

Monetary policy transmission mechanisms in an agent-based macroeconomic model

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Abstract. We study the direct impact and micro-level transmission mechanism of a monetary policy interest rate rise by the central bank in a macroeconomic agent-based model. Model explorations suggest that, the strength and working of the monetary transmission mechanism is highly dependent on the balance-sheet compositions of the central bank, banks, firms and households. In the model, financial sector structure might even block the monetary transmission mechanism altogether, indicating that the mechanism is not a clear cut as conventional theory would suggest.

Keywords: agent-based modelling, monetary economics, monetary transmission, inflation.

1 Monetary policy and inflation

The behavior of inflation since the crisis appears puzzling to many (Blanchard 2016). Despite that, very few central banks have made significant changes to their inflation targeting policy framework (Fay et al. 2016). In these frameworks, inflation is generally defined as a general increase in the overall price level of the goods and services in the economy (Federal Reserve 2015).

Central banks try to influence inflation by controlling the short-term interest rate as well as expectations of future interest rate (Bernanke 2004). Through the expectations hypothesis of the term structure, the long-term interest rate is thought to be an average of expectations of expected future short-term interest rates. If private sector participants expect central banks to increase or decrease interest rates in the future they will bid up (down) the price of long term assets. If the central bank is able to anchor private sector inflation expectations about short-term interest rates this should influence long-term interest rates (Bernanke and Reinhart 2004). Thus a credible central banks commitment to short-term rates can influence long term rates and flatten the yield curve (Woodford 2011).

From different sources in the literature, we identify six major channels through which changes in short-term interest rates influence inflation in a closed economy: a consumption channel, investment channel, asset price channel, lending channel, a balance sheet channel, and a cost channel. Talking about these channels, our starting point will be the actual change in short-term interest rates which consists of two standing facility interest rates – the deposit facility rate and the marginal lending facility rate (European Central Bank 2016). When, we describe the variables influenced by these short-term rates, we also take into account that these effects might be strengthened or weakened by expectations about future central bank interest rates.

The consumption channel (Mishkin 1995) focusses on the decision of households to spend or save. Within this consumption channel several distinct channels can be identified. For example, Ludvigson et al (2002) identify a wealth channel which describes how monetary policy effects asset prices which in turn influences household wealth and spending. Higher (expected) interest rates make consumption less interesting as opposed to saving – the propensity to consume. This in turn decreases inflationary pressures by reducing economic slack and increasing wage pressures. On the other hand, the increased deposit rate causes a direct increase in income and wealth through increased interest payments which can in turn increase consumption and inflation. Figure 1 summarizes these possible transmission mechanisms.

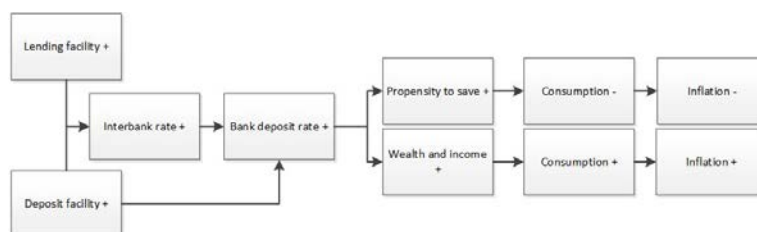


Fig. 1. Consumption channel

Several distinct channels focus on the effects of monetary policy on bank funding costs. The investment channel (Mishkin 1995) assumes banks increase their loan rates as a result of increased funding costs. It then stresses the direct effects of these increased loan rates on the decision of firms to either invest or save. Thus, a central bank rate rise increases interest rates on loans and discourages investment which slows down the economy and reduces inflationary pressures directly. Mishkin (1995) also identifies the asset price channel in which an increase in bank funding costs and subsequently loan rates causes a decrease in firms' net-worth which in turn can reduce investment demand by firms through a wealth effect (Ando & Modigliani 1963). On the supply side, Bernanke and Gertler (1989) point out that the reduced net-worth of firms also means less available collateral. Thus even if firms wanted to invest this would make it more difficult for them to do so. Because of information asymmetries, banks often only grant credit to clients with sufficient collateral. This is called the balance sheet channel. Finally, the lending or credit channel describes the influence of short-term interest rates on the bank lending quantity. As banks funding costs increase they reduce the quantity of credit (Bernanke and Blinder 1992). This reduction in credit then effects investment

and inflation. Figure 2 summarizes the transmission mechanisms associated with these four investment focused channels which all operate through bank funding costs.

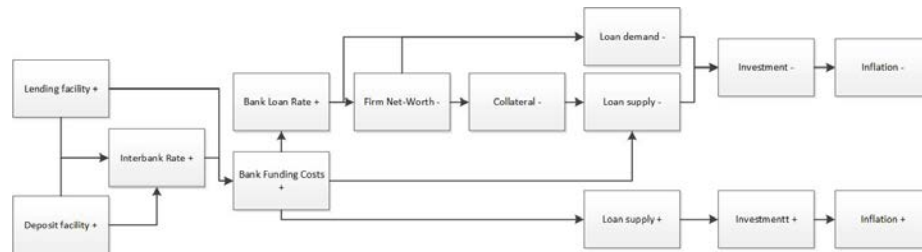


Fig. 2. Investment, asset price, balance sheet and lending channels.

Most of the previous channels target economic demand and through that inflation. Additionally, Barth and Ramey (2002) propose the existence of a cost channel in which changes in interest rates transmit to changes in funding costs for firms and then directly into higher prices. Figure 3 shows how the cost channel works. Authors such as Tillmann (2008) and Gaiotti and Secchi (2006) find empirical evidence for the existence of a cost channel.

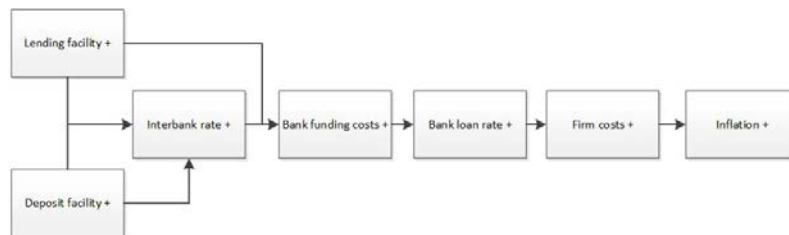


Fig. 3. Cost channel of inflation

So in a closed economy, there are six different channels through which monetary policy influences inflation. These effects are not homogeneous and might even contradict each other. An interest rate increase might increase and decrease inflation at the same time through different channels. Furthermore, additional interaction effects might also play a significant role. For example, increased consumption through the consumption channel might amplify the balance sheet channel as it also causes an increase in firm's net-worth.

There is a large literature on modelling the monetary transmission mechanism. However, due to the top-down nature (de Grauwe 2010) of these models it is difficult to capture the microeconomic dynamics as well as interaction effects that are involved in the monetary transmission mechanism.

Answering the call to develop tools from complexity theory as a complement to existing economic modeling approaches (Battiston et al 2016.), we present a detailed micro-level analysis of the monetary policy transmission mechanism in a macro-economic agent-based model.

2 Model description

The model was implemented using the Java Agent Based Modelling (JMAB) software and is based on the JMAB benchmark model presented by Caiani et al. (2016). To model the monetary policy transmission mechanism in sufficient detail, we add an interbank market to this benchmark model.

In this section, we highlight the essential structure of the model and its crucial decision rules in a format which is inspired by the ‘ODD+D’ protocol devised by Grim et al. (2013). For a full description of the model we refer to Caiani et al (2016).

There are five types of agents: households, two types of firms, banks, a central bank, and a government. All agents have balance sheets and in the model we can construct a stock-matrix connecting agent’s balance sheets. Figure 4 summarizes a typical stock matrix as a simple balance sheet for every agent.

Households (hh)		Capital firms	
Assets: Deposits (D) Firm shares (E^{cf}) Bank shares (E^{bhk})	Liabilities: Net-worth (E)	Assets: Deposits (D) Machines (M)	Liabilities: Loans (L) Shares (E)
Consumption firms		Banks	
Assets: Deposits (D) Machines (M) Inventories (N)	Liabilities: Loans (L) Shares (E)	Assets: Reserves (R) Interbank credit (C) Loans (L) Bonds (B)	Liabilities: Deposits (D) Advances (A) Interbank credit (C) Shares (E)
Central Bank		Government	
Assets: Advances (A) Bonds (B)	Liabilities: Reserves (R) Shares (E)	Assets: Reserves (R) Deposits (D) CB shares (E^{cb})	Liabilities: Bonds (B) Net-worth (E)

Fig. 4. Agent’s representative stock matrices (balance sheets)

Besides the stock-matrix, each agent class is characterized by a number of unique state variables such as lists of employees and clients, but also behavioral parameters, current prices, desires and expectations.

The model is closed (there is no foreign sector) and all model dynamics are endogenous. Spatial dynamics are not explicitly modelled. The model simulates an economy over 400 periods, which can be thought of as quarters of a year.

2.1 Process overview and scheduling

In each simulation period there is a sequence of events:

1. Firms' production planning;
2. Firms' labor demand;
3. Agents determine prices, interest, regulation, and wages;
4. Firms investment in capital accumulation;
5. Capital good market - first interactions;
6. Firms' credit demand;
7. Credit market interactions;
8. Labor market interactions;
9. Firms production;
10. Capital goods market - second interaction;
11. Consumption goods market interaction;
12. Interest, bonds and loans repayment;
13. Wages and unemployment benefit payments;
14. Tax payments;
15. Bank defaults;
16. Dividend payments;
17. Deposit market interactions;
18. Bond purchases;
19. Interbank market interactions;
20. Illiquid bank use central bank lending facilities.

Unless stated otherwise, agents are processed in a random order. Changes in state variables as a result of interactions are immediately updated.

2.2 Interactions

The interactions described in the previous sections take place either as a consequence of a multi-layered network that consists of contractual relationships, or in one of the six markets. Regarding the contractual relationships, we make a distinction between equity, credit, deposit and other contractual claims. Furthermore, there are six different markets in the model: consumption goods, capital goods, labor, credit, bank deposits, and inter-bank reserves. All markets operate under imperfect information and use a matching algorithm, demand agents are allowed to observe a subset of supply agents and then pick the cheapest supplier. The markets are heterogeneous in that the subset of suppliers differ in size and preferred suppliers might play a role in certain markets. For a detailed description of markets, we refer to Caiani et al (2016).

2.3 Heterogeneity and stochasticity

All agent classes are homogeneous in their decision making rules, expectation formations and state variables. The values of their state variables and therefore their decisions will become fully heterogeneous during the simulations.

Stochasticity is introduced in several places in the model. When the model is initialized, the distribution of state variables and debt relationships is random. Then in every simulation period, additional stochasticity is introduced to the model. Each time the market matching protocol operates, this happens via randomized interaction sequences. Furthermore, stochasticity is introduced in several agent decision rules.

2.4 Individual sensing and prediction

All agents are boundedly rational (Sargent 1993) in the sense that they are aware of their own attributes and balance sheet items, but not of most of the system's dynamics and attributes. Agents have access to some system variables, state variables of other agents, and can calculate some variables derived from these or their own state variables. These derived variables are (operating) cash flows, net-present values, and capital- and liquidity ratios. In addition, agents may sense other agents' variables or macroeconomic variables. All agent types form expectations about their state variables. Agent expectations are formed using a simple adaptive strategy in which the previous value of the expectation is adjusted by a weight of its deviation of the actual previous value.

2.5 Individual decision making

In the following section, we describe only those decision rules which are crucial for the monetary transmission mechanism. For an overview of all decision rules, we refer to Caiani et al. (2016). In the notation of variables, subscripts indicate the agent type and time step of the variable. Superscripts indicate expectations (e), demand (d), supply (s) or items in the stock matrix (see figure 4).

The central bank sets the deposit facility rate at a constant rate with the lending facility rate as at a fixed mark-up.

$$i_{cb,t}^A = i_{cb,t}^R + \psi_R \quad (1)$$

Banks are profit maximizing entities that extend three types of credit, which they mainly finance using deposit, interbank loans and otherwise central bank advances. Finally, banks facilitate other agent's transactions.

Every period, they pay their previously committed interest rate, $i_{bnk,t-1}^D$, over their deposit liabilities, $D_{n,t}$, to their depositors,

$$int_{bnk,t}^D = \sum_{n \in D} i_{bnk,t-1}^D D_{n,t} \text{ with } n = \{hh, cf, kf\}. \quad (2)$$

After that, they determine the a generic, internal, interest rate on loans, i_{bt}^L that either adds or subtracts the stochastic variable FN to the average interest rate in the previous period, \bar{i}_{bt-1}^L plus expected changes in funding costs $\Delta fuc_{bnk,t}^e$. This depends on whether or not they meet the target capital ratio,

$$i_{bnk,t}^L = \begin{cases} (\bar{i}_{bnk,t-1}^L + \Delta fuc_{bnk,t}^e)(1 + FN) & \text{if } CR_{bnk,t} < CR_{bnk,t}^T \\ (\bar{i}_{bnk,t-1}^L + \Delta fuc_{bnk,t}^e)(1 - FN) & \text{otherwise.} \end{cases} \quad (3)$$

In principle, the total supply of credit that a bank is willing to offer is infinite. This is possible because banks extend loans by expanding their balance sheets on both sides -by increasing customer's loans and deposits at the same time. That is not to say that banks extend loans recklessly. Instead, banks honor a request for credit by a potential borrower if they perceive the net-present value of this project to be positive. To make this calculation, they use the probability of default, the value of collateral and the interest payments on the loan. The banks makes a net present value calculation for the maturity of the loan, which is twenty periods. In this calculation, banks find the probability that a potential lender defaults, pr_x^D , using a logistics function based on the percentage difference between borrowers operating cash flows and the first trench of payment, $ds^{L^d} = (i_{bt}^l + \frac{1}{n})L^d$,

$$pr_x^D = \frac{1}{1 + \exp\left(\frac{OCF_{xt} - r_x ds^{L^d}}{ds^{L^d}}\right)} \quad (4)$$

Banks will try to attract deposits by setting the interest rates on their deposits, i_{bt}^d . Banks try to attract deposits based on the reserve requirements, $LR_{bnk,t} = \frac{R_{bnk,t}}{D_{bnk,t}}$. If their reserves are below target, they will try to attract additional reserves by decreasing their interest rate by the stochastic term FN and if they are above the required level, they increase their interest rate by the same term,

$$i_{bnk,t}^D = \begin{cases} i_{bnk,t-1}^{-d}(1 - FN) & \text{if } LR_{bnk,t} \geq LR_t \\ i_{bnk,t-1}^{-d}(1 + FN) & \text{otherwise.} \end{cases} \quad (5)$$

Concerning the price of interbank credit, banks try to attract funding by adjust their mark-up over the market price based on their liquidity ratio. The central bank deposit rate provides a floor and its lending rate a ceiling, as for banks it would be saver to lend to or from the central bank. Thus:

$$i_{bnk,t}^{e,ib} = \begin{cases} \bar{i}_{bnk,t}^{ib} + (1 + FN) & \text{if } LR_{bnk,t} < LR_t^T \\ \bar{i}_{bnk,t}^{ib} + (1 - FN) & \text{otherwise.} \end{cases}$$

$$i_{bnk,t}^{ib} = \begin{cases} i_{cb,t}^A & \text{if } i_{bnk,t}^{e,ib} > i_{cb,t}^A \\ i_{cb,t}^R & \text{if } i_{bnk,t}^{e,ib} < i_{cb,t}^R \\ i_{bnk,t}^{e,ib} & \text{otherwise} \end{cases} \quad (6)$$

To determine how much credit the bank supplies or demands on the interbank market, it calculates the amount of reserves they are legally required to hold and their actual liquidity ratio:

$$I_{bt}^S = (LR_{bt} - LR_{bt}^d) * D_{bt}. \quad (6)$$

If they cannot get any reserves on the interbank market they approach the central bank from which they borrow the remainder.

Finally, banks pay dividends. They determine the amount of dividends they pay out based on their desired capital ratio,

$$div_{bnk,t} = \begin{cases} (1 + \alpha^d)(\rho_b * prof) & \text{if } CR_{bt} > CR_t^T \\ \rho_b * prof, & \text{otherwise.} \end{cases} \quad (7)$$

Households make decisions concerning their wage demands and consumption. They update their demanded wage, $w_{hh,t}^d$, adaptively with a stochastic amount, FN . This amount is subtracted from their asked wage if they have been unemployed for over a year, $\sum_{n=1}^4 u_{t-n} > \varphi_u$. However if this is not the case and the aggregate level of unemployment, U_t , is below a certain level, φ_U , households increase their asked wage by this stochastic amount,

$$w_{hh,t}^d = \begin{cases} w_{hh,t-1}^d(1 - FN) & \text{if } \sum_{n=1}^4 u_{hh,t-n} > \varphi_u \\ w_{hh,t-1}^d(1 + FN) & \text{if } \sum_{n=1}^4 u_{hh,t-n} \leq \varphi_u \text{ and } U_t \leq \varphi_U, \end{cases} \quad (8)$$

As for consumption, $c_{hh,t}^D$, households consume a fixed ratio, α^y , of their net income, $y_{hh,t}$, and a fixed ratio, α^q , of their net wealth, q_{ht} , both adjusted for expected inflation, I_{ht}^e .

$$c_{hh,t}^D = \alpha^y \frac{y_{hh,t}}{I_{hh,t}^e} + \alpha^q \frac{q_{ht}}{I_{hh,t}^e}. \quad (9)$$

Both consumption (c) and capital goods (k) make production and pricing decisions trying to maximize output. Firms determine their desired output, o_{xt}^d . This is determined by the amount, v^N , of inventories the firm wants to hold after its expected sales, s_{xt}^e , taking into account its current stock of inventory, inv_{xt-1} .

$$o_{x,t}^d = s_{x,t}^e(1 + v^N) - inv_{x,t-1} \text{ with } x = \{c, k\} \quad (10)$$

Then, to determine the price for its inventories (N in the case of consumption firms and M in the case of capital firms), $p_{x,t}^N$, firms use a mark-up, $\Psi_{x,t}^{ulc}$, over their expected cost price ($ulc_{x,t}^e$) times the amount of labor it wishes to use, l_{xt}^d , both of which were formed using the general adaptive expectations rule,

$$p_{x,t}^N = (1 + \Psi_{x,t}^{ulc}) \frac{ulc_{x,t}^e l_{xt}^d}{o_{xt}^d}. \quad (11)$$

Firms revise their mark-up adaptively depending on their current inventory, inv_{xt-1} , compared to their desired inventory, $inv_{x,t}^d$. They raise their mark-up by a stochastic amount, FN , according to a Folded Normal distribution,

$$\Psi_{x,t}^{ulc} = \begin{cases} \Psi_{x,t-1}^{ulc}(1 + FN) & \text{if } \frac{inv_{xt-1}}{inv_{x,t}^d} \leq v^N \\ \Psi_{x,t-1}^{ulc}(1 - FN) & \text{if } \frac{inv_{xt-1}}{inv_{x,t}^d} > v^N. \end{cases} \quad (12)$$

Consumption firms target a desired production capacity rate of growth, g_{ct}^D , to produce

their desired production by the sum of the past-period value of the firm's stock of capital, with age_{kt-1} indicating the age in period $t-1$ of the batch of capital goods k belonging to the collection K_{ct} of firm c .

$$r_{ct} = \frac{OCF_{ct}}{\sum_{k \in K_{ct-1}} (k^k p^k) (1 - \frac{age_{kt-1}}{k})} \quad (13)$$

The desired production capacity rate of growth, g_{ct}^D , is then determined by the desired rate of capacity utilization, u_{ct}^D , and the previous period rate of profit, r_{ct-1} .

$$g_{ct}^d = \gamma_1 \frac{r_{ct-1} - \bar{r}}{\bar{r}} + \gamma_2 \frac{u_{ct}^D - \bar{u}}{\bar{u}}. \quad (14)$$

Firms derive their demand for capital, i_{ct}^D , as the number of capital units required to replace obsolete capital. Now that firms know their required investments, firms calculate their need for credit by, L_{ct}^D . They calculate their expected expenditures as nominal desired investment, I_{ct}^D , plus the dividends it expects to distribute, Div_{ct}^e , and the share of expected wage disbursements, σ , times wages, $W_{ct}^e N_{ct}^D$. Then, adhering to the pecking order theory (Myers & Majluf 1984), they try to fund these using their operating cash flows first. The remainder is asked on the credit markets,

$$L_{ct}^D = I_{ct}^D + Div_{ct}^e + \sigma W_{ct}^e N_{ct}^D - OCF_{ct}^e. \quad (15)$$

To be able to produce, firms hire workers. Capital goods firms want to hire an amount of workers, N_{kt}^D , based on their desired output, o_{kt}^D . It computes the total goods that can be made with its capital. Then if this is less than what it needs, it fires the last worker it had hired. If it is more it hires some additional workers and labor productivity, μ_N ,

$$N_{kt}^D = \frac{o_{kt}^d}{\mu_N}. \quad (16)$$

Consumption firms additionally use capital for their desired capacity utilization, u_{ct}^D . They try to make optimal use of both labor and capital.

$$u_{ct}^D = \text{Min}(1, \frac{y_{kt}^D}{\mu_N}). \quad (17)$$

Multiplying this by the ratio of real stock of capital, k_{ct} , to the consumption firms labor demand is:

$$N_{ct}^D = u_{ct}^D \frac{k_{ct}}{l_k}. \quad (18)$$

Labor demand then determines whether or not the firm hires or fires its current employees and enters the labor market.

2.6 Initialization

The model was initialized with 8000 households, 100 consumption firms, 20 capital firms, 10 banks, a single central bank, and a single government. The model is a theoretical model that is not based on any particular country. To make sure that the model starts from condition where all debt relationships are in balance (assets are equal to liabilities) for all agents, we initialize the model using the same six step strategy for initializing the model as Caiani et al. (2016). This means, we use the aggregate variables an aggregate version of the model in steady state as the initial values for our model these values are then randomly but equally distributed among agents while at the same time correctly distributing initial creditor debtor relationships.

3 Results

Using Monte-Carlo simulation and analysis of system dynamics, we study the direct impact of a monetary policy interest rate rise by the central bank. We start by studying the first step in the monetary transmission mechanism. The impact of a monetary policy shock on the interbank market. Since the interbank market exists between the spread of the central bank, it is immediately and clearly effected by the interest rate rise, as can be seen in figure 5.

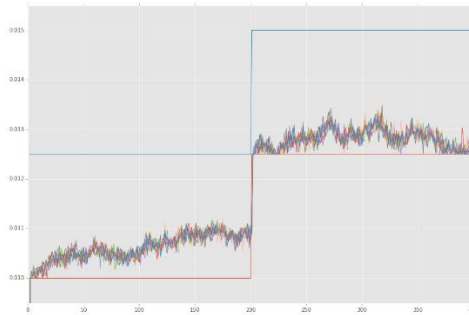


Fig. 5. Central bank deposit and lending facility rates rise in period 200. As a result, the inter-bank market (individual bank ask prices) moves upwards.

However, from that point on the effects of the funding cost channels –investment, balance-sheet, bank-lending and cost channels are negligible. The reason is that banks are largely deposit funded. This means a rise in both the central bank lending facility and interbank funding costs hardly effect average bank funding costs. These are then not passed on to firms and households. Finally, the deposit rate dependent consumption channel is weak as the market forces in the deposit market are stronger then the central bank influence.

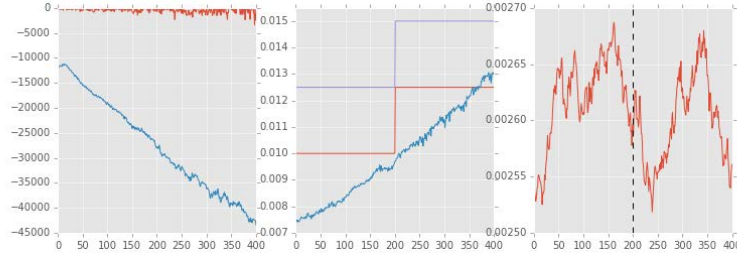


Fig. 6. Left: Average bank liability structure over time. Blue = deposits, red = summed inter-bank and central bank lending facilities. Middle: Central bank rate increase and average loan interest rate. Right: deposit rate with rate hike at 200.

With most of the channels muted monetary policy actions by the central bank do not significantly influence output and inflation in the model. Figure 7 shows how relatively unaffected GDP and inflation are with the only difference occurring as a result of sensitivity to slightly different starting conditions.

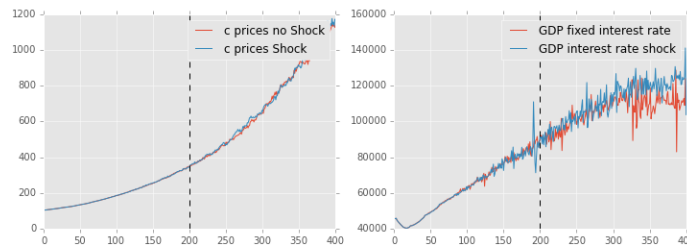


Fig. 7. The effect of monetary policy on consumer prices (left) and GDP (right).

4 Discussion

We show that the effects of monetary policy on output and inflation are not as clear-cut as traditional theory would predict. In our simulations the financial sector largely operating outside the influence of the central bank and therefore does not pass on policy changes to the rest of the economy. This means, central bankers should take into account the structure financial sector when estimating the effects of their monetary policy decisions. Furthermore, even if banks change their behavior as a consequence of monetary policy, the outcomes of monetary policy are hard to predict. Different transmission mechanisms might be dominant depending on the structure of the real sector.

Our macroeconomic agent-based model might help understand the conditions which influence different monetary transmission mechanisms.

To understand these transmission mechanisms, we would like to construct additional scenarios and experiments. First, we plan to reduce the amount of reserves in the model to make banks more dependent on central bank and interbank lending. Then, we will explore the impacts of bigger monetary policy shocks, continuous rises as well as negative interest rates.

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