results reveal that under a liquidity shock it is optimal for the central bank to respond strongly to inflation. The findings also show that when a measure of excess liquidity enters the Taylor rule, central bank losses are reduced, implying therefore that the augmented interest rate rule is better in that it lowers volatility following a liquidity shock. Also, Regime II in Eq. (54) gives the lowest value for $\phi_{\zeta,\, i}$, underscoring the fact (as mentioned in Section 7.1) that this coefficient takes a negative value. A comparison of Regime I and Regime III reveals that they perform (more or less) the same in terms of central bank losses. These two regimes also record the highest values, in comparison to the other regimes under both loss functions. This indicates that the standard Taylor rule alone, and when combined with a reserve requirement rule, is not very effective to reduce macroeconomic and financial volatility. The best policy in terms of central bank losses is the combination of an augmented Taylor rule and a countercyclical reserve requirement rule. Thus, because Regime IV performs the best, this implies that using a reserve requirement rule as a complement to interest rate policy can help to reduce real and financial volatility following a liquidity shock.

[22] Under all the regimes $\phi_Y = 0.2$.

8. Conclusions

The purpose of this paper was to examine the dynamic effects of excess reserves in a New Keynesian general equilibrium model with banking. For this purpose, I extend and modify the framework presented in Agénor and Alper (2012) and Agénor et al. (2013), by allowing the monopoly bank to hold excess reserves. As in Glocker and Towbin (2012), the model explicitly accounts for the fact that banks incur convex costs in holding excess reserves, which are proportional to their deposit holdings. Similar to the practice in a few countries, the bank receives interest payments on reserves from the central bank. Other notable features of the model are that it accounts for credit market imperfections and it incorporates a cost channel because intermediate good-producing firms must borrow in advance to finance their working capital needs. The framework also captures imperfect substitutability between sources of bank funding by assuming that the rate at which banks can borrow from the central bank includes a premium (above the base policy rate), which depends positively on the ratio of central bank borrowing to deposits.

The model was used to explain the main macroeconomic variables responses to a negative supply shock, as well as positive shocks to the base policy rate, the required reserve ratio and liquidity. The results show that under both a negative supply shock and a shock to the policy rate, the refinance rate increases, leading to a rise in demand for financial assets such as deposits and bonds. The higher refinance rate also increases the opportunity cost of holding excess reserves, leading the bank to reduce demand for these assets; as a result, excess reserves fall. A notable finding of this study is that a reserve requirement shock is countercyclical, in the sense that it leads to a contraction in output. In addition, higher reserve requirements lead to an immediate fall in excess reserves. This experiment therefore supports the decision—which has indeed been practiced by many central banks—to increase the required reserve rate in order to sterilize excess reserves. This finding is in line with many other contributions in the literature, which suggest that central banks should raise reserve requirements to reduce excess reserves (see for instance Gray, 2011; Montoro and Moreno, 2011; Robitaille, 2011; and Tovar et al., 2012).

The study also examined two policy rules—an augmented Taylor rule and an endogenous countercyclical reserve requirement rule—separately, as well as the optimal combination of both rules jointly, following a liquidity shock. Given that banks have a voluntary demand for excess reserves, the rationale for the augmented Taylor rule is to investigate whether the volatility of key macroeconomic and financial variables can be reduced when the policy interest rate responds directly to changes in excess reserves. Owing to the fact that reserve requirements have been used widely to mitigate procyclicality and financial volatility, the countercyclical rule is used to determine whether a reserve requirement policy can reduce fluctuations in excess reserves. The findings show that although the augmented Taylor rule is successful in reducing volatility in real variables, the financial variables of the model become more volatile. Also, the findings indicate that if the reserve requirement rate is used in a countercyclical fashion, it can help to stabilize fluctuations in excess reserves. Notably, the results from the optimal policy responses show that combining an augmented Taylor rule, which responds to excess reserves, with a countercyclical reserve requirement rule is more effective—in terms of minimizing central bank losses—to mitigate real and financial volatility associated with liquidity shocks, compared to a standard Taylor rule, coupled with a reserve requirement rule. The findings from this study can be used to inform policymakers—particularly in countries with high excess reserves in the banking sector—of the benefits of using reserve requirements as a complement to an augmented interest rate rule.

The focus of this paper has been mainly on the case where excess reserves are demanded voluntarily by banks. Although this is practical in developing countries, it is important to also note that a number of factors may cause banks to hold excess reserves involuntarily. Therefore, one possible extension of this analysis is to focus on the case where excess reserves are purely involuntary. For instance, in advanced countries such as the U.S., excess bank reserves are involuntarily accumulated due to quantitative easing policies. In this context, the quantity of reserves in the banking system is (almost) completely determined by the central bank, and policy actions can change the quantity of reserves in the system. Given that recent policy discussion is concerned with this type of setting, understanding the transmission in this context should be high on the research agenda. In addition, another possible extension of this analysis is to examine the macroeconomic effects of an increase in short-term securities held by commercial banks. This is important given that—besides reserve requirements—open market operations can be used to manage liquidity. The results from an increase in securities holdings by banks can be compared to the findings in this study to show the advantages of raising reserve requirements to sterilize liquidity in a country with structural excess reserves—which is in line with the practical evidence on central bank policymaking.

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