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Evaluation of unconventional monetary policy in a small open economy

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We find that previous studies might overestimate the extent to what large-scale asset purchases affect real activity. Allowing agents to trade internationally with goods as well as saving via foreign, currency denominated deposits leads to a leakages that result in substantial differences between large-scale asset purchases in a small open economy and an autarky. Moreover, our results show that negative supply side shocks have less severe consequences in a small open economy comparing to an autarky, because they are offset by the real exchange rate depreciation which boosts competitiveness

JEL: E52, F41

Keywords: unconventional monetary policy, financial frictions, small open economy

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Evaluation of unconventional monetary policy in a small open economy*

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1 Introduction

Last financial crisis has pushed central banks in advanced economies into the blind alley - after lowering the nominal interest rates effectively to zero they had to undertake unconventional monetary policy measures to further loosen monetary conditions. Since central banks have lost possibility to decrease short-term interest rates more, they started to influence the expected path of short-term interest rates. This is equivalent to affecting long end of the yield curve [Bernanke, 2012]. Central banks have tried and still try to achieve this by guiding expectations about policy rate in the future (communication tools) or by increasing demand for certain type of assets (balance sheet tools), which also has some signaling power. Both approaches were used over the last few years across the world, however their effects are still unknown, mainly because the unconventional policies are still active.

There is a growing number of papers using DSGE models, which shed some light on different aspects of unconventional policies. Some of the results suggest that the net benefits of these tools are positive [e.g. Gertler and Karadi, 2011; Cúrdia and Woodford, 2010; Del Negro et al., 2010; Jones and Kulish, 2013 and Peersman, 2011]. On the other hand there are studies which state that some types of these tools are not adequate to compensate shocks similar to those which have hit global economy in 2007-2008 [Levin et al., 2010]. [Schuder, 2014] stipulates that effects of expansionary monetary policy during economic crises are on average ambiguous.

Despite growing interest in unconventional monetary policy tools, especially large-scale asset purchases (LSAP), we believe that there is a gap in the DSGE literature concerning international facets of such policies. To the best of our knowledge there are only two papers addressing such problems [Dedola et al., 2013 and Gieck, 2014], but both concentrate on the cooperation of the unconventional policy actions in a two-country model framework. Additional, first one is a study conducted with a real economy model, so it abstracts from exchange rates or prices, which are important regarding evaluation of policy effectiveness. Even though study by Gieck [2014] is the analysis of a nominal economy model, we still find that it lacks issues connected with a certain kind of international spillovers of asset purchases. For instance, the main question we want to address in this paper is the interplay between "leakages" of the policy actions and the degree of openness to the international trade. Another issue of substantial importance is the role of the exchange rate, if it is influenced by asset purchases and how these changes affect economy. Although there is some evidence that central banks react to the changes in the exchange rate nevertheless their quantitative effects are small [Demir, 2014] so we abstract from it.

In this study we try to assess a LSAP in a small open economy (SOE) model based on Gertler and Karadi [2013, GK], which contains both government and private securities purchases as a monetary policy tool for boosting economy when the zero lower bound (ZLB) on nominal interest rate binds. We assume that the small open economy framework similar to [Gali and Monacelli, 2005] is appropriate way to analyze monetary policy observed across the world since even the biggest economies are of relatively small size compared to the rest of the world[1]. Rationale for such choice of framework can be justified with the intuition that policy measures undertaken in a domestic economy do not have any impact on the rest of the world, even though part of the effects can leak out of the domestic economy, because fraction of consumption, investment or government purchases can be composed of imported goods. Additionally, we allow households not only to save via deposits in domestic currency, but also to set aside funds with deposits denominated in foreign currency.

In the section 3 we thoroughly discuss how we have extended the GK model, however in this part we want to briefly explain why we have chosen this model. The two alternatives that were taken into account were Del Negro et al. [2010] and Cúrdia and Woodford [2010]. First one focuses on the role of the illiquid secondary markets for the private securities. This kind of friction hinges on the assumption that only part of the investment can be financed by the financial intermediary. Furthermore each entrepreneur that has investment opportunity runs up against so-called 'resaleability' constraint i.e. only a part of his illiquid assets can be sold. We did not pick this framework, because there is no agent who acts as a bank/financial intermediary as well as the model abstracts from the costs of central bank intermediation. Second model exhibits heterogeneity of households spending opportunities (borrowers and savers) and puts the emphasis on the role of credit spreads. It analyzes purchases of private assets, which mimics first round of quantitative easing in the US (but not the situation we want to analyze - as will be made clear later). The authors admit that model is highly stylized - there is no connection between investment

[1]However abstracting from a SOE assumption in economies like the euro area and the US might be justifiable since they account for 15% and 20% of world GDP (measured in PPP).

and the output capacity of the economy, because whole investment spending is treated as consumption. We underline that we want to take a closer look at both macro and financial variables and that is why we find the model proposed by Cúrdia and Woodford [2010] as insufficient.

Our results show that ignoring both international trade and financial international channels results in a substantial overestimation of shocks that can push nominal interest rate to zero as well as leads to a false image of effectiveness of a LSAP. In terms of a peak effect of output and inflation, a LSAP brings about approximately one third of its effects in a SOE compared to a closed economy case. This comparison is relatively less unfavorable for financial variables, because in a closed economy a LSAP program is roughly 2.5 times more efficient in contrast to a SOE setup in reviving real activity.

In the next section we justify choice of the UK as a country of interest. Additionaly, next section summarizes quantitative easing in the UK - this information is helpful in the calibration of shocks in section 4. Section 3 includes description of our model. Section 4 reports the results of several simulations showing how a LSAP program affects real activity in both a SOE and a closed economy. Finally, section 5 concludes.

2 QE design: case of the UK

We choose economy of the UK, because it features the characteristics of a small open economy. According to the World Bank database in 2013 ratio of exports to GDP was 29.8% and 31.7% in case of imports. When it comes to the latter, we have to take into account export contents of imports. Based on OECD's Structural Analysis Database (STAN) in the mid-2000s about 21.3% of the UK exports was composed of imported goods, so the rest ought to be treated as the true value added of domestic sector. Adjusting exports for imported goods, we finally end up with 23.5% as the value of exports to GDP.

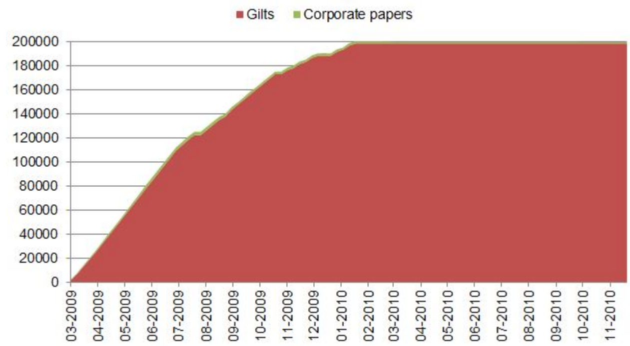
Before describing our framework we want to shed some light on the mechanism of monetary stimulus in the UK based on Joyce et al. [2011]. In contrast to the QE1 in the US, which was composed of the private securities, the Bank of England's MPC approved an asset purchases program called Asset Purchase Facility (APF), that was almost entirely composed of UK government bonds (gilts). During ten months starting from March 2009 BoE bought £200bn of assets, which was equal to 14% of GDP and to the one third of domestic bonds held by the private sector. Average structure of assets purchased throughout that time is depicted in figure 1.

Observe that purchases of private securities played a minor role in the credit easing. Authors suggest that channels that transmit assets purchases to the real economy are: policy signaling, portfolio balance, liquidity premia, confidence and bank lending. They postulate that the second one is the most important for the transmission mechanism, since it directly pushes up prices of assets, hence putting a downward pressure on yields. It also reduces credit spreads, which allows households to consume and firms to invest more than it would have been possible in the scenario without policy. Increased prices of private securities and government bonds make their holders better off so they can spend more. Importance of this channel is underlined also when it comes to the operationalization of the purchases by the BoE, because program was tailored such that the long end of the yield curve was of primary interest. Moreover, purchases were targeted to non-bank financial intermediaries, since such firms are especially keen on looking for higher returns. They are willing to buy another type of riskier assets, hence lowering yields of other assets than those purchased by the central bank.

There is already some empirical evidence about the importance of the last channel, namely bank lending. Joyce and Spaltro [2014] show that during the first round of British QE the increase in the growth rate of credit action was relatively small, though QE was statistically significant for bank lending dynamics. In this study we focus solely on the balance sheet aspects of QE, since it is complex to address all these channels in one medium-scale model.

With regard to other papers that try to assess effects of LSAP we ought to mention study by Weale and Wieladek [2015]. Using Bayesian VAR estimated on the UK data they find that in period from March 2009 to May 2013 LSAP of 1% of GDP on average boosted CPI by 0.3%, while for GDP this increase totaled 0.18%. Their results are more in favor of quantitative easing than previous ones based on the similar methodology [e.g. Baumeister and Benati, 2013].

Figure 1: Structure of QE in the UK



Source: Bank of England database; sterling millions.

3 Model

GK model in its original form includes financial intermediaries that channel funds from households to non-financial firms. It enables households to save via deposits at banks/financial intermediaries. The distinct feature of this model is the endogenous capital constraint - banks have limited capability to get the funds from households due to an agency problem. Each period bankers are able to divert the fraction of banks' assets. We extend GK framework by adding small open economy properties. First of all, we allow households to save abroad in a form of foreign currency denominated deposit accounts. Additionally, consumption and investment goods are composed of goods produced at home (H superscript) and in the foreign economy (F superscript). Goods that are used abroad are denoted by asterisks. Since there are three agents that can be active on the financial market we use h, p and g subscripts to denote assets acquired by respectively: households, banks and government/central bank.

Before describing model *in extenso* here we present actions of each agent. Households maximize utility function which is composed of consumption and disutility from work. Households' incomes result from labor, dividends from non-financial firms and banks, domestic and foreign deposits. Their incomes are spent on: consumption, purchase of domestic and foreign depostis, transfer to entering bankers as well as lump-sum taxes. Banks are run by incumbent and entering bankers - members of households. Bankers maximize discounted sum of future payouts to households. This perpetual value is a function of net worth (equity capital) of bankers (banks). Net worth is composed of gross return on assets minus the cost of deposits. Banks have two types of assets: loans extended to intermediate goods producers and domestic government bonds. Banks are constrained in obtaining deposits from households due to the fact that rach banker is able to steal part of her or his bank's assets[2]. Bankers will not do that if the value of the discounted sum of future payouts to households is larger than the value of assets possible to divert. Capital goods producers create new capital using final output. They are also subject to adjustment costs. New capital is sold to intermediate goods producers. Intermediate goods producers finance new capital only by loans obtained from banks. They produce intermediate goods with capital and labor. Their output is bought by retail firms which combine this with imports of foreign intermediate goods. Retailers are subject to nominal rigidities - only part of them can reset prices each period. Central bank in tranquil periods runs monetary policy according to the Taylor rule, while during the financial market disruptions it purchases financial assets. Finally, government collects lump-sum taxes paid by households and issues bonds. These funds are used on government spending and debt service costs.

3.1 Households

Economy is inhabited by infinitely many identical households. Each household consumes, saves and supplies labor. Representative household can save in domestic banks (deposits denominated in the home currency) and foreign banks (deposits denominated in the foreign currency). Household consists of two types of members: workers and bankers. The former type supplies labor L_t to intermediate goods producers and gets wage W_t and the latter manages a financial intermediary. The fraction of household members that are bankers is f, so workers fraction totals $1 - f$. Household members can switch between their types - the probability of being a banker next period is σ. This means that every period $(1 - f)\,\sigma$ bankers pay out retained earnings to household. At the same time household transfers funds to the same number of new bankers allowing them to set up a bank. Let C_t be a consumption. Then each household maximizes expected stream of discounted utility flows u_t:

$$\max_{C_t, L_t, D^H_{h,t}, D^F_{h,t}} u_t = E_t \sum_{i=0}^{\infty} \beta^i \left[ln\left(C_{t+i} - \bar{h}\, C_{t+i-1}\right) - \tfrac{\chi}{1+\varphi} L_{t+i}^{1+\varphi} \right] \tag{1}$$

where $0 < \beta < 1$ is a discount factor, $0 < \bar{h} < 1$ is a consumption habit formation and χ, $\varphi > 0$ are respectively: the relative utility weight of labor and the inverse Frisch elasticity of labor supply. We allow for habit formation to capture consumption dynamics. Let $D^H_{h,t}$ be deposits in domestic banks, $D^F_{h,t}$ deposits in foreign banks, T time-invariant lump-sum tax collected by the government, X time-invariant total transfer the household gives to its members that enter banking , Π_t dividends from non-financial firms and banks (that are nonzero only outside the steady-state), e_t nominal exchange rate defined as

[2]Bank can obtain deposits from all households except the one which its manager/banker is a member.

a quantity of domestic currency needed to purchase a unit of foreign currency. Both types of deposits pay riskless interest rates, respectively: R_t and R_t^*, which are the same in the steady-state. Following Schmitt-Grohé and Uribe [2003] we induce stationarity of model's variables by assuming that the return on foreign deposit is not only a function of the foreign riskless interest rate but also a risk premium component. This premium is a concave increasing function of foreign deposits, which means that it depends positively on the amount of foreign deposits from the last period, however this increase declines with respect to the amount of deposits in foreign banks[3]. We use a functional form of the risk premium as in Schmitt-Grohé and Uribe [2003]: $\Psi\left(x_t\right) = \mathrm{e}^{\psi(\overline{x}-x_t)}$, where ψ is elasticity parameter and $\overline{x}$ is a steady-state value. The maximization of the expected stream of discounted utility flows u_t is subject to the following budget constraint:

$$P_t C_t + D_{h,t}^H + e_t D_{h,t}^F + P_t X = W_t L_t + P_t \Pi_t + P_t T + R_{t-1} D_{h,t-1}^H + R_{t-1}^* \Psi\left(e_t D_{h,t}^F\right) e_t D_{h,t-1}^F \tag{2}$$

Optimization yields the following first order conditions:

$$u_{C,t} = \frac{1}{C_t - \bar{h}\, C_{t-1}} - \bar{h}\beta E_t \frac{1}{C_{t+1} - \bar{h}\, C_t} = P_t \lambda_t \tag{3}$$

$$u_{L,t} = \chi L_t^{\varphi} = \lambda_t W_t \tag{4}$$

$$E_t \Lambda_{t,t+1} R_t = 1 \tag{5}$$

$$E_t \Lambda_{t,t+1} \frac{e_{t+1}}{e_t} \Psi\left(e_t D_{h,t}^F\right) R_t^* = 1 \tag{6}$$

where $\Lambda_{t,t+1} = \beta \frac{\lambda_{t+1}}{\lambda_t} \pi_{t+1}$. Note that after combining (5) and (6) we get the uncovered interest parity condition:

$$E_t \Lambda_{t,t+1} \frac{e_{t+1}}{e_t} = E_t \frac{R_t}{\Psi\left(e_t D_{h,t}^F\right) R_t^*}$$

which states that the expected exchange rate movement is a function of the interest rate differential. Note that this relation depends also on the external risk premium.

3.2 Banks

Banks extend loans to intermediate goods producers, which in turn are used to finance the purchase of capital. Let Z_t be the net period income flow from a loan financing a unit of capital, Q_t the market value of a unit of capital, δ the depreciation rate and ξ_t random disturbance - capital quality shock - described later. The gross return on a loan from period $t-1$ to t is given by:

$$R_{k,t} = \frac{Z_t + (1-\delta)\, Q_t}{Q_{t-1}} \xi_t \tag{7}$$

Denote the market value of domestic government bond that pays a unit of home currency by q_t and the price level by P_t, then we can analogously define the gross return on long-term government bond as:

$$R_{b,t} = \frac{1/P_{t-1} + q_t}{q_{t-1}} \tag{8}$$

[3] It is worth mentioning that the risk premium depends on the whole country's net foreign assets. Since each household is infinitesimally small it does not take into account its influence on total net foreign assets. Thus when deriving first order conditions of representative household we treat $\Psi\left(\cdot\right)$ as exogenous to the household's choice.

Let N_t be the net worth of bankers (or banks' equity capital), $S_{p,t}$ amount of loans and $B_{p,t}$ the sum of the long-term domestic government bonds that banks hold in their portfolio. Representative bank's aggregate balance sheet is given by:

$$Q_t S_{p,t} + q_t B_{p,t} = N_t + D^H_{h,t} \tag{9}$$

where the left-hand side of equation presents assets and the right-hand side liabilities. Net worth is the difference between the gross return on assets and the cost of deposits. It evolves according to:

$$N_t = R_{k,t} Q_{t-1} S_{p,t-1} + R_{b,t} q_{t-1} B_{p,t-1} - R_{t-1} D^H_{h,t-1} \tag{10}$$

Combining (9) and (10) we get bank's equity capital law of motion:

$$N_t = \sigma \left[\left(R_{k,t} - R_{t-1} \right) Q_{t-1} S_{p,t-1} + \left(R_{b,t} - R_{t-1} \right) q_{t-1} B_{p,t-1} + R_{t-1} N_{t-1} \right] + X \tag{11}$$

which depends on the retained earnings (the net profits of the bank times probability of staying a banker next period) plus the transfer from the household to entering bankers. Each banker seeks to maximize the discounted sum of future payouts to her or his household - given by (12). The discount factor is equal to $\widetilde{\Lambda}_{t,t+1}$ which is the modified intertemporal marginal rate of substitution. This modification will be justified later.

$$\max_{S_{p,t}, B^H_{p,t}, D_t} V_t = E_t \sum_{i=1}^{\infty} (1-\sigma)\sigma^{i-1} \widetilde{\Lambda}_{t,t+1} N_{t+i} \tag{12}$$

subject to (9), (10) and:

$$V_t \geqslant \theta Q_t S_{p,t} + \Delta\theta q_t B_{p,t} \tag{13}$$

The last constraint is introduced to curb bank's capability to obtain deposits from households. Each period each bank has an opportunity to embezzle fraction θ of loans and $\Delta\theta$ of bonds[4]. Satisfying (13) means that the perpetual value of banks is greater than the value of diverted funds. In other words bankers will not try to steal funds and transfer it to households, because they lose in doing so.

Before describing the solution to the banker's problem let's define the shadow value of net worth, which is weighted average across exiting and current bankers:

$$\Omega_{t+1} = (1-\sigma) + \sigma \frac{\partial V_{t+1}}{\partial N_{t+1}} \tag{14}$$

The right-hand side of the equation above says that for exiting bankers, marginal value of equity capital is one because they just give these funds to households, whereas continuing bankers use the equity capital to increase assets and consequently expand perpetual value.

Now we can turn back to the optimization of representative bank (12). Define 'augmented' stochastic discount factor as $\widetilde{\Lambda}_{t,t+1} = \Lambda_{t,t+1}\Omega_{t+1}$, then the solution can be characterized by[5]:

$$E_t \widetilde{\Lambda}_{t,t+1} \left(R_{k,t+1} - R_t \right) = \frac{\lambda_t}{1+\lambda_t} \theta \tag{15}$$

$$E_t \widetilde{\Lambda}_{t,t+1} \left(R_{b,t+1} - R_t \right) = \frac{\lambda_t}{1+\lambda_t} \Delta\theta \tag{16}$$

Both equations show how the excess return on each type of asset depends on the tightness of financial frictions. If (13) does not bind, than excess returns are zero, because λ_t is zero. The bigger the pressure,

[4] As in Gertler and Karadi [2013] we assume that $0 < \Delta, \theta < 1$, which means that a fraction of diverted bonds must be lower than loans (private securities).

[5] λ_t is the Lagrange multiplier related to (13).

the higher spread between the lending rate and the risk-free interest rate. Notice that for the constant level of the risk-free rate, rising tightness leads to higher borrowing costs, thus the level of investment is lower than it otherwise would have been the case. This stems from the assumption that banks are the ultimate source of credit in the economy. Lower demand for private securities issued by firms is equal to the lower physical capital available for the intermediate goods producers. Note that the excess returns are smaller for bonds than for loans by Δ. It originates from the fact that bankers are able to divert smaller part of bonds portfolio than of private loans. This assumption is crucial for the central bank purchases effects.

Due to the possibility of diverting the funds from banks, bankers have limited ability to expand their assets. This can be expressed in the following way[6]:

$$Q_t S_{p,t} + \Delta q_t B_{p,t} \begin{cases} = \phi_t N_t & \text{if } \lambda_t > 0 \\ < \phi_t N_t & \text{if } \lambda_t = 0 \end{cases} \tag{17}$$

where leverage ratio is a function of embezzlement parameter θ and interest rates and can be expressed as follows:

$$\phi_t = \frac{E_t \widetilde{\Lambda}_{t,t+1} R_t}{\theta - E_t \widetilde{\Lambda}_{t,t+1} \left(R_{k,t+1} - R_t\right)} \tag{18}$$

Note that the bigger share of hypothetically diverted assets θ, the lower leverage ratio ϕ_t. In other words if banking sector is less trustworthy, it is harder to acquire funds from households, because they are aware of the fact that banks have greater incentives to cheat. Observe also that an upward movement in the risk-free rate or in the excess return on capital leads to the higher leverage. Looking at the (17) we see that an increment of leverage allows banks to expand their portfolios for the given net worth (equity capital). This, in turn, increases stock of capital used by the intermediate goods producers. From the equity capital law of motion (11) we know that higher excess returns and the risk-free rate make bankers better off, because future stream of profits is larger. As a result it is less beneficial to divert funds - see (13).

3.3 Intermediate goods producers

Intermediate goods producers operate constant returns to scale production function with two inputs: capital and labor. Their output is sold to retailers. Let $Y_{m,t}$ be the aggregate production of intermediate goods, A_t technology level, K_t capital stock, L_t labor. Then:

$$Y_{m,t} = A_t K_t^{\alpha} L_t^{1-\alpha} \tag{19}$$

where α is output elasticity of capital. Producers maximize profits given by $P_{m,t} Y_{m,t} - W_t L_t - Z_t K_t$ subject to the production function given by (19), which yields following first order conditions:

$$W_t = P_{m,t}(1-\alpha)\frac{Y_{m,t}}{L_t} \tag{20}$$

$$Z_t = P_{m,t}\alpha\frac{Y_{m,t}}{K_t} \tag{21}$$

Equation (20) is the demand for labor and (21) is the gross profit per unit of capital transferred to banks. At the end of each period producers are left with the undepreciated capital that can be sold at the open market. Firms face the decision about the level of investment I_t. Thus, capital law of motion is defined by:

$$K_{t+1} = \xi_{t+1}\left[I_t + (1-\delta)K_t\right] \tag{22}$$

[6]Full derivation can be found in the appendix.

where ξ_{t+1} is a capital quality shock. The rationale for introducing such a kind of shock is a desire to capture an economic obsolescence - an analog to the physical depreciation. Introduction of the capital quality shock results in an exogenous source of variation in the return to capital. Investment is financed by loans obtained from banks. Obtaining a loan is identical to the situation when a firm issues state-contingent private security S_t bought by banks. Funds raised in that way are used to purchase capital $I_t + (1-\delta) K_t$. Combining it with (22) yields $K_{t+1} = \xi_{t+1} S_t$, which means that the amount of capital next period is equal to loans extended today adjusted for the capital quality shock. We assume that the financing process between firms and banks is frictionless, which contrasts with the constraints in the deposit market. Frictionless setup enables firms to commit to the payment of future stream of profits to banks. Next period payoff on a unit of capital is equal to $(Z_{t+1} + (1-\delta) Q_{t+1}) \xi_{t+1}$ - the gross profit on unit of capital plus the value of undepreciated unit of capital (adjusted for ξ_{t+1}). Note that a negative capital quality shock lowers this payoff and makes bankers worse off. Banks efficiently monitor financial standing of firms. Hence, firms rely entirely on loans and financial intermediaries are the only source of credit.

3.4 Capital goods producers

Capital goods producers create new capital using final output. They are also subject to adjustment costs. New capital is sold to intermediate goods producers at the price Q_t which is obtained after solving the following problem:

$$\max_{I_t} E_t \sum_{\tau=t}^{\infty} \Lambda_{t,\tau} \left\{ (Q_\tau - 1) I_\tau - f\left(\frac{I_\tau}{I_{\tau-1}}\right) I_\tau \right\} \tag{23}$$

After optimization we get:

$$Q_t = 1 + f\left(\frac{I_t}{I_{t-1}}\right) + \frac{I_t}{I_{t-1}} f'\left(\frac{I_t}{I_{t-1}}\right) - E_t \Lambda_{t,t+1} \left(\frac{I_{t+1}}{I_t}\right)^2 f'\left(\frac{I_{t+1}}{I_t}\right) \tag{24}$$

Profits (existing only outside the steady-state) are transferred to households. Note that the lower level of investment provokes worse situation of financial intermediaries, which in order to satisfy (17) have to decrease leverage, hence their net worth.

3.5 Retail firms

Retail firms package variety of intermediate goods produced at home into final domestic aggregate and combine it with imported goods. It means that at the first stage of production intermediate goods are the only one input. The domestic output is consumed at home and exported. It is given by a CES aggregate:

$$Y_{H,t} = \left[\int_0^1 Y_{H,f,t}^{\frac{\varepsilon-1}{\varepsilon}} df \right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{25}$$

$$Y^*_{H,t} = \left[\int_0^1 Y^{*\frac{\varepsilon-1}{\varepsilon}}_{H,f,t} df \right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{26}$$

where $\varepsilon > 1$ is the elasticity of substitution between intermediate goods, $Y_{H,f,t}$ and $Y^*_{H,f,t}$ are the outputs by a intermediate good producer f . Retailers simply repackage intermediate goods, so $Y_{f,t} = Y_{H,f,t} + Y^*_{H,f,t}$ is equal to $Y_{m,t}$. It also means that the marginal cost of goods produced domestically equals the price paid to intermediate goods producers.

From (25) and (26) we know that domestic and foreign demand functions for the intermediate goods are given by:

$$Y_{H,f,t} = \left(\frac{P_{H,f,t}}{P_{H,t}}\right)^{-\varepsilon} Y_{H,t} \tag{27}$$

$$Y^*_{H,f,t} = \left(\frac{e_t P^*_{H,f,t}}{e_t P^*_{H,t}}\right)^{-\varepsilon} Y^*_{H,t} \tag{28}$$

Assuming that the law of one price (LOOP) holds $P_{H,t} = e_t P^*_{H,t}$, we can rewrite (28) as:

$$Y^*_{H,f,t} = \left(\frac{P_{H,f,t}}{P_{H,t}}\right)^{-\varepsilon} Y^*_{H,t} \tag{29}$$

Assumption that the domestic prices are equal to the foreign prices times nominal exchange rate simplifies pricing scheme since we can look at the problem of intermediate goods producers without dividing it into exported goods and those used domestically. Nominal rigidities are introduced following Calvo [1983] scheme. Assuming that only random fraction $1-\gamma$ of retailers can adjust prices, the optimal price $P^{NEW}_{H,t}$ is reset such that retailers maximize expected discounted profits so optimal price must meet standard first order condition:

$$E_t \sum_{i=0}^{\infty} \gamma^i \Lambda_{t,t+i} \left[\frac{P^{NEW}_{H,t}}{P_{H,t+i}} - \mu P_{m,t+i}\right] \left(Y_{H,f,t+i} + Y^*_{H,f,t+i}\right) = 0 \tag{30}$$

where $\mu = \frac{1}{1-1/\varepsilon}$. Furthermore, we define price dispersion for the domestic goods as:

$$\Delta_{p,t} = \int_0^1 \left(\frac{P_{H,f,t}}{P_{H,t}}\right)^{-\varepsilon} df = (1-\gamma)\left(\frac{P^{NEW}_{H,t}}{P_{H,t}}\right)^{-\varepsilon} + \gamma \left(\frac{P_{H,f,t}}{P_{H,t}}\right)^{-\varepsilon} \Delta_{p,t-1}$$

The right-hand side can be decomposed into two parts. First one pertains to producers that can reset price and the second concerns those who must leave price unchanged. Analogously, for the exported goods price dispersion is given by:

$$\Delta^*_{p,t} = \int_0^1 \left(\frac{e_t P^*_{H,f,t}}{e_t P^*_{H,t}}\right)^{-\varepsilon} df = (1-\gamma)\left(\frac{P^{*NEW}_{H,t}}{P^*_{H,t}}\right)^{-\varepsilon} + \gamma \left(\frac{e_t P^*_{H,f,t}}{e_t P^*_{H,t}}\right)^{-\varepsilon} \Delta^*_{p,t-1}$$

Note that assumption that LOOP holds implies $\Delta_{p,t} = \Delta^*_{p,t}$. Finally, aggregate domestic goods price index $P_{H,t}$ evolves according to:

$$P_{H,t} = \left[(1-\gamma)\left(P^{NEW}_{H,t}\right)^{1-\varepsilon} + \gamma \left(P_{H,t-1}\right)^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}} \tag{31}$$

In the second step retailers combine goods produced at home and imported. We define Y_t as the final output bundle:

$$Y_t \equiv \left[(1-\nu)^{\frac{1}{\omega}} Y_{H,t}^{\frac{\omega-1}{\omega}} + \nu^{\frac{1}{\omega}} Y_{F,t}^{\frac{\omega-1}{\omega}}\right]^{\frac{\omega}{\omega-1}} \tag{32}$$

where $Y_{H,t}$ and $Y_{F,t}$ are domestic and foreign goods consumed in home country, ν is an index of openness[7] and $\omega > 0$ is elasticity of substitution between goods produced domestically and imported. Demand functions for the two types of goods are obtained after minimizing $P_t Y_t = P_{H,t} Y_{H,t} + P_{F,t} Y_{F,t}$ subject to (32):

$$Y_{H,t} = (1-\nu)\left(\frac{P_{H,t}}{P_t}\right)^{-\omega} Y_t \tag{33}$$

[7] Analogously $1-\nu$ is a measure of home bias.

$$Y_{F,t} = \nu \left(\frac{P_{F,t}}{P_t} \right)^{-\omega} Y_t \tag{34}$$

where P_t is the consumer price index given by:

$$P_t \equiv \left[(1-\nu) P_{H,t}^{1-\omega} + \nu P_{F,t}^{1-\omega} \right]^{\frac{1}{1-\omega}} \tag{35}$$

Final goods are consumed by households, purchased by the domestic government, used by capital goods producers and the central bank (as a cost of its intermediation on the finacial market).

3.6 Foreign behavior

We showed earlier that $P_{F,t} = e_t P_t^*$, where P_t^* is the world price index. Foreign demand for domestic goods is modeled similarly as in Gertler et al. [2007] and its functional form is given by:

$$Y_{H,t}^* = \left[\left(\frac{P_{H,t}^*}{P_t^*} \right)^{-\iota} Y_t^* \right]^{\varpi} \left(Y_{H,t-1}^* \right)^{1-\varpi} \tag{36}$$

where $0 \leq \varpi \leq 1$ is a smoothing parameter, and Y_t^* and P_t^* are exogenously determined levels of foreign output and prices. Having defined foreign demand on domestic goods, we can express net exports as:

$$NX_t = P_{H,t} Y_{H,t}^* + -P_{F,t} Y_{F,t} \tag{37}$$

and the foreign deposits as:

$$e_t D_{h,t}^F = -NX_t + e_t R_{t-1}^* \left[\mathrm{e}^{\psi \left(\overline{e D_h^F} - e_t D_{h,t}^F \right)} \right] D_{h,t-1}^F \tag{38}$$

3.7 Central bank assets purchases

Central bank buys assets in order to curb excess returns, which emerge when banking sector aggregate balance sheet is constrained. Financial tightness measured by λ_t considerably raises the cost of capital, thus lowering stock of capital. In such situation central bank acts as an additional financial intermediary who buys part of the assets. Thanks to that financial market disruption is less acute. Central bank intermediation replaces financial intermediaries demand for domestic bonds and private securities.

Large-scale assets purchases are financed by an interesting-bearing reserves $D_{g,t}$. In contrast to private intermediaries, central bank can credibly commit to pay its debt, so that it is not constrained with regard to obtaining the funds. Central bank's balance sheet is given by:

$$Q_t S_{g,t} + q_t B_{g,t} = D_{g,t} \tag{39}$$

We assume that any profits (or losses) are transferred to (or covered by) the government. Next assumption concerns cost of intermediation - intuitively central bank is less efficient then private intermediaries so we assume that administrative costs of a LSAP are equal to τ_s and τ_b per unit of private loans and government bonds[8]. This means that the net benefits of assets purchases arise only in case of substantial market disruption i.e. when excess returns are abnormally high.

Finally, let's combine market clearing conditions for each type of asset traded in the domestic financial market with constraint of the banks' aggregate balance sheet (17):

$$Q_t \left(S_t - S_{g,t} \right) - \Delta q_t \left(B_{g,t} - B_t \right) \leqslant \phi_t N_t \tag{40}$$

[8]We keep both costs at zero as in original calibration of the model.

Observe that when the constraint on obtaining funds (17) is binding, condition above is slack and central bank assets purchases increase the total quantity of private loans S_t. In the frictionless case, central bank crowds out private securities since condition above holds with equality. Notice that in this setup LSAP consisting of bonds is less efficient then the equivalent program made up of private securities, because of the relative seizure rate i.e. Δ.

3.8 Long-term bonds yields

Large part of the literature concentrates on the impact of large scale asset purchases on bond yields and credit spreads, however these excess returns are not observable. Let $R^n_{b,t+1+i} = R_{b,t+1+i}\frac{P_{t+1+i}}{P_{t+i}}$ be the ex post nominal gross return on domestic government bond from period $t+1+i$. Then the nominal price of this security is equal to:

$$P_t q_t = \sum_{i=1}^{\infty} \frac{1}{E_t \Pi_{j=1}^{i} R^n_{b,t+j}} \tag{41}$$

Additionally, we define $\Psi_{t+j} = \frac{R^n_{b,t+j}}{R^{n*}_{b,t+j}}$ as the ratio of the observed nominal return to its value in a frictionless environment. Using this ratio we can express nominal price of the government bonds as:

$$P_t q_t = \sum_{i=1}^{\infty} \frac{1}{E_t \Pi_{j=1}^{i} \Psi_{t+j} R^{n*}_{b,t+j}} \tag{42}$$

Finally, the net nominal yield to maturity of such security can be computed as follows:

$$\sum_{s=1}^{\infty} \frac{1}{\left(1 + i^n_{b,t}\right)^s} = \sum_{i=1}^{\infty} \frac{1}{E_t \Pi_{j=1}^{i} \Psi_{t+j} R^{n*}_{b,t+j}} \tag{43}$$

Note that these assets have infinite horizon of future stream of payments. In order to approximate these consoles to ten-year government bonds we use the same technique as in GK. They assume that ten-year bond is equivalent to perpetual console in terms of its price, although payoff structure is different. For the first ten years it yields a coupon amounting to a unit of domestic currency (so it is identical to the console described above). After that period a final payment (principal) is made and it equals the steady-state value of government bond price.

3.9 Government

Government purchases G_t of public goods and bears the debt service costs equal to the net interest on constant debt $\bar{B}$. Additionaly government covers central bank's intermediation costs τ_s and τ_b. On the income side there are time-invariant lump-sum taxes T and the net revenues from the central bank intermediation net transaction costs. Taking into account the balance sheet of central bank we can express the consolidated government budget constraint as follows:

$$P_t G_t + (R_{b,t-1} - 1)\bar{B} + \tau_s + \tau_b = P_t T + (R_{k,t} - R_{t-1} - \tau_s) Q_{t-1} S_{g,t-1} + (R_{b,t} - R_{t-1} - \tau_b) q_{t-1} B_{g,t-1} \tag{44}$$

When making the decision about nominal interest rates in normal times monetary authority takes into account previous level of nominal interest rate i_{t-1}, inflation π_t and the log-deviation of output from the flexible-price (natural) equilibrium level Y^N_t. Thus, monetary policy is run according to:

$$i_t = \max\left[1, \rho_{ir} i_{t-1} + (1-\rho_{ir})\left[\kappa_\pi \pi_t + \kappa_y\left(\log Y_t - \log Y^N_t\right)\right] + \epsilon_t\right] \tag{45}$$

where ϵ_t is an exogenous monetary shock. Thus, when the gross nominal interest rate resulting from the Taylor rule is lower than one, the central bank sets one. Such rule implies that the central bank is constrained and cannot set the net nominal interest rate at a negative level. To link nominal and real interest rates we use Fisher relation:

$$1 + i_t = R_{t+1} \frac{P_{t+1}}{P_t} \tag{46}$$

During the significant financial market disruption monetary policy conducted in a standard way is not sufficient as the central bank cannot push interest rates lower, however to further ease monetary conditions it runs large-scale assets purchases. At the beginning of the crisis central bank buys fractions $\varphi_{s,t}$ and $\varphi_{b,t}$[9] of the outstanding stocks of private assets and of long-term government bonds, so: $S_{g,t} = \varphi_{s,t} S_t$ and $B_{g,t} = \varphi_{b,t} B_t$.

3.10 Resource constraint and equilibrium

Final output is divided between consumption, investment, government purchases and costs of central bank intermediation Φ_t. Aggregate resource constraint is as follows:

$$Y_t = C_t + I_t + f\left(\frac{I_t}{I_{t-1}}\right) I_t + G_t + \Phi_t \tag{47}$$

where the last term is the cost of central bank intermediation $\Phi_t = \tau_s Q_{t-1} S_{g,t-1} + \tau_b q_{t-1} B_{g,t-1}$. In order to close the model, we need market clearing in markets for loans, domestic government bonds and labor. The quantity of extended loans is equal to the sum of newly acquired and undepreciated capital:

$$S_t = I_t + (1 - \delta) K_t \tag{48}$$

The quantity of the long-term government bonds is constant:

$$B_t = \bar{B} \tag{49}$$

Private assets and government bonds deposit markets clear:

$$S_t = S_{p,t} + S_{g,t} \tag{50}$$

$$B_t = B_{p,t} + B_{g,t} \tag{51}$$

Intermediate goods market clears:

$$Y_{m,t} = \left(Y_{H,t} + Y^*_{H,t}\right) \Delta_{p,t} \tag{52}$$

Finally, labor demand equals supply.

[9] We assume that both parameters values evolve according to AR(2) stationary processes.

4 Model analysis

In this section we discuss the results of several simulations. First one is a comparison of responses of a model economy to a capital quality shock in a SOE and a closed economy when the central bank is able to set negative nominal interest rates. Second one repeats first exercise, although this time monetary authority is constrained by the ZLB (here we also report IRFs of a SOE and a closed economy). Third simulation presents the effects of the negative capital quality shock in a SOE under three different scenarios. Next we compare them with a closed economy setup. Finally, we show the differences in responses of model variables given it is a SOE or not. The last exercise is called crisis experiment, since we try to calibrate a LSAP value such that it mimics first round of assets purchases undertaken by BoE via APF.

Since the purchases composed of either private securities or government bonds have identical impact on model economy (they are the same when taking into account proportional advantage in seizure rate of bonds Δ) we analyze policy shock associated with the purchases of government bonds as it was the case in the UK.

4.1 Calibration

Parameters values are identical to those in GK, which makes our results comparable with their findings. When it comes to the parameters describing a SOE version of the model we take values from Gertler et al. [2007] for calibrating the exports of domestic goods (36) and these are: $\iota = 1$, $\varpi = 0.15$, from De Paoli [2009]: $\omega = 5$. With regard to theparameter of external risk premium it is set at the low value of $\psi = 0.00001$ - thus it has a little effect on a model dynamics, though it stationarizes the model variables. Last choice concerns parameter of openness. We pick such value that in the steady-state ratio of imports to final output totals roughly 30%, which is the average value of imports to GDP in period 2008-2013, so $\nu = 0.30$. The same applies to the calibration of steady-state exports. As noted before in the UK exports adjusted for imports totals 23.5% of GDP and this is the same in our model.

All the exercises were conducted as stochastic simulations in Dynare [Adjemian et al., 2011]. To compute impulse response functions at the ZLB we make use of OccBin toolkit [Guerrieri and Iacoviello, 2015]. OccBin is an algorithm that solves occasionally binding constraints using first-order perturbation method in a piecewise way to approximate solution.

4.2 Capital quality shock

First exercise shows how model economy behaves after a negative capital quality shock hits. Figure 2 illustrates response of variables. After the hit economy loses its potential to produce as much as could have been produced, even though stock of capital does not change. This is because capital is more obsolete and its effective amount is reduced. Hence, one should expect drop in the intermediate and consequently the domestic output. In both economies we observe quite similar paths of final output, however the drop of output is more persistent in a closed economy - in a SOE it returns to the steady-state after eighteen quarters, whereas in a closed economy it takes more than twenty periods. Not surprisingly in a SOE final output shrinks more in initial periods. It bottoms out four quarters after the shock at the level 33% below the steady-state (in a closed model this deviation reaches 31%). This fact can be attributed to the deprecation of domestic currency (increase of real exchange rate) in initial five periods, which makes imports price higher and it makes more profitable to export them than consume at home. Additionally, higher imports price contributes to the increase in inflation. Another difference concerns a nominal interest rate set by central bank, which reacts stronger in a closed economy. This stems from the lower inflation, which in a SOE is compensated by the real exchange rate depreciation.

Capital quality shock similarly affects the capital price in both environments. Since the stock of capital is less effective, return on this type of asset is lower and its price decreases. Another financial variable - real risk-free rate - declines more in a closed economy, because of the differences in nominal interest rate set by the central bank. Excess returns on capital and domestic bonds behave similarly, though they rise stronger in a SOE, because of weaker response of inflation.

Table 1: Parameters

Parameter	Value	Description
β	0.995	Discount rate
h	0.815	Consumption habit parameter
χ	3.482	Relative utility weight of labor
$\frac{B}{Y}$	0.450	Steady-state domestic government bonds supply
φ	0.276	Inverse Frisch elasticity of labor supply
θ	0.345	Fraction of capital that can be diverted
Δ	0.500	Proportional advantage in seizure rate of government debt
X	0.006	Transfer to the new bankers
σ	0.972	Probability of being a banker next period
α	0.330	Capital share
δ	0.025	Depreciation rate
η_i	1.728	Inverse elasticity of investment to the price of capital
ε	4.167	Elasticity of substitution
γ	0.779	Probability of keeping the price constant
$\frac{G}{Y}$	0.200	Steady-state ratio of government expenditures to final output
ρ_{ir}	0.500	Taylor rule inertia
κ_π	1.500	Inflation coefficient in the Taylor rule
κ_X	-0.125	Markup coefficient in the Taylor rule
ι	1.000	Elasticity of export demand
ϖ	0.150	Exports smoothing
ω	5.000	Elasticity of substitution between domestic and foreign goods
ν	0.300	Index of openness
ψ	0.00001	External risk premium

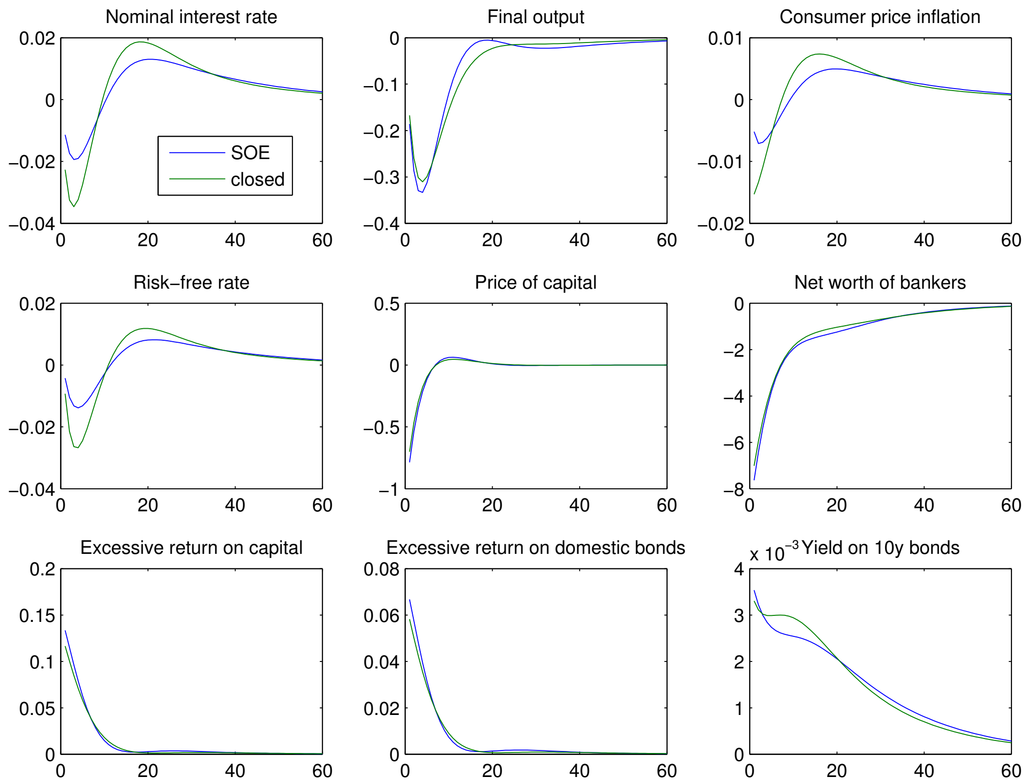
4.3 Capital quality shock and the ZLB

Second simulation repeats previous one, however here we take into account the fact that the monetary authority is constrained by the ZLB. We assume that capital quality shocks hit the economy consecutively in first four periods and each one is equal to -1.5%. Such obsolescence of capital induces negative nominal interest rate, however it is impossible to set nominal interest rate at the level implied by Taylor rule. ZLB binds for three quarters in a SOE and for eight periods in a closed economy. As in previous simulation consumer price inflation drops more heavily in a closed economy. Again this is due to the real exchange rate movement, which increases in initial periods and makes imports more expensive. After fifth period onwards it depreciates substantially and reaches level of 1% below its steady-state value. Domestic currency depreciation helps in boosting competitiveness of exports. Thus, final output bottoms out only 7.5% below the steady-state in a SOE and 18.5% in a closed economy.

Due to the significant scale of capital quality shock, price of capital in a closed economy plummets by 22.8% of its steady-state value, whereas in a SOE it declines by 14.5% of the steady-state value. This dramatic change in assets prices provokes drop in the net profits of banking system, which makes bankers worse off. Now they cannot transfer additional funds to households, so we can expect additional drop in the consumption. Increased excess return on capital means that there is a larger spread between the rates at which funds are borrowed and lent. In other words for a constant value of the risk-free rate paid on deposits, there is a larger cost of obtaining the funds. This leads to the decreased demand for loans. Since loans are the ultimate source of financing the investment, we can anticipate that it will be even more subdued. As the bottom-left panel shows excess return on private securities jumps 4.3% above the steady-state in a closed economy and 3.2% in a SOE.

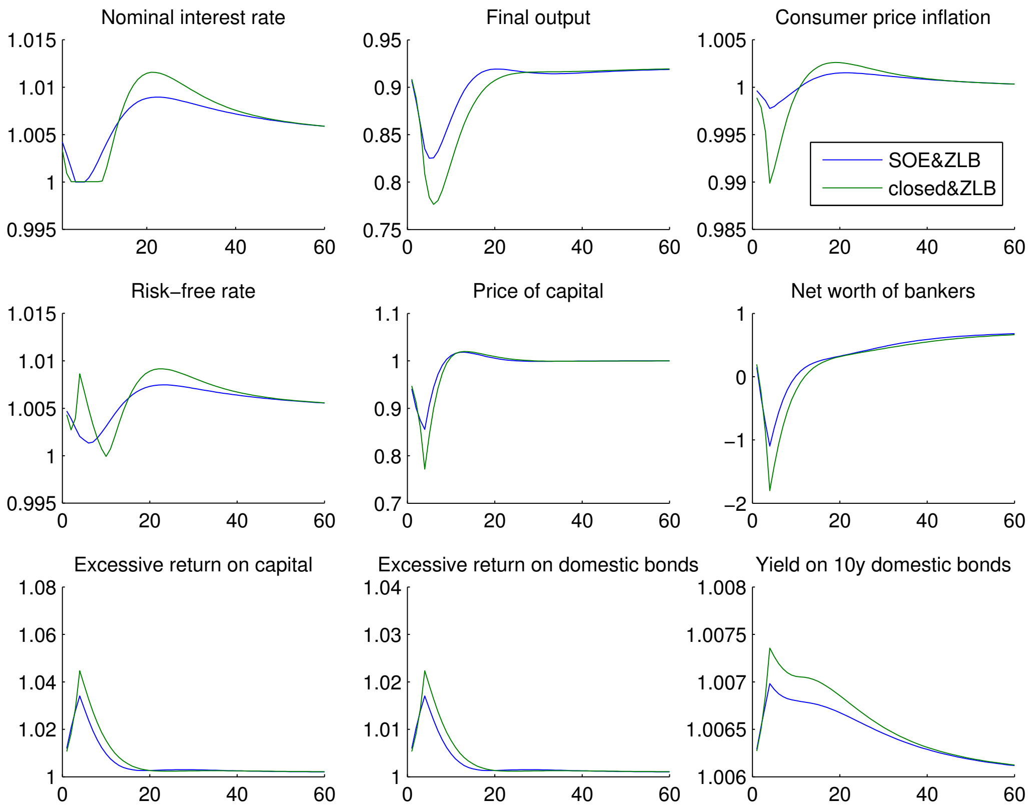
Although the differences between a SOE and a closed economy are not large with regard to financial variables, the description of impulse transmission mechanism from financial markets to the real activity states that all these small discrepancies affect the economy within multiple channels. Moreover a SOE can compensate these negative shocks due to the international trade. This intuition is proved by the significant difference in IRF of final output.

Figure 2: Capital quality shock



Note: Percentage point deviations from the steady-state.

Figure 3: Capital quality shock and the ZLB



Note: IRFs are reported in levels.

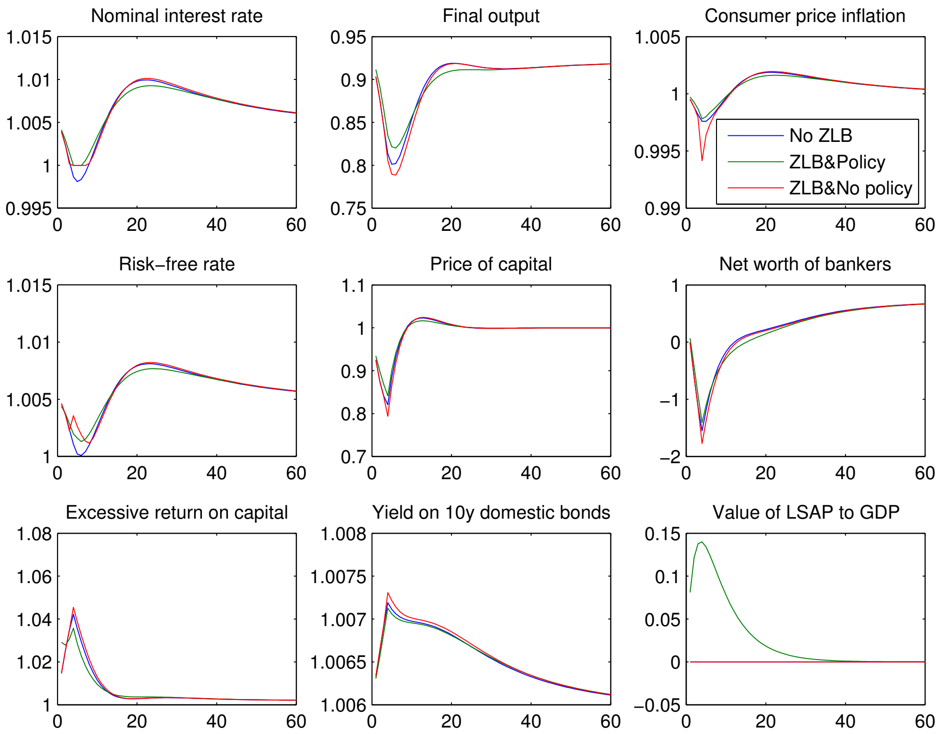
Summing up, two preceding experiments show that a crisis resulting from a negative capital quality shock is less severe in a SOE, especially when the ZLB is binding. When monetary authority can set negative rate these differences are not significant, however constraining monetary policy makes the same scenario quite different. In the next section we analyze the same situation, but we allow for the unconventional policy.

4.4 Crisis experiment

In the last section we assume that the sequence of negative capital quality shocks pushes the central bank nominal interest rate to zero and necessitates the use of unconventional policy to further ease monetary conditions. As was mentioned earlier, we set shocks values in order to approximate first round of a LSAP in the UK. BoE interest rate has reached effective ZLB (equal to 0.5%) in the first quarter of 2009, after that APF was approved and initially equaled £75bn, but after one year the amount of assets bought totaled £200bn. To make our simulation close to the case of a LSAP in the UK we make up a scenario in which in the first four quarters economy is hit by negative capital quality shocks, each equal to -1.5%, and at the same time monetary authority decides to start a LSAP with intention to buy domestic government bonds equal to 14% of the final output within period of four quarters. After that time acquired assets are slowly sold back to the financial intermediaries. Figure 4 presents reaction of nine variables in a SOE model in the policy scenario and alternative - without non-standard measure. Blue lines correspond to the environment with no constraint on nominal interest rates, which serves as a benchmark for comparison between unconstrained monetary policy and the other two cases.

ZLB is effective for three quarters if a LSAP is active and for four quarters with no policy in place. When the central bank buys bonds the path of the nominal interest rate is different than in the other two

Figure 4: Crisis experiments in a SOE under three scenarios

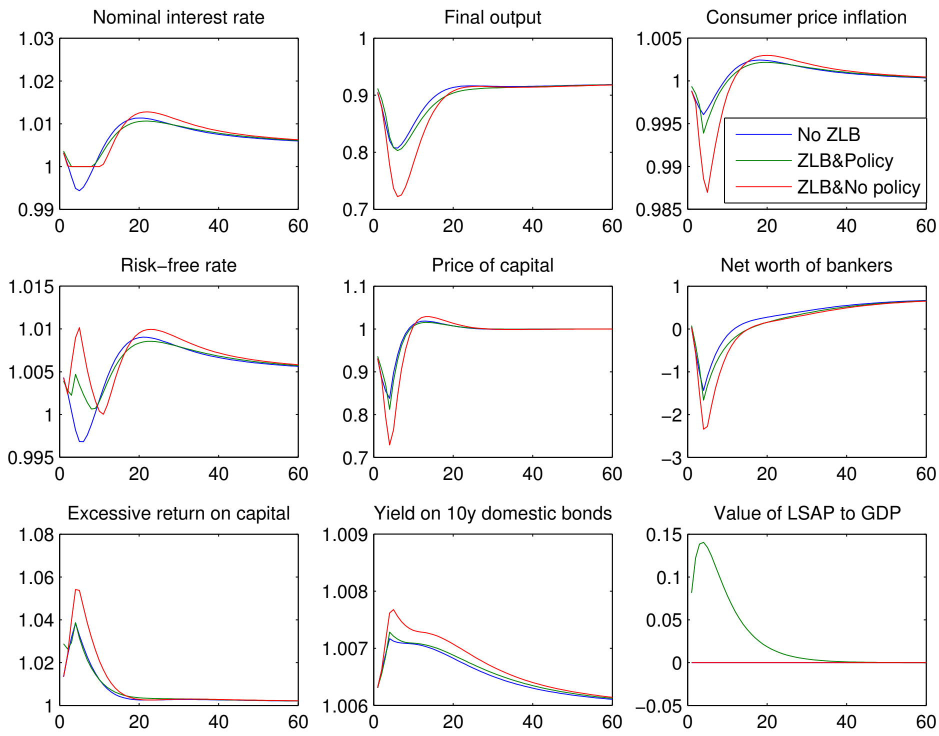


Note: IRFs are reported in levels.

scenarios. Nominal interest rate hikes take place earlier in case of LSAP, because of its substantial size that makes monetary conditions very loose. This is proved by the response of final output which declines by 14.4% without LSAP and by 11% in the alternative scenario, which is lower then in unconstrained case (13%). Inflation goes down below 5.9% of the steady-state without policy, while further easing of monetary policy can compensate this decrease to 2.2% (in unconstrained case it would have decreased by 2.4%). In the first five quarters in no policy scenario, the risk-free rate on domestic deposits is a mirror image of inflation, since during this time nominal interest rate is constant and equal to zero. As the bottom-left panel shows, without policy excess return on capital rises 4.4% above the steady-state level. This spike can be limited by the central bank intermediation which decreases spreads between lending and borrowing rates to 3.4% (so it decreases it by 22 p.p. comparing it with no policy). Note that the LSAP limits the drop of capital price by nearly 11 p.p. (from -20.6% to -15.8%). This means that the cost of borrowing for investment is lower than it would have been the case in no policy setup. Summing up, due to the LSAP of such magnitude, economy is in even better situation than in the case of the unconstrained monetary policy.

Figure 5 illustrates asset purchases in a closed economy. Observe that in a SOE dissimilarities were not as large as in a closed economy. This can be justified by the lack of the international trade channel. In this setup all the funds that are intermediated by central bank circulate through domestic economy. In previous case part of the LSAP leaked to the rest of the world since final output was partially composed of foreign goods.

Figure 5: Crisis experiments in a closed economy



Note: IRFs are reported in levels.

4.5 Effects of LSAP

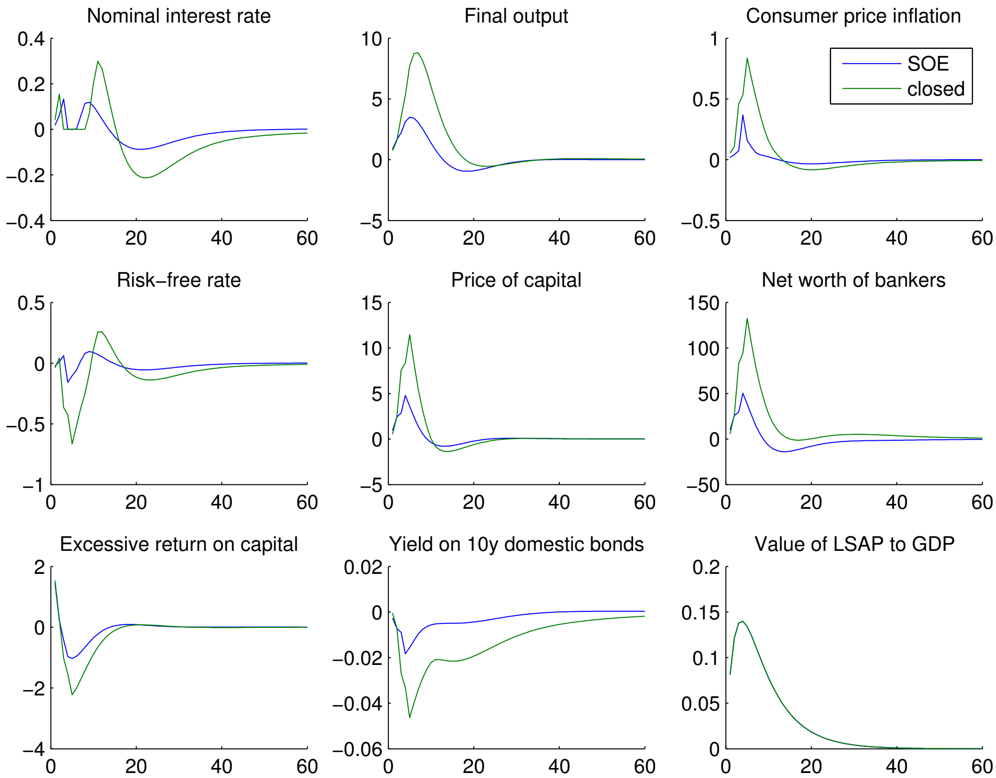
So far we compared different scenarios under both setups, but still we are not able to address question posed at the beginning of this study. Does the international openness matter for the effectiveness of LSAP? To what extent does the unconventional monetary policy leak to the rest of the world?

To solve this problem we simulate a SOE and a closed economy models with policy and no policy as in the last example so we choose the negative quality shock of -1.5% to hit economy for four consecutive quarters. At the same time we allow for conducting a LSAP. Next we calculate the difference between each model variable when policy is in place and when there are no non-standard measures implemented. Finally, we divide those values by the steady-state level of a given variable. Such exercise shows differences in the effectiveness of unconventional policies in both cases.

Figure 6 presents the effects of running a LSAP and the counterfactual scenario without policy. In a closed economy benefits of purchasing assets are two times higher in case of final output and even larger with regard to inflation (than in case of a SOE). Not surprisingly excess returns on capital are initially quite similar in both economies - this is because in both cases central bank buys only domestic government bonds. Hence, prices and returns react in the same way. Moreover it affects net worth of bankers similarly, however as opposed to a SOE, in a closed economy all this net worth, after being transferred to household, is devoted to the consumption of domestic products, while in a SOE part of the increased consumption demand leaks to the rest of the world. In the next periods we can observe rising discrepancies. This is caused by the fact that in a closed economy whole monetary stimulus circulates within domestic sector, while open economy transfers part of the increased demand abroad (as imports). Besides the international trade channel, we have to bear in mind that in a SOE households are allowed to invest in foreign deposits, which means that domestic banks cannot raise as much funds as would have been possible in a closed economy. Hence, domestic financial intermediaries are not able to expand their lending in a way it would have been done in an autarky.

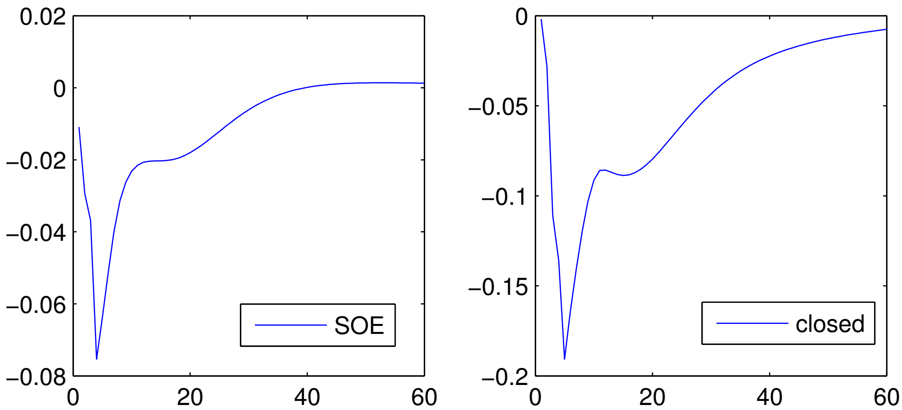
Large part of the literature dealing with the effects of unconventional policy concentrates on the measurement of increase in final output and inflation, but also particular importance is attached to the reduction

Figure 6: Effectiveness of a LSAP in a SOE and a closed economy



Note: Differences between policy and no policy scenarios, both relative to the steady-state (in p.p.).

Figure 7: Reduction of ten-year government bonds yields



Note: Differences between the annualized yields in the policy and no policy cases, both reported as p.p.

of the long-term yields, which is intermediate objective of a LSAP. Our analysis suggests that a LSAP can reduce long-term yields at most by 7.5 basis points when taking into account international linkages, while in a closed economy it decreases yields by 19.1 basis points.

5 Concluding remarks

The aim of our study was to show that ignoring international dimension leads to the overestimation of a LSAP's impact on the real activity. To prove that we extended model designed by Gertler and Karadi [2013] in a way that it is a small open economy. We conducted several simulations suggesting that international dimension has a non-negligible role in a transmission of a LSAP to the real activity. We find that a LSAP similar to the first round of APF purchases run by BoE is three times less effective in terms of final output when a model economy is opened. Even though our model is based on a well-known, workhorse version we have to treat those results with caution. We still believe that there is a room for further improvement of the model.

The most important limitation is the fact that in our model central bank intermediation is not targeted to the non-bank financial institutions as was the case in the UK. BoE decided to buy assets from non-banks simply because it leads to an increase in the broad money aggregate. Note that when a LSAP is targeted to insurers or pension funds, central bank credits them with newly created reserves that are held as deposits in their banks. As a result not only central bank's balance sheet expands, but also private bank's balance sheet gets bigger since it has new assets (reserves) and liabilities (deposits). However if the central bank buys assets from banks it expands their balance sheet, because of creating reserves and acquiring gilts, but no such effect occurs within private bank's balance sheet, since it just changes the structure of its assets without changing its overall value, i.e. it has more reserves instead of gilts. Based on the evidence from [Joyce and Spaltro, 2014], it might be beneficial to introduce some kind of heterogeneity to the banking system. Estimation conducted on the data at the bank level showed that smaller banks respond stronger to a LSAP with regard to lending growth. Moreover, in terms of the banking sector it should be underlined that financial system in the UK is global, so that model should be extended in a way that allows domestic financial intermediaries acquiring foreign assets. That would certainly limit effects of a LSAP. Finally, we ignored the fact that throughout the time BoE's MPC used forward guidance as the additional tool to influence agents' expectations. This means that the effects stemming from the unconventional policy have to be divided between more than two tools.

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Appendix

Derivations

Equations (17) and (18) can be derived as follows:

$$E_t\widetilde{\Lambda}_{t,t+1}N_{t+1} = E_t\widetilde{\Lambda}_{t,t+1}\left[-R_{t+1}D_{h,t}^H + N_{t+1} + R_{t+1}D_{h,t}^H\right] =$$

$$= E_t\widetilde{\Lambda}_{t,t+1}\left[R_{t+1}\left(N_t - Q_tS_{p,t} - q_tB_{p,t}\right) + R_{k,t+1}Q_tS_{p,t} + R_{b,t+1}q_tB_{p,t}\right] =$$

$$= E_t\widetilde{\Lambda}_{t,t+1}\left[R_{t+1}N_t + \left(R_{k,t+1} - R_{t+1}\right)Q_tS_{p,t} + \left(R_{b,t+1} - R_{t+1}\right)q_tB_{p,t}\right] = \theta Q_tS_{p,t} + \Delta\theta q_tB_{p,t}$$

Now using the fact that $\Delta\left(R_{k,t+1} - R_{t+1}\right) = \left(R_{b,t+1} - R_{t+1}\right)$ we get:

$$E_t\widetilde{\Lambda}_{t,t+1}\left[R_{t+1}N_t + \left(R_{k,t+1} - R_{t+1}\right)Q_tS_{p,t} + \left(R_{k,t+1} - R_{t+1}\right)\Delta q_tB_{p,t}\right] = \theta Q_tS_{p,t} + \Delta\theta q_tB_{p,t}$$

Which is the same as:

$$E_t\widetilde{\Lambda}_{t,t+1}R_{t+1}N_t + E_t\widetilde{\Lambda}_{t,t+1}\left(R_{k,t+1} - R_{t+1}\right)\left(Q_tS_{p,t} + \Delta q_tB_{p,t}\right) = \theta\left(Q_tS_{p,t} + \Delta q_tB_{p,t}\right)$$

Or equivalently:

$$\frac{E_t\widetilde{\Lambda}_{t,t+1}R_{t+1}}{\theta - E_t\widetilde{\Lambda}_{t,t+1}\left(R_{k,t+1} - R_{t+1}\right)}N_t = Q_tS_{p,t} + \Delta q_tB_{p,t}$$

Equilibrium

Below we list equations that define equilibrium:

1. Marginal utility of consumption

$$\lambda_t = \frac{1}{\left(C_t - \bar{h}\,C_{t-1}\right)} - hab\beta E_t\frac{1}{\left(C_{t+1} - \bar{h}\,C_t\right)}$$

2. Euler equation

$$E_t\Lambda_{t,t+1}R_t = 1$$

3. Stochastic discount rate

$$\Lambda_{t,t+1} = \beta\frac{\lambda_{t+1}}{\lambda_t}$$

4. World interest rate

$$E_t\Lambda_{t,t+1}\frac{rer_{t+1}\pi_{t+1}}{rer_t\pi_{t+1}^*}\left[\mathrm{e}^{\psi\left(\overline{rer}\overline{D_h^F} - rer_tD_{h,t-1}^F\right)}\right]R_t^* = 1$$

5. Labor market equilibrium

$$p_{m,t}(1-\alpha)\frac{Y_{m,t}}{L_t} = \frac{\chi L_t^{\varphi}}{\frac{1}{(C_t - hab\,C_{t-1})} - hab\beta E_t\frac{1}{(C_{t+1} - hab\,C_t)}}$$

6. Excess value of a unit of assets relative to deposits

$$mu_{s,t} = E_t \widetilde{\Lambda}_{t,t+1} \left(R_{k,t+1} - R_t \right)$$

7. Excess value of a unit of long term government bonds relative to deposits

$$mu_{b,t} = E_t \widetilde{\Lambda}_{t,t+1} \left(R_{b,t+1} - R_t \right)$$

8. Value of the risk-free rate

$$nu_t = E_t \widetilde{\Lambda}_{t,t+1} R_t$$

9. Indifference condition between capital and government bond excess returns

$$mu_{b,t} = \Delta mu_{s,t}$$

10. Expected shadow value of a unit of wealth

$$\Omega_{t+1} = (1-\sigma) + \sigma \left[mu_{s,t} \phi_t \left(1 - \varphi_{s,t}\right) + mu_{b,t} \phi_t \left(1 - \varphi_{b,t}\right) x + nu_t \right]$$

11. Proportion of value of government bonds relative to capital value within banks

$$x_t = \frac{q_t B_{p,t}}{Q_t S_{p,t}}$$

12. Optimal capital leverage

$$\phi_t = \frac{nu_t}{\left[\left(1 - \varphi_{s,t}\right) + \Delta x \left(1 - \varphi_{b,t}\right) \right] \left(\theta - mu_{s,t} \right)}$$

13. Aggregate capital

$$Q_t S_{p,t} = \phi_t N_t$$

14. Financial intermediaries net worth

$$N_t = Ne_t + Nn_t$$

15. Existing banks' net worth accumulation

$$Ne_t = \sigma \left[\left(R_{k,t} - R_{t-1} \right) \left(1 - \varphi_{s,t-1} \right) \phi_{t-1} + \left(R_{b,t} - R_{t-1} \right) \left(1 - \varphi_{b,t-1} \right) \phi_{t-1} x_{t-1} + R_{t-1} \right] N_{t-1}$$

16. New banks' net worth

$$Nn_t = 0.006$$

17. Marginal value product of effective capital

$$Z_t = p_{m,t} \alpha \frac{Y_{m,t}}{K_t}$$

18. Return to capital

$$R_{k,t} = \frac{Z_t + (1-\delta) Q_t}{Q_{t-1}} \xi_t$$

19. Long term government bond return

$$R_{b,t} = \frac{Xi + q_t}{q_{t-1}\pi_t}$$

20. Nominal yield to maturity

$$ib_t = \frac{Xi}{q_t} + 1$$

21. Intermediate good production function

$$Y_{m,t} = A_t K_t^{\alpha} L_t^{1-\alpha}$$

22. Optimal net investment decision

$$Q_t = 1 + \frac{\zeta}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2 + \zeta \frac{I_t}{I_{t-1}}\left(\frac{I_t}{I_{t-1}} - 1\right) - E_t \Lambda_{t,t+1}\left(\frac{I_{t+1}}{I_t}\right)^2 \zeta \left(\frac{I_{t+1}}{I_t} - 1\right)$$

23. Capital accumulation equation

$$K_{t+1} = \xi_{t+1}\left[I_t + (1-\delta)K_t\right]$$

24. Wholesale, retail output

$$Y_{m,t} = \left(Y_{H,t} + Y_{H,t}^*\right)\Delta_{p,t}$$

25. Price dispersion

$$\Delta_{p,t} = \gamma \Delta_{p,t-1}\pi_{H,t}^{\epsilon} + (1-\gamma)\left[\frac{1-\pi_{H,t}^{\gamma-1}}{1-\gamma}\right]^{\frac{-\epsilon}{1-\gamma}}$$

26. Markup

$$X_t = \frac{1}{p_{m,t}}$$

27. Optimal price choice

$$F_t = \left(Y_{H,t} + Y_{H,t}^*\right) p_{m,t} p_{H,t}^{-1} + \Lambda_{t,t+1}\gamma \pi_{H,t+1} F_{t+1}$$

28.

$$H_t = \left(Y_{H,t} + Y_{H,t}^*\right) p_{H,t}^{-1} + \Lambda_{t,t+1}\gamma \pi_{H,t+1} H_{t+1}$$

29. Optimal price choice

$$p_{H,t}^{NEW} = \frac{\epsilon}{\epsilon - 1}\frac{F_t}{H_t}$$

30. Domestic price inflation

$$\pi_{H,t} = \frac{p_{H,t}}{p_{H,t-1}}\pi_t$$

31. Domestic price index

$$\pi_{H,t}^{1-\epsilon} = \gamma + (1-\gamma)\left(\pi_{H,t}^{NEW}\right)^{1-\epsilon}$$

32. Final output composition

$$Y_t = \left[(1-\nu)^{\frac{1}{\omega}} Y_{H,t}^{\frac{\omega-1}{\omega}} + \nu^{\frac{1}{\omega}} Y_{F,t}^{\frac{\omega-1}{\omega}}\right]^{\frac{\omega}{\omega-1}}$$

33. Demand functions

$$\frac{Y_{H,t}}{Y_{F,t}} = \frac{1-\nu}{\nu}\left(\frac{p_{H,t}}{p_{F,t}}\right)^{-\omega}$$

34. Price index

$$1 = \left[(1-\nu)p_{H,t}^{1-\omega} + \nu p_{F,t}^{1-\omega}\right]^{\frac{1}{1-\omega}}$$

35. Price of imported goods

$$p_{F,t} = rer_t$$

36. Price of exported goods

$$p_{H,t} = rer_t p_{H,t}^*$$

37. Exported final goods

$$Y_{H,t}^* = \left[\left(p_{H,t}^*\right)^{-\iota} Y_t^*\right]^{\varpi}\left(Y_{H,t-1}^*\right)^{1-\varpi}$$

38. Net export

$$nx_t = p_{H,t}Y_{H,t}^* - p_{F,t}Y_{F,t}$$

39. Fisher equation

$$1 + i_t = R_{t+1}\pi_{t+1}$$

40. Government

$$G_t = \bar{G}$$

41. Interest rate rule

$$i_t = \max\left[1\,, \rho_{ir}i_{t-1} + (1-\rho_{ir})\left(\kappa_\pi \pi_t + \kappa_y\left(\frac{X_t}{\frac{\epsilon}{1-\epsilon}}\right)\right)\right]$$

42. Bond policy

$$\varphi_{b,t} = \epsilon_{b,t}$$

43. Aggregate resource constraint

$$Y_t = C_t + I_t + f\left(\frac{I_t}{I_{t-1}}\right) I_t + G_t + \tau_s Q_{t-1} S_{g,t-1} + \tau_b q_{t-1} B_{g,t-1}$$

44. Capital quality shock

$$\xi_t = \rho_\xi \xi_{t-1} + e_{\xi,t}$$

45. Bond policy shock

$$\epsilon_{b,t} = \rho_{1,b}\epsilon_{b,t-1} + \rho_{2,b}\epsilon_{b,t-2} + e_{b,t}$$

46. Effective capital

$$K_t = \xi_t S_t$$

47. Wages

$$w_t = p_{m,t}\left(1-\alpha\right)\frac{Y_{m,t}}{L_t}$$

48. Financial intermediaries' corporate bond holdings

$$S_{p,t} = S_t$$

49. Financial intermediaries' Long term Treasury holdings

$$B_{p,t} = \left(1-\varphi_{B,t}\right)\overline{B}$$

50. Deposits in domestic currency

$$D_{h,t}^H = Q_t S_{p,t} + q_t B_{p,t} - N_t$$

51. Deposits in foreign currency

$$D_{h,t}^F = -\frac{nx_t}{rer_t} + R_{t-1}^*\left[\mathrm{e}^{\psi\left(\overline{rer}\,\overline{D_h^F} - rer_t D_{h,t-1}^F\right)}\right] D_{h,t-1}^F \frac{1}{\pi_t^*}$$

Foreign price, interest rate and output are exogenous AR(1) processes.