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Devaluation with Exchange rate Floor in a Small Open Economy

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Abstract:
In recent years, central banks in the Czech Republic and Switzerland used exchange rate floor commitment to use unlimited FX interventions to keep the exchange rate above the declared floor rate to persistently devalue their currency and stimulate inflation. Central banks in other small open economies, such as Sweden and Israel, faced similar challenges and could have chosen this instrument as well. In this paper, I develop an extension to dynamic stochastic general equilibrium (DSGE) models that could be used to esimate impact of such devaluations with exchange rate floor. As an illustration, I apply the extension to models estimated for Sweden and the Czech Republic. In particular, I simulate impact of a 5 percent devaluation with the exchange rate floor used as an unconventional monetary policy instrument with interest rates at the zero lower bound. In the first year after the devaluation, the annual consumer price in inflation increases by 0.8 percent in Sweden and 1.8 percent in the Czech Republic. The long-term exchange rate pass-through to consumer prices is 40 percent and 65 percent, respectively. The increase in inflation is highly dependent on the persistent nature of the devaluation.

Keywords: Exchange Rate Floor, Devaluation of Currency, Unconventional Monetary Policy Instrument, Dynamic Stochastic General Equilibrium Models, Exchange Rate Pass-Through
JEL: E31, E37, E58, F41

Abstract

In recent years, central banks in the Czech Republic and Switzerland used exchange rate floor—commitment to use unlimited FX interventions to keep the exchange rate above the declared floor rate—to persistently devalue their currency and stimulate inflation. Central banks in other small open economies, such as Sweden and Israel, faced similar challenges and could have chosen this instrument as well. In this paper, I develop an extension to dynamic stochastic general equilibrium (DSGE) models that could be used to esimate impact of such devaluations with exchange rate floor. As an illustration, I apply the extension to models estimated for Sweden and the Czech Republic. In particular, I simulate impact of a 5 percent devaluation with the exchange rate floor used as an unconventional monetary policy instrument with interest rates at the zero lower bound. In the first year after the devaluation, the annual consumer price inflation increases by 0.8 percent in Sweden and 1.8 percent in the Czech Republic. The long-term exchange rate pass-through to consumer prices is 40 percent and 65 percent, respectively. The increase in inflation is highly dependent on the persistent nature of the devaluation.

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1 Introduction

In recent years, central banks in the Czech Republic and Switzerland used exchange rate floor—commitment to use unlimited FX interventions to keep the exchange rate above the declared floor rate—to persistently devalue their currency and stimulate inflation. Central banks in other small open economies, such as Sweden and Israel, faced similar challenges and could have chosen to use this instrument. In this paper, I develop an extension to DSGE models that captures impact of such devaluation with exchange rate floor. In particular, it could be used to simulate impact on inflation after the devaluation.

The extension is based on the assumption that devaluation leads to permanent depreciation of exchange rate to the floor rate. During the time exchange rate commitment is in place, it means that central bank is successful in maintaining exchange rate at or above the floor rate. Such assumption is justified by, in principle, unlimited amount of newly created money that the central bank can use to finance FX interventions to devalue the currency. After the termination of the commitment, exchange rate generally moves away from the floor. In the simulation, I assume there are no clear expectations about direction of this movement; the expectations then do not affect the simulated response of inflation after the devaluation. If there are expectations about direction of the exchange rate movement, their impact could be potentially modeled with anticipated shocks to exchange rate: shocks that are expected to affect exchange rate after the termination of the commitment (not done in this analysis).

Next, I briefly outline the intuition behind the methodological extension. The full description is in Section 3.2. When modeling permanent depreciation of nominal exchange rate, I built upon how temporary depreciations of nominal exchange rate are modeled within DSGE models. Such depreciation of nominal exchange rate could be modeled as a shock to the exogenous process in the uncovered interest parity (UIP) condition. The shock usually represents "country risk premium shock" but it could be more broadly interpreted as exogenous exchange rate shock (i.e., shock that affects economy through its impact on exchange rate). DSGE models work with real rather than nominal exchange rate. After the shock, real exchange rate initially depreciates but then it—as all other real variables in the model—returns to its initial value (see Figure 1). Real exchange rate expresses the real price of foreign relative to domestic currency. It is equal to nominal exchange rate multiplied by a ratio of domestic to foreign price level. Foreign prices are assumed not to be affected by a shock in the small domestic economy. It implies that, after the shock, the percentage depreciation (increase) of real exchange is equal to percentage deprecation (increase) of nominal exchange rate less percentage increase of domestic price level. Putting it differently, percentage depreciation (increase) of nominal exchange rate is equal to the sum of the percentage depreciation (increase) of real exchange rate and the percentage increase of domestic price level (see Figure 1).

When I model devaluation with exchange rate floor, I assume that it does not lead to structural change in economy. I show that it then does not lead to change in the structure of DSGE model and devaluation with exchange rate floor (i.e., permanent depreciation of nominal exchange rate) could be modeled as a shock to the same exogenous process in the equation of the same form as the uncovered interest parity (UIP) condition. The shock now represents "change in the real exchange rate trend and its impact on inflation" but it could be again broadly interpreted as an exogenous exchange rate shock (i.e., shock that affects economy through its impact on exchange rate). Since the structure of the model is the same, the shock leads to the same temporary depreciation of real exchange rate, which then has the same impact on domestic prices. However, nominal exchange rate is now constant to the exchange rate floor. Using previously defined relation, sum of percentage depreciation (increase) of real exchange rate and percentage increase of domestic prices has to be constant as well. Permanent depreciation of nominal exchange rate therefore leads—beside temporary depreciation of nominal exchange rate—to an additional depreciation of real exchange rate and increase in domestic prices (see Figure 2). In Section 3.2, I interpret this additional depreciation as long-term (trend) depreciation of real exchange rate and compute its impact on domestic prices. To my best knowledge, there is no established methodology for computing this impact and I therefore propose a simple method built upon three blocks: import intensity of various sectors in economy, gradual learning about effectiveness of the exchange rate floor, and price stickiness.

The methodological extension in this paper constitutes a contribution to current DSGE literature as previous methodologies could be used to simulate only impact of devaluations that lead to a temporary depreciation of nominal exchange rate (e.g., Montoro & Ortiz (2013) and Benes *et al.* (2013)). The methodological extension has potentially also wide practical application. Central banks could apply it to DSGE models they are currently using to estimate expected impact of devaluation with exchange rate floor. It could help them to decide whether to use this rather than other unconventional monetary policy instruments. Importantly, if they decide to use this instrument, it could help them to determine by how much to devalue the currency to achieve the desired increase of inflation.

I apply the methodological extension to the model of Christiano *et al.* (2011), which has been constructed and estimated for the Swedish economy. I choose this model as it is one of the most widespread and respected small open economy models in DSGE literature. I apply the extension to an already constructed and estimated model to be able to focus in this paper just on the properties of the methodological extension. In the simulation, devaluation is used as an unconventional monetary policy instrument with interest rates at the ZLB in order to persistently devalue nominal exchange rate by five percent. According to the simulation, the annual inflation increases by 0.8 percent, 0.7 percent, and 0.3 percent in the three years after devaluation; the long-term exchange rate pass-through is about 40 percent. The increase in inflation is highly dependent on the persistent nature of the devaluation.

The paper is organized as follows. Section 2 briefly describes the structure and estimation of the DSGE model of Christiano *et al.* (2011). Section 3 introduces the methodology of the exchange rate floor. Section 4 presents the results of the simulation. Section 5 concludes with a brief application of the extension to the devaluation with exchange rate floor (exchange rate commitment) that the Czech National Bank introduced in November 2013.

2 Model description

Devaluation with the exchange rate floor could be simulated with any standard small open economy DSGE model, assuming it is appropriately adjusted as discussed in Section 3. I therefore do not build a model of my own, but rather use a model of Christiano *et al.* (2011), along with the code the authors have provided. The model is one of the most widespread and comprehensive in this branch of literature. Additionally, it has two structural features that enhance the precision of the simulation. First, the goods part of the economy consists of multiple sectors, including the consumption sector, and the exchange rate pass-through could be thus estimated specifically for consumer prices. Second, UIP condition is of such form that estimated persistence of risk premium process is a good proxy for persistence of exchange rate floor shock in the adjusted model.

In this section, I just briefly describe the main buildings blocks of the model. More rigorous and detailed description can be found in the original paper.

Foreign economy stands for the rest of the world, and it is assumed to be exogenous to developments in the small domestic economy. Relations among the three foreign variables—GDP, consumer inflation, and nominal interest rate—are represented by a VAR model, which is estimated using Cholesky decomposition with this ordering of variables.

Domestic economy is modeled more comprehensively. The goods production part consists of consumption, investment, government, and export sectors. The final consumption good is an aggregate of homogenous domestic good and homogenous imported consumption good. The homogenous domestic good is an aggregate of differentiated intermediate domestic goods, produced using capital and labour as the two production inputs. The homogenous imported consumption good is an aggregate of differentiated intermediate imported consumption goods, produced using the homogenous foreign good as the only input. Structure of the investment sector is the same only the homogenous imported good is produced by importers (intermediate producers) specific for this sector. Government sector uses only one input, homogenous domestic good. Export good sector uses both inputs, which are produced analogously to the first two sectors; unlike them, it produces differentiated goods, which are then aggregated into homogenous export good and sold to foreign economy. The aggregation technology in all sectors is Dixit-Stiglitz function and intermediate producers of domestic and of imported goods in all three sectors operate under monopolistic competition and are subject to nominal rigidities in form of Calvo stickiness and inflation indexation. Lastly, prices of imported goods are sticky in domestic currency, what implies so-called local currency pricing.

The model incorporates financial frictions, similar to financial accelerator of Bernanke *et al.* (1999), and introduces three new types of agents. Capital producers combine undepreciated capital from previous period with current final investment good to produce new capital. Financial intermediaries collect deposits from households to finance loans of entrepreneurs. Entrepreneurs use loans and their own net worth to buy capital and then rent it to intermediate producers of domestic good. The effective value of capital, which the entrepreneurs rent, is a multiplication of the purchased capital and idiosyncratic productivity shock. Financial intermediaries could observe these shocks only after paying monitoring costs, thus leading to asymmetric information between borrowers and lenders. Under the asymmetric information, the optimal debt contract is the standard debt contract, and the amount that financial intermediaries are willing to lend to entrepreneurs is a function of their net worth. This gives rise to balance sheet constraints and dependence of entrepreneurs' capital investments on their net worth.

Labour market is modeled with search and matching framework, introduced first by Mortensen & Pissarides (1994). The prominent role here plays employment agencies, which constitute an intermediary between continuum of workers from representative households and producers of intermediate domestic goods. The agencies are divided into N cohorts, and each period one cohort sets its wage through Nash bargaining with workers. The wage then stays in effect for $N-1$ periods, adjusted only according to inflation indexation.

At the beginning of each period, the workforce of each employment agency is first reduced by exogenous separations and then increased by newly hired unemployed workers. The number of newly hired workers is a function of the number of vacancies that an agency posted in the previous period. Furthermore, after realization of workers' productivity shocks, employment agencies set a cut-off level and workers with productivity below it are laid off. These three processes determine the extensive margin, employment in the economy. Intensive margin, the number of hours worked per employee, is determined at the end of each period such that marginal cost of workers from an additional hour is equal to marginal benefit of agencies from it.

Additionally to labour, households optimize also with respect to consumption and domestic bonds, resulting in the standard Euler equation. Their optimization with respect to foreign bonds, combined with the assumption of their perfect substitutability with domestic bonds, gives rise to UIP condition; its specific form will be discussed at the end of this section.

Government expenditures follow an AR(1) stochastic process and government revenues flow from capital, payroll, labour income, and consumption taxes. In addition, government levies from households lump-sum taxes or pays them lump-sum transfers such that its budget is balance in each period. Central bank interest rate policy is determined by the usual Taylor rule with interest rate smoothing. Model is closed by market clearing conditions in domestic economy and the balance of payments condition between domestic and foreign economy.

Model economy features multiplied real rigidities. Working capital requirements imply that domestic intermediate good producers must borrow money to pay for a part of their wage bill in advance. Producers of intermediate import goods must do the same for a part of the foreign output they import. Moreover, households display habit persistence in their utility from consumption, capital good producers face investment adjustment costs, and domestic intermediate good producers pay fixed costs and could vary utilization of the rented capital.

The stochastic structure of the model consists of one unit root exogenous process with stationary AR(1) innovations, seven stationary AR(1) exogenous processes, and nine white noise shocks. Unit root exogenous process represents labour augmenting technology of domestic intermediate good producers and introduces unit root trend into quantity variables and real wages. Stationary AR(1) processes represent the innovations to the labour augmenting technology of domestic intermediate good producers and the neutral technology of these producers. Further, these processes represent marginal efficiency of investment of capital good producers; consumption and labour preference of households; country risk premium in UIP condition; government expenditures; and entrepreneurial wealth. Concerning white noise shocks, five of them represent markups of producers of intermediate domestic goods, intermediate export goods, and intermediate imported goods for consumption, investment, and export sectors; three of them represent shocks to output, inflation, and interest rate in the foreign economy VAR model; and the last one stands for monetary policy shock.

In the estimations and the empirical part, the paper uses the log-linearized version of the model. The parameters of the model are partly calibrated and partly estimated with Bayesian inference for Sweden on a sample of nineteen variables spanning period 1995Q1–2010Q3. Among the nineteen variables are the three foreign variables, constructed as trade-weighted averages, and then domestic sectoral inflation rates, nominal interest rate, GDP and its main components, total hours worked, unemployment, real wage, real exchange rate, real stock prices, and corporate interest rate spread. Interest rates, inflation rates, and hours worked are taken in levels. The remaining variables are taken in logarithms and first-differenced.

I do not estimate the model on the updated sample as the last seven years were a rather turbulent period for Swedish and global economy, characterized also by the use of unconventional monetary policy instruments such as quantitative easing, negative interest rates, and forward guidance. Extending the already large-scale model of domestic economy for the impact of these instruments would be rather difficult (see, for example, Falagiarda (2014) for quantitative easing). Extending the foreign VAR model—to account for the impact that the use of these instruments in the global economy had on Sweden—would be even more challenging.

Next, I describe the uncovered interest parity (UIP) condition. To make it more illustrative, I will work with its logarithmic transformation:

$$R_t - R_t^* = \log S_{t+1} - \log S_t + \log \phi_t, \tag{1}$$

where R_t and R_t^* are domestic and foreign nominal interest rates, S_t is the nominal exchange rate in terms of domestic currency per unit of the foreign currency, and ϕ_t is risk adjustment term defined as

$$\phi_t = \exp(-\tilde{\phi}_a(a_t - a) + \tilde{\phi}_s(R_t - R_t^* - (R - R^*)) + \tilde{\phi}_t), \tag{2}$$

where a_t are net foreign assets of domestic economy in real domestic prices; variables without subscript represent steady state values; $\tilde{\phi}_a$ and $\tilde{\phi}_s$ are positive parameters; and $\tilde{\phi}_t$ is exogenous risk premium.

The term $-\tilde{\phi}_a(a_t - a)$ in (2) reflects that higher net foreign assets, lower indebtedness of domestic relative to foreign households, imply that domestic financial assets are less risky relative to foreign assets and the required interest rate on them is thus relatively lower. Following Schmitt-Grohe & Uribe (2003), the main purpose of this term is to induce stationarity of net foreign assets and consequently of other variables in the model.

The term $\tilde{\phi}_s(R_t - R_t^* - (R - R^*))$n (2) reflects that lower domestic relative to foreign interest rate makes domestic assets perceived to be relatively less risky as the borrowers in domestic economy face relatively lower interest rate burden. The main purpose of this term is, however, to make UIP condition more in line with the empirical evidence. First, VAR models investigating impact of monetary shocks show that interest rate increase leads, at least initially, to negative changes in the nominal exchange rate [see, e.g., a seminal paper of Eichenbaum & Evans (1995)]. Second, regressions of the realized nominal exchange rate changes on previous period interest rate differentials produce statistically significant negative estimates, rather than coefficient of 1, resulting in the so-called "forward discount puzzle" [see, e.g., seminal paper of Fama (1984)]. Consistent with this evidence, the prior mean of $\tilde{\phi}_s$ is set to 1.25, a value lower than 1, and the estimated value is 1.1.

Variable $\tilde{\phi}_t$ in (2) is an $AR(1)$ process that represents exogenous variations in relative riskiness between domestic and foreign assets. In practice, its interpretation is however much wider, and it represents non-fundamental shocks to the nominal exchange rate: changes in the nominal exchange rate that are not resulting from development in domestic or foreign variables, but rather come exogenously.

3 Methodology of exchange rate floor

In this section, I define and discuss what devaluation with the exchange rate floor means in the context of this paper, and then incorporate such defined the exchange rate floor into DSGE framework. The general definition of devaluation with the exchange rate floor is that it is a commitment of central bank to use unlimited FX interventions to keep the nominal exchange rate at or above the declared floor rate.

3.1 Modeling assumptions

A more rigorous definition is as follows: devaluation with the exchange rate floor is an exogenous shock that leads to permanent depreciation of nominal exchange rate to floor rate. In the following lines, I discuss plausibility of the two parts of this definition.

First, I focus on the part that it "leads to permanent depreciation of nominal exchange rate to the floor". During the time exchange rate commitment is in place, it means that central bank is successful in maintaining exchange rate at or above the floor rate. Such assumption is justified by, in principle, unlimited amount of newly created money that the central bank can use to finance FX interventions to devalue the currency. After the termination of the commitment, exchange rate generally moves away from the floor. In the simulation, I assume there are no clear expectations about direction of this movement; it then does not affect the simulated response of inflation to the devaluation. If there are expectations about direction of exchange rate movement, their impact could be modeled with anticipated shocks to exchange rate: shocks that are expected to affect exchange rate after the termination of the commitment (not done in this analysis).

Second, the assumption that devaluation is an exogenous shock implies that the exchange rate floor affects economy only through persistent depreciation of the nominal exchange rate. It therefore does not account for other channels: most notably, higher FX reserves of central banks that result from interventions in the FX market to weaken the currency and maintain the exchange rate floor.

A comprehensive analysis of the exchange rate floor should consider also this channel in addition to the exchange rate channel discussed in this paper.

Furthermore, to be able to simulate impact of other exogenous shocks in the economy, I make a stricter assumption about the path of exchange rate after devaluation with exchange rate floor. In the previous definition, I have assumed that exchange rate depreciates permanently to the floor rate after the devaluation. Now, I additionally assume that exchange rate does not move freely above the floor but stays exactly equal to the floor. I then simulate impact of other exogenous shocks with a DSGE model in which UIP condition is replaced with fixed exchange rate equation.

From theoretical perspective, the additional assumption could be justified by presence of appreciation pressures, which counter potential depreciations resulting from other shocks in economy, and thus make exchange rate equal to the floor. These pressures could, for example, come from two following sources. First one is the appreciation trend of currency due to economic convergence of a country to a more developed large foreign economy (as in the case of the Czech Republic). Second potential source is inflow of foreign capital to domestic economy. This can occur because domestic economy and its assets are viewed as safe haven in times of widespread economic crisis (as in the case of Switzerland). Additionally, it could occur because the domestic economy chooses devaluation with the exchange rate floor rather than some other unconventional monetary policy instruments, which generally lead to lower short-term and long-term interest rates. If these instruments are chosen in other countries, interest rate in domestic economy is higher compared to them, and its assets are in higher demand.

The assumption is mostly supported by experience of the Czech Republic and Switzerland. In the Czech Republic, the exchange rate immediately after introduction of the exchange rate floor overshoot the floor rate by approximately 2 percent, stayed around that value for a year and a half, then decreased to the floor rate and stayed there for the following two years. In Switzerland, the exchange rate stayed at or slightly above the floor for the entire duration of the exchange rate floor.

3.2 Modeling of devaluation with the exchange rate floor

3.2.1 Exchange rate floor equation

First, I introduce methodology of devaluation with the exchange rate floor with other exogenous shocks in the model being zero. Later, I show that it is also consistent with non-zero values of the shocks. In DSGE model specified in the previous parts of the paper, the UIP condition in (1) is replaced with the following equation:

$$E_t S_{t+1} = S_t, \tag{3}$$

where S_t represents the nominal exchange rate. Given S_t is devalued to the floor rate at t, exchange rate is expected to stay permanently at the floor rate. It also actually stays equal to floor rate since the exchange rate floor is a shock that hits economy at t and other exogenous shocks are, for now, assumed to be zero.

In DSGE model, exchange rate, as well as all other prices, is expressed in real terms. Definition of the real exchange rate is

$$Q_t = \frac{P_t^* S_t}{P_t}, \tag{4}$$

where Q_t is the real exchange rate, P_t^* is foreign price level, and P_t is domestic (consumer) price level.

Equation (3) can be then expressed in terms of the real exchange rates and inflations. First, I multiply both sides of the equation by terms that are equal to 1:

$$E_t \left\{ S_{t+1} \frac{P_{t+1}^*}{P_{t+1}} \frac{P_{t+1}}{P_{t+1}^*} \right\} = S_t \frac{P_t^*}{P_t} \frac{P_t}{P_t^*}. \tag{5}$$

Then, I use the definition of the real exchange rate from (4), definition of inflation as an increase in the price level, and rearrange the equation:

$$E_t \left\{ Q_{t+1} \right\} = E_t \left\{ Q_t \frac{\Pi_{t+1}^*}{\Pi_{t+1}} \right\}. \tag{6}$$

Log-linearizing the equation around constant steady state gives

$$\begin{aligned} E_t \hat{Q}_{t+1} &= \hat{Q}_t + E_t \hat{\Pi}_{t+1}^* - E_t \hat{\Pi}_{t+1}, \\ \hat{Q}_t - E_t \hat{Q}_{t+1} &= E_t \hat{\Pi}_{t+1} - E_t \hat{\Pi}_{t+1}^*, \end{aligned} \tag{7}$$

where all variables are now log-deviations from constant steady state. The above equation expresses the same relationship as equation (3). In particular, for the nominal exchange rate to stay in expectations constant, decrease in the real exchange rate must be in expectations equal to inflation differential between domestic and foreign economy. Assuming for now no other shocks in economy, expectations are equal to actual values.

Further, I assume that developments in a small open economy do not affect price level in the large foreign economy. Permanent depreciation of nominal exchange rate in domestic economy thus does not have impact on foreign inflation and equation (7) can be rewritten as:

$$\hat{Q}_t - E_t\hat{Q}_{t+1} = E_t\hat{\Pi}_{t+1}, \tag{8}$$

It is documented across empirical literature, and DSGE models are calibrated and estimated accordingly, that pass-through of nominal exchange rate changes into consumer prices is incomplete [see, e.g., McCarthy (2007)]. In other words, depreciation of nominal exchange rate is larger than the resulting increase in consumer prices. Permanent depreciation of nominal exchange rate thus, beside temporary depreciation of real exchange rate, leads also to long-term (trend) depreciation of real exchange rate. Further, trend depreciation of real exchange rate affects also domestic prices. Domestic inflation can then be divided into the part that results from the real exchange rate deviation and the part that results from the real exchange rate trend. In Section 3.2.2, I will discuss in detail the impact of real exchange rate trend on consumer prices. In the rest of this Section, I will treat them as one variable, $\hat{\tau}_{q,t}$.

In DSGE literature, trend parts of variables are usually assumed to follow a unit root process with stationary AR(1) innovations. The change in the trend is thus represented by the AR(1) innovations. (see, e.g. Smets & Wouters (2007) and Del Negro *et al.* (2015) for real quantity variables with such trends). I follow this convention and assume that real exchange rate and its impact on consumer prices, $\hat{\tau}_{q,t}$, follow such unit root process:

$$\hat{\tau}_{q,t} = \hat{\tau}_{q,t-1} + \hat{s}_{q,t}, \tag{9}$$

The change in real exchange rate and its impact on consumer inflation then follows an AR(1) process:

$$\hat{s}_{q,t} = \rho_q \hat{s}_{q,t-1} + \varepsilon_{q,t}, \tag{10}$$

Equation (8) can then be rewritten in terms of stationary and trend parts of variables as follows:

$$\{\hat{q}_t + \hat{q}_{TREND,t}\} - E_t\{\hat{q}_{t+1} + \hat{q}_{TREND,t+1}\} = E_t\{\hat{\pi}_{TREND\_IMPACT,t+1} + \hat{\pi}_{t+1}\},$$
$$\hat{q}_t - E_t\hat{q}_{t+1} = E_t\hat{\pi}_{t+1} + E_t\{\hat{q}_{TREND,t+1} - \hat{q}_{TREND,t} + \hat{\pi}_{TREND\_IMPACT,t+1}\},$$
$$\hat{q}_t - E_t\hat{q}_{t+1} = E_t\hat{\pi}_{t+1} + E_t\hat{s}_{q,t+1}, \tag{11}$$

where (11) uses that $E_t\hat{s}_{q,t+1}$ represents expected change in real exchange rate trend and its expected impact on inflation. The last equation expresses that, for the nominal exchange rate to stay in expectations constant, decrease in the real exchange rate deviation must be in expectations equal to domestic inflation and the exogenous process (representing change in real exchange rate trend and its impact on inflation). Again, assuming for now no other shocks in economy, expectations are equal to actual values.[1]

Solving (11) forward and using that the real exchange rate deviation is a stationary variable—its expected value approaches 0 as time period approaches infinity—the real exchange rate deviation in period t could be expressed as

$$\hat{q}_t = E_t\{\sum_{s=1}^{\infty} \hat{\pi}_{t+s} + \hat{s}_{q,t+s}\}. \tag{12}$$

Real exchange rate deviation in period t has to increase as much as the expected sum of future domestic inflation and the future values of $\hat{s}_{q,t}$ such that there is then enough room for it to decrease back to zero.

Given $\hat{s}_{q,t}$ is an $AR(1)$ process, its expected future value is completely determined by shock to them in period t (and period $t-1$ value of this process, which is assumed to be zero). Further, using log-linearized version of DSGE model means that impulse responses of endogenous variables to exogenous shocks are linear. Sum of future inflation can then also be expressed as a linear function of the shock to exogenous process $\hat{s}_{q,t}$ in period t. In sum, the real exchange rate deviation in period t is a linear function of the shock to the exogenous process $\hat{s}_{q,t}$ in period t.

Further, Equation (11) holds when expected percentage change in the nominal exchange rate is zero, what can be expressed as follows:

$$E_t \log S_{t+1} - \log S_t = 0 = E_t\{\hat{q}_{t+1} - \hat{q}_t + \hat{\pi}_{t+1} + \hat{s}_{q,t+1}\}, \tag{13}$$

[1] In the following lines, I will for simplicity refer to the Equation 11 with added expected foreign inflation as the exchange rate floor equation: $\hat{q}_t - E_t\hat{q}_{t+1} = E_t\hat{\pi}_{t+1} - E_t\hat{\pi}^*_{t+1} + E_t\hat{s}_{q,t+1}$

where $E_t \log S_{t+1} - \log S_t$ is approximately the expected percentage change in the nominal exchange rate. The equation could be rewritten to represent also non-zero percentage change in the nominal exchange rate between period t and $t-1$:

$$\log S_t - \log S_{t-1} = \hat{q}_t - \hat{q}_{t-1} + \hat{\pi}_t + \hat{s}_{q,t}. \tag{14}$$

Given that shock to exogenous process $\hat{s}_{q,t}$ in period t is assumed to be the only shock affecting model economy, the real exchange rate deviation in period $t-1$, $\hat{q}_{t-1}$, is zero. Further, linearity of DSGE model again implies that domestic inflation in period t, $\hat{\pi}_t$, is just a linear function of the shock. Using previous result that $\hat{q}_t$ is linear in shock to $\hat{s}_{q,t}$, percentage change in the nominal exchange rate is just a linear function of the shock. Appreciation of the nominal exchange rate to the exchange rate floor in period t could then be attained by choosing the appropriate value of the shock.

In sum, a shock to $\hat{s}_{q,t}$ (change in real exchange rate trend and its impact on inflation) is an exogenous shock that leads to permanent depreciation of nominal exchange rate. The shock thus exactly fits the definition of devaluation with the exchange rate floor in Section 3.1.

Lastly, I discuss two technical issues concerning the use of DSGE model for simulation of devaluation with exchange rate floor.

First, when the exchange rate floor equation is used as a part of DSGE model to simulate such devaluation, it has to be extended for a term depending on net foreign assets, $\tilde{\phi}_a \hat{a}_t$. Inclusion of this term is necessary for ensuring stationarity of net foreign assets and, consequently, of other variables in the model [see, Schmitt-Grohe & Uribe (2003)]. The drawback of including this term is that (3) no longer holds and exchange rate is thus not expected to be exactly constant. The coefficient $\tilde{\phi}_a$ is, however, set to low value of 0.01, as in the UIP condition in (1), and the deviation of exchange rate from being constant is then negligible: for a 5 percent devaluation considered in the empirical part, exchange rate deviates at most by 0.05 percentage points. The exchange rate floor equation then becomes:

$$\hat{q}_t - E_t \hat{q}_{t+1} = E_t \hat{\pi}_{t+1} - E_t \hat{\pi}^*_{t+1} + E_t \hat{s}_{q,t+1} + \tilde{\phi}_a \hat{a}_t. \tag{15}$$

Second, I assume that the real exchange rate trend affects the model only through the exogenous process in the exchange rate floor equation and through its impact on inflation discussed in the next section; the trend or its innovations are thus not present in any of the remaining equations of the DSGE model. I discuss this assumption in detail in the Appendix B.

3.2.2 Impact of real exchange rate trend on inflation

To my best knowledge, there is no established methodology of computing impact of changes in real exchange rate trend on consumer prices. I therefore propose a simple method based upon three components: import intensity of various sectors in economy, gradual learning about effectiveness of the exchange rate floor, and price stickiness.

First, I use import intensity of various sectors in Swedish economy to compute relation between real exchange rate trend and inflation. Depreciation of real exchange rate after devaluation with exchange rate floor results from depreciation of nominal exchange rate. To compute impact of long-term (trend) depreciation of real exchange rate on consumer prices, it is thus necessary to compute impact of the underlying depreciation of nominal exchange rate on these prices. For now, I assume that pass-through of this depreciation into prices is instant. Later in the section, I relax these assumptions. As an illustration, I consider a one percent depreciation of nominal exchange rate.

Following the usual practice in DSGE methodology, I assume that it is optimal for importers in all sectors to charge a constant percentage mark-up over their marginal costs, represented by the nominal exchange rate. Assuming instant pass-through, importers thus increase their prices as much as the depreciation (increase) of nominal exchange rate. Based on Christiano *et al.* (2011), share of imported goods in final consumption goods is 0.25, and one percent depreciation of the nominal exchange rate thus results to 0.25 increase in consumer prices through price of imported consumption goods. Additionally, share of imported goods in final investment goods is 0.43, capital goods are produced just from the investment goods, capital share in production of domestic goods is 0.375, and share of domestic goods in final consumption goods is 0.75. When all these channels are combined, one percent depreciation of the nominal exchange rate results in 0.12 percent increase in consumer prices through price of imported investment goods.

In total, one percent depreciation of nominal exchange rate results in 0.37 percent increase in consumer prices (pass-through to consumer prices is thus incomplete). Now, I compute relationship between depreciation of real exchange rate and consumer prices. First, using the definition of the real exchange rate from (4), change of the real exchange rate between two consecutive periods is given by

$$\frac{Q_{t+1}}{Q_t} = \frac{S_{t+1}}{S_t}\frac{P^*_{t+1}}{P_t}\frac{P_t}{P_{t+1}}. \tag{16}$$

Taking logarithm of both sides of equation results in

$$\log\frac{Q_{t+1}}{Q_t} = \log\frac{S_{t+1}}{S_t} + \log\frac{P^*_{t+1}}{P^*_t} + \log\frac{P_t}{P_{t+1}}. \tag{17}$$

Next, price level in large foreign economy is exogenous to developments in small domestic economy and logarithm of a variable is equal to the minus logarithm of the inverse of the variable:

$$\log\frac{Q_{t+1}}{Q_t} = \log\frac{S_{t+1}}{S_t} - \log\frac{P_{t+1}}{P_t}. \tag{18}$$

Lastly, I use that logarithm of ratio of two variables is approximately their percentage difference. One percent depreciation of the nominal exchange rate, together with increase in consumer prices by 0.37 percent, then leads to 0.63 percent depreciation of the real exchange rate. Consumer prices thus increase by 0.59 ($=\frac{0.37}{0.63}$) times the depreciation of the real exchange rate.

Second, I assume gradual learning about effectiveness of the exchange rate floor. The intuition behind it is as follows. If the depreciation of the nominal exchange rate was temporary (due to usual shocks to risk premium process in uncovered interest parity (UIP) condition), nominal exchange rate would gradually decrease below the floor (see Figure 1). When the depreciation of nominal exchange rate is permanent (i.e., devaluation with exchange rate floor), nominal exchange rate stays constant at the exchange rate floor (see Figure 2). Difference between exchange rate floor and path of exchange rate after temporary depreciation could be interpreted as the magnitude of appreciation pressures that central bank resisted. I assume that agents (firms) in the economy gradually learn about ability of central bank to resist such appreciation pressures and that once central bank resisted them, the agents (firms) believe it will continue to resist them also in the future. In each period, firms then pass to prices the additional increase in difference between exchange rate floor and path of exchange rate after temporary depreciation. Since the exchange rate pass-through is incomplete, the resulting impact is (long-term, trend) depreciation of real exchange rate and increase in consumer prices.

Using computations from the beginning of this section and assuming, for now, no price stickiness, 63% of the difference between exchange rate floor and temporary depreciation would be long-term (trend) depreciation of real exchange rate and the remaining 37% of the difference would be increase in consumer prices.

Third, I account for the price stickiness in the economy. I follow Calvo (1983) and assume that only some fraction of firms can change price in any given period. I set this fraction according to prior rather than posterior means in Christiano *et al.* (2011), as the posterior values are estimated to suit specifically business cycle properties of the economy. Using these values, only one quarter of firms can change the price in any given period.

Consequently, in the first period after devaluation with exchange rate floor, one quarter of firms respond to trend depreciation of real exchange rate in that period. In the second period after devaluation, again one quarter of firms respond to trend depreciation in that period. Additionally, those of this one quarter of firms that could not change the price in the previous period (three quarters of them) respond also to previous period trend depreciation of real exchange rate. In the following periods, firms change prices according to this simple pattern (i.e., one quarter of firms respond to current trend depreciation of real exchange rate and, if they have not done it already, also to trend depreciation from previous periods). Accounting for price stickiness, impact of change in real exchange rate trend on inflation is not constant but follows the pattern outlined above (see Figure 2 for the exact form).

Impact of the trend of the real exchange rate on output could not be computed based on this simple method. To my best knowledge, there is no other method that could be used for this purpose. Having only the response of output to the temporary part of real exchange rate depreciation after devaluation with exchange rate floor, I limit the discussion in the empirical part to inflation.

3.2.3 Calibration of the exchange rate floor equation

Now, I calibrate the autoregressive (AR) coefficient of exogenous process $E_t\hat{s}_{q,t}$ in the exchange rate floor equation to get a fully specified DSGE model with the exchange rate floor. First, I show that DSGE model with the exchange rate floor equation in (15) is virtually the same as DSGE model with the log-linearized UIP condition in (1), except for different exogenous processes in the two equations. For the ease of exposition, I reproduce the slightly rearranged exchange rate floor equation here:

$$0 = E_t\{\hat{q}_{t+1} + \hat{\pi}_{t+1} - \hat{\pi}^*_{t+1}\} - \hat{q}_t + \tilde{\phi}_a \hat{a}_t + E_t \hat{s}_{q,t+1}. \tag{19}$$

Using definition of the real exchange rate in (4) and assuming no trend part of domestic and foreign inflation, the log-linearized UIP condition from (1) is as follows:

$$\hat{R}_t - \hat{R}^*_t = E_t\{\hat{q}_{t+1} + \hat{\pi}_{t+1} - \hat{\pi}^*_{t+1}\} - \hat{q}_t + \tilde{\phi}_a \hat{a}_t + \tilde{\phi}_s(\hat{R}_t - \hat{R}^*_t) + \tilde{\phi}_t. \tag{20}$$

The first difference is that there is no interest rate differential in the exchange rate floor equation, while it is present in the UIP condition with coefficient equal to $1 - \tilde{\phi}_s$. In model of Christiano *et al.* (2011), $\tilde{\phi}_s = 1.1$ and interest rate differential is thus multiplied by -0.1. In response to devaluation with the exchange rate floor, deviation of foreign interest rate is zero since it is exogenous to developments in domestic economy. Further, $\hat{R}_t$ is a deviation of domestic 3-month policy rate from steady state in decimal form, and it thus attains small values. When this already small value is multiplied by -0.1, the entire term becomes practically insignificant.

Another difference is that exogenous process in the UIP condition, interpreted as country risk premium, is also in one of the remaining equations of the DSGE model, the Balance of Payments equation. The magnitude of the exogenous process, and then its impact on model dynamics, is however small. As has been discussed for the exchange rate floor equation, the nominal exchange rate increase in period t is equal to expected sum of innovations to the real exchange rate trend and expected sum of inflation thereafter, and individual innovations are then relatively small. The same applies to the UIP equation, as the two equations are virtually the same, only innovations to the real exchange rate trend are now replaced by country risk premium exogenous process. Beside this difference, the equations of the DSGE model with the UIP condition and DSGE model with the exchange rate floor equation are the same.

Concerning exogenous processes in the exchange rate floor and the UIP equations, they are both interpreted as drivers of non-fundamental changes in the nominal exchange rate: changes that are not resulting from development in domestic or foreign variables, but rather come exogenously. Autoregressive coefficient of the process in the UIP condition is, along with other parameters, estimated in model of Christiano *et al.* (2011) such that the model approximates propagation of these non-fundamental exchange rate changes to deviations of domestic variables and, in particular, their pass-through to deviation of inflation. Autoregressive coefficient could be interpreted as representing in a reduced form other, not directly modeled structural features of economy affecting propagation of the exchange rate (e.g., tariff and non-tariff barriers, relative stock of inventories and distribution lags in the import sector). As discussed, structure of the two models is virtually the same: the UIP and exchange rate floor equations are virtually the same, and other model equations are virtually the same. Assuming additionally that the unmodeled structural features, represented by autoregressive coefficient, are also not affected by the introduction of the exchange rate floor, then propagation of non-fundamental exchange rate changes, induced by the shocks in the UIP and exchange rate floor equation, should then be the same. For this to hold, the autoregressive coefficients of the two exogenous processes have to be the same, and they are set equal to the value of the autoregressive coefficient of exogenous process in the UIP condition in the model of Christiano *et al.* (2011). Impulse responses of the shocks to the two exogenous processes are then almost the same, confirming that interest rate differential in the UIP condition and country risk premium in balance of payments equation have little impact.

3.3 Modeling of other exogenous shocks

3.3.1 Alternative modeling of the devaluation

Devaluation with the exchange rate floor could be equivalently captured by a DSGE model combining the exchange rate floor equation in (15), in which the nominal exchange rate is constant in expectations, and equation in which the nominal exchange rate is actually constant (fixed), given by[2]

$$\hat{q}_{t-1} - \hat{q}_t = \hat{\pi}_t - \hat{\pi}_t^* + \hat{s}_{q,t}. \tag{21}$$

In particular, DSGE model with exchange rate fixed in expectations would be used in period t to obtain value of shock to innovations of the real exchange rate trend and value of endogenous variables for period t. Then, given values of these variables for period t, model which actually fixed exchange rate in (21) would be used from $t+1$ onwards. Equivalence between these two approaches to modeling of devaluation with the exchange rate floor comes from using a

[2]The equation differs from the fixed nominal exchange rate equation commonly used in DSGE models, which is without innovations to the trend: $\hat{s}_{q,t}$. The intuition for including this term is the same as the intuition for including $\hat{s}_{q,t+1}$ in the exchange rate floor equation, discussed in Section 3.2.1.

log-linear approximation of DSGE model, which implies that agents behave as if they were certain that variables in future would be equal to their expected value (so-called certainty equivalence). Given the same rest of the model, the same values of period t variables and no other exogenous shocks, (15) evaluated from period t onwards then implies the same $\{\pi_{t+s}\}_{s=1}^{\infty}$ and $\{q_{t+s}\}_{s=1}^{\infty}$ as (21) evaluated from period $t+1$ onwards. The same rest of the model then also implies the same sequence of remaining endogenous variables. DSGE model with the exchange rate floor equation in (15) thus also captures situation when devaluation occurs between period $t-1$ and t, and agents in the model perceive the nominal exchange rate as actually, and not only in expectations, constant from period t onwards.

3.3.2 Impact of exogenous shocks

Now, I consider impact of other exogenous shocks in the model. As discussed, shock to exogenous process $E_t\hat{s}_{q,t+1}$ (change in real exchange rate trend and its impact on inflation) leads permanent depreciation of nominal exchange rate to the exchange rate floor in period t. Further, under the last assumption made in Section 3.1, exchange rate does not move freely above the exchange rate floor but stays equal to it. The other exogenous shocks then have no impact on exchange, and their propagation is as if the exchange rate was fixed rather than flexible. It could not be modeled by the exchange rate floor equation in (15), implying the nominal exchange rate is fixed in expectations. If this equation was used, then, for example, a shock that has persistently negative impact on domestic inflation and no impact on foreign inflation would lead to lower real exchange rate deviation in period t because sum of the future domestic inflation deviations is now lower [see (12)]. Consequently, the nominal exchange rate in period t would be lower than without this shock and thus not constant at the floor rate [see (14)]. To ensure fixed the nominal exchange rate in response to other exogenous shocks, it has to be explicitly modeled as in (21). According to this equation, a shock that decreases domestic inflation and does not affect foreign inflation leads to depreciation of the real exchange rate deviation of equal size, and the nominal exchange rate thus stays constant.

To sum it up, the overall impact of the exchange rate floor is equal to the sum of the impact of the shock to the innovations of the real exchange rate trend and different impact of other exogenous shocks due to the fixed nominal exchange rate. These two effects can be summed up thanks to the linearity of DSGE model, which implies that the impact of sum of exogenous shocks is equal to the sum of impacts of individual shocks.

Three things could be said about different impact of other exogenous shocks under fixed compared to flexible exchange rate. First, the different impact has no effect on expected future value of endogenous variables evaluated at the time of devaluation since the expected future value of exogenous shocks is 0.

Second, the DSGE model with the UIP condition in (20), representing flexible exchange rate regime, implies higher ex ante volatility of inflation than the DSGE model with fixed exchange rate equation in (21) for following reasons. First, exogenous process in the UIP condition, interpreted as country risk premium, is subject to random shocks, while value of exogenous process in fixed exchange rate equation, interpreted as innovations to the real exchange rate trend, is determined by the magnitude of devaluation with the exchange rate floor. Under the flexible exchange rate, there is therefore, due to shocks to the exogenous process in the UIP condition, additional volatility in economy in addition to and independent of volatility due to other exogenous shocks in the model. Second, the UIP condition magnifies the response of inflation to other domestic exogenous shocks. For example, consider a domestic exogenous shock that results in a prolonged increase in domestic inflation and no change in inflation of the large foreign economy. As discussed, interest rate differential and net foreign assets have only small impact on dynamics of the UIP condition in (20), and expected domestic inflation is thus equal to expected decrease (appreciation) of the real exchange rate. Prolonged period of expected increase in domestic inflation thus implies a prolonged period of expected real exchange rate appreciation. Real exchange rate is a stationary variable in the flexible exchange rate model as there is no trend part and it consists only of the deviation; its current rate, therefore, has to depreciate such that the expected appreciations moves it back to the initial value. Real exchange rate depreciation then, for example through higher import prices and higher foreign demand, results in further increase in inflation and thus its magnified response to the domestic shock. On contrary, fixed exchange rate equation diminishes response of inflation to domestic exogenous shocks. Consider the same shock as before. Real exchange rate equation in (21) now implies an appreciation of the current real exchange rate in response to increase in domestic inflation. Appreciation then leads to decrease in inflation and thus its diminished response. Third, the UIP and fixed exchange rate equations have only small impact on propagation of foreign shocks. The reason is that the shocks affect the foreign and domestic inflation such that their differential, and then the impact on the real exchange rate, is small.

Lastly, the actual effect of different impact of exogenous shocks under the fixed exchange rate depends on the actual realization of shocks: it could lead with equal probability to higher and lower inflation since the distribution and impulse responses of shocks are symmetric.

3.4 Zero lower bound on interest rates

Devaluation with the exchange rate floor is assumed to be used as an unconventional monetary policy instrument at the zero lower bound (ZLB); central bank uses it after it has exhausted the possibility to stimulate economy through its main monetary policy instrument, nominal interest rate. The central bank then does not increase interest rate in response to higher inflation resulting from the devaluation of the nominal exchange rate. In particular, I assume that central bank keeps interest rate at ZLB, and thus does not increase it in response to devaluation, during the following four quarters. The four quarters cover the main part of inflation response to the temporary part of the real exchange rate depreciation; extending the period further, for example to eight quarters, have only marginal impact on simulation results in the empirical part.

I model ZLB with piecewise linear algorithm introduced in Guerrieri & Iacoviello (2015) and applied to similar context as in this paper in Del Negro *et al.* (2015). The algorithm works as follows. Equilibrium conditions of log-linearized DSGE model could be represented by

$$\Gamma_{2,\tau} E_\tau\{s_{\tau+1}\} + \Gamma_{0,\tau} s_\tau = \Gamma_{1,\tau} s_{\tau-1} + \Psi_\tau \varepsilon_\tau, \tag{22}$$

where s_τ represents all endogenous variables, including the exogenous processes, and ε_τ are shocks to the exogenous processes. Devaluation with the exchange rate floor occurs in period $\tau = t$ and, for $\tau \leq t+3$, central bank does not change interest rate in response to it, and the interest rate rule is given by $\hat{R}_t = 0$. For $\tau \geq t+4$, central bank returns to standard monetary policy and adjusts interest rate according to Taylor rule. For $\tau \geq t+4$, equilibrium equations in (22) are thus of standard form, with the same matrices for all periods. The solution of such system of equations is for $\tau \geq t+4$ given by

$$s_\tau = \mathcal{T} s_{\tau-1} + \mathcal{R} \varepsilon_\tau. \tag{23}$$

Solution for $\tau = t+3$ is obtained recursively by substituting solution from (23) for $E_\tau s_{\tau+1}$ in (22) and then rearranging the equation such that s_τ is expressed as a function of $s_{\tau-1}$ and ε_τ. Solutions for $\tau = t+2, t+1, t$ is then obtained in analogous way, always substituting solution obtained in previous step for $E_\tau s_{\tau+1}$ in (22). The solution for $\tau = t+3, t+2, ..., t$ is then given by

$$s_\tau = \mathcal{T}_\tau s_{\tau-1} + \mathcal{R}_\tau \varepsilon_\tau, \tag{24}$$

where

$$\mathcal{T}_\tau = \left(\Gamma_{2,\tau}\mathcal{T}_{\tau+1} + \Gamma_{0,\tau}\right)^{-1} \Gamma_{1,\tau}, \tag{25}$$

$$\mathcal{R}_\tau = \left(\Gamma_{2,\tau}\mathcal{T}_{\tau+1} + \Gamma_{0,\tau}\right)^{-1} \Psi_\tau. \tag{26}$$

4 Results

In this section, I discuss response of consumer price inflation to a five percent devaluation with the exchange rate floor. Before moving to results, I make some general remarks about this devaluation. First, it is set to five percent just as an illustration. The response of variables is linear in the nominal exchange rate change, and the chosen magnitude thus has no impact on relative response of inflation. Second, results for output are not discussed. The reason is that they are incomplete because the response of output to trend depreciation of real exchange rate could not be estimated with the employed methodology (for more information, see Section 3.2.2). Third, devaluation is assumed to be used as an unconventional monetary policy instrument at the zero lower bound. Higher inflation brought about by the devaluation is thus desirable, and central bank does not increase interest rate in response to it (for more information, see Section 3.4). Fourth, there are assumed to be no changes in economy in anticipation of the devaluation, and it therefore has non-zero impact on inflation and other model variables only after it is actually implemented.

4.1 Impact of devaluation with exchange rate floor

I apply the methodological extension to the model of Christiano *et al.* (2011), which has been estimated and calibrated for Sweden. Figure 3 displays impulse response of inflation to the devaluation (i.e, without the devaluation, response of inflation would be zero). The first subplot shows quarterly CPI inflation.

The second subplot shows the annual rate, the sum of the last four quarterly rates. The third subplot shows the exchange rate pass-through to consumer prices, the cumulative sum of quarterly inflation rates. I will focus just on the most relevant information in this figure. In the first three years, the annual inflation is 0.8 percent, 0.7 percent, and 0.3 percent, and exchange rate pass-through is about 40 percent.

The response of inflation is sum of responses to temporary real exchange rate deviation and permanent depreciation of real exchange rate trend (see Figure 4).

The response to the deviation could be divided into three channels. First one is higher price of imported consumption goods, which constitute 25 percent of consumption basket. Second one is higher price of imported investment goods that leads to higher price of capital, higher marginal costs of domestic producers, and then higher price of domestic goods, which constitute the remaining 75 percent of consumption basket. Third one is higher share of less expensive domestic goods in both domestic and foreign demand, which leads to higher domestic output and, consequently, more intensive use of production inputs. This, in turn, increases marginal costs of domestic producers and then the price of domestic goods. Fourth channel usually discussed in literature is the change in composition of consumption basket due to higher share of less expensive domestic goods in consumption. The employed DSGE model, however, does not account for this channel as the equilibrium conditions are locally approximated (log-linearized) around a constant steady state. For small changes, as those resulting from a five percent devaluation, the local approximation is precise and the impact of this channel is thus small.

The response of inflation to the depreciation of real exchange rate trend is due to the first and second channel discussed above. Impact through the third and fourth channel is not accounted for. Increase in marginal costs due to likely trend growth in output is, however, likely to be small as, in the long-run, economy is not subject to rigidities such as investment adjustment costs and only gradual capital accumulation of entrepreneurs, but can freely adjust to minimize the costs. Change in the composition of the consumption basked due to less expensive domestic goods is likely to be small, too, since elasticities of substitution between domestic and imported goods are in general low [see, for example, Feenstra *et al.* (2014)]. Additionally, the two channels have opposite impact on inflation and thus partially cancel out. Not accounting for these channels should therefore have only marginal impact on results.

Figure 4 displays response of inflation to the real exchange rate deviation and depreciation of real exchange rate trend. The temporary deviation has small impact on inflation: in the first year, the annual inflation is about 0.4 percent and then it is insignificant. The implied exchange rate pass-through (to consumer prices) is about 6 percent. This small impact through the first and second channel is due to high nominal rigidities in form of Calvo price stickiness combined with, by definition, only temporary effect of the deviation on real exchange rate. In particular, the Calvo coefficient for importers of consumption and investment goods is 0.87 and 0.79; the implied average duration of the price change is then about eight and five quarters. Domestic importers, which differentiate the imported homogenous foreign good and their marginal costs are thus represented by the real exchange rate, therefore expect that their price will remain effective for a long period and that their marginal costs will gradually return to steady state during it. As a result, the price of imported consumption and investment goods increases only slightly. Low increase in the price of imported investment goods then leads only to a small increase in the marginal costs of domestic producers. The price stickiness of these producers is again high, with Calvo coefficient equal to 0.89 and average duration of price change being nine periods, and they therefore increase the price of domestic goods just by a small amount.

Small impact on inflation through the third channel is explained again by high price stickiness of domestic producers combined with only a moderate increase in marginal costs due to only a moderate increase in the output.

Figure 4 shows that depreciation of real exchange rate trend has large impact on consumer prices. Annual inflation is about 0.45 percent, 0.65 percent, and 0.4 percent in the first three years, and the implied exchange rate pass-through is about 35 percent. The large impact is due to the first and second channel: the large increase in prices of imported consumption and investment goods. The intuition behind the large impact is that the trend depreciation is viewed as a long-lasting change in real exchange rate, and price stickiness in the economy thus has lower effect.

The permanent nature of the nominal exchange rate devaluation is therefore crucial for its impact on inflation. As discussed, if the devaluation was non-permanent, explained by the temporary real exchange rate deviation, the pass-through to consumer prices would be only about 6 percent.

4.2 Impact of other exogenous shocks

As discussed in Section 3.3.2, devaluation with the exchange rate floor changes propagation of other exogenous shocks in the model such the they affect economy as if the exchange rate was fixed rather than flexible. Next, I compute volatility of inflation under exchange rate floor and under flexible exchange rate, using a model with the fixed exchange rate equation in (21) and a model with the UIP condition in (20). Parameters in the model, including persistence and volatility of exogenous processes, are set to values calibrated and estimated in Christiano *et al.* (2011). As in previous simulations in this section, the length of the sample is 16 quarters and the interest rate is at the ZLB. Further, number of iterations is set to 10 000, and the model economy is in each of the 16 quarters subject to a random sample of all exogenous shocks. Assuming this set-up, the standard deviation of annualized quarterly inflation is 1.59 percent under exchange rate floor rather than 1.8 percent under flexible exchange rate. The results support the discussion in Section 3.3.2 that introduction of exchange rate floor leads to lower volatility of inflation.

5 Conclusion

In this paper, I developed an extension to DSGE models that could be used to estimate impact of devaluation with exchange rate floor on inflation. As an illustration, I applied this extension to the DSGE model of Christiano *et al.* (2011), which has been calibrated and estimated for Sweden.

Additionally, I briefly consider here another interesting policy application of the extension. I use the extension to estimate the impact of devaluation with exchange rate floor (exchange rate commitment) conducted by the Czech National Bank (CNB) in November 2013. At that time, CNB devalued the currency by approximately 5 percent and used the devaluation as an unconventional monetary policy instrument: it kept interest rates at ZLB and it thus did not increase them in response to higher inflation resulting from the devaluation. In these two respects, this analysis is thus the same as the baseline simulation considered for Sweden. I also use the model of Christiano *et al.* (2011) but set the parameters to the values calibrated and estimated for the Czech Republic in Rysanek *et al.* (2012).

In the analysis, I focus just on the impact of devaluation with exchange rate floor through permanent depreciation of nominal exchange rate. I therefore do not account for different propagation of other exogenous shocks due to limited variability of nominal exchange rate around the floor rate. This would require that I myself calibrate and estimate model of Christiano *et al.* (2011) on the Czech data after 2013, a task I leave to future research.

According to the simulation, the annual inflation increases by 1.8 percent, 0.9 percent, and 0.3 percent in the three years after devaluation, and the long-term exchange rate pass-through is about 65 percent (see Figure 5). According to the simulation, devaluation helped Czech Republic to avoid a prolonged period of deflation; without it, the inflation would be −0.6 percent in 2014, −1.4 percent in 2015, and −0.2 percent in 2016 (see Figure 6).

The impact of the devaluation on inflation is higher for the Czech Republic than for Sweden for two main reasons. First, price stickiness of importers is estimated to be lower for the Czech Republic than for Sweden (e.g., average duration of price change is about four quarters for importers of consumption goods in the Czech Republic and eight quarters in Sweden). Second, persistence of exogenous process in UIP condition is estimated to be higher for the Czech Republic than for Sweden. This persistence could be broadly interpreted as a proxy for other factors affecting pass-through to inflation (e.g., distribution lags and management of inventories in the import sector).

Other researchers have already studied impact of devaluation with exchange rate floor conducted by the CNB in November 2013. Using DSGE model with shadow shocks in UIP condition, Bruha & Tonner (2017) estimate that devaluation increased inflation by 1.2 percent in 2014 and 1.8 percent in 2015. For comparison, simulation in this paper implies increased inflation by 1.8 percent in 2014 and 0.8 percent in 2015. Using synthetic control method, Opatrny (2017) estimates that the effect is only slightly positive and not statistically significant at standard levels.

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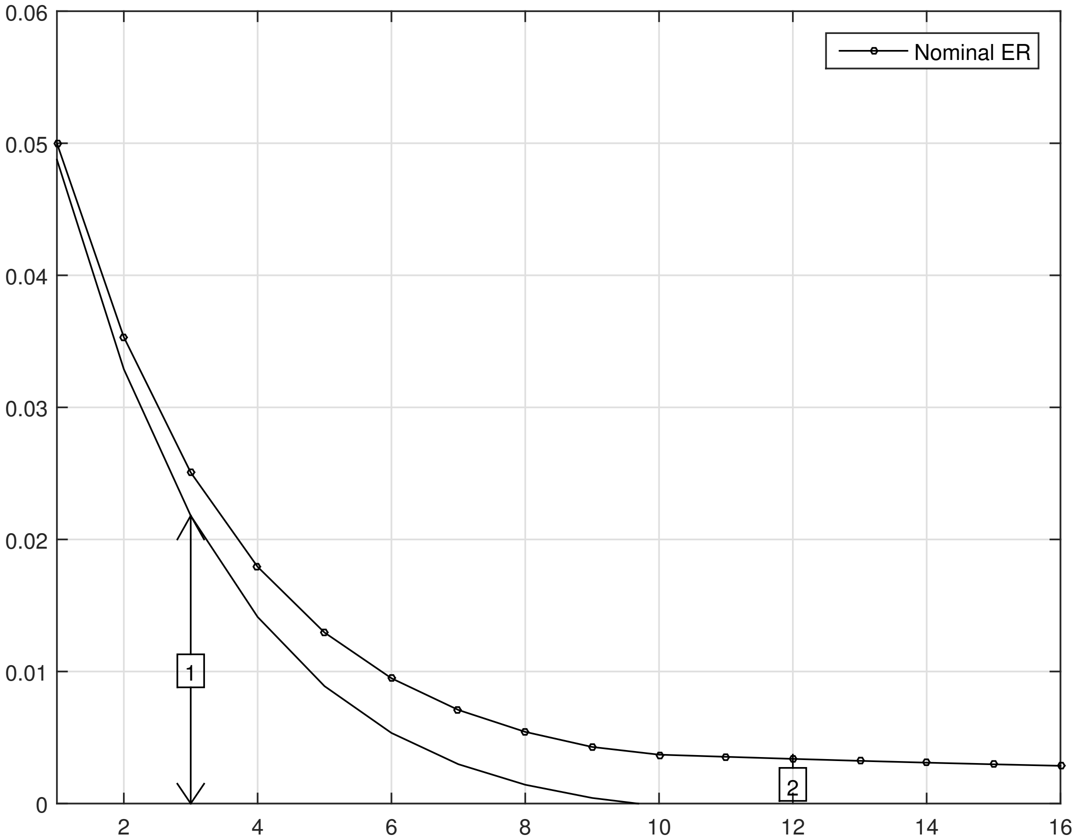
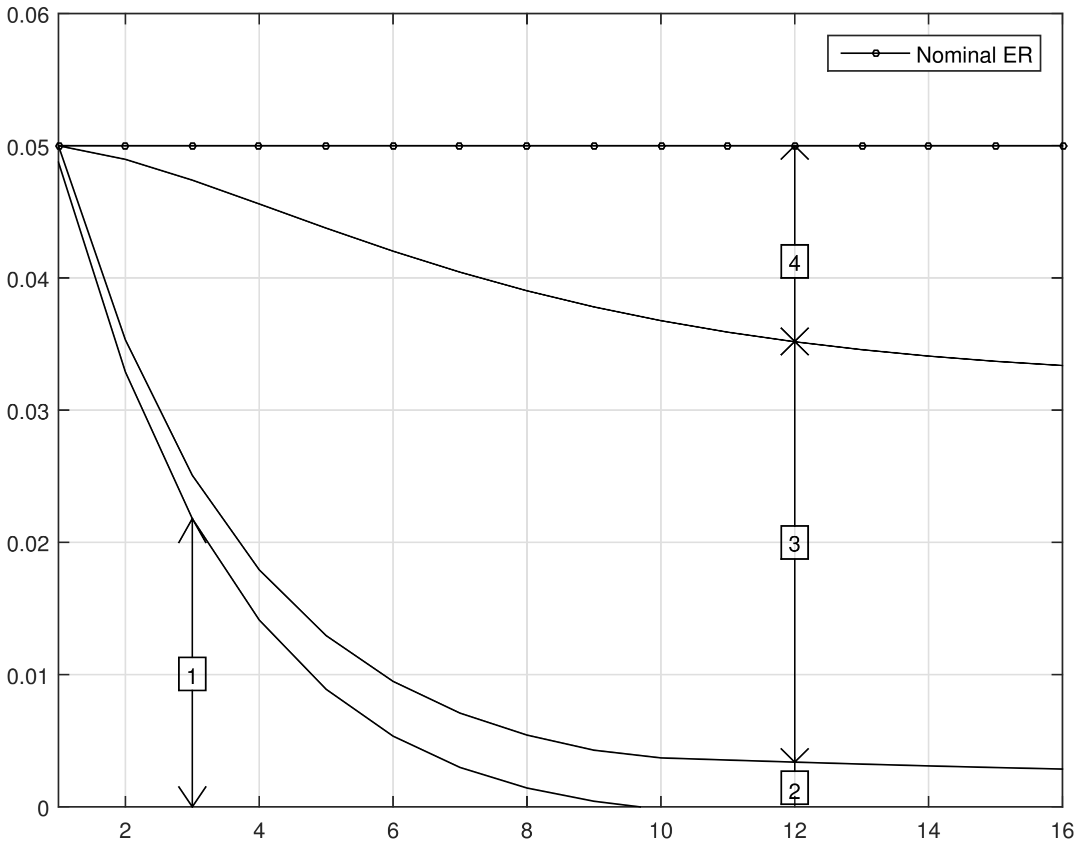
A Figures

Figure 1: Temporary depreciation of nominal exchange rate



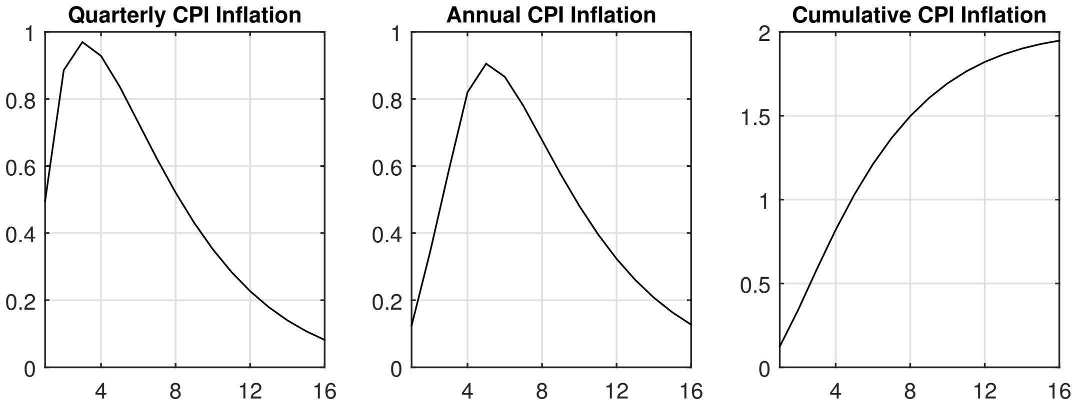
Notes: 1 - Temporary depreciation of real exchange rate, 2 - Increase in domestic consumer prices. Source: Author's own computations.

Figure 2: Devaluation with the exchange rate floor (permanent depreciation of nominal exchange rate)



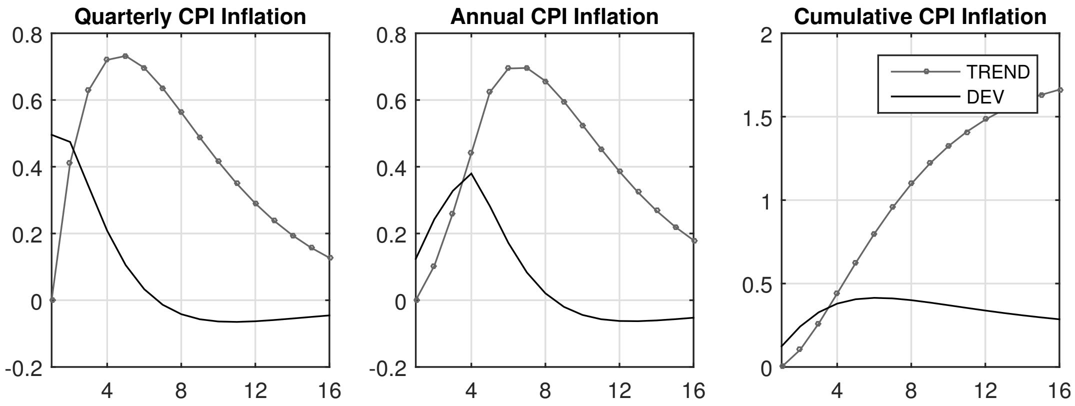
Notes:. 1 - Temporary depreciation of real exchange rate, 2 - Increase in domestic consumer prices (due to temporary depreciation of real exchange rate), 3 - Long-term (trend) depreciation of real exchange rate, 4 - Increase in domestic consumer prices (due to real exchange rate trend). Source: Author's own computations.

Figure 3: Devaluation with the exchange rate floor (Sweden)



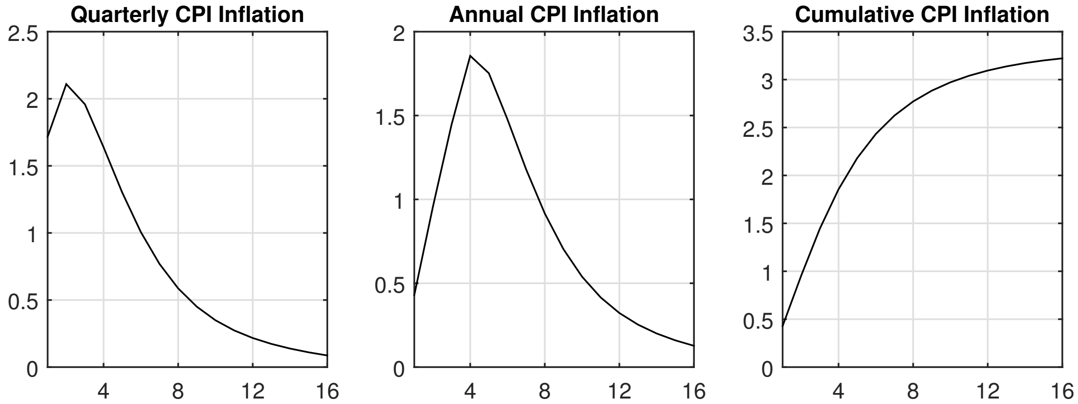
Notes: Figure shows the impulse response of inflation to devaluation with exchange rate floor (i.e, without the devaluation, the response of inflation would be equal to zero). The magnitude of devaluation is set to 5 percent. Source: Author's own computations.

Figure 4: Devaluation with the exchange rate floor: decomposition of inflation (Sweden)



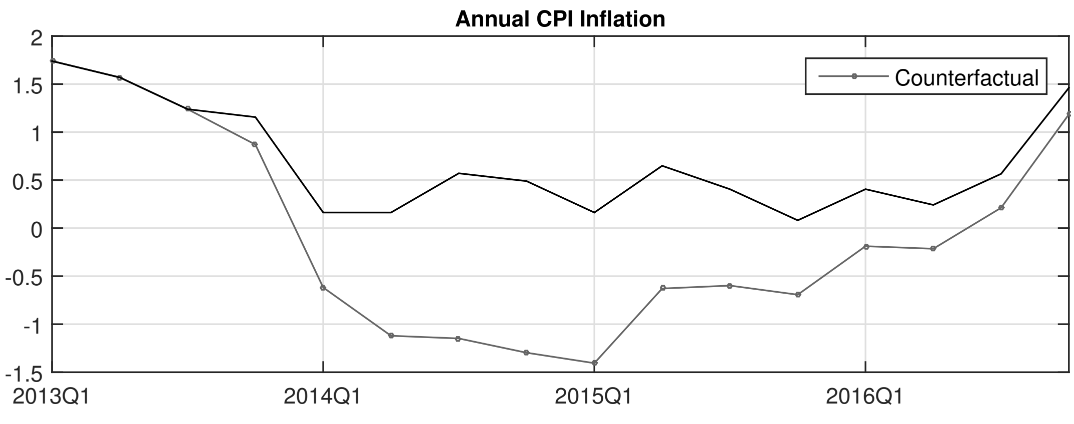
Notes: Figure shows the impulse response of inflation to devaluation with exchange rate floor (i.e, without the devaluation, the response of inflation would be equal to zero). The magnitude of devaluation is set to 5 percent. Response of inflation is due to real exchange rate trend (TREND) or temporary real exchange rate deviation (DEV). Source: Author's own computations.

Figure 5: Devaluation with the exchange rate floor (Czech Republic)



Notes: Figure shows the impulse response of inflation to devaluation with exchange rate floor (i.e, without the devaluation, the response of inflation would be equal to zero). The magnitude of devaluation is set to 5 percent. Source: Author's own computations.

Figure 6: Devaluation with the exchange rate floor: counterfactual analysis (Czech Republic)



Notes: Source: Czech Statistical Office. Author's own computations.

B Appendix B: Methodology of exchange rate floor—Other equations of the DSGE model

The assumption that real exchange rate is not present in other equations than the exchange rate floor equation is used because the real exchange rate induces trend in other variables such that model equations cannot be stationarized. In other words, model equations cannot be adjusted such that they include only (stationary) deviations of variables from trend and (stationary) innovations to the trend, but no (non-stationary) trends. I will illustrate it on an aggregation function for the final consumption good in the model of Christiano *et al.* (2011) described in Section 2:

$$C_t = [(1-\omega_c)^{1/\eta_c}(C_t^d)^{(\eta_c-1)/\eta_c} + \omega_c^{1/\eta_c}(C_t^m)^{(\eta_c-1)/\eta_c}]^{\eta_c/(\eta_c-1)}, \tag{27}$$

where ω_c is import share in consumption goods; η_c is elasticity of substituion between domestic and imported consumption goods; and C_t, C_t^d, and C_t^m are final, domestic, and imported consumption goods. The equation has to hold also for the trends of variables:

$$C_{t,TREND} = [(1-\omega_c)^{1/\eta_c}(C_{t,TREND}^d)^{(\eta_c-1)/\eta_c} + \omega_c^{1/\eta_c}(C_{t,TREND}^m)^{(\eta_c-1)/\eta_c}]^{\eta_c/(\eta_c-1)},$$

and rearranging the equation gives

$$1 = (1-\omega_c)^{1/\eta_c}\left(\frac{C_{t,TREND}^d}{C_{t,TREND}}\right)^{(\eta_c-1)/\eta_c} + \omega_c^{1/\eta_c}\left(\frac{C_{t,TREND}^m}{C_{t,TREND}}\right)^{(\eta_c-1)/\eta_c}.$$

Due to incomplete exchange rate pass-through, increase in the real exchange rate trend leads to trend increase in imported consumption good prices relative to domestic consumption good prices. Further, increase in the real exchange rate trend is exogenous, induced by devaluation with the exchange rate floor, and it is thus not accompanied by structural changes in economy such as changes in relative productivity of imported and domestic goods. Trend increase in relative prices of imported and domestic goods then, due to expenditure switching effect, leads to trend decrease in relative quantities of imported and domestic goods. Ratio of imported to final consumption goods thus decreases, and ratio of domestic goods to final consumption goods increases. Both these ratios are non-stationary as the real exchange rate trend is modeled as a non-stationary, unit root variable.

Expressing variables as a multiplication of a non-stationary trend and a stationary deviation, as is common in DSGE literature, (27) is equal to

$$C_{t,TREND}c_t = [(1-\omega_c)^{1/\eta_c}(C^d_{t,TREND}c^d_t)^{(\eta_c-1)/\eta_c} + \omega_c^{1/\eta_c}(C^m_{t,TREND}c^m_t)^{(\eta_c-1)/\eta_c}]^{\eta_c/(\eta_c-1)},$$

$$c_t^{(\eta_c-1)/\eta_c} = (1-\omega_c)^{1/\eta_c}\left(\frac{C^d_{t,TREND}}{C_{t,TREND}}c^d_t\right)^{(\eta_c-1)/\eta_c} + \omega_c^{1/\eta_c}\left(\frac{C^m_{t,TREND}}{C_{t,TREND}}c^m_t\right)^{(\eta_c-1)/\eta_c},$$

where $\frac{C^m_{t,TREND}}{C_{t,TREND}}$ and $\frac{C^d_{t,TREND}}{C_{t,TREND}}$ are non-stationary, and the equation cannot be log-linearized around a constant steady state. More generally, presence of non-stationary variables implies that equilibrium equations of the DSGE model cannot be locally approximated (e.g., by log-linearization), what is necessary for solving large-scale DSGE models, as the model of Christiano *et al.* (2011) used in this paper. For comparison, non-stationary labour augmenting technology growth induces the same trend in all quantity variables of the DSGE model, and the equilibrium equations then can be stationarized. In (27), the trends of all variables are equal and the ratios of the trends are then 1.

The assumption of no impact of trend of variables on cyclical deviations is used in literature in DSGE models estimated on exogenously detrended variables through Hodrick-Prescott filter (e.g., Smets & Wouters (2003) for closed economy and Brzoza-Brzezina & Makarski (2011) for small-open economy). Treatment of the real exchange rate trend in this paper is thus similar to treatment of trends in those studies with one important difference: in this analysis, the real exchange rate trend is part of one equation, the exchange rate floor equation, since leaving out the trend would imply that the nominal exchange rate deviations are constant rather than the nominal exchange rate itself, as is needed.

As a robustness analysis, I approximate how not accounting for the trends of variables affect simulation of devaluation with the exchange rate floor. I use for it a model of Christiano *et al.* (2011) with few simplifications; the main one comprises of replacing search and matching employment frictions with monopolistically competitive labour unions subject to Calvo stickiness in wages. Exchange rate floor is modeled by (15), which is employed in the empirical part and includes also net foreign assets and the trend of inflation, as will be described later.

The idea behind the analysis is that small changes in trends of variables—as those resulting from a five percent devaluation of the nominal exchange rate considered in the empirical part of the paper—could be locally approximated by log-linearization like the deviations from the trends.[3] In particular, using log-linearized steady state equations, innovations to trend of variables are expressed as a linear function of the innovations to the trend of the real exchange rate. The innovations are then included in the log-linearized equilibrium equations. Difference between these and the original log-linearized equilibrium equations could be then conveniently illustrated by considering three components of these equations: structural parameters, steady state ratios, and log-deviations of variables.

Structural parameters, including for example Calvo stickiness coefficients and elasticities of substitution, are assumed not to be affected by trends of variables.

Changes in steady state ratios are approximately equal to the difference between innovations to the trend of variables in the numerator and denominator. Steady state ratios, and consequently also changes in them, are in the log-linearized equations always multiplied by log-deviations. Innovations to the trend of variables are approximately percentage changes in the trend of variables in decimal form, and log-deviations are approximately percentage deviations in decimal form. For the five percent devaluation considered in the empirical part, these percentage changes and deviations are small, and the multiplication of innovations and log-deviations is then approximately zero.

Log-linearized equations could be always transformed such that they include log-deviations only in periods $t-1$, t, and $t+1$. With no trend growth, log-deviations represent log-deviations of variables from their constant steady states. With trend growth, all variables in the log-linearized equations must be log-deviations from the trend in period t. Log-deviation of a variable in $t-1$ then consists of two parts: log-deviation of the variable from its $t-1$ trend and innovation to trend between periods t and $t-1$. Similarly, log-deviation of a variable in $t+1$ consists of expected log-deviation from its expected $t+1$ trend and the expected innovation to the trend between periods $t+1$ and t.

Next, I simulate devaluation with the exchange rate floor in the model which has innovations to the trend of variables in equilibrium equations and in the unadjusted model without the innovations. Inclusion of the innovations leads only to marginal difference in inflation. The main reason for this is only the small magnitude of the innovations to the trends. First, (12) and

[3]For larger devaluations of the nominal exchange rate, local approximation of changes in trend becomes imprecise, but the same holds also for local approximation of deviations from the trends as the entire local approximation of DSGE model equations is inappropriate.

(14) show that devaluation of the nominal exchange rate is equal to sum of innovations to the real exchange rate trend and sum of inflation from that period onwards. Individual innovations to the real exchange rate trend are thus small in comparison with magnitude of the devaluation. Second, innovations to the trend of other variables are mostly in absolute value equal to or lower than innovations to the real exchange rate trend. In sum, based on the robustness analysis, not including trends of variables in other DSGE model equation than the exchange rate floor equation should have only small impact on simulation results.

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