MONETARY POLICY TRANSMISSION MECHANISM IN SMALL OPEN ECONOMY WITH HETEROGENEOUS AGENTS

by

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Abstract

MONETARY POLICY
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The paper studies the monetary transmission mechanism through the response of aggregate real consumption to the increase in key policy rate. It uses Dynamic Stochastic Partial Equilibrium model for small open economy, incorporating heterogeneity of agents in productivity. The channels of monetary transmission are interest rate directly, price level, exchange rate and wage, and the responses of the latter to interest rate swing are given exogenously. The model is calibrated for Ukraine, and the response of the exogenous macro variables is calibrated using Quarterly Projection Model by Central Bank of Ukraine. The paper finds that consumption falls by 0.3% in a 1-year period, and indirect effect dominates direct, with price level being the main driver of the response. The exchange rate channel places third by contribution in the decomposition of 1-year response and second for an immediate (1-month) consumption response, turning out to be significant driver of consumption change.

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ACKNOWLEDGEMENTS

I would like to express enormous gratitude to my thesis advisor Sergii Kiiashko, whose constant support and help make this project come into life. He was always open and ready to help, and without his contribution and guidance the world would not be able to get to know how important exchange rate channel is in the monetary transmission mechanism.

Chapter 1

INTRODUCTION

Monetary policy attempts to effect main aggregate macroeconomic variables, since its task is price, macro, and financial stability, which depend on the movement in main macroeconomic variables. In order to implement monetary policy main task, monetary policy executives develop range of instruments. The way instruments effect targeted variables is called monetary policy transmission mechanism.

In New Keynesian conventional framework, monetary policy impacts aggregate demand (Gali 2008). One of the main components of aggregate demand is households' consumption. In the same conventional approach to monetary policy transmission, two effects on consumption appear: direct substitution effect (through Euler equation) and indirect income effect. Economists derive aggregate demand with a representative agent, based on assumption that all agents make decisions in the same way, and even if it is not true, the differences among agents do not change aggregate levels responses. In the framework of representative agent, direct effect accounts for almost the entirety of interest rate influence on the macroeconomy.

However, analysis of time-series data showed that effect of interest rate is insignificant after controlling for income (Campbell and Mankiw 1989; Yogo 2004; Canzoneri, Cumby, and Diba 2007), leading naturally to a switch of emphasis towards indirect effect of monetary policy. Heterogeneous agent models, which account for differences in agents' wealth and different effect of monetary policy on this wealth, allow exactly for counting for income effect. Why so? Micro empirical literature proves that a vast heterogeneity in consumption responses is largely driven by the level and structure of households' wealth (Misra and Surico 2014; Cloyne and Surico 2016). Therefore, wealth distribution of agents is crucial for understanding how monetary policy affects consumption, and hereby for achieving the goals of monetary policy.

There are already a few papers studying monetary transmission in heterogenous agent models (Kaplan, Moll, and Violante 2018; Auclert 2017; Bondarenko 2018), with monetary transmission mechanism operating through different channels. Literature focuses primarily on channels entailing redistribution of wealth among agents. Those are earnings and income heterogeneity channel, portfolio channel, savings redistribution and interest rate channel (Bondarenko 2018; Kaplan, Moll, and Violante 2018). However, in existing literature analysis was conducted for closed economies, naturally abstracting from exchange rate channel of monetary policy, though exchange rate channel is important for small open economies like Ukraine.

There are plenty of papers describing empirically the influence of exchange rate fluctuations on consumption (Ho and Iyke 2018; Bahmani-Oskooee and Xi 2015). A possible reason why small open economies are vulnerable to exchange rate swings is financial dollarization (for example, in Ukraine 40% of loans are in dollars (Khvedchuk, Sinichenko and Topf 2019)), which amplifies the effect of movements in exchange rate on aggregate demand.

Exchange rate fluctuations may be caused by shocks or structural forces beyond the scope of the monetary policy, but also by telic interest rate swings. For example, an increase in interest rate attracts foreign capital and currency appreciates, and vice versa. That is why, in open economies with a certain level of dollarization, several possible additional channels appear for monetary policy to have an impact on wealth redistribution and consequently, on aggregate consumption. The first channel is direct effect on wealth (when agents save/borrow in foreign currency, exchange rate depreciation increases their assets/debt values in national currency).

The second influences the propensity to save (when foreign currency depreciates, agents may prefer to save more in that currency due to their expectations of later appreciation). Final effect on consumption consists of the two previous effects, complemented by the effect of exchange rate change on a price level, known as imported inflation.).

The main question here is how monetary transmission works in open economies with heterogeneous agents and certain level of dollarization, how it disseminates from interest rate changes to effect on consumption. In developing countries central banks are actively inspecting the way monetary transmission mechanism works. As evidence suggests, exchange rate channel is one of the main channels for monetary policy to operate. Therefore, having a model capturing the strength of this channel is crucial for any central bank.

A Dynamic Stochastic Partial Equilibrium model for small open economy, incorporating heterogeneity of agents in productivity and therefore income, is viewed as the best tool to model the response of aggregate consumption to interest rate changes within the above described framework.

The structure of paper proceeds as follows. Chapter 2 contains literature overview. Chapter 3 presents the model and method of solving it. Chapter 4 specifies calibration and estimation of the Impulse Response Functions of the exogenous variables. Chapter 5 presents the discussion of the results. Chapter 6 concludes.

Chapter 2

LITERATURE REVIEW

I am going to present papers related to core components of my research question: importance of heterogeneous agents while talking about monetary policy transmission; current developments in open economy literature; and empirical works confirming the importance of the two factors above.

THEORETICAL MODELS WITH HETEROGENEOUS AGENTS FOR CLOSED ECONOMY

Auclert (2017) largely contributes to recent developing of theoretical framework of monetary policy transmission, introducing heterogeneity among consumers as another channel of monetary transmission mechanism. Debtors and savers have different marginal propensities to consume, that is why when debtors benefit from monetary policy, consumption increases more than when savers benefit from it. Employing partial equilibrium framework, he establishes that distribution amplifies the effect on aggregate consumption.

Further development of HA present in macro models moves to union with standard New Keynesian models. Gornemann, Kuester and Nakajima (2016) in New Keynesian business-cycle model with rich household heterogeneity show that aggregate consumption is more responsive to shocks.

Another incorporation of heterogeneous agents into NK framework is performed by Kaplan, Moll, and Violante (2018), who conclude that the effect of interest rate change on consumption through labor income is more significant than the effect produced by representative agent framework. They also compare HANK model with existing representative agent models, showing its advantages over the latter and empirically realistic results (distributions).

Luetticke (2017) evaluates monetary policy effect in economy with agents differing in the obtained labor income. They choose between liquid and illiquid assets for their portfolio, and make this choice depending on the type of income they receive. He employs DSGE New Keynesian business cycle model to show that aggregate consumption falls more in response to MP tightening. The stronger reaction of consumption is due to the high marginal propensities to consume of liquidity-poor agents, which constitute the sizable part of population when model is calibrated to US data.

All in all, the presence of HA makes models' results empirically realistic by placing emphasis on income effect of monetary policy transmission channel, and modifies the response of aggregate consumption relative to RA models.

THEORETICAL SMALL OPEN ECONOMY RANK MODELS WITH NO HETEROGENEITY

Some models for small open economies concentrate on the non-trivialities brought by the presence of exchange rate channel. For example, Senbeta (2011) extends the standard small open New Keynesian DSGE by adding a constraint on availability of the foreign exchange for firms in low income countries, which rely heavily on imported capital and imported inputs for their production. The author's results confirm the higher vulnerability of low income countries to shocks by generating more volatile responses of main macroeconomic variables to domestic and external shocks, in comparison to the standard NK DSGE model.

Others study the optimal monetary policy in a small open economy. To give an instance, Velasco and Parrado (2002) derived the optimal interest rate and exchange rate policies. The optimal interest rate responds to home productivity shocks, government spending, and foreign interest rate movement, while optimal exchange rate regime, given intertemporal elasticity of substitution being less than

1, is managed float, when central bank intervenes from time to time to correct the direction of exchange rate path.

Faia and Monacelli (2007) in their analysis of optimal monetary policy introduce home bias in consumption. The authors show that the higher weight on home goods over imported goods in people's preferences complements the common for this type of models optimal policy aim of markup stabilization with some degree of exchange rate stabilization.

Overall, the monetary policy has been heavily studied in small open economies, however, for the purposes of existing analysis representative agent models were used.

EMPIRICAL MODELS CONSIDERING THE EFFECT OF HA ON MONETARY POLICY TRANSMISSION

Generally, analysis of time-series data on micro level shows that effect of interest rate is insignificant after controlling for income, meaning income effect should dominate direct interest rate effect in theoretical models.

For example, Canzoneri, Cumby, and Diba (2007) estimate negative correlations between policy rate (FED rate) and Euler equation rate, undermining the reliability of models equating those rates.

Yogo (2004) suggests the use of weak instrumental variables to resolve the existing puzzle of estimating the intertemporal elasticity of substitution. Given income, elasticity of substitution is insignificant in 11 sample developed countries.

Campbell and Mankiw (1989) develop a simple-framework model with two types of agents, who are permanent income and hand-to-mouth consumers. By means of empirical models they verify that the presence of such two types fit the data best. Permanent income consumers' consumption does not react to changes in real interest rate and depends on future expected income only. The presence of current income consumers explains the existence of predictable movements in aggregate consumption.

On the contrary, RANK models use permanent income consumers by assuming they do not respond to transitory income shocks, that is why income effect in RA models is small. However, Jappelli and Pistaferri (2010) show that consumption changes in response to future expected income shocks, both transitory and permanent, with the reaction to the latter being much bigger.

Based on data from UK and USA, Cloyne and Surico (2016) estimated that households response differently to temporal swings in interest rate, depending on their wealth position: agents without debt do no respond, agents with debt increase spending, and lenders also increase spending but less than debtors.

EMPIRICAL MODELS STUDYING THE CONTRIBUTION OF EXCHANGE RATE IN MP TRANSMISSION MECHANISM

Empirical literature uniformly establishes that the influence of exchange rate on consumption is huge. Moreover, dollarized economy is more vulnerable to monetary shocks.

Ho and Iyke (2017) evaluate the effect of exchange rate uncertainty on real consumption in Asian countries with the help of dynamic penal data technique. They divide uncertainty into temporary and permanent components and state that the effect of transitory uncertainty is insignificant while permanent uncertainty in exchange rate impedes consumption.

Bahmani-Oskooee and Xi (2015) state that even though earlier main drivers of consumption were interest rate and income, with economies becoming more open the exchange rate strengthens as a driver for most macroeconomic variables including consumption. By using dataset on 12 emerging economies, authors show that the effect of exchange rate uncertainty is negative for consumption of all countries in the short run, and only transmitted to the long run consumption in half of the countries.

Yeyati (2016) gathers possible theoretical explanations and consequences of differing views on dollarization, and empirically tests several hypotheses using data on developing and developed countries. He finds that a dollarized economy is more vulnerable to monetary shocks, and therefore have higher inflation rates, is more vulnerable to banking crisis and exhibits slower-growing, more volatile output.

Chapter 3

MODEL

My benchmark model is HANK by Kaplan, Moll, and Violante (2018), and main innovation is turning the closed economy into an open one, thereby introducing exchange rate channel of interest rate effect on consumption. The model is partial equilibrium model, where households take prices (price level, interest rates, wage) exogenously.

SETUP

Households. The economy is populated by a continuum of households indexed by their holdings of domestic currency assets b, foreign currency assets a, and their idiosyncratic labor productivity z. Labor productivity follows Poisson process with two states, productive and unproductive, with Poisson intensities $\lambda_{1,2} = \left[\frac{1}{3}, \frac{1}{3}\right]$. The fourth index of households, *e*, is due to the two possible expected states of the economy, related to exchange rate: normal functioning and crisis with sharp devaluation of domestic currency. The exchange rate follows another Poisson process with intensities $\phi_{1,2} = \left[\frac{1}{10} . \frac{1}{15}\right]$. Those intensities mean the following: the first number is the probability of switching from State 1 to State 2, the second number is the probability of transition from State 2 to State 1.

Time is continuous. At each instant in time t, the state of the economy is the joint distribution $\mu_t = (da, db, dz)$.

Households receive utility flow u from consuming $c_t > 0$. The function u is strictly increasing and strictly concave in consumption. Preferences are time-separable, and the future is discounted at rate $\rho \geq 0$.

Households divide their income among consuming and saving. There are two options for savings: domestic currency assets and foreign currency assets. Interest rates are exogenous. Interest rate for domestic currency assets is higher than interest rate for foreign currency assets (in progress to be derived under uncovered interest rate parity). Nevertheless, households are motivated to save in foreign currency under the expectation of crisis (devaluation) with certain probability.

There are four budget constraints for the agents. They can save/borrow in domestic and foreign domestic currency assets up to borrowing constraints (these are two first constraints). The minimums for b is negative, meaning agents can borrow only up to a certain threshold. The minimum for a is zero, meaning agents cannot borrow in foreign currency. There are also two law of motions for domestic and foreign currency assets.

Agents consume two types of products, domestic and foreign. With foreign price being set to 1, each household's nominal consumption is

$$P_t c_t^d + 0.5 e_t c_t^f$$

where price of a foreign good is set to 2.

Aggregation of real consumption possesses CES properties:

$$c_t = \left(\alpha {c_t^d}^{\epsilon} + (1-\alpha){c_t^f}^{\epsilon}\right)^{1/\epsilon}$$

Aggregate price level follows

$$P^{agr} = \left[P^{\frac{\epsilon}{\epsilon-1}}\alpha^{\frac{1}{1-\epsilon}} + (0.5e)^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{1-\epsilon}}\right]^{\frac{\epsilon-1}{\epsilon}}$$

Derivations may be found in Appendix A.

Agents maximize lifetime utility subject to budget constraints:

$$\max E_o \int_0^{\infty} e^{-\rho t} u(c_t) dt$$

s.t.

$$db_t = \left(w_t z_t + r_t^b(b_t)b_t - d_t - \chi(d_t, a_t, e_t) - P_t^{agr} c_t\right)dt$$

$$da_t = \left(r_t^a(a_t)a_t + \frac{d_t}{e_t}\right)dt$$

$$b_t \geq b_{min}$$

$$a_t \geq 0$$

$r_t^b(b_t)$ is exogenously given interest rate for domestic currency in period t. It is exogenous for households since the model is partial equilibrium, and interest rate is determined by central bank. $w_t z_t$ is every time period income, consisting of exogenous market wage and stochastic productivity draw for each agent.

d_t is deposit, amount of money transmitted from domestic currency account to foreign currency account. As in real life of developing countries, it is not costless to transform your savings into more reliable currency savings, therefore agents incur transactions costs $\chi(d_t, a_t, e_t)$.

$$\chi(d_t, a_t, e_t) = \chi_0 |d_t| + \chi_1 \left|\frac{d_t}{a_t e_t}\right|^{\chi_2} a_t e_t$$

This transaction cost has two components that play distinct roles. The linear component generates an inaction region in households' optimal deposit policies because for some households the marginal gain from depositing or withdrawing the first dollar is smaller than the marginal cost of transacting $\chi_0 > 0$. The convex component $(\chi_1 > 0, \chi_2 > 1)$ ensures that deposit rates are finite, $|d_t| < \infty$ and hence household's holdings of assets never jump. Finally, scaling the convex term by foreign currency assets a in domestic currency denomination delivers the desirable property that marginal costs $\chi\,(d,a,e)$ are homogeneous of degree zero in the deposit rate $\frac{d}{ae}$ so that the marginal cost of transacting depends on the fraction of illiquid assets transacted, rather than the raw size of the transaction.

$r_t^a(a_t)$ is exogenously given interest rate for foreign currency in period t, and a_t is amount of assets in foreign currency.

Solution is presented by Hamilton-Jacobi-Bellman equation for decision rules for consumption (both domestic and imported goods) and deposits:

$$\rho V_{kl}(a,b) \;= \max\; u(c) + V_{b,kl}(a,b)\big[wz_k + r^b(b)b - d - \chi(d,a,e) -$$
$$- P_t^{agr} c_t\big] + V_{a,kl}(a,b)\left(r^a(a)a + \frac{d}{e}\right) + \lambda_k(V_{-kl} - V_{kl}) + \phi_k(V_{k-l} - V_{kl}),$$

where $V_{kl}(a,b)$ – value function in state k productivity and state l exchange rate;

$V_{b,kl}(a,b)$ – derivative of the value function with respect to b

$V_{a,kl}(a,b)$ – derivative of the value function with respect to a

Both value functions derivates are multiplied by the respective laws of motions of assets

and by Kolmogorov equation for stationary joint distribution of domestic and foreign currency assets holdings and labor income (wage multiplied by productivity):

$$\partial_t G_k(a,b,t) = -\partial_a G_k(a,b,t)s_k^a - \partial_b G_k(a,b,t)s_k^b - \lambda_k G_k(a,b,t) + \lambda_{-k} G_{-k}(a,b,t),$$

where $G_k(a,b,t)$ – cumulative distribution function in state of productivity k. Although households expect exchange rate crisis, it never happens in economy, therefore joint distribution is derived on the productivity Poisson process only.

After taking derivatives with respect to a, b and deriving stationary distribution, which means time derivative is zero:

$$0 = \partial_a\left(s_k^a(a,b)g_k(a,b)\right) - \partial_b\left(s_k^b(a,b)g_k(a,b)\right) - \lambda_k g_k(a,b) + \lambda_{-k}g_{-k}(a,b)$$

$$\int\int (g_1(a,b) + g_2(a,b))\, dadb = 1\ or$$

$$\iiint g(a,b,z)dadbdz = 1$$

Derivation procedure of such type of equations is intuitively described in Achdou et al (2017) Online appendix.

FOC:

$\langle d \rangle \qquad \frac{V_{a,kl}(a,b)}{e_t} = V_{b,kl}(a,b)\left(1 + \chi_d'(d_t, a_t, e_t)\right)$

$\langle c \rangle \qquad u_c'(c_t) = P^{agr}V_{b,kl}(a,b)$

Households take as given in equilibrium:

- returns to domestic and foreign currency assets
- exchange rate
- productivity
- wage
- price level

NUMERICAL SOLUTION

To solve the stationary HJB equation, I use an implicit upwind finite difference method along the lines of Achdou et al. (2014).

My upwind method splits the drift of b, $w_t z_k + r^b(b,t)b_t - Pc_t^d - ec_t^f - d_t - \chi(d_t, a_t, e_t)$ into two parts

$$s^c = w_t z_k + r^b(b,t)b_t - c_t$$

$$s^d = -d_t - \chi(d_t, a_t, e_t)$$

and upwinds these separately. The first part is 'savings from consumption', which are stored as domestic currency assets, and the second part is savings directed to foreign assets account, adding to foreign currency assets.

I denote grid points by $b_i, i = 1, \dots, I, a_j, j = 1, \dots, J, z_k, k = 1,2, e_l, l = 1,2$, n is number of iterations, and

$$V_{i,j,k,l} = V(b_i, a_j, z_k, e_l)$$

My upwind finite difference approximation is given by

$$\frac{V_{ijkl}^{n+1} - V_{ijkl}^{n}}{\Delta} + \rho V_{ijkl}^{n+1} = u\left(c_{ijkl}^{n}\right) + V_{b,ijkl}^{n+1,B}\left(s_{ijkl}^{c,B}\right)^{-} + V_{b,ijkl}^{n+1,F}\left(s_{ijkl}^{c,F}\right)^{+} +$$
$$V_{b,ijkl}^{n+1,B}\left(s_{ijkl}^{d,B}\right)^{-} +$$
$$V_{b,ijkl}^{n+1,F}\left(s_{ijkl}^{d,F}\right)^{-} + V_{a,ijkl}^{n+1,B}\left(\frac{1}{e_k} d_{ijkl}^{B}\right)^{-} + V_{a,ijkl}^{n+1,F}(\left(\frac{1}{e_k} d_{ijkl}^{F}\right)^{+} + r^a(a)a_j) +$$
$$\lambda_k\left(V_{ij-kl}^{n+1} - V_{ijkl}^{n+1}\right) + \phi_l(V_{ijk-l}^{n+1} - V_{ijkl}^{n+1}),$$

where upper index B means backward difference, F means forward difference, and $(x)^+$ denotes $\max(x,0)$ and $(x)^-$ denotes $\min(x,0)$.

Chapter 4

CALIBRATION

In order to estimate the response of consumption to interest rate change, I calibrate the model to Ukrainian economy to mimic the behavior of individuals living in a developing country, highly susceptible to frequent economic crises followed by currency depreciation. Apart from parameters of the model, I also calibrate reaction paths of exchange rate, aggregate price level and wage in response to interest rate shock, since these parameters are exogenous to agents in my partial equilibrium model.

Two objectives should be achieved in calibrating the model. First, the distribution of assets in foreign and domestic currencies should be realistic, meaning it should match real savings of Ukrainians in both currencies. Second, responses of price variables to interest rate fluctuation should replicate the actual ones in Ukraine after movement in Central Bank policy rate.

Table below presents calibration of the main parameters. My model is developed in annual terms, therefore all prices are annual. For CRRA utility function I use $\gamma = 1$, which is standard in the literature. Next go rates in different currencies on deposits and loans. The return on domestic deposits respond to Ukrainian realities as of the beginning of 2020. I used National Bank of Ukraine data for weighted average annual rates for households for deposits and loans. The big spread between credit and deposit rate is very realistic for 'waiting for crisis' circumstances and necessary to capture additional costs of borrowing (bank fees etc.). Deposit rate in foreign currency is lower according to uncovered interest rate parity.

Annual nominal wage is normalized to 1, domestic price level (1) and foreign price level (0.5) differs by exchange rate, which is 2 in non-crisis state of the world and jumps to 6 (3 times higher) in the moment of crisis, reflecting the potential the hryvnia response (as in 2014-2015). There are also two productivity types, lower and higher.

Table 1. Calibrated parameters

Parameter	*Explanation*	*Calibration*
γ	Constant positive relative risk aversion parameter from utility function	2
r_a	Nominal deposit and credit rate for foreign currency	0.08
$r_b\ for\ deposits$	Nominal deposit rate for domestic currency	0.1
$r_b\ for\ loans$	Nominal credit rate for domestic currency	0.2
ρ	Discount rate	0.12
w	Nominal wage	1
$z_{1,2}$	Productivity of two types	$[0.5, 1]$
$e_{1,2}$	Exchange rate for two states: normal and crisis	$[2,6]$
P	Domestic price level	1
$P^{foreign}$	Foreign price level	0.5

QPM MODEL

In order to estimate the response of aggregate macro variables (price level, exchange rate and wage) to the negative shock of the interest rate, I use Quarterly Projection model used by Central Bank of Ukraine, in line with other Central Banks estimating the monetary transmission.

The QPM is a semi-structural model, meaning it combines the fundamental principles of economic theory (the vision of economists on how their subject matter should work) and data-driven refinements. It is a reduced-form New Keynesian model designed to capture the main characteristics of the Ukrainian economy. Monetary policy in this model affects real variables only in the short term because of nominal and real economic rigidities, e.g. sticky prices. In the long term, however, economy converges to its sustainable growth path, where variables are at their natural levels, e.g. potential output or NAIRU. The monetary policy has no effects on dynamics of these natural levels. Thus, it is neutral in the long term.

The model covers four main pillars of Ukrainian economy, namely

1. Aggregate demand side, which is represented by real GDP, depending on its value in the previous period to feature the absence of drastic changes in GDP level under normal economy functioning, real exchange rate and real credit rate to represent the effect on domestic consumers and importers, and also wages, terms of trade, government transfers and risk-premium;
2. Aggregate supply side, the resulting variable of which is inflation level in Ukraine. Due to the differing nature and drivers behind the components of inflation, they were grouped into core inflation (clothes, food, services), raw food inflation, petrol and gas inflation, and administratively regulated prices. All the groups depend on inflation expectations of households, analysists and firms, target level of inflation, real output, real exchange rate (to account for imported inflation) and other components (e.g. harvest, wages);
3. Interaction with the other world, captured by nominal exchange rate UAH/USD, which is defined by the uncovered interest rate parity. It proclaims that higher interest rate leads to an evaluation of UAH due to the increase in foreign investors demand for financial instruments denominated in hryvna; and vice versa;

4. Monetary policy rule, based on Taylor rule, which defines the forecast of an interest rate. It exhibits the trade-off between sticking to low inflation target and at the same time not hampering the GDP growth.

Main instrument of targeting inflation, namely interest rate, effects inflation through aggregate demand deviation from the potential level and exchange rate. Exchange rate influences overall inflation level though imported inflation, and GDP gap raises or lowers domestically driven prices.

In the model, the steady states of some main variables are explicitly calibrated in accordance with the NBU's targets and theoretically consistent relationships among variables. However, to satisfy the logic of the model, other steady states are not calibrated, but endogenously calculated. The model is in gaps, therefore it does not matter my model and QPM have different steady states, I may still use the responses. Unfortunately, some of the QPM's steady states are not constant, that is why IRFs are not converging to the starting steady states. In my model though, the responses should converge. That is why I modified IRFs from QPM so that they converge to the steady states. I also proportionally increased the responses, so that their effect is clearer while discussing graphical results.

Impulse Response Functions from QPM to the one percentage point increase in annual interest rate are presented below. IRFs span the period of 20 quarters (5 years). We see that exchange rate appreciates, while aggregate price level drops, and nominal wage decreases a little less than price level. The IRF in pictures are presented for log of variables, therefore numbers are interpreted as percentage deviations already in percent (multiplied by 100%). All responses are annualized.

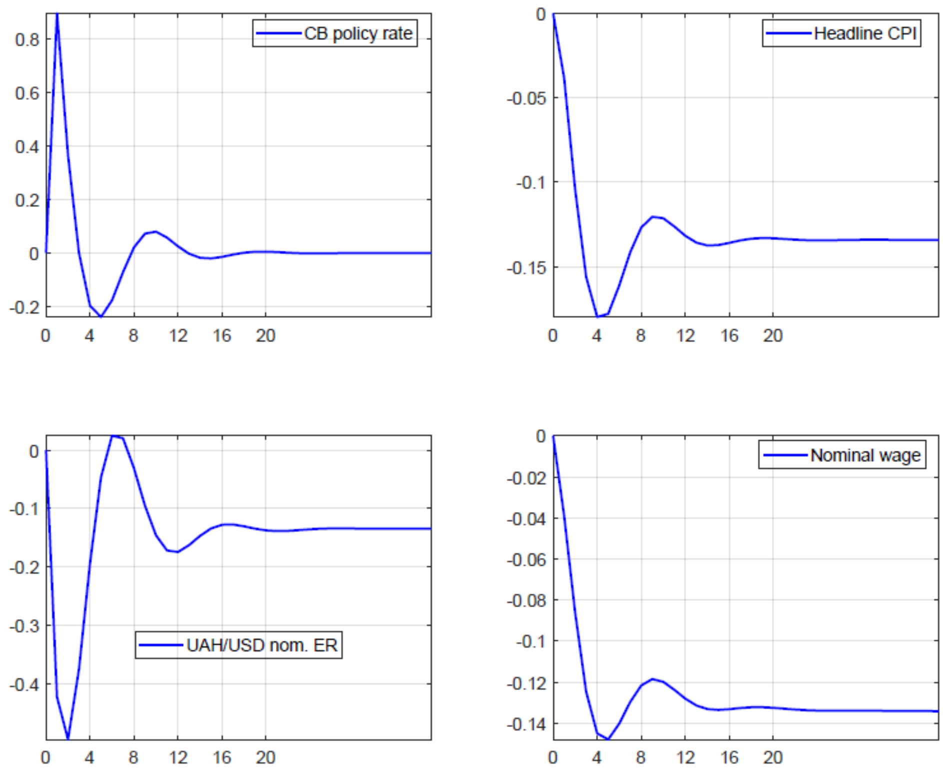


Figure 1. Impulse Response Functions to Interest Rate one-percentage-point negative shock

Modified IRFs are presented below. The logic of responses is preserved; however, they converge to steady states and are amplified in magnitude. They span 36 months ahead (3 years), since in this period IRFs from QPM are approximating initial steady states.

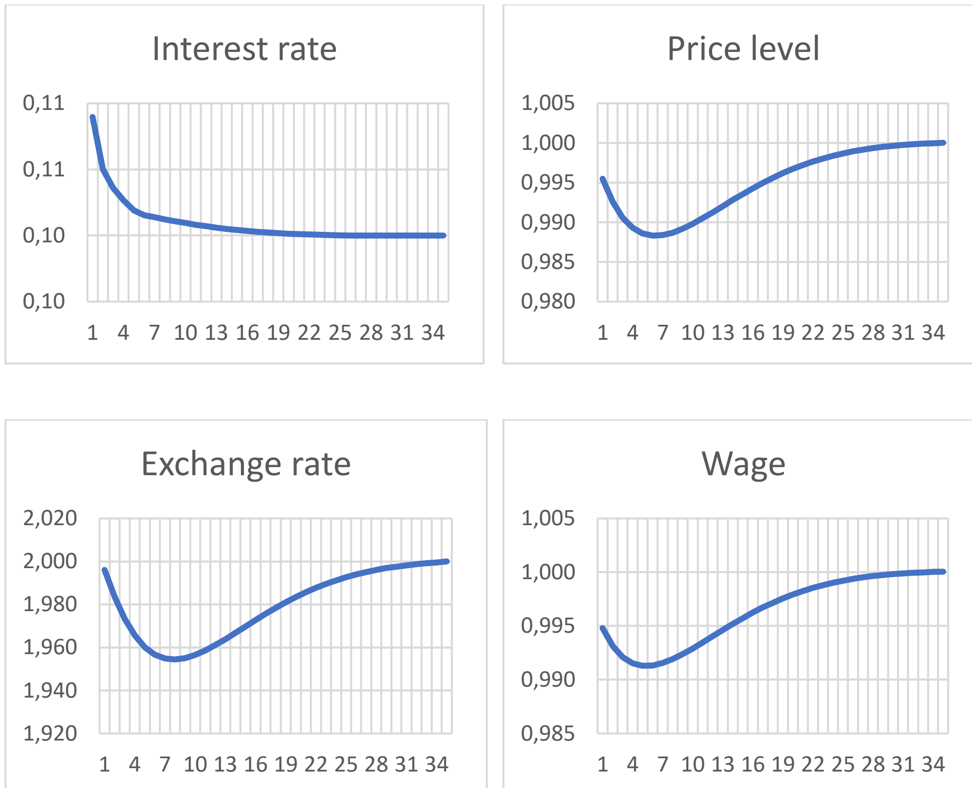


Figure 2. Modified IRFs to the Interest Rate one-percentage-point negative shock

Chapter 5

EQUILIBRIUM BEHAVIOR

My first results describe optimal consumption and savings in domestic and foreign currency assets for low-productivity households (low type) and high-productivity households (high type) in a normal state of the economy (no sharp devaluation), and distribution of wealth in both currencies.

From now on, DC – domestic currency, FC – foreign currency.

In the figure below (Figure 3) the consumption pattern for both low- and high-productivity agents is similar, with real consumption growing for agents with larger wealth in both currencies. However, for the same level of assets in both currencies, high-type agents consume a little more on average because their labor earnings are higher.

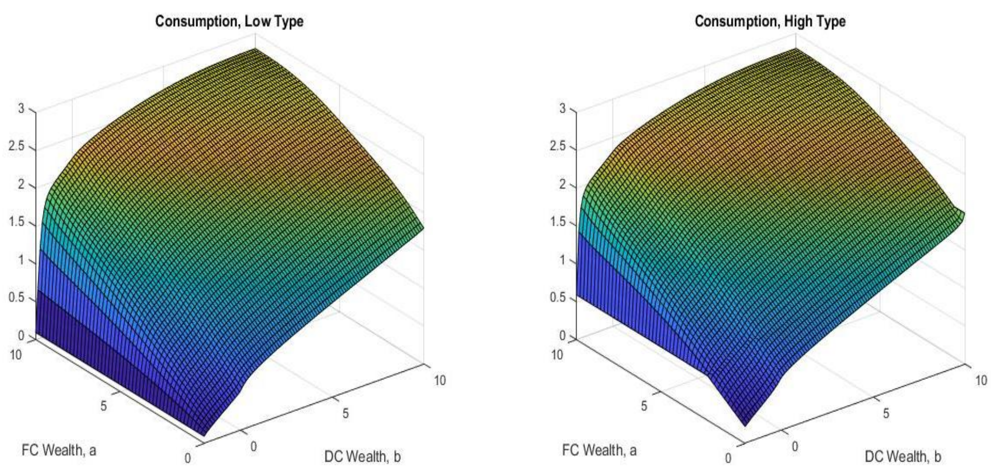


Figure 3. Optimal consumption

Optimal savings patterns in both currencies resemble each other for low- and high-productivity agents as well (Figure 4). Both types borrow in domestic currency, but the high-type ones' debt is far smaller than low-type ones' and savings are higher for the same asset positions, as is better illustrated in level curves of savings given either foreign currency assets (Figure 5) or domestic (Figure 6).

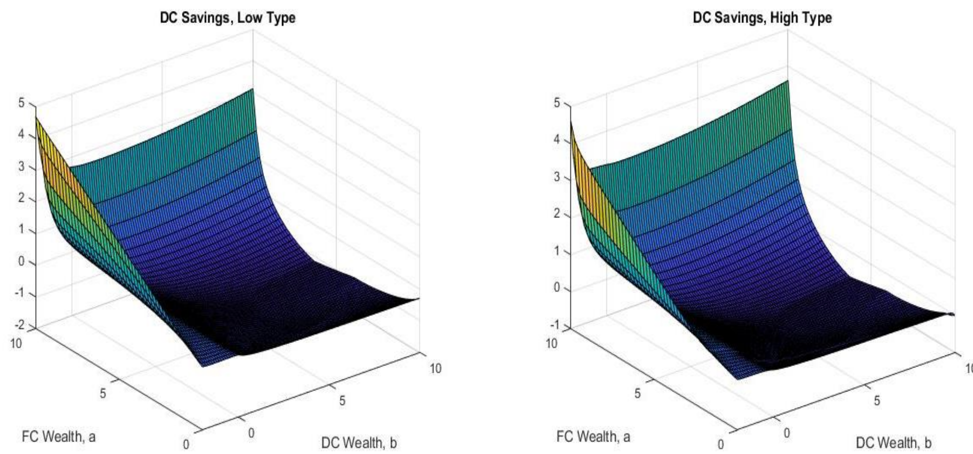


Figure 4. Optimal savings in domestic currency

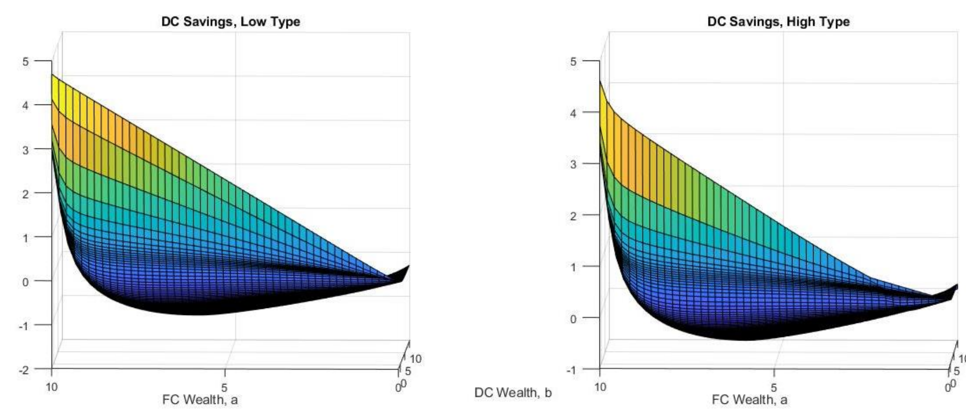


Figure 5. Optimal savings in domestic currency for foreign currency asset position

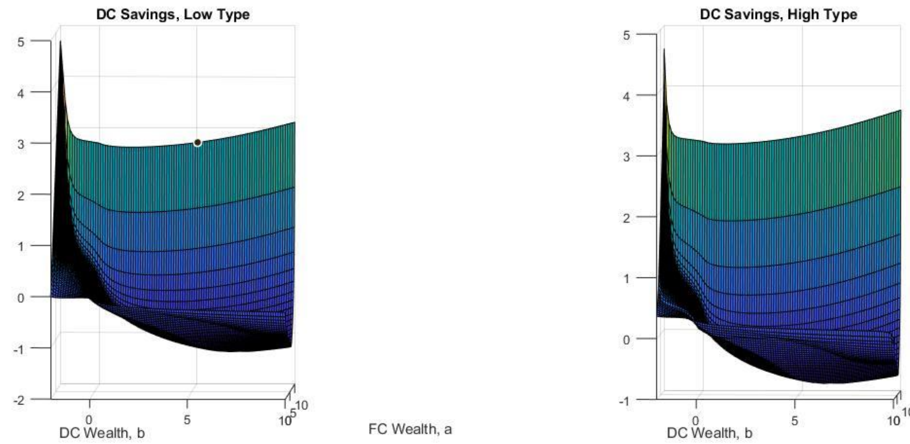


Figure 6. Optimal savings in domestic currency for domestic currency asset position

Similar picture is observed for savings in foreign currency (Figure 7). For the same position in domestic currency asset, low-type agents tend to borrow more than high-type agents.

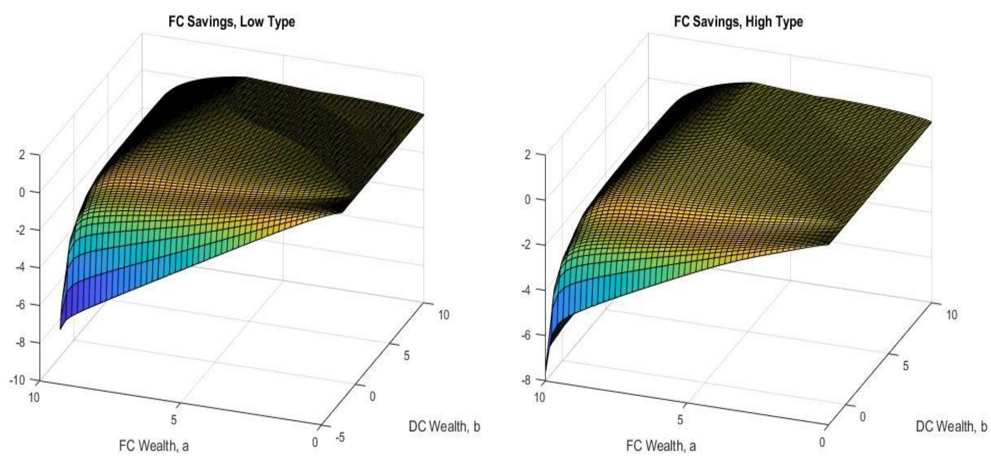
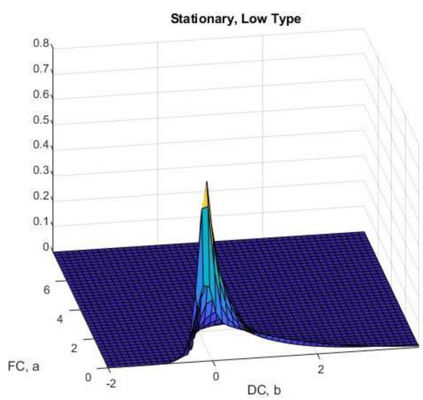


Figure 7. Optimal savings in foreign currency

Finally, distribution of assets in two currencies is realistic (Figure 8). We can see that the biggest share of low-type agents is concentrated around zero in holding of their assets in domestic currency and 0.5 in holding foreign currency assets. Significant portion borrows in domestic currency and therefore, have negative DC assets. Unlike that, high-type agents mean lies in the positive DC and FC asset holdings. Given that wage is calibrated to be 1 and exchange rate 2 in non-crisis period, average non-productive agent keeps around one his annual wage is savings in foreign currency and nothing in domestic currency, while highly productive agent keeps around one his annual wage in DC assets and three-four his annual wages in FC assets (Figure 9).



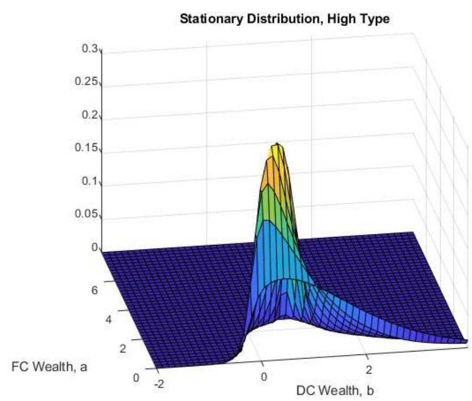


Figure 8. Stationary distribution of wealth

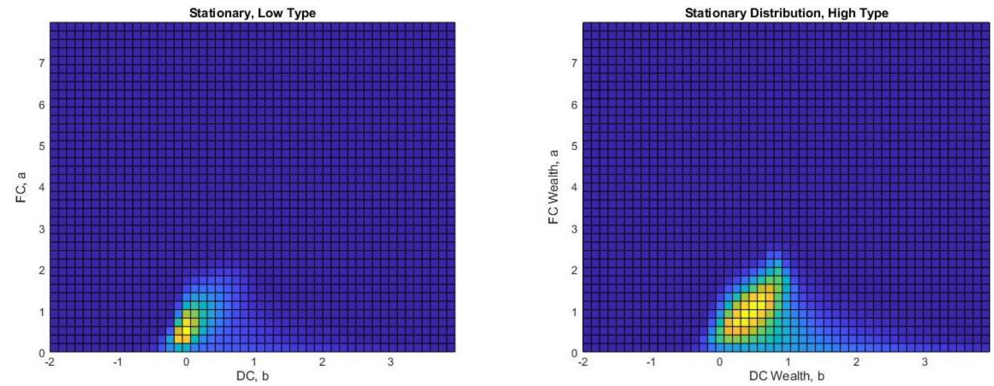


Figure 9. Stationary distribution of wealth from a different angle

MIT SHOCK

After investigating the properties of the model in steady state, the next step is to study the economy's impulse response after an "MIT shock", i.e. an unanticipated (zero probability) shock followed by a deterministic transition. The shock in the model is going to be an interest rate change. System to be solved is

$$\begin{cases} \rho V_{kl}(a,b,t) \ = \max\ u(c_t) + V_{b,kl}(a,b,t)\big[w_t z_k + r^b(b,t)b_t - d_t - \\ -\chi(d_t, a_t, e_t) - P_t^{agr} c_t\big] + V_{a,kl}(a,b,t)\left(r^a(a,t)a_t + \frac{d_t}{e_t}\right) + \\ +\lambda_k\big(V_{-kl}(a.b,t) - V_{kl}(a.b,t)\big) + \phi_k\big(V_{k-l}(a.b,t) - V_{kl}(a.b,t)\big) + \\ +V_{t,kl}(a,b,t) \\ \partial_t g_k(a,b,t) = \ \partial_a\big(s_k^a(a,b,t) g_k(a,b,t)\big) - \ \partial_b\left(s_k^b(a,b,t) g_k(a,b,t)\right) - \\ -\lambda_k g_k(a,b,t) + \lambda_{-k} g_{-k}(a,b,t) \\ \iiint g_t(a,b,z)\,dadbdz = 1 \text{ for each t} \end{cases}$$

TRANSITION DYNAMICS

As the result, I obtain the time path for equilibrium wealth distributions of assets in both currencies (for four states of economy due to productivity and exchange rate uncertainty) and consumption time path for each household in response to a movement in interest rate.

On the figure below, one sees the answer to the main question of the paper, namely how aggregate consumption reacts to the negative shock of interest rate in the open economy with heterogeneous agents, able to save in two currencies and hedge the risks of domestic currency devaluation. As we see, in response to a one-percentage-point increase in interest rate, real aggregate consumption drops by 0.5% in the first month. Several channels play role here.

Firstly, due to the higher interest rate per se (direct or substitution effect) agents have higher incentive to save in comparison with steady state. Secondly, due to the negative monetary shock wages go down, leaving agents with less purchasing power (indirect or income effect). Thirdly, price level does down and boosts consumption (indirect effect). Finally, uncovered interest rate parity suggests that exchange rate appreciates, therefore it becomes cheaper to buy foreign currency. Since agents in the model always expect exchange rate shock in the future, even though it never occurs, it is a good chance for them to buy more of foreign currency at the cost of lowering consumption.

The next section will present the decomposition of the aggregate effect, explaining in more detail this particular aggregate response.

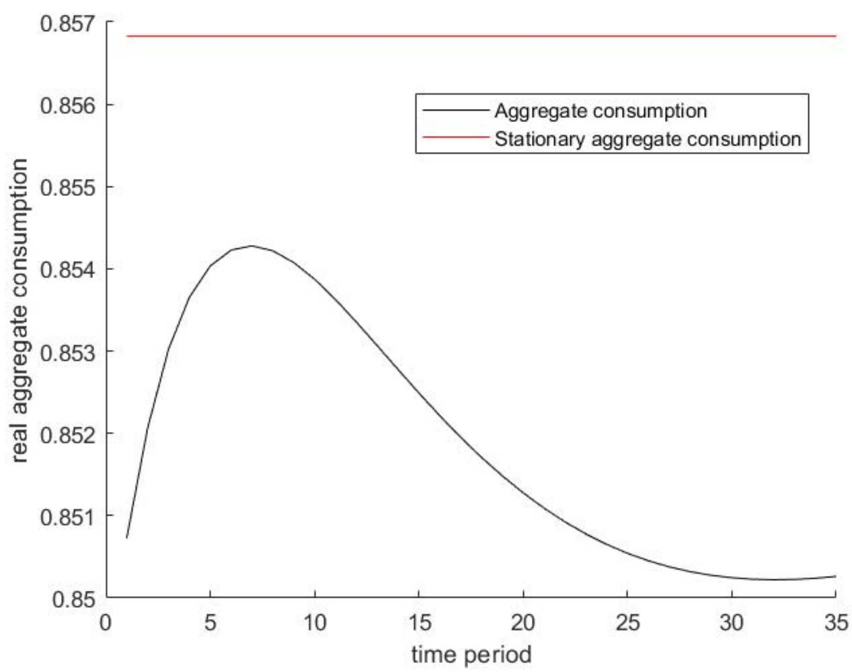


Figure 10. Aggregate consumption response to negative interest rate shock, 3 years ahead

MONETARY POLICY IN THE MODEL

I am interested in analyzing the response of the economy to a one-time unexpected interest rate shock. I assume that the economy is initially in steady state with monetary policy following the Taylor rule. Then shock happens to the Taylor rule with some deterministic decay back to zero. To examine the economy's response to this shock, I decompose the total effect of a monetary shock into direct (partial equilibrium effect, direct response to changes in interest rate) and indirect (general equilibrium, reaction of prices, wage, exchange rate to interest change and their effect on consumption) effects.

Consumption may be written as a function of the sequence of equilibrium prices.

Let $\{\Gamma_t\}_{t\geq 0} = \{r_t^b, r_t^a, w_t, e_t\}$. Now I define aggregate consumption for each period t:

$C_t(\{\Gamma_t\}_{t\geq 0}) = \int c_t\ (a, b, z, e;\ \{\Gamma_t\}_{t\geq 0}) d\mu_t,$

where $c_t\ (a, b, z, e;\ \{\Gamma_t\}_{t\geq 0})$ is the household consumption policy function and $\mu_t\ (da, db, dz;\ \{\Gamma_t\}_{t\geq 0})$ is the joint distribution of domestic and foreign currency assets and idiosyncratic productivity.

By totally differentiating aggregate consumption, I obtain the decomposition of the effect into two of the main interest:

$$dC_0 = \int_0^\infty \frac{\partial C}{\partial r^b} dr_t^b dt + \int_0^\infty \left(\frac{\partial C}{\partial r^a} dr_t^a + \frac{\partial C}{\partial w} dw_t + \frac{\partial C}{\partial e} de_t\right) dt\ ,$$

where $\int_0^\infty \frac{\partial C}{\partial r^b} dr_t^b dt$ is direct effect and $\int_0^\infty \left(\frac{\partial C}{\partial r^a} dr_t^a + \frac{\partial C}{\partial w} dw_t + \frac{\partial C}{\partial e} de_t\right) dt$ is indirect one.

I approximate the derivatives numerically. The formal definitions of the terms above are, starting from the first term and analogously for the rest of them

$$\int_0^\infty \frac{\partial C}{\partial r_t^b} dr_t^b dt \;=\; \int_0^\infty (\int \frac{\partial c_t\left(a,b,z,e;\{r_t^b,\overline{r^a},\bar{w},\bar{e}\}_{t\geq 0}\right)}{\partial r_t^b} d\mu_t^{r^b}) dr_t^b dt,$$

where $\mu_t^{r^b} = \mu_0\left(da, db, dz; \{r_t^b, \overline{r^a}, \bar{w}, \bar{e}\}_{t\geq 0}\right)$. That is, this term is the aggregate partial-equilibrium consumption response of a continuum of households that face a time-varying interest rate path $\{r_t^b\}_{t\geq 0}$, but paths for foreign currency asset return r^a , wage w, and exchange rate e that are held constant at their steady-state values.

RESULTS

The overall response of consumption was presented above. Decomposition reveals the main channels of the monetary transmission. As one can see in the Table 2, the largest share in the one-year average effect on consumption belongs to price level change, which promotes consumption increase. Interest rate change and exchange rate change affect consumption almost equally, while wage influence turns out to be the second largest.

Interesting, but in the first period decomposition demonstrates differing strength of mechanism components, with leading influence of wage, followed by exchange rate, interest rate change and finally, price level. This happens because price level reacts to monetary policy with some delay and reaches minimum after wage starting to converge. Immediate and strong response of agents to the exchange rate appreciation reflects the modeled fear of crisis, when people aim at backing themselves up with foreign currency savings.

Table 2. Decomposition of the consumption response

	First-month change, % from stationary level	In % of overall effect	Average consumption response over the year, % from stationary level	In % of overall effect
Overall consumption change	-0.71	100	-0.29	100
Interest rate change	-0.23	32.7	-0.15	49.8
Exchange rate change	-0.28	40	-0.19	66
Price level change	0.15	-21.6	0.31	-106.8
Wage change	-0.35	49	-0.26	91

In the picture below the decomposed transition is presented (Figure 11). As we see, the paths of each of the components differ, changing components' weight in the effect on consumption response in every period. Therefore, their shares logically can be compared in the first-month response and one-year span response of interest. In both cases indirect effect (wage+price+exchange rate) clearly dominates the direct one (interest rate). The model is very sensitive to the responses of macro variables to interest rate, which are given exogenously. It captures the existing strength of monetary transmission channels and produces results reflecting the influence of those channels.

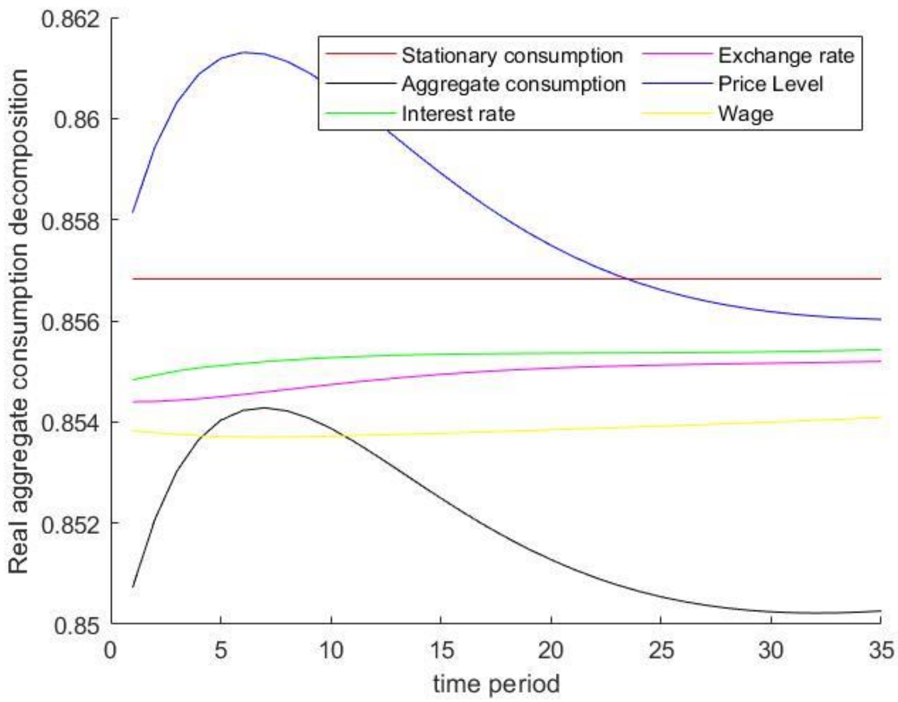


Figure 11. Decomposition of consumption response to interest rate increase

Chapter 6

CONCLUSION

It is crucial for Central Banks to understand how monetary policy transmission effects the main variables of interest, among which is consumption. The main question of the model is how monetary transmission works in open economies with heterogeneous agents and certain level of dollarization, how it disseminates from interest rate changes to effect on consumption.

This paper uses Partial Equilibrium Stochastic model in order to answer the above question. The responses of main macro variables price level, exchange rate, and wage, which are affected by interest rate swings and in turn have an influence on consumption, are calibrated using Quarterly Projection Model, used by Central Banks. The answer is that consumption falls by 0.7% in the first month in response to one percentage point increase in interest rate. It also falls by 0.3% over the period of 1 years.

The decomposition of this effect suggests that the largest share in the 1-year effect on consumption belongs to price level change, which promotes consumption increase. Interest rate change and exchange rate change affect consumption almost equally. They both make consumption fall, as well as the wage decrease. Wage influence turns out to be the second largest. Together indirect effect accounts for significantly larger share of the overall efect, matching the empirical evidence.

However, the model is very sensitive to the responses of macro variables to interest rate, which are given exogenously. It captures the existing strength of monetary transmission channels and produces results reflecting the influence of those channels.

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APPENDIX A

Aggregate price level

Let's maximize aggregate consumption, consisting of domestic good and foreign good, subject to budget constraint

To make my life easier, I derive the aggregate price level P^{agr}

$$P^{agregate} = \frac{Pc^d + 0.5ec^f}{\left(\alpha {c_t^d}^{\epsilon} + (1-\alpha){c_t^f}^{\epsilon}\right)^{1/\epsilon}} = \frac{I}{c}$$

To derive it, solve optimization problem

$\max c = \left(\alpha {c^d}^{\epsilon} + (1-\alpha){c^f}^{\epsilon}\right)^{1/\epsilon}$

st $I = Pc^d + 0.5ec^f$

$$< c^d > c^{\frac{1-\epsilon}{\epsilon}} \alpha {c^d}^{\epsilon-1} = \lambda P$$

$$< c^f > c^{\frac{1-\epsilon}{\epsilon}} (1-\alpha) {c^f}^{\epsilon-1} = \lambda 2e$$

$$c^d = \left(\frac{P}{e}\frac{1-\alpha}{\alpha}\right)^{\frac{1}{\epsilon-1}} c^f$$

$$c^f = \frac{I}{P\left(\frac{P}{0.5e}\frac{1-\alpha}{\alpha}\right)^{\frac{1}{\epsilon-1}} + e}$$

$$P\left(\frac{P}{0.5e}\frac{1-\alpha}{\alpha}\right)^{\frac{1}{\epsilon-1}} + e = \frac{P^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}} + 0.5e^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}}{0.5e^{\frac{1}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}}$$

$$c^f = \frac{0.5e^{\frac{1}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}}{P^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}} + 0.5e^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}}I = \frac{0.5e^{\frac{1}{\epsilon-1}}(1-\alpha)^{\frac{1}{1-\epsilon}}}{P^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{1-\epsilon}} + 0.5e^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{1-\epsilon}}}I$$

$$c^d = \frac{P^{\frac{1}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}}}{P^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}} + 0.5e^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}}I = \frac{P^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{1-\epsilon}}}{P^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{1-\epsilon}} + 0.5e^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{1-\epsilon}}}I$$

$$P^{aggregate} =$$

$$\frac{I}{\left(\alpha\left(\frac{P^{\frac{1}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}}}{P^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}} + 0.5e^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}}I\right)^{\epsilon} + (1-\alpha)\left(\frac{e^{\frac{1}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}}{P^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}} + 0.5e^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}}I\right)^{\epsilon}\right)^{1/\epsilon}}$$

$$P^{aggregate}$$

$$= \frac{1}{\left(\alpha\left(\frac{P^{\frac{1}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}}}{P^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}} + 0.5e^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}}\right)^{\epsilon} + (1-\alpha)\left(\frac{0.5e^{\frac{1}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}}{P^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}} + 0.5e^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}}\right)^{\epsilon}\right)^{1/\epsilon}}$$

$$P^{aggregate} = \frac{P^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}} + 0.5e^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}}{(1-\alpha)^{\frac{1}{\epsilon}}\alpha^{\frac{1}{\epsilon}}\left(\left(P^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}}\right) + \left(0.5e^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}\right)\right)^{1/\epsilon}}$$

$$= (1-\alpha)^{\frac{-1}{\epsilon}}\alpha^{\frac{-1}{\epsilon}}\left[P^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{\epsilon-1}} + 0.5e^{\frac{\epsilon}{\epsilon-1}}a^{\frac{1}{\epsilon-1}}\right]^{\frac{\epsilon-1}{\epsilon}}$$

$$= \left[P^{\frac{\epsilon}{\epsilon-1}}\alpha^{\frac{1}{1-\epsilon}} + (0.5e)^{\frac{\epsilon}{\epsilon-1}}(1-\alpha)^{\frac{1}{1-\epsilon}}\right]^{\frac{\epsilon-1}{\epsilon}}$$